TECTONIC CONTROLS ON HYDROTHERMAL FLUID FLOW IN A RIFTING AND MIGRATING ARC, TAUPO VOLCANIC ZONE, NEW ZEALAND

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Keywords: *inherited structure, permeability, fault-fluid interactions, geothermal, epithermal.*

ABSTRACT

Tectonic controls on the localization of high-temperature (>250°C) fluid flow are evaluated for geothermal systems of the Taupo Volcanic Zone (TVZ), New Zealand. Most geothermal systems occur within an actively rifting arc (~150 km-long) dominated by silicic volcanism and they occur in association with major faults near caldera bounding structures or within accommodation zones that transfer extension between rift segments. Geothermal systems are hosted in a thick sequence (1 to >3 km) of Quaternary volcanic deposits that rest unconformably on weakly metamorphosed Mesozoic argillite and sandstone (termed greywacke). Permeability controls in selected geothermal systems, including Kawerau, Rotokawa, and Wairakei-Tauhara, can be summarized as follows: 1) intergranular host-rock porosity and permeability; 2) fault-fracture network permeability produced by tectonism, volcanism, and/or dike injection (magmatism); 3) pipe-like vertical conduits produced by volcanic and hydrothermal eruptions; and 4) hydrothermal alteration, mineral deposition and dissolution that may cause heterogeneity in the porosity and permeability of a fluid reservoir. Such controls influence fluid flow within three distinctive depth zones: 1) a feed zone (>2000 m depth), 2) a reservoir zone (<200–2000 m depth), and 3) a discharge zone (0-200 m depth). Our presentation sets reservoir-scale geological models in a regional tectonic context, constrained by field and remote (aerial photography) investigations of fault architecture, and geophysical models of the sub-surface.

1. INTRODUCTION

Understanding controls on the localization of hydrothermal fluid flow at reservoir and regional scale are relevant to well siting and exploration, respectively. Here we present a conceptual model for controls on fluid flow within and below the reservoir, based on a synthesis of resistivity and geological maps, which show the locations and extents of geothermal systems and their relations to tectonic and volcanic structures, plus hydrological information on deep flow rates, stratigraphic and structural controls on permeability, and the locations, discharges, and extents of surface hot spring activity (Rowland and Simmons, 2012). In particular, we consider the geometry of structures from near the brittle-ductile transition to the surface and, for structures active at depth within and below the reservoir, in relation to the regional-scale rift architecture. We show that inherited structures within basement greywacke influence the pattern of active faults within the Taupo Volcanic Zone (TVZ), and likely localize magmatic and hydrothermal fluid flow.

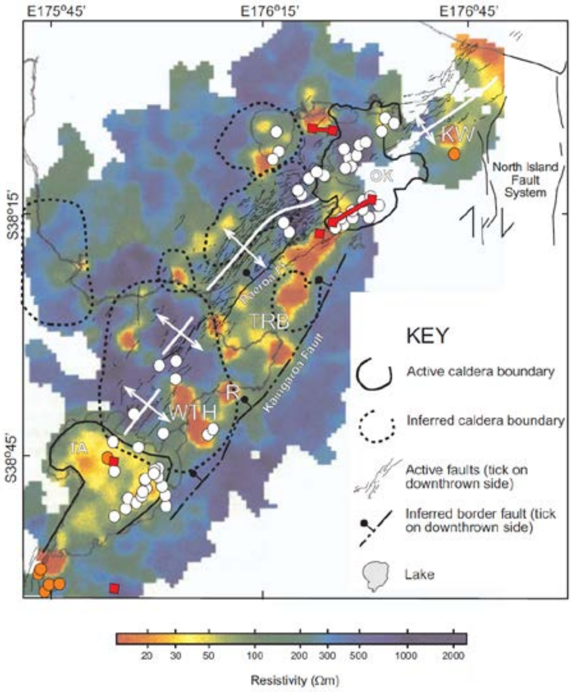

Figure 1: Geothermal fields of the TVZ as delimited by regions of low-resistivity (<30 Ωm), in relation to calderas, rift faults, and <61 ka volcanic vents (white and orange circles: silicic and andesitic, respectively; red squares: basalt, dikes if linked by a red line) (after Rowland et al., 2010). KW: Kawerau; OK: Okataina; R: Rotokawa; TA: Taupo; TRB: Taupo-Reporoa Basin; WTH: Wairakei-Tauhara.

