STRUCTURAL CONTROLS ON REGIONAL AND RESERVOIR SCALE HYDROTHERMAL FLOW

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SUMMARY – The central Taupo Volcanic Zone contains over twenty high-temperature (>250°C) geothermal systems. Upwelling plumes are distributed semi-regularly across an area of ~2000km^2, much as one would expect in the case of porous flow above a regional-scale hotplate positioned at depths of 6-8km. However, the central TVZ is not uniformly porous, comprising a layered Quaternary cover sequence of varying material properties that overlies a more competent basement of equivocal rock type. Furthermore, the region is dissected by numerous faults, and in places is punctured by dikes. Structures have a strongly preferred NE-SW orientation, and are offset every ~20km by transverse accommodation zones, a consequence of the rifting process. We argue that the stratigraphy of the central TVZ interplays with rift architecture to influence the style of fault-fluid interactions at the regional and reservoir scale. Upwelling plumes are localised where rift architecture enhances vertical permeability deep within the convective regime. Focused flow through faults and fractures well-oriented for reactivation (i.e., steeply dipping NE- and NW-trending structures) likely predominates within basement rocks. In contrast, porous flow through fault-bounded compartments characterises the flow regime in the reservoir. Connected gaping fractures over vertical intervals exceeding 500m are not favoured at this structural level. In fact, the highest rates of focused flow are observed to discharge from hydrothermal eruption vents.

1. INTRODUCTION

Understanding whether and how structures influence hydrothermal flow is of importance to geothermal and mineral exploration. Theoretical, observational and experimental work on fault-fluid interactions (e.g. Caine *et al*., 1996; Evans *et al*., 1997; Sibson, 2000) together with a greater understanding of the rifting process (e.g. *Ebinger et al.*, 1999) set the scene for considering the hydrology of the TVZ in new light (eg., Rowland and Sibson, 2004). This paper utilises these advances to address the issue of structural control on regional and reservoir scale hydrothermal flow.

2. THE CENTRAL TVZ

In its modern (<340ka) form, the TVZ comprises a magmatically and structurally segmented rift system (Fig. 1) (Wilson *et al.*, 1995; Rowland and Sibson, 2001). Volcanism in the northern and southern segments is dominated by cone-building eruptions of andesite, whereas the central segment is dominated by explosive eruptions of rhyolite. These have in-filled calderas and rift basins with >15,000km^3 of low-cohesion air-fall deposits, poorly-to-moderately welded ignimbrites and lavas (Wilson *et al.*, 1995). Basalts occur rarely at the surface (<1% total volume of exposed volcanic rocks), but are presumably significant at mid-crustal depths given the enormous natural heat output through this region (c. 4200 ± 500MW$_{th}$) (Bibby *et al.*, 1995). The stratigraphy thus comprises a >2km thick Quaternary cover sequence of pyroclastic and volcanic rocks intercalated with lake sediments, which overlies a more competent basement of equivocal rock type, most likely greywacke and cooled intrusions. NW-SE directed extension of ~10mm/yr across the central TVZ is mostly accommodated by normal faulting, fracturing, and dike intrusion (Rowland and Sibson, 2001). These brittle structures exhibit a preferred NE-SW orientation within discrete rift segments, which are partitioned on a length scale of ~20km. Transverse accommodation zones transfer extensional strain between adjacent segments. Seismicity is dominated by widespread seismic swarm activity with occasional moderate-to-large earthquakes (M_L<6.5), defining a seismogenic zone 6-8km deep (Bibby *et al.*, 1995). Focal mechanisms and an associated stress inversion indicate a predominance of normal faulting with a subhorizontal least principal stress direction trending 148° (Hurst *et al*., 2002), near-perpendicular to the trend of recently active faults (Rowland and Sibson, 2001).

3. HYDROTHERMAL FLOW

3.1 Regional-scale flow

Over 20 geothermal systems, many of which are relatively long-lived (> 100ka), are distributed semi-regularly across the central TVZ. Relationships between geothermal systems, which are delimited by areas of low resistivity, Quaternary basins and rift structure are shown in

Figure 1 – The central TVZ; A) DEM showing major basins and plateaus. MP: Mamaku Plateau, PB: Paeroa Fault Block, T-R: Taupo-Reporoa Basin, KP: Kaingaroa Plateau, WG: Whakatane Graben; B) Relationship between volcanic domes, calderas, geothermal systems (delimited using the 30Wm resistivity contour) and rift architecture, shown by rift axes (black bar and white arrows). Inset shows tectonic setting; C) Electrical resistivity of the central TVZ (nominal array spacing = 500 m) (after Bibby 1995), annotated with the two active calderas, Taupo and Okataina. NIDFB: North Island Fault Belt.

