

# TECTONIC STRUCTURE AND PERMEABILITY IN THE TAUPŌ RIFT: NEW INSIGHTS FROM ANALYSIS OF LIDAR DERIVED DEMS

Villamor, P.<sup>1</sup>, Nicol, A.<sup>2</sup>, Seebeck, H.<sup>1</sup>, Rowland, J.<sup>3</sup>, Townsend, D.<sup>1</sup>, Massiot, C.<sup>1</sup>, McNamara, D.D.<sup>4</sup>, Milicich, S.D.<sup>1</sup>, Ries, W.<sup>1</sup> and Alcaraz, S.<sup>5</sup>

<sup>1</sup>GNS Science, 1 Fairway Drive, Avalon, Lower Hutt 5010

<sup>2</sup>University of Canterbury, Christchurch, New Zealand

<sup>3</sup>University of Auckland, Auckland, New Zealand

<sup>4</sup>Department of Earth and Ocean Sciences, National University of Ireland, Galway, Ireland

<sup>5</sup>GNS Science, Wairakei, Taupo, New Zealand

[p.villamor@gns.cri.nz](mailto:p.villamor@gns.cri.nz)

**Keywords:** *Tectonic structure, permeability, active normal faults, geothermal system, Taupo Rift, LiDAR.*

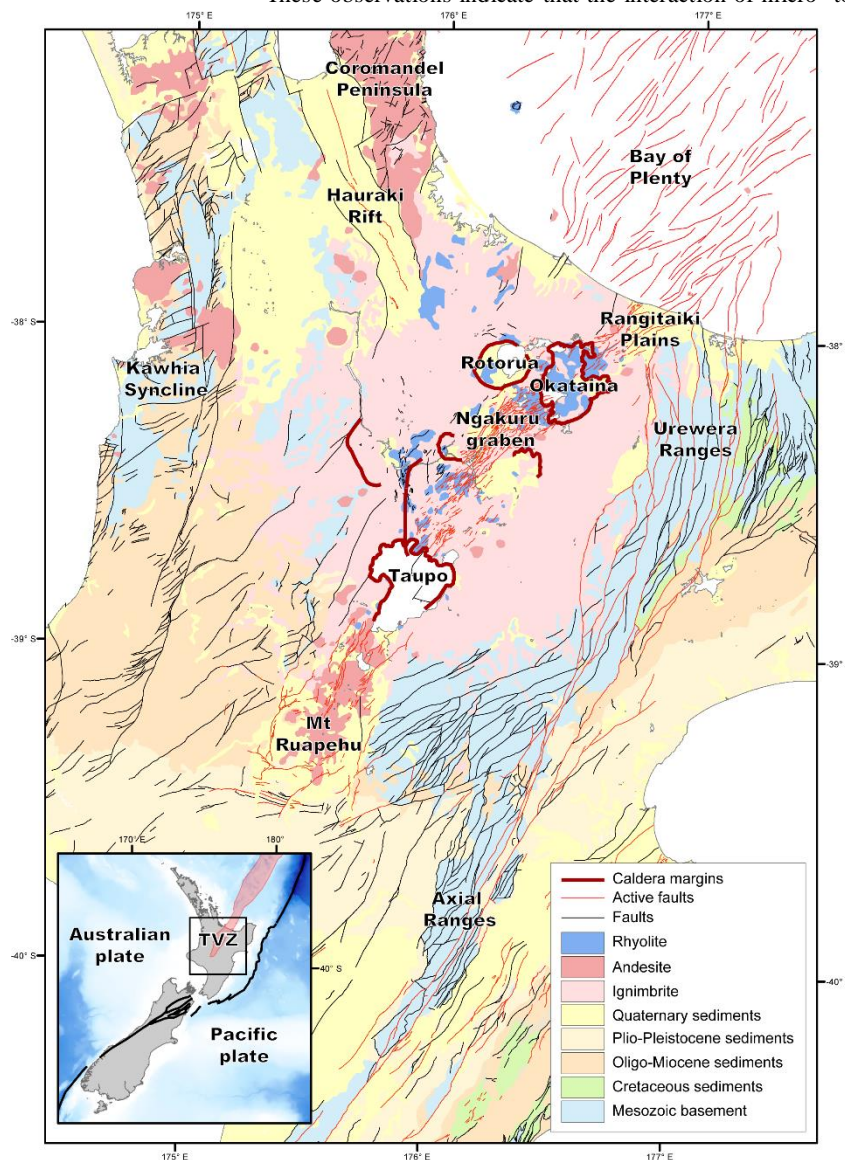
## ABSTRACT

The bulk permeability of upper crustal rocks in the Taupō Rift, central North Island, New Zealand is a function of the development and intersection of active and inherited faults, caldera collapse structures, and/or lithology. To date, major fault trends within the rift have been described as: 1) 030-045°, the dominant rift trend of north of Lake Taupō; 2) 050-065°, the dominant rift trend north of the Ngakuru Graben; 3) 355-005°, inherited basement trends that may influence caldera collapse structures and; 4) 330°, approximately parallel to the structural trends within the basement and Hauraki Rift. Preliminary LiDAR interpretations within and on the eastern margin of the Taupō Rift indicate that an additional set of active faults trending 070-085° could also play an important role in the crustal permeability of the region.

All fault trends identified within the Taupō Rift can be found within basement rocks. In outcrops of Mesozoic basement to the east and west of the central Taupō Rift, predominant 355-005° fault trends are found, while 070-085° (with minor 030-045°) trends are observed to the south. Northwest of the rift, 330° trends are present in the basement along with active and inactive faults of the Hauraki Rift. These trends within the Taupō Rift are supported at various scales by geological mapping, geophysical imaging and borehole analysis.

The surface expression of geothermal activity in the TVZ occurs predominantly in the rhyolitic dominant central section. In a few cases, geothermal fields are directly associated with large crustal scale faults (e.g., Te Kopia, Waikite, Orakei Korako). Regions within the rift with high densities of faults and their associated intersections do not often spatially

correlate with high temperature geothermal systems. In these highly faulted areas, inferred high crustal permeability most likely facilitate the down-welling of cold ground waters providing recharge to the upwelling geothermal plumes. These observations indicate that the interaction of micro- to



**Figure 2: Structural elements of the Taupō Rift. See text for fault references. Geology modified from Edbrooke et al. (2015).**

macro-scale faults (and associated high and low permeability zones), with the geothermal systems is a complex phenomenon which requires multidisciplinary approaches to understand.