2. VOLCANIC AND TECTONIC SETTING OF GEOTHERMAL ACTIVITY IN THE TAUPO VOLCANIC ZONE

The young (<340 ka) TVZ comprises a magmatically and structurally segmented rift system that initially developed ~2 Ma within Mesozoic metasedimentary basement (Fig. 1: Wilson et al., 1995; Rowland and Sibson, 2001). Cone-building eruptions of andesite dominate to the north and south of a central rhyolitic segment, which is dominated by explosive eruptions that have in-filled calderas and rift basins with more than 15,000 km^3 of air-fall deposits, ignimbrites and lavas (Houghton et al., 1995; Wilson et al., 1995). Rhyolitic dome complexes resulting from effusive volcanism also pepper the central segment. Basalts are rarely observed at the surface (<1% total volume of exposed volcanic rocks), but must be significant

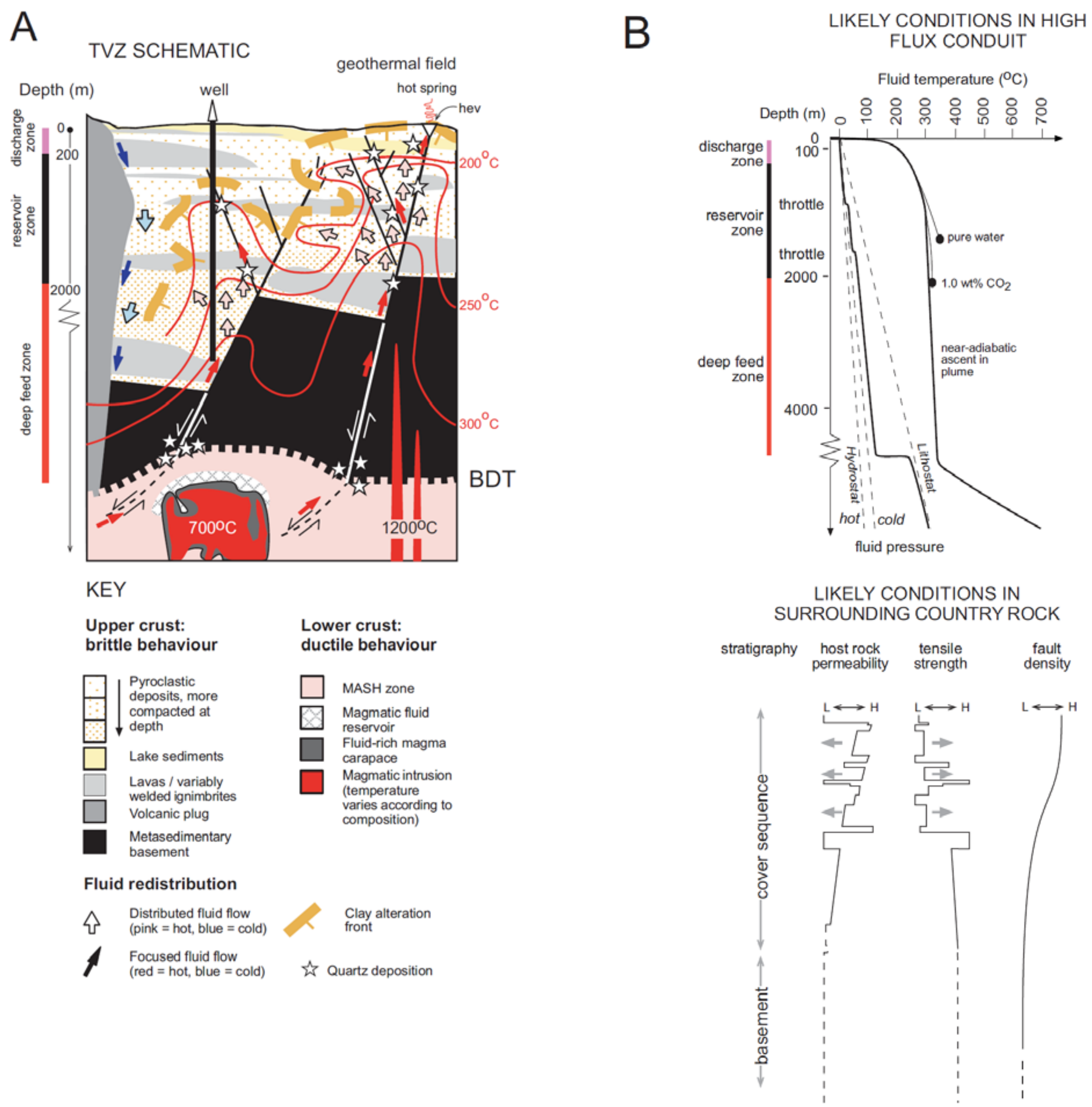

Figure 2: a) Schematic section showing likely fluid flow conditions within a geothermal system, which transects a relatively impermeable basement and an overlying cover sequence, which comprises weak and porous lithologies intercalated with and punctured in places by more competent and less permeable layers (from Rowland and Simmons, 2012). BDT: brittle-ductile transition; hev: hydrothermal eruption vent. Color coded depth intervals represent the discharge zone, reservoir zone, and deep feed zone discussed in the text. b) Expected temperature and pressure conditions in producing geothermal well as located in (a) and variations in natural conditions with depth for a location nearby. The position and gradient of the transition between hydrostatic and lithostatic pressure is uncertain but is probably located between 5 and 8 km depth. L: low, H: high, grey arrows indicate the effects of mineral deposition (ground preparation) on the natural conditions.

in the magmatic system given the enormous natural heat flow through the central TVZ (Bibby et al., 1995; Wilson et al., 1995). About 10 mm/yr NW-SE extension across central TVZ (Darby and Meertens, 1995; Wallace et al., 2004) is accommodated by ~20km-long arrays of subparallel normal faults, vertical extension fractures and dike