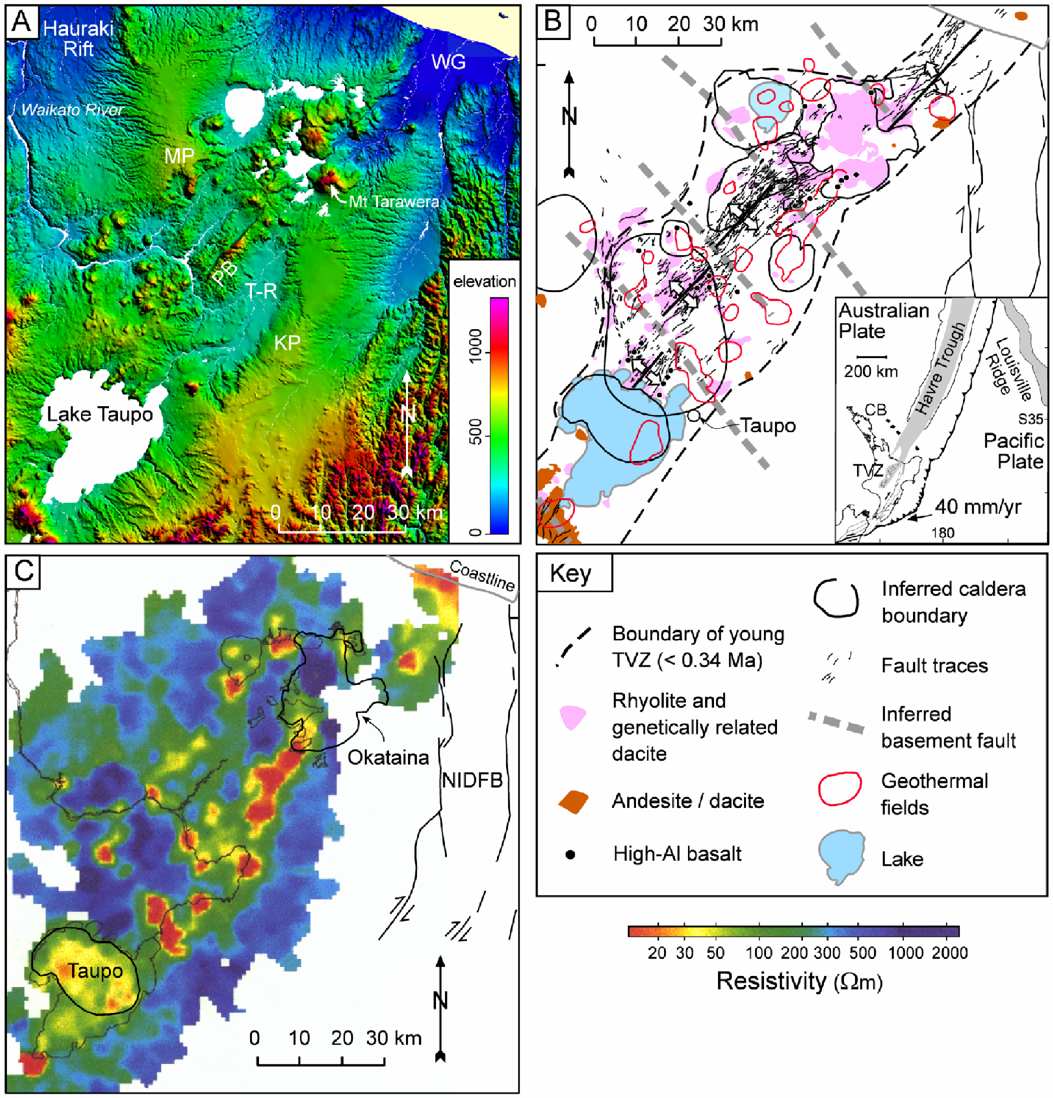

Fig. 1. Two elongate zones of low resistivity extend from Taupo Volcano to the Okataina Volcanic Centre parallel to the tectonic grain. These conductive zones bound the highly dissected Taupo Fault Belt. Several zones of low resistivity trend perpendicular to the rift axes and coincide spatially with accommodation zones and inferred NW-trending basement structures (Wan and Hedenquist, 1981). Together, the geothermal systems discharge on the order of $10^8 m^3$ of 250°C fluid annually (Sibson and Rowland, 2003). This largely meteoric flux accounts for approximately 70% of the total heat transfer through the region, with plumes transferring heat over the full depth of the seismogenic zone (McNabb, 1975; Hochstein, 1995). Geothermal output is distributed bimodally with higher flux on the eastern margin (Bibby *et al*., 1995). This distribution may reflect a regional localisation of magmatic input to the lower crust beneath the Taupo-Reporoa Basin, as suggested by recent interpretations of MT data (Heise *et al*., 2007). Of relevance is an apparent negative correlation between belts of high heat output and surface faulting. Seismicity shows a similar negative correlation, with relatively few events in high heat flux regions (Bibby *et al*., 1995), perhaps because magmatic intrusion reduces shear stresses below that required for fault rupture.

Nonetheless, when considered in the context of rift architecture, the regional distribution of the geothermal systems bears a demonstrable relationship to structure. Sixty percent of geothermal systems occur within accommodation zones; and some exhibit NW-SE trending features; e.g. shallow and deep isotherms, gravity contours, geochemical anomalies, and/or shallow hydrology. Overall, 80% of geothermal systems, channelling ~90% of the total natural heat output, correlate spatially with rift architecture in the form of splays or linkage structures at the lateral tips of large normal faults, known buried faults, and accommodation zones and inferred basement structures between rift segments (Rowland and Sibson, 2004). Such regional-scale correlation of geothermal systems with rift architecture suggests structural control at depth within the convective regime (Rowland and Sibson, 2004).

3.2 Reservoir-scale flow