## 1. INTRODUCTION

In the Taupō Rift and other extensional areas worldwide, the importance of normal faults and their architecture (fault relays, step overs, fault tips) as either fluid conduits or baffles has been widely studied (e.g., Curewitz & Karson, 1997; Bellani et al., 2004; Rowland & Sibson, 2004; Faulds & Hinz, 2015). Zones of enhanced permeability are found around damaged fault intersection and tip zones, potentially facilitating the large scale up- and down- welling of ground water associated with geothermal systems such as those found in the Taupō Volcanic Zone (TVZ) (Bibby et al., 1995). Research on structural controls on magma localisation (Seebeck & Nicol, 2009) and geothermal fluid flow (Rowland & Sibson, 2004) in the Taupō Rift, and on the distribution of epithermal deposits and prospects in the Coromandel Volcanic Zone (Rowland et al., 2017), highlights the role of the intersection between the active faults of the Taupō Rift (030-045° and 050-060°), inherited basement fabrics (355-005° and 330°) and volcanic structures (e.g., caldera margins, andesitic and rhyolitic volcanoes) in enhancing permeability.

This paper brings attention to the potential role of 070-085° faults (active and inactive) in enhancing permeability in the context of intersection with the other well-studied dominant trends. Previous mapping of faults has relied on modern (post-1990) and vintage (1940-1965) aerial photography, low-resolution DEMs (pixels 5-20 m), and field mapping. This study utilises a high-resolution digital elevation model (pixels <1 m) derived from LiDAR data commissioned by the Bay of Plenty Regional Council (BoPRC) to aid in identification of active faults and geomorphic trends that may reflect a tectonic origin. We use new and published information on mapped faults, and subsurface fault and fracture analysis from geothermal boreholes and 3D geological models of geothermal reservoirs to aid in the understanding of tectonic and structural controls of permeability in the Taupō Rift.

## 2. FAULTING IN THE TAUPŌ RIFT

Normal faults of the Taupō Rift accommodate predominantly NW-SE extension of ~12 mm/yr in the central North Island of New Zealand (Villamor & Berryman, 2001; Wallace et al., 2004; Lamarche et al., 2006; Seebeck et al., 2014a). The range of fault orientations and earthquakes focal mechanisms observed across the region indicate active faulting has developed in response to a three-dimensional strain field, predominantly normal with respect to the rift margins with a varying component of right-lateral strike-slip (Seebeck et al., 2014a). The rift intersects two recently active rhyolitic centres (Taupō and Okataina) outside which active faults are interpreted to be of mainly tectonic origin (Robinson et al., 2009; Rowland et al., 2010; Villamor et al., 2011). Intra-arc extension has formed in response to the clockwise rotation of the eastern North Island (relative to western North Island) in response to continental collision at the southern end of the Hikurangi margin and rollback of the subducting Pacific Plate along the Kermadec-Tonga trench to the north (e.g., Wallace et al., 2004, 2009; Seebeck et al., 2014a,b). Normal faulting is thought to have initiated 1-2 Myr ago (Wilson et al., 1995) resulting in total crustal extension estimated at between ~20 and 80% (Davey et al., 1995; Stratford & Stern, 2006; Nicol et al., 2007).

Active faults in the rift display a range of trends. These trends and their key elements are summarised next.

### 2.1. 030-045° (Figure 1, 2)

The dominant trend of active faults north of Lake Taupō including the Paeroa Fault (Fig. 2) is 030-045°. Faults of this trend are sub-parallel to the trend of the arc front and to the strike of the underlying subducting plate, some caldera margins and basaltic eruption vents. Outside the Taupō Rift, this trend is also found along the Coromandel Peninsula to the northwest, and Axial Ranges and forearc region to the east, and offshore in the western platform (Edbrooke et al., 2015; Giba et al., 2010).



**Figure 2: Example of active fault scarp (Paeroa Fault).**

### 2.2. 050-065° trend (Figure 1)

Active faults north of the Ngakuru Graben strike 050-065°, approximately 20°E of the dominant rift trend, and intersect the margins of the Okataina Volcanic Centre (OVC). The intersection zone between 030-045° and 050-065° trending faults results in a highly complex zone of cross cutting and intersecting fault geometries (Fig. 3). This fault trend is dominant in the northern-most extent of the onshore rift across the Rangitaiki Plains.

### 2.3. 355-005° trend (Figure 1)

These N-S trending faults are parallel to terrane boundaries and bedding in Mesozoic basement greywacke rocks across the central North Island. Moderately to steeply dipping basement outcrops to the east and west of the Taupō Rift (e.g., Urewera Ranges and Kawhia syncline, respectively) where these faults parallel the trend of active faults. As basement fabric and terrane boundaries are generally sub-parallel either side of the Taupō Rift, similar inherited basement fabrics (fault trends and bedding geometry) could therefore be inferred at depth beneath the volcanic cover in the rift.

### 2.4. 330° trend (Figure 1)

The dominant fault and basement fabric trend to the northwest of the Taupō Rift is 330° (e.g., Hauraki Rift, including the active Kerepehi Fault). This fault trend is sub-parallel to lineaments crossing the active Taupō Rift which may define rift segmentation (Rowland & Sibson, 2001). This trend is also sub-parallel to the extension direction associated with the



bending of the Pacific Plate to the east of the Taupō Rift (Seebeck et al., 2014a)

#### 2.4. 070-085° trend (Figure 1)

At the southern termination of the Taupō Rift, active faults trending 070-085° are parallel to faults mapped in basement immediately to the east (Fig. 1). The active faults may reactivate these inherited basement faults in the complex stress and strain field at the termination of the rift (Villamor & Berryman, 2006).

Faults of this orientation are also present along the southern margin of OVC (e.g., Leonard et al., 2010) and sections of the 1987 M<sub>L</sub> 6.3 Edgecumbe normal fault surface rupture (Beanland et al., 1989). Secondary faulting with this trend is mapped in the Ngakuru Graben on the footwall of the Paeroa Fault, and inferred to continue to the west into the graben axis (Downs et al., 2014).

### 3. INSIGHTS FROM DETAILED FAULT MAPPING WITH HIGH RESOLUTION DTMS

High resolution DEMs derived from LiDAR data are helping produce detailed active fault maps for large regions of New Zealand where available. These land surface models help identify active fault scarps that are either too subtle to be picked up from aerial photographs (e.g., Langridge & Villamor 2007) or are obscured by vegetation (Langridge et al., 2014). In the Taupō Rift, LiDAR is available for most of the Bay of Plenty region and for small sectors of Taupō District.