intrusion (Rowland and Sibson, 2001; Seebeck and Nicol, 2009; Rowland et al., 2010). Seismicity is dominated by widespread swarm activity with occasional moderate-to-large earthquakes (M_L< 6.5) (Bryan et al., 1999), defining a seismogenic zone 6 to 8 km deep, which is presumably commensurate with the depth of convecting hydrothermal fluids (Bibby et al., 1995).

Geothermal systems mostly are located within the central TVZ (Fig. 1). Images of electrical conductivity at shallow depth (<500 m) delimit their position and footprint (Stagpoole and Bibby, 1998). Figure 1 illustrates the spatial relationships between the distribution of geothermal systems, Quaternary basins, and rift structure. Two elongate zones of low resistivity extend from Taupo caldera to Okataina volcanic centre parallel to the tectonic grain. These bound a densely faulted region on the west side of central TVZ, which is notably devoid of present day geothermal activity, though young sinters attest to activity in the recent past (Drake et al., this volume). The largest TVZ geothermal systems (Mokai, Rotorua, Waiotapu, Waimangu, Te Kopia, Orakeikorako, Wairakei-Tauhara) occur near or on caldera bounding structures or at the lateral tips of major faults. Several zones of low resistivity trend perpendicular to the rift axes, coinciding spatially with transfer zones between rift segments and inferred NW-striking structures in the underlying greywackes (Wan and Hedenquist, 1981; Rowland and Sibson, 2004).

3. CONCEPTUAL MODEL FOR FLUID FLOW FROM DEEP FEED ZONE TO SURFACE

Rowland and Simmons (2012) described controls on permeability in six geothermal systems (Broadlands-Ohaaki, Waiotapu, Rotokawa, Waimangu, Orakeikorako, Te Kopia) and one epithermal prospect (Ohakuri). They thereby developed a conceptual model for fluid flow across the full depth of a hydrothermal plume, focusing on the interplay between tectonic, magmatic and hydrologic processes over three overlapping but distinct depth intervals (Fig. 2). These are here designated the discharge zone, the reservoir zone, and the deep feed zone, as summarized from Rowland and Simmons (2012) below.