Exploitable geothermal reservoirs typically lie between 0.5 and 2.5 km depth and at temperatures greater than 240°C, coextensive with the deepest host environment for epithermal mineralization. Although rift architecture may play a role in the regional localisation of geothermal systems, there are few clear-cut examples of fault localisation at the reservoir-scale. The physical character of the reservoir in five selected geothermal systems is summarised in Table 1. Of these systems, Waiotapu produces the most natural heat (610MW_{th}), and Waimangu the greatest rate of focussed discharge (>100 l/s). The stratigraphy in each of the selected systems is broadly similar. Weak, high porosity, pyroclastic rocks and their reworked equivalents predominate, though more competent units are intercalated (eg. andesite, rhyolite, dacite), or occur as basement (greywacke metasediments). Generally, the vertical thickness of the more competent lithologies is less than 100m, though buried domes and flows are known to exceed several hundred meters in vertical extent on the periphery of Waiotapu and at depths greater than a few hundred meters at Rotokawa and Broadlands-Ohaaki. Lake sediments (generically named Huka Group) function as a barrier to vertical fluid movement within three of the selected systems (Broadlands-Ohaaki, Waiotapu, Rotokawa). Porous flow of ascending hot fluid predominates beneath this low permeability horizon, with lateral movement at the permeability interface and associated cooling on the periphery of the upwelling plume (eg. Simmons and Browne, 2001). Leakage to the surface is enhanced at the unit boundary or where a pathway has been created consequent on drilling (e.g. Broadlands-Ohaaki), tectonic fracturing or hydrothermal eruption (e.g. Waiotapu, Rotokawa).

None of the selected systems show a strong link between fault control and localisation of discharge. Rather, hydrothermal eruption vents are the principal localising structure for discharge. These highly-brecciated vents provide convenient pipes of high-permeability for focused flow, which presumably will endure until mineral deposition and hydrothermal alteration reduces permeability to that of the host rocks. Hydrothermal eruption vents do not exceed depths >500m (eg. Rotokawa), notwithstanding Frying Pan Lake, which is co-located within a pre-existing volcanic vent.

