

## Exploring Structure and Stress from Depth to Surface in the Wairakei Geothermal Field, New Zealand

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### ABSTRACT

Structures such as fractures and faults have an important role as fluid flow pathways in geothermal fields, as the reservoir rocks hosting geothermal resources can often have little to no intrinsic permeability. As such, understanding and characterizing this structural network is vital to developing reservoir models and field operation and development plans that will maximize the potential of a geothermal resource. Presented here are the preliminary results of three recent studies, micro-earthquake analysis, borehole logging, and active fault mapping, carried out in the Wairakei Geothermal Field to determine the structural character of the system, if and how it contributes to fluid flow, and how the structural observations from these studies inform and relate to each other. Across all three techniques a dominant NE-SW structure strike orientation is observed with lesser population of N-S, E-W and NW-SE, consistent with the broad Taupo Volcanic Zone observed trend. Further analysis of the data is required to resolve important structural questions around the Wairakei Geothermal Field including: whether the data supports the model of the Wairakei Geothermal Field being an expression of enhanced permeability due to its location in an inferred rift accommodation zone, how the links between observed structures at the surface and subsurface can be resolved, and what role to these structures play in geothermal fluid flow from depth to surface?

### 1. INTRODUCTION

Geothermal resources hosted within crystalline, volcanic, and plutonic rocks, and indurated, metamorphic basement rocks have permeability invariably confined to faults and fractures, with small contributions made by intrinsic permeability (Brace, 1980; Wood et al., 2001; Sausse et al., 2006; Davatzes and Hickman, 2010; Dezayes et al., 2010). As such, geological investigation that reveals insights into the architecture of a geothermal resource's structural (fault and fracture) system is vital for a resource's development. The Wairakei Geothermal Field (WGF), located within the Taupo Volcanic Zone (TVZ), is one such resource, as the deeper reservoirs (>1.5 km) are hosted within compact, altered volcanoclastics and lava flow deposits.

In this paper we discuss recently acquired data from active fault mapping (Villamor et al., 2015), borehole televiwer (BHTV) logging (Massiot et al., 2013), and microseismicity datasets (Sepúlveda et al., 2013; 2015) in the WGF in order to provide new insights into the structural character of the field, how this structural data relates to the current model of the WGF being situated within an accommodation zone, and how structures are contributing to geothermal fluid flow in the field. Additionally we lay out plans for ongoing research and detailed analyses of these latest datasets.