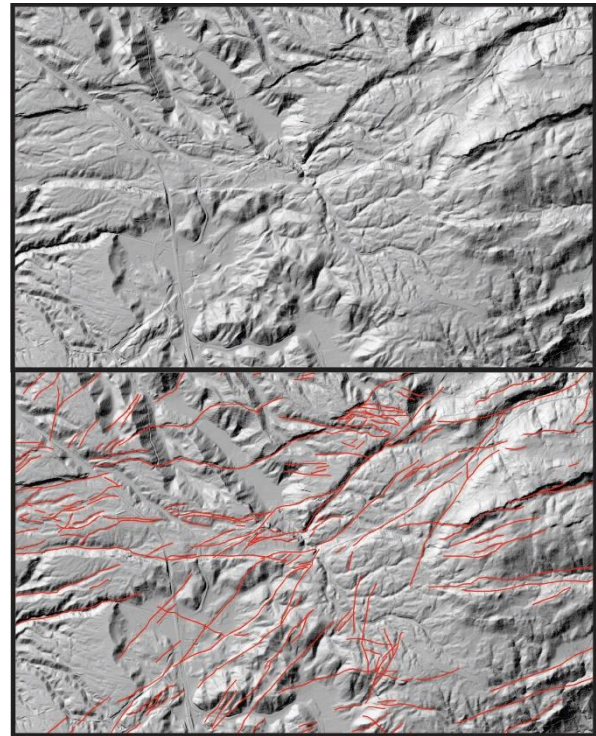
Detailed active fault mapping (including features that could be potentially active) was produced for land use planning purposes for the Rotorua District Council (Villamor et al., 2010) (Fig. 3). That mapping showed: a) the presence of previously unmapped, potentially active, fault scarps in the Taupō-Reporoa basin; b) a higher density of active faulting in the Ngakuru Graben than previously mapped; and c) the absence of active faulting in large areas within the Okataina Volcanic Centre (vegetation cover hindered fault mapping in this area) (Fig. 4). These faults were included in Leonard et al. (2010) in a simplified form.

The LiDAR data examined for this study covers an area of 16800 km<sup>2</sup> which includes the Rangitikei Plains (updating Begg and Mouslopoulou, 2010), the southern Ngakuru graben, and the Taupō-Reporoa Basin (Fig. 1). With respect to the fault trends described for the Taupō Rift, the high-resolution mapping (Villamor et al., 2010 and this study; Fig. 4) suggests that:

- The 070-085° trend is somewhat more prominent in the active rift north of Lake Taupō than previously mapped (Fig. 4). Faults of this trend are found: a) along the northern margin of OVC in coincidence with some northern lake boundaries (e.g., Lake Rotorua; Lake Rotoehu; Manawahe Fault) and b) south and west of the OVC (Highlands Road area and south of lake Rotorua). In these areas, this fault trend is dominant and exemplified by long fault scarps with substantial throws. Further south in the Ngakuru graben abundant short traces (with small throws) with these trends are observed. To the east of the main locus of rifting, sparse fault traces within the Taupō-Reporoa basin have been identified. These faults could be potentially active and further work is required to understand their rates of activity. This faults could be structurally connecting the Taupō Rift with the Dextral Fault Belt in the Axial Ranges.

- The dominant 030-045° trend is also found in newly mapped traces in Taupō-Reporoa basin. These fault scarps could either represent active faults with low slip rates or faults that have recently ceased activity.

- The 355-005° trend is observed by geomorphic lineations that intersect the eastern margin of OVC. These lineations are sub-parallel to the eastern caldera boundary as defined by the trend of gravity gradients (e.g., Seebeck et al., 2010).



**Figure 3: Example of active faults in the northern Ngakuru graben. Hillshade model generated from BoPRC LiDAR data (see text for details).**

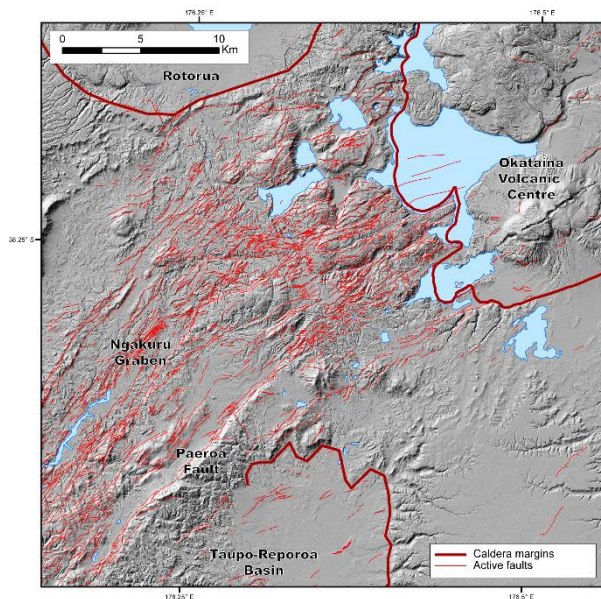
### 4. FAULT INTERSECTIONS AND ENHANCED PERMEABILITY

In this section, we summarise the different fault and fracture trends found in several geothermal fields in the Taupō Rift (Fig. 5 and 6). We also summarise the trends found in some areas without up-welling hot water plumes but which also have complex fault intersections. Evidence for different fault trends comes from mapped active faults and inactive faults, geophysical data (mainly resistivity, magnetism and gravity), and borehole image analysis of faults and fractures.

For the Taupō Rift, active faults are those defined by observed displacements within the last 25,000 years (e.g., Langridge et al. 2016). Inactive faults refer to lineaments that represent basement faults of unknown age and faults that ceased activity prior to 25,000 years before present. Fault data is compiled from: existing geological maps (Edbrooke, 2001; 2005; Leonard et al. (2010); Townsend et al., 2008; Lee et al., 2011), the New Zealand active fault database (Langridge et al., 2016); and recent high resolution mapping (Villamor et al., 2010; this study and are shown in Fig. 6 for sites of interest to this study.

Geophysical evidence shows two major types of structures that add to the structural complexity often Taupō Rift. Firstly, NW and E-W lineaments from aeromagnetic data using upward continuation and edge detection methodologies

(Henderson et al., 2016). The NW trends have also been detected in previous geophysical studies and have been regarded as controlling some segments boundaries of the Rift (Rowland and Sibson, 2001). Secondly, semi-circular to rectangular gravity anomalies have been associated to caldera boundaries and considered a major player in the rift permeability (Seebeck et al., 2010; Bertrand et al., 2015)