The triggering mechanisms for hydrothermal eruptions are varied and not always related to structural control (e.g. Browne and Lawless, 2001). Nonetheless, the alignment of some hydrothermal vents parallel to the tectonic grain is indicative of deeper-seated structures at Broadlands-Ohaaki, Rotokawa, Waimangu and Waiotapu. Whether the inferred structures play an active or passive role during eruption is unknown, but of critical importance to the development of episodic and localised permeability across the reservoir. The Waiotapu eruptions may have been driven by the gradual accumulation of gas (mainly CO_2) beneath the silica-sealed tips of fractures in the upper part of the geothermal system (e.g. Hedenquist and Henley, 1985). Provided sub-surface boiling occurs at any depth, gas pressure may build up beneath the fracture tip and eventually exceed the overburden plus the tensile strength of the rock. A hydrothermal eruption ensues if the rupture reaches the ground surface. However, such an accumulation of gas generally occurs only down to a few tens of meters and resultant eruptions are small. Alternatively, sudden decreases in reservoir pressure consequent on tectonic faulting or dike intrusion may drive higher-pressure accumulations of gas, triggering large eruptions with no warning (Browne and Lawless, 2001). Dike intrusion may enhance the criticality of the system by priming the reservoir with gas and heat. Nairn *et al.* (2005) argue that the hydrothermal eruptions at Waiotapu were primed by the intrusion of the same basalt dike system that drove the ~AD1315 Kaharoa rhyolite eruptions at nearby Tarawera volcano.

Porous flow clearly predominates at the reservoir-scale, although faults do dissect some systems (e.g. Orakeikorako, Waiotapu) and are in places inferred to control the distribution of hydrothermal eruption vents. Thus, although regional-scale hydrothermal flow appears to be localised by rift architecture, faults and fractures are, perhaps surprisingly, of little obvious influence within the reservoir. The reasons for this apparent dichotomy in structural control are explored below.

Table 1. Attributes of the reservoir in selected geothermal systems of the TVZ

Geothemal system	Discharge rates (highest example)	Discharge location	Character of permeability	Structural context in reservoir
Broadlands-Ohaaki	30 - 90 l/s	Geothermal well	Anisotropic focused high-flux vertical flow over depth intervals > 500m. Natural flow distributed through porous layers.	Unknown
Waiotapu	5 - 10 l/s	Champagne Pool, hydrothermal eruption vent	Anisotropic focused high-flux vertical flow in vents over depth intervals > 350m. Elsewhere distributed through porous units.	Caldera boundary faults dissect southern section of field, rift parallel normal faults bound NE edge of field and likely dissect
Rotokawa	< 10 l/s	Hydrothermal eruption vent	Anisotropic focused vertical flow in vents to depths > 400m? Elsewhere distributed through porous units.	Hydrothermal vents aligned on NE-SW trend, parallel to rift fabric
Waimangu	100 – 120 l/s	Hydrothermal eruption vent, superimposed on a volcanic vent	Anisotropic focused high-flux vertical flow to depths > 100m?	Basalt fissure at caldera-rift fabric intersection
Orakei Korako	< 15 l/s (combined spring discharge over the Umukuri sinter sheet)	Distributed within fault blocks	Distributed through porous compartments	Rift parallel fault blocks bounded by 2nd order normal faults, which act as flow barriers to depths > 50m

4. FAULT-FLUID INTERACTIONS

Brittle structures influence fluid flow in two end-member ways, whether providing gutters for channel flow or acting as low-permeability baffles that compartmentalise the flow regime (Rowland and Sibson, 2004). Their hydrological influence varies in space and time according to the mode of brittle failure, the stratigraphy, the seismic (and/or magmatic) cycle, and the rate of sealing through hydrothermal cementation.