### 2. GEOLOGICAL AND STRUCTURAL SETTING

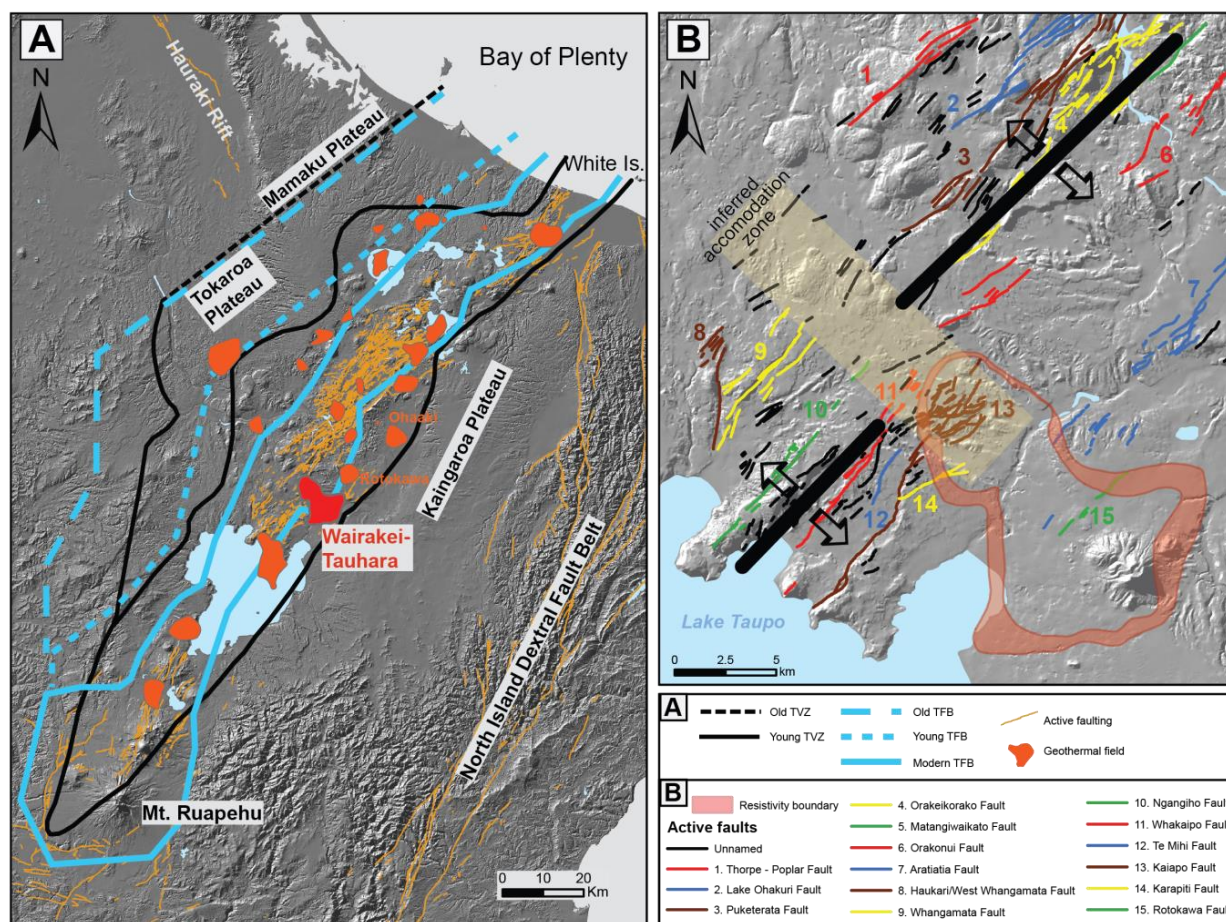
#### 2.1 Structural Components of the Taupo Volcanic Zone

The TVZ represents a rifting arc structure formed as a result of subduction of the Pacific Plate beneath the North Island of New Zealand. Chronologically, volcanic products of the TVZ can be grouped into the Old TVZ (2-0.35 Ma) and the Young TVZ (last 350 ka) (Wilson et al., 1995; Figure 1A). The rifting zone of the TVZ, referred to as the Taupo Fault Belt (TFB; also referred to as the Taupo Rift), is dominated by NE-SW striking faults and has experienced a NW-SE extension direction since >4 Ma (Acocella et al., 2003; Nicol et al., 2006; Seebeck et al., 2014; Figure 1A).

The TVZ also contains other notable structural orientations. Mordriniak and Studt (1959) interpreted NNW-SSE striking faults from gravity and magnetic data, while Cochrane and Tianfeng (1983) used landsat data, aerial photos, and second order residual gravity anomalies to infer NW-SE and NNW-SSE trending faults in greywacke basement across the TVZ. The NNW-SSE striking basement faults were inferred to be continuations of the Hauraki Rift. Other studies of basement fault trends (air photo lineaments and field mapping of basement greywacke exposure to the SE of Lake Taupo) show NW-SE and N-S oriented structures (Spörli, 1987). N-S trending structures are also defined within the TFB by topographical mapping and seismic interpretation, and are inferred to be reactivated basement fabrics (Seebeck et al., 2010). Acocella et al. (2003), report NW-SE, N-S and E-W structural fabrics from measurements of fault traces and joints across the TVZ and TFB.