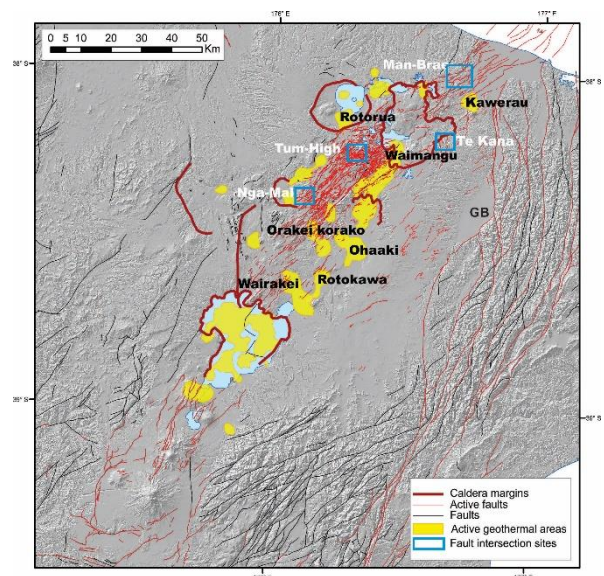
**Figure 4: Example of fault patterns in the central Taupō Rift. High fault densities in the northern Ngakuru graben are newly derived from high resolution LiDAR ground surface elevation data (this study).**

Borehole imaging provides direct observation of the subsurface fracture orientations in geothermal reservoirs and structural controls on geothermal fluid flow (McNamara et al., 2017 and references therein). The published fracture trends observed in boreholes of the Wairakei, Rotokawa and Kawerau Geothermal Fields (summarised in Fig. 6) show all the main trends observed in the active faults as described above.

Numerous fractures are typically observed along the entire length of imaged boreholes (~500-1000 m), but permeable zones (interpreted from pressure-temperature-spinner log; Massiot et al. this volume) only cover ~10-100 m-long intervals. Permeable zones contain fractures of 030-045° trend at Wairakei and Rotokawa, which in both cases are also the dominant trend outside of the permeable zones. Additional subordinate fracture trends in permeable zones include 060° and 330° at Wairakei (McLean and McNamara, 2011); and 335-005° trend at Rotokawa (McNamara et al., 2015; Massiot et al., 2017). Scatter in fracture orientation often precludes distinction between 030-045° and 050-065° fracture sets. In addition, Wallis et al. (2013) observe that intersecting fractures (at borehole scale) are concentrated in permeable intervals, though do not report their orientations.

In addition to fracture orientation, other factors influencing geothermal-reservoir scale permeability documented in image logs include: lithology, high apparent fracture thickness; high fracture density; localised rotations of the intermediate stress orientation or a combination of any or all these factors (McLean & McNamara, 2011; Wallis et al.,

2012; Massiot et al., 2013; McNamara et al., 2015; McNamara et al., 2016; McNamara et al., 2017; Massiot et al., 2017).



**Figure 5: Distribution of high temperature geothermal fields within the Taupō Volcanic Zone and other locations with intersecting fault trends (blue squares). Geothermal areas defined by low apparent resistivity (<30  $\Omega$ m) after Bibby et al. (1995). Man-Brae, Manawahe-Braemar faults; Te Kana, Te Kanakana fault; Nga-Mal, southern Ngakuru-Maleme faults; Tum-High, Tumuni-Highlands Rd faults; Gb, Galatea Basin.**

#### 4.1 NZ geothermal fields as examples of structural relationship that enhance permeability

Fig. 6 compiles fault and fracture trends present in a selection of geothermal areas of the Taupō Rift. These data show that the first order fault trends identified through detailed geomorphic, geological and active fault studies are present at reservoir scale within the geothermal systems. Observations of fault and fracture orientation within any particular geothermal field are strongly dependent on the proximity and orientation of large fault or volcanic structures, even if they are not directly intersected by these phenomena.

#### 4.2 Other areas of potential enhanced permeability not linked to active geothermal fields

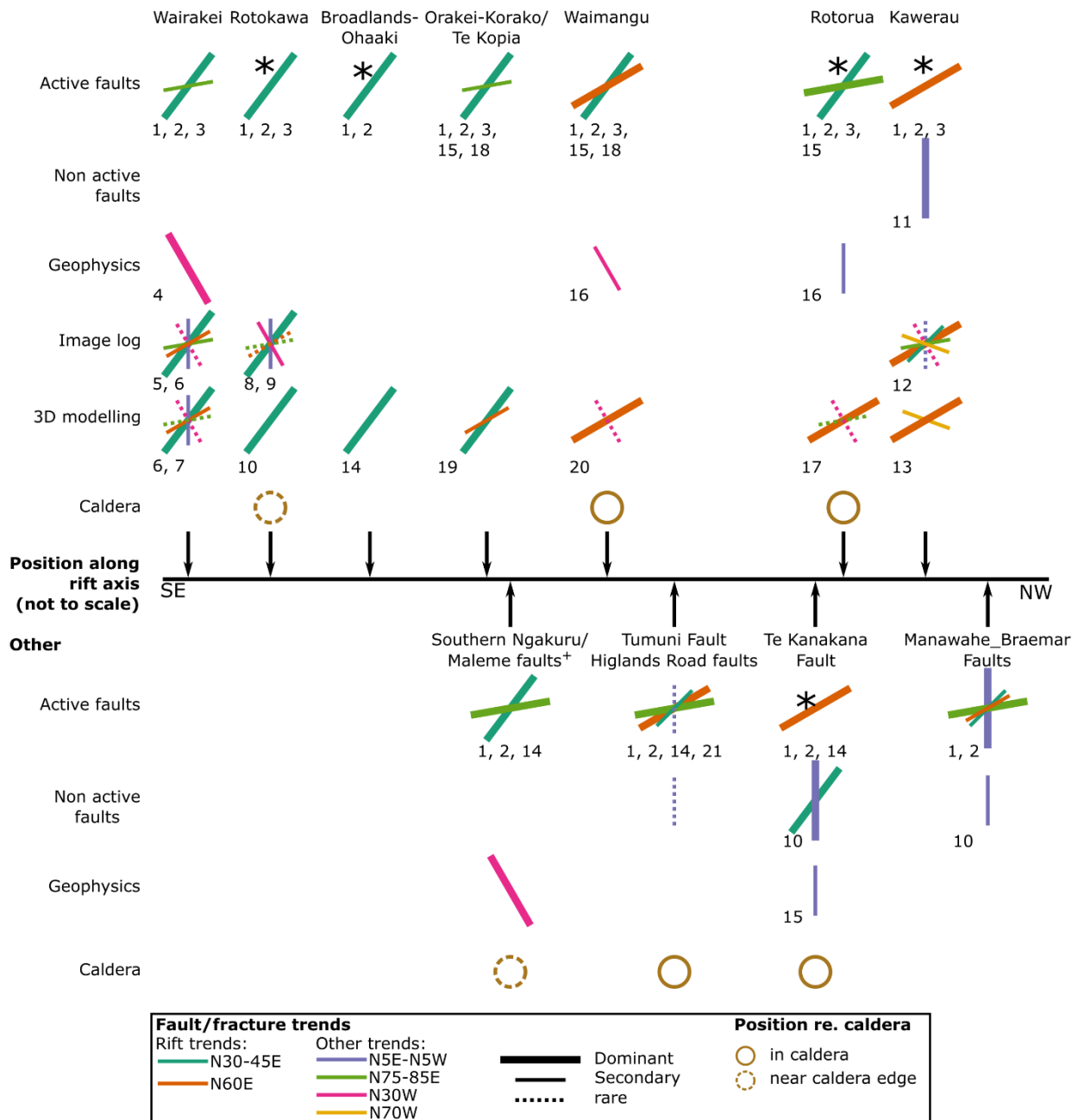
Fig. 6 shows selected areas that display similar surface trend combinations to those of the geothermal fields (Fig. 5 and 6). While there are many areas of fault intersections along the whole rift, we have focused on the areas within the sector of the Taupō Rift that have higher heat flow, the central rhyolitic sector (as defined by Wilson et al., 1995), where most of the currently active geothermal fields are located, and where we have large areas of high resolution mapping of faults. We also note that some of these areas are not linked to active geothermal fields, while others could be linked to fossil systems (Fig/ 6). There is currently no borehole image data in these areas.