3.1 Discharge zone (surface to <200 m)

Hydrothermal eruption vents and hot springs transect zones of clay alteration and thus localise fluid pathways to the surface within the discharge zone. At this level fluid flow is constrained by: 1) the presence of weak rock, which is poorly suited to the development of open fractures; 2) low differential stress which nonetheless promotes development of short (<100 m) permeable fractures of almost any orientation; 3) silica deposition which isolates vertical conduits that provide fluid to hot springs; and 4) interaction between ascending columns of hot water and cold meteoric water, which generates a short wavelength effect that breaks up the flow and discharge of hot water into discrete hot springs. Ingress of cold water can occur in zones of high permeability.

3.2 Reservoir zone (<200 to 2000 m deep)

The reservoir zone is the depth interval in which boiling conditions may develop. The main controlling factors on fluid flow are: 1) development of a vertically extensive fault-fracture network; 2) the geomechanical properties of the host rocks (primary porosity-permeability and tensile strength); 3) transformation (both weakening and strengthening) of host rocks due to hydrothermal alteration, which affects brittle failure; 4) basement faults which localize growth faults in the Quaternary cover sequence; and 5) complexity arising from interplay of lithological and structural controls on fluid movement. Within the reservoir zones of the central TVZ, the stratigraphy is dominated by weak volcanic rocks, which favor the development of clay-rich cores in faults with large displacements, except locally where faults cut competent lavas and welded ignimbrites. Faults in this zone likely behave as baffles causing compartmentalized fluid flow, which is distributed within fault blocks (e.g., Orakeikorako: Rowland and Sibson, 2004), and accounts for large volumes of hydrothermal alteration (10 to ≥100 km^3). The juxtaposition of permeable against low permeability rock types, or the presence of a well-developed low permeability fault core, may result in fault parallel localization of fluid flow within such compartments (Dempsey et al., in review).

3.3 Deep feed zone (>2000 m depth)

The deep feed zone extends from >2000 m depth to the brittle-ductile transition, the inferred base to the convection system (Bibby et al., 1995). At this depth, low porosity rocks comprising greywacke basement and the lower part of the Quaternary cover sequence limit fluid movement to fault-fracture networks. The main factors constraining fluid flow are: 1) magmatic intrusion, which mainly supplies heat and energy, but which can also facilitate fracture extension at the tip of a dike; 2) proximity to the brittle-ductile transition, which limits the downward flow of water; 3) the tensile strength of host rocks which is generally high; and 4) near-hydrostatic fluid pressure, which is maintained because brittle failure relieves the build-up of fluid overpressures.

Juxtaposition of basement blocks against more permeable volcaniclastic materials may guide buoyant fluid flow and recharge. However, it is more likely at this depth that hydraulic connectivity will be fault-controlled via structures favorably-oriented for reactivation in the prevailing stress field (Townend and Zoback, 2000). For NW-SE directed extension, NNE-to-ENE striking structures of moderate to steep dip (45-90°) and WNW-to-NNW striking sub-vertical structures are favored to reactivate as normal and strike-slip faults, respectively, perhaps renewing permeability through post-earthquake non-alignment of asperities.

In this zone the temperature gradient is probably adiabatic, except near the base of the convection zone, where heat transfer changes from convection above the brittle-ductile transition to conduction below it (see temperature profile, Fig. 2b), and where partially to fully sealed conduits induce elevated pore fluid pressures. Except for these sites, mineral deposition is probably minimal. An important corollary to this point is that in the absence of effective fault sealing through mineral deposition, pre-existing faults with significant gouge development remain weak over much of their vertical extent, and are therefore prone to reactivation. These structures presumably are rooted in creeping shear zones in the ductile mid-crust. This is particularly likely because the depth to the base of the seismogenic zone has lessened through time as a result of thermal weakening (Villamor and Berryman, 2006). Creep on these shear zones may dynamically enhance permeability within the ductile regime, providing a suitable mechanism for channeling any overpressured liquids across the brittle-ductile transition via the fault-valve mechanism (Fig. 13: Sibson, 1992; Cox et al., 2001). Furthermore, their reactivation may be expected to exert control on the geometry of the more complex fault-fracture network within the reservoir zone.