The expected orientations of the three brittle modes of failure (faults, extension fractures, and extensional-shears) are steep (dip > c. 60°) for an 'Andersonian' extensional stress regime, in which the greatest principal stress σ_1, equals the overburden σ_V, and $\sigma_1 \geq \sigma_2 \geq \sigma_3$. Permeability in the σ_1/σ_2 plane is increased by both macroscopic and microscopic extension fracturing, providing the cracks remain open (Sibson, 2000). This effect is enhanced as the pore fluid pressure P_f, approaches σ_3, with open gapes when the tensile overpressure condition, $P_f > \sigma_3$, is met. Of the three possible failure modes, extension fractures and extensional shears may be considered suitable conduits for high flux flow as may mixed-mode meshes, comprising en échelon faults linked by such gaping fractures. Conditions governing the development of each mode of brittle failure are discussed more fully elsewhere (e.g. Sibson, 2000). Gaping fractures will only develop to depths >1000m if the minimum tensile strength of the host-rock is >5MPa. In the TVZ, moderately-welded ignimbrites and rhyolite domes may range in strength up to T=10MPa with intact andesite and greywacke perhaps reaching T=15MPa. Such rocks rarely exceed 100m in vertical extent within the reservoir, which for the most part comprises high-porosity, weak (T<<5MPa) lithologies. A 100-200m-thick layer of cohesionless tuffs and breccias commonly occupies the shallow stratigraphy in the geothermal areas. Excluding this cohesionless layer, most rocks in the TVZ, though weak, could sustain extension fractures and extensional shears to depths <500m, perhaps a little deeper for pore fluid pressures up to 20% above hydrostatic. Nevertheless, it is doubtful that the contrast between intrinsic and secondary permeability would be sufficient to focus flow within gaping fracture networks except within the clay-rich lake sediments. Thus the stratigraphy within the selected TVZ geothermal systems is unfavourable for the development of interconnected open fractures across a vertical extent >>500m, at least in the early stages of hydrothermal activity. Over time, silicification may impart tensile strength to the host rocks (e.g. Ohakuri), permitting development and linkage of gaping fractures across the full depth of the reservoir.

Faults are the most common brittle failure mode at the surface within the central TVZ. Strictly speaking, faults are not gaping structures, though they may be highly permeable during and immediately after seismic events. Whether and over what time scale a normal fault behaves as a conduit is critically affected by: (1) the rate and effectiveness of sealing by hydrothermal cementation (also applicable to other failure modes), (2) the material properties of the host-rock and its permeability structure relative to the fault zone, and (3) the ratio of fault core to damage zone (eg. Caine *et al.*, 1996; Rowland and Sibson, 2004). In low-porosity rocks (e.g. rhyolite domes, andesites, basement greywackes) normal faults are expected to enhance permeability through cataclastic brecciation and through the misfit of opposing walls. Damage zones likewise provide high-permeability conduits. High fault permeability is especially likely post-failure on low-displacement faults cutting competent low-porosity host rocks, with a strong directional permeability parallel to σ_2 resulting from the mutual intersection of faults and fractures. In contrast, within high-porosity sedimentary or volcanic rocks, various combinations of cataclastic grain-size reduction, deformation bands, porosity collapse, development of clay smears along faults, hydrothermal alteration and cementation of fault gouge, and juxtaposition of impermeable against permeable strata, may reduce permeability with respect to the host-rock by up to several orders of magnitude. Since fault core development increases with finite displacement, first order faults (i.e. those that cut the entire seismogenic zone) likely behave as baffles to flow directed across their surfaces, particularly within high-porosity rock units where they form low-permeability septa between porous compartments. Thus, in the central TVZ the stratigraphy at the reservoir-scale favours the development of fault baffles, rather than conduits, and porous flow prevails.

Complexities arise as a consequence of fault growth and interaction (Curewitz and Karson, 1997), or structural overprinting (e.g. Berger *et al.*, 2003), which affect the permeability distribution within fault zones. As a result, fluid flow may be focused through interconnected fault-fracture networks within more extensive fault and/or fracture systems. Fault irregularities in the direction of slip, for example, may lead to the development of highly-permeable dilational zones within extensional step-overs. Such structures are an important mechanism for the localisation of hydrothermal fluid flow in strike-slip settings, and are often inferred to control the distribution of epithermal bonanza-deposits. As discussed below, normal fault systems are also associated with sub-vertical zones of enhanced permeability that could potentially focus flow. In particular, normal fault growth and interaction generates and tectonically-maintains discrete zones of enhanced vertical permeability at linkage zones between fault segments (e.g. Rowland and Sibson, 2004), transfer fault intersections with rift faults, and lateral fault-tips (Curewitz and Karson, 1997).

4.1 Influence of rift architecture

The central TVZ is a segmented rift; continuity of structures in the σ_2 direction is disrupted at accommodation zones. This architecture produces predictable variations in structural anisotropy, with implications for permeability. These variations are considered below in the context of our simplistic stratigraphic model, comprising a layered cover sequence of mostly high-porosity cohesionless material overlying a more competent basement of low intrinsic permeability.