## 5. DISCUSSION AND CONCLUSION

The dominant fault trends found in all the study sites (fault intersections with and without geothermal activity; Fig. 5 and 6) are the currently active faults. Borehole data presents more fault trends that data sets analysed in the surface or with



## Geothermal Fields



**Figure 6: Dominant, secondary and rare fault trends identified from surface fault mapping, deep geophysics, borehole image logs and 3D geological modelling. Top: geothermal fields. bottom: areas without up-welling hot water plumes but which also have complex fault intersections.**

+ Areas close to fossil sinters; references associated with fossil geothermal activity.

References: 1: Langridge et al. (2016); 2: Leonard et al. (2010); 3: Seebeck et al. (2014a); 4: Rowland et al. (2017); 5: Massiot et al. (2013); 6: McNamara et al. (2016); 7: Alcaraz et al. (2010); 8: McNamara et al. (2015); 9: Massiot et al. (2017); 10: Wallis et al. (2013); 11: This study; 12: Wallis et al. (2012); 13: Milicich et al. (2013); 14: Milicich et al. (2003); 15: Villamor et al. (2010); 16: Seebeck et al. (2010); 17: Alcaraz and Barber (2015); 18: Rowland & Simmons, (2012); 19: Purwandono et al. (2015); 20: Tschirter & White (2014); 21: Nicol et al. (2009).

geophysics, thanks to the higher resolution of the data. The major trends found in boreholes usually coincide with the major trends of active faults in the surface.

All secondary trends found in boreholes are represented by inherited structures observed in the exposed basement outside the current active rift. The secondary 070-085° trend is found all over the rift but seems to be more pronounced to the south of Rotorua city. In contrast, the N-S trend is better represented

to the north, while still present but minor to the south of Rotorua. This change in dominance of secondary trends is also reflected in the basement structures. The 070-085° trend is clearly represented in the basement outside the rift, particularly south of Lake Taupō (Fig. 1). Basement structures in the Axial Ranges to the east of the rift, between Lake Taupo and Rotorua (the region west of the rift at that latitude and to the north is covered with thick Quaternary

volcanics), display a combination of 070-085° and 000°. In this region, the active faults of the Axial Dextral Fault Belt change from 030° to 000°. That combination of trends is clearly represented by the boundary faults of the Galatea Basin (Fig. 5). North of Rotorua, the N-S trend is clearly represented in the active strike-slip faults outside the rift and in the rift itself as the Axial Dextral Fault Belt intersects the rift (Mouslopoulou et al., 2007).

Active fault datasets do not show the 330° trend found from geophysical evidence and in the Hauraki Rift active and inactive faults, that trend is displayed as secondary in borehole data. Also, a secondary 300° trend found in borehole data and 3D geological modelling in the Kawerau Geothermal Field is not present at other sites and may represent similar faults seen in basement of the Raukumara Peninsula.

There is no clear pattern of what type of intersections may favour geothermal activity (Fig. 5 and 6). It could be that the type of intersection is not relevant to the presence of geothermal fields, or that the datasets used here are limited. Current data gaps are:

- Lack of LIDAR data in large areas of rift.
- Some geothermal fields are located in very young geomorphic surfaces and thus active faults are not well represented.
- Borehole results are scarce.
- Sites with boreholes have only 2; 3; and 10 boreholes each, which is not sufficient for reliable statistics.
- Structures determined from 3D geological modelling of the geothermal fields are restricted by the low density of wells in some geothermal fields.
- There is a lack of high resolution micro-seismicity monitoring across the TVZ that would provide increased indirect observations of structural trends.

In the Taupō Rift, there are numerous sites (we have only pointed out a few in Fig. 5 and 6), where the active faults intersect with each other, or intersect with basement structures. Some of those sites are associated with the currently active geothermal fields. However, other sites lack current or recent geothermal activity, despite being located (at least some of them) in close proximity to volcanic vents (Fig. 5 and 6), active in at least the last ~ 100,000 years (considering vents as proxy to presence of fossil heat source). Therefore, while fault intersections in the Taupō Rift certainly enhance permeability, they do not guarantee presence of geothermal activity. However, sites similar to those selected as example of dense fault intersection, with no associated geothermal fields, can still have a major role in the geothermal activity of the Taupō Rift. Those are possibly areas of enhanced permeability that favours down flow.

If it were true that fault intersections per se do not guarantee presence of geothermal activity, could we distinguish peculiar settings within the rift (assuming close proximity to a heat source) where the fault intersections present will favour geothermal activity? We discuss next the potential role of major crustal structures and caldera margins. Intersections of the major geophysical trends with the active faults of the Taupō Rift are invoked to produced rift segmentation, and thus accommodation zones that favour permeability and geothermal activity (Rowland & Sibson, 2004, Rowland & Simmons, 2012). Some of these geophysical anomalies are major basement structures, such as contacts between

basement terranes) or structures parallel to them (Rowland et al., 2017). The presence of crustal faults rooted into this deep crustal weakness zones seems to enhance permeability at deeper crustal levels. Similarly, intersections of active faults with caldera margins are also considered to play a major role in the location of geothermal fields (Seebeck et al., 2010; Rowland et al., 2012). Caldera faults represent a very different crustal weakness to the major basement terrane boundaries mentioned above. Caldera faults will only affect the crust to depths above the location of the emptied magma chamber~ 5 km (Smith et al., 2005).