4. GEOMETRY OF BRITTLE STRUCTURES WITHIN THE FEED ZONE AND LOWER RESERVOIR

4.1 Conceptual model of geometry of structural permeability networks from the brittle-ductile transition to the surface

Controls on structural permeability networks over the full depth of the hydrothermal plume are implicit in the previous section and summarized here. The geometry of the near-surface structural network is likely complex reflecting upward growth of faults into a strongly anisotropic assemblage of rocks that vary in thickness from meters to 100s of meters. Nonetheless, control by basement faults

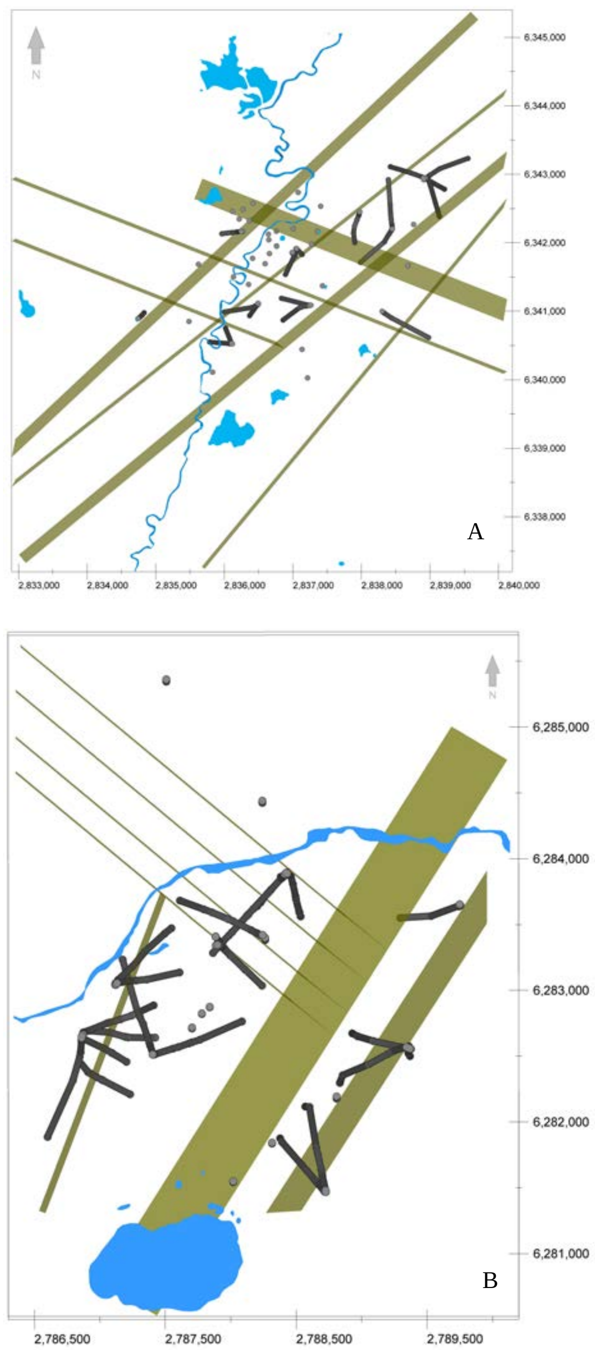

Fig. 3: Plan projections of faults (green) interpreted from offsets in drillhole stratigraphy at a) Kawerau and b) Rotokawa geothermal fields. Blue: lakes and rivers. Projections of drillholes are also shown.

that are favourably-oriented for reactivation and which therefore control the development of rift basins, will influence the strike of structural elements within this network. With increasing depth, the geometry of any fault-fracture network simplifies and localizes onto these inherited and reactivated basement faults.