Rowland and Sibson (2001) show that TVZ faults downthrown to the NW and SE show strong spatial polarity, and defined rift axes locations where a clear switch in the dominant dip direction was observed. Offsets between rift segments are referred to as accommodation zones and have been described as hard-linked (transfer/strike-slip faults) and soft-linked (relay structures) in different areas of the rift (Rowland and Sibson, 2001; Acocella et al., 2003; Spinks et al., 2005; Begg and Mouslopoulou, 2010; Seebeck et al., 2010). These proposed accommodation zones appear to correlate spatially with inferred NW-SE and NNW-SSE striking basement faults (Rowland and Sibson, 2001) and with the spatial distribution of the TVZ geothermal fields (Rowland and Sibson, 2004).

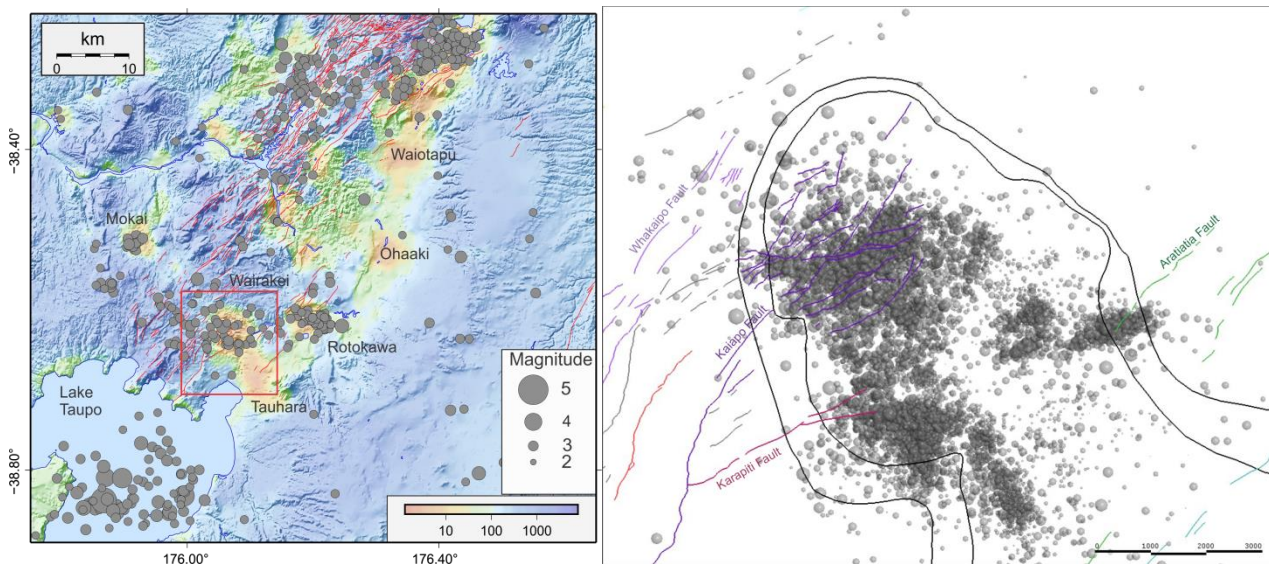
Faulting in the TFB is described as pure normal to normal with a small strike-slip component (Villamor and Berryman, 2001; Hurst et al., 2002; 2008). The dominant NE-SW fault strike orientation, focal mechanisms, and stress data from BHTV logging define a vertical stress component ( $\sigma_1$ ;  $S_v$ ), a NE-SW oriented maximum horizontal stress component ( $\sigma_2$ ;  $S_{Hmax}$ ), and a horizontal minimum stress component ( $\sigma_3$ ;  $S_{Hmin}$ ) aligned approximately NW-SE across the TVZ (Villamor and Berryman, 2001; Hurst et al., 2002; 2008; McLean and McNamara, 2011; Townend et al., 2012; Wallis et al., 2012; McNamara et al., 2013; Seebeck et al., 2014; McNamara et al., 2015), which is consistent with the extensional setting of the region. Evidence of strike-slip faulting in the TVZ and TFB is uncommon though is inferred from a number of sources; a) steepness of fault dips, b) en echelon geometry of faults, c) horsetail splaying of major NE-SW trending faults and, d) the intersection of the North Island Dextral Fault Belt (NIDFB) with the TVZ where strike-slip faults in the basement of the TVZ are inferred (Cole, 1990; Rowland and Sibson, 2001). Active fault scarps, which show excellent surface expression in the TVZ, show very little geomorphic evidence of strike-slip displacement of creeks, rivers, terrace risers and other morphological features (Villamor and Berryman, 2001).