While major basement structures and caldera margins are certainly creating the right environment to enhance fracturing and permeability, not all the geothermal fields (current and fossil) in the Taupō Rift are located in such settings (Fig.5). It is possible that other lineaments, not parallel to the basement terranes and not considered as major to date, such as the 070-085° trend described here, may also play an important role. For example, the presence of these across-major-basement-structure trends can produce structural corners of basement blocks (as they intersect with other major trends) of enhanced permeability, similarly to those described for epithermal gold mineralisation in the Coromandel region (Rowland et al., 2017). It is important to note that we have used the caldera boundaries delineated mainly with surface geology evidence (e.g., Leonard et al., 2010). However, geophysical data suggests that there could be more calderas currently buried under thick volcanic deposits (Bertrand et al., 2015). Our Fig. 5 will need to be updated with respect to the link between geothermal fields and caldera boundaries.

Local changes in the stress tensor and associated fracture trends could also be responsible for enhancing permeability, as documented in borehole image logs (Massiot et al., 2013; McNamara et al., 2015). There are also locations in the Taupō Rift where active normal faults intersect, and where strike-slip movement in any of the intersecting trends is absent or very minor. This occurs at the southern termination of the rift (Mt Ruapehu latitude), with intersection of ~N-S and E-W trends of purely normal active faults (Villamor & Berryman, 2006). Both fault trends have ruptured within the last 2000 years (Villamor et al., 2004). Also, the Tumunui-Highlands Rd area displays similar characteristics but for the intersection of the 030-045° and 060° fault trends (Fig. 5 and 6), with both trends being currently active and almost purely normal. For both fault trends to be able to rupture as purely normal faults, the Sigma 2 and Sigma 3 axes of the stress tensor need to have similar magnitudes. While the cause of such local changes still needs to be explored for the Taupō Rift, it is likely that magma process may play an important role.

In this paper, we have explored potential connections of geothermal fields with fault intersection, but we have not focus on the presence of heat sources in the crust, which will be ultimately responsible for the high temperature needed to generate a geothermal field. The interaction with the heat source and the rift architecture around it can control which role may nearby fault intersections take in the geothermal activity of the rift. At the scale of the rift, geothermal systems of the Taupō Volcanic Zone trend approximately parallel and perpendicular to the trend of the arc front volcanoes, Taupō Rift, and the strike of the underlying Pacific Plate (which is the ultimate source of the elevated heat flow within the region) (Bibby et al., 1995; Wilson et al., 1995; Reyners et al., 2006; Eberhart-Phillips et al., 2008). Beneath the brittle-ductile transition, low resistivity anomalies, interpreted as partial melt (Heise et al., 2010), are located directly beneath

the rift axis (Seebeck et al, 2014a). The resistivity structure within the brittle upper crust indicates rising, narrow plumes of hot water beneath some of the geothermal fields (Bibby et al., 1995; Heise et al., 2010; Bertrand et al., 2012). Some of the plumes are, however, offset from the surface geothermal fields which indicates that geological structure influences heat transport and mass flow across the region (Bertrand et al., 2012). In regions where the densities of normal fault traces and intersections are high, such as the Ngakuru graben, high resistivities at depths of 1.5-3 km (Heise et al., 2010; Bertrand et al., 2012) in combination with low residual gravity (Seebeck et al., 2010), suggest limited geothermal alteration has occurred within the volcanic cover (e.g., Bibby et al., 1995). This in turn suggests that these regions could be possible cold down-welling zones associated with convection of up-welling hot water further to the east where active surface faulting is limited.

In conclusion, while the main active fault trends in the Taupō Rift are well known and seem relatively simple when considered at a small scale (e.g., 1:250 000 of the active fault database), in detail the structure can be quite complex. Detailed structure shows that the rift displays several active and inactive fault trends that produce numerous fault intersections of different characteristics. Not all intersections are associated with geothermal activity and those that are seem to be quite varied in character. Those with lack of association to geothermal activity could play an important role in the down flow and thus influence the geothermal activity of the rift. We are currently investigating, if other rift structural and kinematic characteristics, could explain whether certain fault intersections could be more prone to produce geothermal activity than others.

## ACKNOWLEDGEMENTS

This research is funded by the Government of New Zealand (via GNS Science's *New Zealand Geothermal Future programme*). Active fault mapping in the Rotorua District was co-funded by Rotorua District Council. We thank BoPRC for provision of LiDAR data. The Universities of Canterbury and Auckland (New Zealand), and Galway (Ireland) provided support for Nicol, Rowland and McNamara, respectively,

## REFERENCES

- Alcaraz, S., Sepulveda, F., Lane, R., Rosenberg, M., Rae, A., Bignall, G.: A 3-D Representation of the Wairakei Geothermal System (New Zealand) using "Earth Research" Geothermal Visualisation and Modelling Software. *GRC Transactions*, 34. (2010).
- Alcaraz, S. & Barber, J.: A 3-D geological model of the Rotorua Geothermal Field. *Proc 37th New Zeal Geoth Workshop*. (2015).
- Beanland, S., Berryman, K. R., & Blick, G. H.: Geological investigations of the 1987 Edgecumbe earthquake, New Zealand. *New Zeal J Geol Geophys*, 32(1), 73-91. (1989).
- Begg, J.G., and Mouslopoulou V.: Analysis of late Holocene faulting within an active rift using lidar, Taupo rift, New Zealand. *J Volcanol Geoth Res*, 190(1/2), 152-167. (2010). doi: 10.1016/j.jvolgeores.2009.06.001.
- Bellani, S., Brogi, A., Lazzarotto, A., Liotta, D., Ranalli, G.: Heat flow, deep temperatures and extensional structures in the Larderello Geothermal Field (Italy): constraints on geothermal fluid flow. *J Volcanol Geoth Res*, 132(1), 15-29. (2004).
- Bertrand, E.A., Caldwell, T.G., Bannister, S., Soengkono, S., Bennie, S.L., Hill, G.J., & Heise, W. Using array MT data to image the crustal resistivity structure of the southeastern Taupo Volcanic Zone, New Zealand. *J Volcanol Geoth Res*, 305, 63-75. (2015)
- Bertrand, E A., Caldwell, T.G., Hill, G.J., Wallin, E.L., Bennie, S. L., Cozens, N., & Wameyo, P.: Magnetotelluric imaging of upper-crustal convection plumes beneath the Taupo Volcanic Zone, New Zealand. *Geophys Res Lett*, 39(2). (2012).
- Bibby, H.M., Caldwell, T.G., Davey, F.J., Webb, T.H.: Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. *J. Volc. Geoth. Res.*, 68(1-3), pp. 29-58. (1995).
- Curewitz, D., & Karson, J.A.: Structural settings of hydrothermal outflow: Fracture permeability maintained by fault propagation and interaction. *J Volcanol Geoth Res*, 79(3-4), 149-168. (1997). [https://doi.org/10.1016/S0377-0273\(97\)00027-9](https://doi.org/10.1016/S0377-0273(97)00027-9)
- Davey, F. J., Henrys, S. A., & Lodolo, E.: Asymmetric rifting in a continental back-arc environment, North Island, New Zealand. *J Volcanol Geoth Res*, 68(1), 209-238. (1995).
- Downs, D.T., Rowland, J.V., Wilson, C.J.N., Rosenberg, M.D., Leonard, G.S., & Calvert, A.T.: Evolution of the intra-arc Taupo-Reporoa Basin within the Taupo Volcanic Zone of New Zealand. *Geosphere*, 10(1), 185-206. (2014).
- Edbrooke, S.W.: Geology of the Auckland area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences Limited. *Institute of Geological & Nuclear Sciences 1:250,000 geological map 3*. 74 p. + 1 map. (2001).
- Edbrooke, S.W.: Geology of the Waikato area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences. Institute of Geological & Nuclear Sciences 1:250,000 geological map 4. 68 p. + 1 map. (2005).
- Edbrooke, S.W., Heron, D.W., Forsyth, P.J. & Jongens, R.: Geological Map of New Zealand, 1:1,000,000. GNS Science Geological Map 2. 2 sheets. Lower Hutt, New Zealand. GNS Science. (2015).
- Faulds, J.E., Hinz, N.H.: Favorable tectonic and structural settings of geothermal systems in the Great Basin region, western USA: Proxies for discovering blind geothermal systems. *Proc World Geoth Congress*, Melbourne, Australia. (2015).
- Giba, M., Nicol, A., & Walsh, J. J.: Evolution of faulting and volcanism in a back-arc basin and its implications for subduction processes. *Tectonics*, 29(4). (2010)
- Heise, W., Caldwell, T.G., Bibby, H.M., Bennie S.L.: Three-dimensional electrical resistivity image of magma beneath an active continental rift, Taupo Volcanic Zone, New Zealand. *Geophys Res Lett*, 37, L10301, doi:10.1029/2010GL043110. (2010).