4.2 Geometry of structural networks from 3D visualization of selected geothermal systems

Data synthesized in three-dimensional models for geothermal exploration, development and production allows visualization of the major components of structural networks at depths accessible by drilling (generally <3000 m) and commensurate with the deep feed zone and lower levels of the reservoir. Small-offset faults (<50 m) and fractures cannot be resolved in these models, which are constrained by drillhole stratigraphy and, generally to a lesser extent, other data as monitoring allows (temperature, induced microseismicity, pressure tests, tracer tests). The resolution of these models in effect acts as a filter on the data: the inferred structures are of a scale that they likely root onto, or are, basement faults.

4.2.1 Kawerau, Rotokawa and Wairakei-Tauhara geothermal fields

Drillhole stratigraphic datasets from Kawerau, Rotokawa, and Wairakei-Tauhara geothermal fields have been used to construct three-dimensional geological models of the accessible reservoir (e.g., Sepúlveda et al., 2012). As is the case for all explored fields of the TVZ, hydrothermal fluids ascend through a Quaternary cover sequence dominated by highly porous volcaniclastic and lacustrine sediments, and rhyolitic and andesitic lavas, which either demonstrably or presumably overlie a relatively low permeability greywacke basement. In addition, intrusive silicic rocks have been encountered in some drill holes (e.g., at Kawerau). In each geological model, NW- and NE-striking faults are required to satisfy vertical offsets in stratigraphic contacts between drillholes (Kawerau, Rotokawa: Fig. 3), and temperature distribution and residual gravity models (Wairakei-Tauhara, Sepúlveda et al., 2012).

5. BASEMENT STRUCTURES INFERRED FROM INTERROGATION OF HIGH RESOLUTION AERO MAGNETIC DATA

Downs et al., (in review) processed high-resolution aeromagnetic data, acquired by Glass Earth Ltd from April to July 2005, to investigate the subsurface within the Taupo-Reporoa Basin. Data were reduced to the pole and an upward continuation filter at various wavelengths was applied to target structures at depths <4800 m, commensurate with the level of the deep feed zones and reservoirs. Magnetic lineations apparent in the processed data trend NE, parallel to the structural grain of the TVZ, and also NNW and NNE (Fig. 4). These latter two trends appear to align with major crustal-scale features outside the TVZ, with those in the Hauraki Rift and North Island Fault System, respectively. Several geothermal fields are located along these across-strike lineaments, which are inferred to represent reactivated basement faults.

6. DISCUSSION

N-to-NW-trending alignments of geothermal fields (Rowland and Sibson, 2004), <61 ka volcanic vents (Rowland et al., 2010), and margins of rhombic shaped caldera boundaries (e.g., Seebeck et al., 2010), occur within the central TVZ and are coincident with boundaries between rift segments (Fig. 1). Moreover, N-to-NW-striking structures are inferred at depth within investigated geothermal fields based on drillhole stratigraphy, hydrological and geophysical data as described above. These observations support the notion that N-to-NW-striking structures represent an important controlling fabric on rift architecture and fluid flow within the TVZ (Rowland and Sibson, 2004). We argue below that such structures are likely the longest-lived tectonic element within the TVZ and have influenced the localisation of hydrothermal flow for the past >15 Ma.