**Figure 1: A) Map showing the location of the Taupo Volcanic Zone and its component subdivisions (based on volcanology and structure), the location of the Taupo Fault Belt, and locations of geothermal fields in the North Island of New Zealand (modified from Wilson and Rowland, 2016). B) Map showing the location of the Wairakei and Tauhara geothermal fields (defined by Risk et al. (1984) resistivity boundary), local active faults (Langridge et al., 2015), and the inferred accommodation zone, rift segments and axes from Rowland and Sibson (2001) (modified from Villamor et al., 2015).**

Focal mechanism studies of small earthquakes in the TVZ show a combined normal and strike-slip component, while larger events were pure normal faulting (Anderson et al., 1990; Bibby et al., 1995; Hurst et al., 2002). A strike-slip stress regime has been noted for the southern TVZ based on focal mechanism studies done on earthquakes in the mid-crust (~40 km), southeast of Mt. Ruapehu (Reyners, 2010), however, geomorphic expression of current fault activity and paleoseismic studies suggest purely normal faulting in multiple directions inferring radial extension (Villamor and Berryman, 2006a).

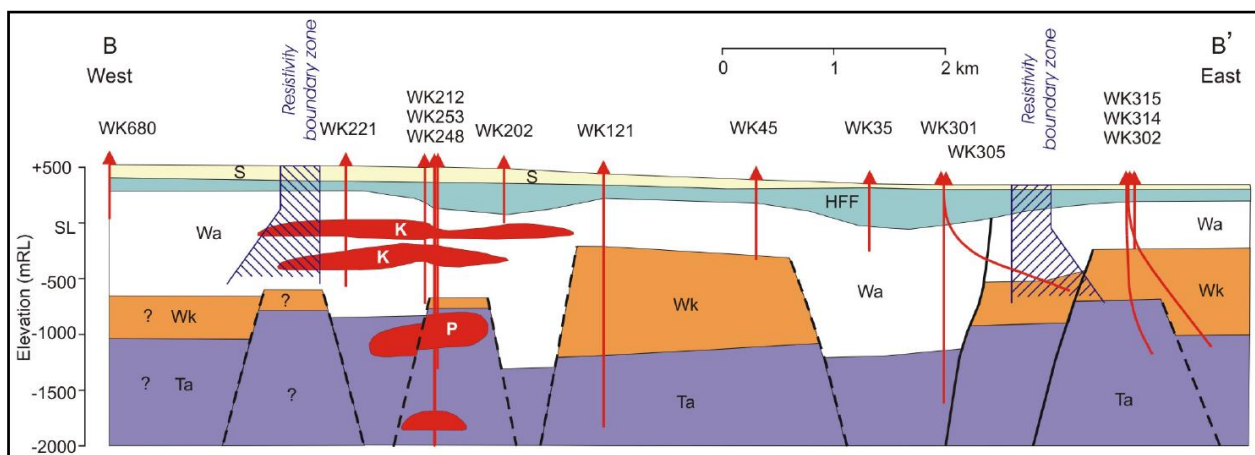
Correlation of the seismicity to active structures and geothermal expression remains equivocal. There are areas with seismicity where no surface faulting is identified, yet some seismicity does occur in close proximity to identified NE-SW oriented surface faulting (Hunt and Latter, 1982; Sherburn et al., 1990; Sherburn, 1992; Sepúlveda et al., 2012; Sepúlveda et al., 2013; Sepúlveda et al., 2015). Some geothermal fields (e.g. Wairakei, Rotokawa, Mokai, and Kawerau) correlate spatially with earthquake locations. For example, earthquake locations (Geonet database, www.geonet.org.nz, last accessed 25<sup>th</sup> Jan 2016) of events with local  $M_f$  magnitudes 2.5 – 5.5, occurring between 2001 and 2015, show clusters of activity near the Wairakei and Rotokawa geothermal fields (Figure 2). While some spatial correlation can be made between the seismicity and the geothermal fields only some of these identified fields contain faults with surface expression (Wairakei, Waimangu-Waiotapu). Other geothermal fields, (with or without mapped faults) appear to be aseismic (e.g. Taheke-Tikitere, Broadlands-Ohaaki, and Tauhara). In addition determining seismicity due to geothermal field operation from natural seismicity due to rifting or volcanological TVZ activity is difficult, making it hard to fully explain these complicated, observed spatial patterns.