- Henderson, S.M., Christie, A.B., Soengkono, S., Howie, K., Smith, B., Coote, A., Cahill, J.: Glass Earth staged exploration for epithermal gold-silver deposits in the southern Hauraki goldfield and Taupo Volcanic Zone, North Island, 2003-2013. In 'Mineral deposits of New Zealand Exploration and Research' (Ed. A.B. Christie) AusIMM Monograph 31, The Australian Institute of Mining and Metallurgy, Carlton Victoria, Australia. (2016). ISBN 978 1 925100 53 2
- Lamarche, G., Barnes, P.M., Bull J.M.: Faulting and Extension Rate over the last 20,000 Years in the Offshore Whakatane Graben, New Zealand Continental Shelf. *Tectonics*, 25, TC4005, doi:10.1029/2005TC001886. (2006).
- Langridge, R.M., Villamor, P.: Hastings District LiDAR fault trace survey. *GNS Science consultancy report 2007/145*. pp. 43. (2007).
- Langridge, R.M., Ries, W.F., Farrier, T., Barth, N.C., Khajavi, N., & De Pascale, G.P.: Developing sub 5-m LiDAR DEMs for forested sections of the Alpine and Hope faults, South Island, New Zealand: Implications for structural interpretations. *J Struc Geol*, 64, 53–66. (2014).
- Langridge, R.M., Ries, W.F., Litchfield, N.J., Villamor, P., Van Dissen, R.J., Barrell, D.J.A., Rattenbury, M.S., Heron, D.W., Haubrock, S., Townsend, D.B. and Lee, J.M.: The New Zealand active faults database. *New Zeal J Geol Geophys*, 59(1), 86-96. (2016).
- Lee, J.M., Bland, K.J., Townsend, D.B., & Kamp, P.J.J.: Geology of the Hawke's Bay area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences Limited. Institute of Geological & Nuclear Sciences 1:250,000 geological map 8. 86 p. + 1 map. (2011)
- Leonard, G.S., Begg, J.G., Wilson C.J.N.: Geology of the Rotorua area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences Limited. Institute of Geological & Nuclear Sciences 1:250,000 geological map 5. 99 p. + 1 map. (2010).
- Massiot, C., McLean, K., McNamara, D.D., Sepúlveda, F., Milicich, S.: Discussion between a reservoir engineer and a geologist: integrating completion test data and borehole image logs. *This volume*.
- Massiot, C., McNamara, D.D., Lewis, B.: Interpretive review of the acoustic borehole image logs acquired to date in the Wairakei-Tauhara Geothermal Field. *GNS Science report 2013/04*. p. 26. (2013).
- Massiot, C., Nicol, A., McNamara, D.D., Townend, T.: Evidence for tectonic, lithologic, and thermal controls on fracture system geometries in an andesitic high-temperature geothermal field. *J Geophys Res: Solid Earth* (122). (2017).
- McLean, K., McNamara, D.D.: Fractures interpreted from acoustic formation imaging technology: correlation to permeability. *Proc 36th Workshop on Geothermal Reservoir Engineering*, Stanford. (2011).
- McNamara, D.D., Massiot, C., Lewis, B., Wallis, I.: Heterogeneity of structure and stress in the Rotokawa Geothermal Field. *New Zeal J Geophys Res: Solid Earth*, 120(2). (2015). doi: 10.1002/2014JB011480.
- McNamara, D.D., Bannister, S., Villamor, P., Sepúlveda, F., Milicich, S.D., Alcaraz, S., Massiot, C.: Exploring Structure and Stress from Depth to Surface in the Wairakei Geothermal Field, New Zealand. *Proc 41st Workshop on Geothermal Reservoir Engineering*. (2016).
- McNamara, D.D., Massiot, C., Milicich, S.M.: Characterizing the subsurface structure and stress of new Zealand's geothermal fields using borehole images. *Energy Procedia*, 125, 273-282, (2017).
- Milicich, S.D., Bignall, G., Rae, A.J., Rosenberg, M.D.: Lithological and Structural Controls on Fluid Flow and Hydrothermal Alteration in the Western Ohaaki Geothermal Field (New Zealand)— Insights from Recent Deep Drilling. *Geoth Res Council Transactions*, 32, 765–770. (2003).
- Milicich, S. D., Wilson, C. J. N., Bignall, G., Pezaro, B., & Bardsley, C.: Reconstructing the geological and structural history of an active geothermal field: A case study from New Zealand. *J Volcanol Geoth Res*, 262, 7–24. doi: 10.1016/j.jvolgeores.2013.06.004. (2013).
- Mouslopoulou, V., Nicol, A., Little, T.A. Walsh, J.J.: Displacement transfer between intersecting regional strike-slip and extensional fault systems. *J Struc Geol* 29, 100-116. (2007).
- Nicol, A., Mazengarb, C., Chanier, F., Rait, G., Uruski, C. Wallace, L. Tectonic evolution of the active Hikurangi subduction margin, New Zealand, since the Oligocene. *Tectonics* 26, TC4002, doi:10.1029/2006TC002090 (2007).
- Nicol, A., Walsh, J., Mouslopoulou, V., Villamor, P.: Earthquake histories and Holocene acceleration of fault displacement rates. *Geology*, 37, pp. 911-914. (2009).
- Purwandono, A.F., Alcaraz, S.A., Rowland, J.V.: Three Dimensional Conceptual Model of Orakeikorako and Te Kopia Geothermal Systems, Taupo Volcanic Zone, New Zealand. *Proc 37th New Zeal Geoth Workshop*. (2015).
- Robinson, R., Nicol, A., Walsh, J.J., & Villamor, P.: Features of earthquake occurrence in a complex normal fault network: Results from a synthetic seismicity model of the Taupo Rift, New Zealand. *J Geophys Res: Solid Earth*, 114(B12). (2009).
- Rowland, J.V., & Sibson, R.H.: Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand. *Geofluids*, 4(4), 259–283. doi: 10.1111/j.1468-8123.2004.00091.x. (2004).
- Rowland, J.V. and Simmons, S.F.: Hydrologic, magmatic, and tectonic controls on hydrothermal flow, Taupo Volcanic Zone, New Zealand: Implications for the formation of epithermal vein deposits. *Economic Geology*, 107(3), 427-457. (2012).
- Rowland, J.V., Wilson, C J., and Gravley, D.M.: Spatial and temporal variations in magma-assisted rifting, Taupo