<u>Anisotropy in rift segments</u>

Within the cover sequences, large normal faults (± dikes) form at high angle to any pre-existing layering anisotropy. Providing a permeability contrast exists between faults and host-rock, cross-strike hydraulic connectivity is reduced, regardless of whether individual faults behave as baffles or conduits to flow. Superposition of structural anisotropy upon any inherited layering anisotropy therefore enhances flow along the axis of the rift. Flow is either focussed through conduits at fault intersections, or distributed through porous blocks bounded by faults, the latter of which is more likely at the reservoir-scale in the TVZ. Episodic rupture events may provide transient high-permeability pathways bleeding fluids across horizontal layers, as may small faults and minor structures. Flow parallel to the rift axis is further enhanced by the common intersection of stress-controlled brittle structures in dilational jogs and fault-fracture meshes, particularly in low permeability rocks and mineralised zones. These interactions are especially important in basement rocks, which are characterised by enhanced axial and cross-stratal flow within fault zones well-oriented for reactivation (i.e., steeply dipping NE- and NW-trending structures). If present, dike arrays likewise produce a permeability anisotropy directed along-strike. Sills contribute to the layering anisotropy, and if of sufficient dimension, may drive localised hydrothermal convection cells during cooling (McNabb, 1975).

<u>Anisotropy in accommodation zones</u>

Accommodation zones are regions of local stress heterogeneity, which develop as a result of rift segmentation. Models explaining rift segmentation invoke control by: (1) reactivation of pre-existing structures; or (2) the elastic thickness of the rifting plate (e.g. Ebinger *et al.*, 1999). In either case, accommodation zones are likely characterised by locally enhanced and tectonically maintained vertical permeability as a consequence of: (1) the development of sub-vertical pipe conduits at the intersection of rift faults with reactivated pre-existing basement faults; or (2) increased fracturing associated with a lowered mean stress in the interaction zone between neighbouring rift segments or large normal faults. Where the latter prevails, accommodation zones are kinematically analogous to non-transform offsets between overlapping mid-ocean ridges, which also appear to be favourable sites for hydrothermal venting. Additionally, large normal faults terminate laterally within accommodation zones – their lateral fault-tip damage zones also provide high permeability conduits for vertical upflow.

Regional-scale localisation of geothermal plumes

Segmented rift fabrics may therefore generate bulk permeability anisotropy that is to some extent predictable, with rift segments characterised by enhanced hydraulic communication parallel to the rift axis and accommodation zones characterised by enhanced and tectonically maintained vertical hydraulic communication. Intersections between active rift faults and caldera boundary faults also are expected to generate localised pipes of enhanced vertical permeability (e.g. Nairn *et al.*, 1994). Additionally, localised sill development within rift segments**,** particularly towards the base of the seismogenic zone, may impose a hotplate effect, producing a near-uniform distribution of hydrothermal convective cells over restricted areas (McNabb, 1975). Since permeability maintenance in the presence of hydrothermal mineral deposition depends on recurrent brittle failure, particularly deep in the plume, rift architecture may be an important influence on the localisation of upflow zones. In evolved rift systems with long-lived hydrothermal flow, this model predicts that geothermal systems will be preferentially located in accommodation zones rather than within rift segments, which constitute the major recharge zones. These predictions are consistent with the distribution of geothermal fields in the TVZ, where 60% occur in NW-SE trending belts of low resistivity coincident with accommodation zones, and none occurs within densely faulted portions of rift segments. The rather more regular distribution of geothermal systems within the Taupo-Reporoa Basin may reflect an increased magma input and possible sill development at lower-crustal depths.

5. CONCLUSION

Within the central TVZ, brittle structures interact with hydrothermal fluids in two end-member ways. Fracture flow parallel and perhaps perpendicular to the tectonic grain occurs within the deep convective zone. In contrast, porous flow through fault-bounded compartments prevails within the geothermal reservoir. This change in fault-fluid behaviour arises as a consequence of a two-tiered stratigraphy, comprising relatively tight basement rocks, overlain by highly porous, generally low-cohesion cover sequences. The character of permeability in the basement, together with the pattern of rift architecture, strongly affects the localisation of upwelling plumes. Whereas rift segments favour axial flow and recharge, accommodation zones likely encompass regions of enhanced and tectonically-maintained vertical permeability. This is of particular importance in cases where geothermal systems are relatively long-lived.

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