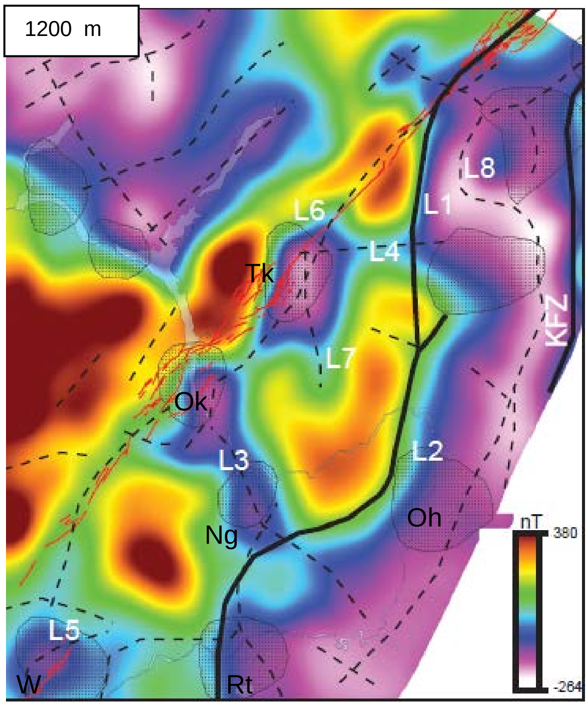

Fig. 4: Upward continued (1200 m) aeromagnetic map (from Downs et al., in review) of the eastern half of the central TVZ, showing the Paeroa fault zone (red lines), magnetic lineations (L1-L8) and the eastern border fault to the TVZ (KFZ – Kaingaroa fault zone). Geothermal fields shown by shaded polygons (selected fields labelled: Rt: Rotokawa, W: Wairakei, Ng: Ngatamariki, OK: Orakeikorako, Tk: Te Kopia, Ohaaki: Oh).

Relevant to this argument are studies from the >2000 km-long East African Rift System, which demonstrate that lengths of discrete rift segments scale with the thickness of the seismogenic zone (Ebinger et al., 1999). Kinematic coherency along the strike of the rift system requires that displacement accrued within each rift segment is transferred between segments in 'accommodation zones' via relay ramps and distributed strain (soft-linkage) or via transfer faults oriented at high-angle to the axis of rifting (hard-linkage). In east Africa, accommodation zones coincide with the projection of cross-rift Proterozoic basement structures (Le Turdu et al., 1999), which are optimally oriented for reactivation as transfer faults beneath the younger cover material (Ring, 1994).

Within the TVZ, we thus interpret that partitioning of the rifted arc into discrete segments of ~ 20 to 30 km in length is a mechanical consequence of extension of a 6 to 8 km-thick brittle layer (Rowland and Sibson, 2001). At map scale, soft-linkage of rift segments predominates within the Quaternary volcaniclastic basins of the TVZ (Rowland and Sibson, 2004). However, from the observations described earlier, we infer that favourably-oriented basement faults transfer displacement between adjacent rift segments at depth.

Such structures are likely the longest-lived tectonic elements within the TVZ for the following reasons:

- The <2 Myr-old TVZ represents the most recent NE-SW-trending locus of heat and mass transfer in a >15 Myr record of similarly-oriented magmatism, rifting and hydrothermal activity associated with subduction of the Pacific Plate beneath the North Island of New Zealand (Rowland et al., 2010).

- Lateral migration of the locus of arc magmatism, presumably concomitant with roll-back of the subducting slab, is supported by the southeastward younging of hydrothermal activity (Rowland and Sibson, 2004; Christie et al., 2007; Mauk et al., 2011); volcanism (Stern 1985; Wilson et al., 1995), and normal faulting (Davey et al., 1995; Villamor and Berryman, 2006).

- Today, as presumably the case for the entire interval of arc magmatism and associated extension, the length scale of the rifted arc (currently >120 km in subareal extent), far exceeds the thickness of the seismogenic zone, which is currently 6 to 8 km within the TVZ and <35 km west of the TVZ(Sherburn and White, 2005): mechanical segmentation should be a feature of the rifted arc from the initiation of extension through to today.

- The N-to-NW-striking basement fault zones that align with those inferred within the TVZ have considerable along-strike continuity: they are well-positioned to operate as transfer faults during successive eastward jumps in the loci of rifting.

7. CONCLUSION

Inherited basement faults are well-oriented for reactivation as transfer faults between adjacent rift segments throughout the entire period of NE-SW-oriented Late Miocene-to-present arc magmatism and extension in the central North Island. Interplay between such transfer faults and NE-striking rift faults enhance vertical permeability, which may be exploited by magmatic and hydrothermal fluids. Development of pull-apart basins at junctions between the strike-slip transfer faults and dip-slip rift faults may be particularly important localizing structures for heat and mass transfer at depths commensurate with the feed zone and lower reservoir.

ACKNOWLEDGEMENTS

JR and DD thank MSI Deep Geothermal and the Geothermal Resources of New Zealand GNS Science programme for funding this work. CS thanks MRP Ltd for financial support.

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