- Volcanic Zone, New Zealand: *J Volcanol Geoth Res*, 190(1), 89-108. (2010).
- Rowland, J.V., Bahiru, E.A., Schofield, M., Hamilton, A., Pickle, R., Zuquim, M.D.P., Eccles, J.D.: Tectonic and Structural Controls on Late Miocene-to-Recent Epithermal Gold-silver Mineralisation, Northern New Zealand. *Mineral Deposits of New Zealand – Exploration and Research*. (in press). (2017).
- Seebeck, H. and Nicol, A.: Dike intrusion and displacement accumulation at the intersection of the Okataina Volcanic Centre and Paeroa Fault zone, Taupo Rift, New Zealand, *Tectonophysics*, 475(3), 575-585. (2009).
- Seebeck, H., Nicol, A., Stern, T., Bibby, H., Stagpoole, V. Fault controls on the geometry and location of the Okataina Caldera, Taupo Volcanic Zone, New Zealand. *J Volcanol Geoth Res* 190 (1/2), 136-151, doi:10.1016/j.jvolgeores.2009.04.011. (2010).
- Seebeck, H., Nicol, A., Villamor, P., Ristau, J., Pettinga, J.: Structure and kinematics of the Taupo Rift, New Zealand, *Tectonics*, 33, 1178–1199. (2014a).
- Seebeck, H., Nicol, A., Giba, M., Pettinga, J., Walsh, J.: Geometry of the subducting Pacific plate since 20 Ma, Hikurangi margin, New Zealand. *J Geol Soc London* 171, 131-143. Doi: 10.1144/jgs2012-145. (2014b).
- Smith, V.C., Shane, P., & Nairn, I.A. Trends in rhyolite geochemistry, mineralogy, and magma storage during the last 50 kyr at Okataina and Taupo volcanic centres, Taupo Volcanic Zone, New Zealand. *J Volcanol Geoth Res*, 148(3–4), 372–406. (2005). doi: 10.1016/j.jvolgeores.2005.05.005
- Stratford, W.R., & Stern, T.A.: Crust and upper mantle structure of a continental backarc: central North Island, New Zealand. *Geophys J Int*, 166(1), 469-484. (2006).
- Townsend, D., Vonk, A., Kamp, P.J.J.: Geology of the Taranaki area: scale 1:250,000. Lower Hutt: GNS Science. Institute of Geological & Nuclear Sciences 1:250,000 geological map 7. 77 p. + 1 map (2008).
- Tschirter, C.; White, P. Three-dimensional geological model of the greater Lake Tarawera catchment. GNS Science Consultancy Report 2013/155. 42 p. (2014). Available at: <https://www.boprc.govt.nz/media/417987/three-dimensional-geological-model-of-the-greater-lake-tarawera-catchment.pdf>
- Villamor, P.; Van Dissen, R.J.; Alloway, B.V.; Palmer, A.; Litchfield, N.J.: The Rangipo (Desert Road) Fault: the most hazardous fault in the Taupo Volcanic Zone?. *Institute of Geological & Nuclear Sciences client report 2004/34*. 58 p. - plus maps. (2004).
- Villamor, P., Ries, W., Zajac, A.: Rotorua District Council hazard studies: active fault hazards. *GNS Science consultancy report 2010/182*. p. 28. (2010).
- Villamor, P. and Berryman, K.R.: A late Quaternary extension rate in the Taupo Volcanic Zone, New Zealand, derived from fault slip data, *New Zeal J. Geol Geophys*, v. 44, pp. 243-269. (2001).
- Villamor, P. and Berryman, K.R.: Late Quaternary geometry and kinematics of faults at the southern termination of the Taupo Volcanic Zone, New Zealand, *New Zeal J Geol Geophys*, 49 (1), 1-21. (2006)
- Villamor, P., Berryman, K.R., Nairn, I.A., Wilson, K., Litchfield, N., and Ries, W.: Associations between volcanic eruptions from Okataina volcanic center and surface rupture of nearby active faults, Taupo rift, New Zealand: Insights into the nature of volcano-tectonic interactions: *Geol Soc Am Bull*, 123(7-8), 1383-1405. (2011).
- Wallace, L., Beavan, J., McCaffrey, R., & Darby, D.J.: Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. *J Geophys Res B: Solid Earth*, 109, 1–21. doi: 10.1029/2004JB003241. (2004).
- Wallace, L.M., Ellis, S., & Mann, P.: Collisional model for rapid fore-arc block rotations, arc curvature, and episodic back-arc rifting in subduction settings. *Geochem, Geophys, Geosystems*, 10(5). doi: 10.1029/2008GC002220. (2009).
- Wallis, I.C., McNamara, D.D., Rowland, J.V., Massiot, C.: The nature of fracture permeability in the basement greywacke at Kawerau geothermal Field, New Zealand. *Proc 37th Workshop on Geothermal Reservoir Engineering*, Stanford. (2012).
- Wallis, I.C., Bardsley, C., Powell, T., Rowland, J.V., Brien, J.M.O.: A structural model for the Rotokawa Geothermal Field, New Zealand. *New Zeal Geoth Workshop 2013 Proceedings*. (2013).
- Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Waever, S.D., Briggs, R.M.: Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review, *J Volcanol Geotherm Res.*, 68, 1-28. (1995).