**Figure 2: A) Resistivity map (modified from Bibby et al. 1998) of the region north of Lake Taupo with labeled geothermal fields and locations of earthquakes (grey circles) above magnitude 2.5 and shallower than 34 km from the New Zealand GeoNet earthquake catalogue ([www.geonet.org.nz](http://www.geonet.org.nz) ; last accessed 22<sup>nd</sup> December 2015). The red square represents the map presented in Figure 2B. B) Map of the WGF showing the locations of earthquakes above magnitude 0 and shallower than 4 km from the Wairakei Seismic Network, for the period 2009-2015.**

## 2.2 Structural Components of the Wairakei Geothermal Field

Historically, structural studies of the WGF have relied on digital terrain model analysis, rare outcrop exposure, and local fault trench excavations (Villamor et al., 2015). Seismic surveys reveal little about subsurface structures due to interference from high natural ground level noise and high attenuation (Mordriniak and Studt, 1959; Hunt et al., 2009). Geophysical surveys (gravity and magnetic) (Mordriniak and Studt, 1959; Rogan, 1982; Hunt, 1991; Soengkono and Hochstein, 1992; Stagoole and Bibby, 1999) combined with studies of regional basement structures, and drill-hole data were used to define a regional NE-SW striking graben situated under the WGF (Rowland and Sibson, 2001; Rae et al., 2007; Rosenberg, et al., 2009). Further study on the drilled geometries of deeper WGF formations supports this model (Figure 3) (Rosenberg et al., 2009, Bignall et al., 2010).



**Figure 3: Structural 2D interpretation of the Wairakei Geothermal Field (from Rosenberg et al., 2009). Faults are simplified (inferred as dashed) to highlight controls on thickness of Waiora Formation and Wairakei Ignimbrite. Abbreviations: Superficial (S); Huka Falls Fm. (HFF); Waiora Fm. (Wa); Karapiti Rhyolites (K); Poihipi Rhyolites (P); Wairakei Ignimbrite (Wk) and Tahorakuri Fm. (Ta). mRL: meters with respect to sea level.**

Field scale studies on fault traces and outcrop (Grindley, 1965; Rowland and Sibson, 2001; Sepúlveda et al., 2012) provide detailed structural data at WGF. Fracture orientation data from limited, exposed outcrop in the area around the WGF shows a dominant NE-SW fracture strike orientation with subordinate N-S and NW-SE oriented populations (Rowland and Sibson, 2001; Acocella, 2003; Sepúlveda et al., 2012). Fault traces, scarps, and lithological offsets between adjoining wells defined active, NE-SW striking, steeply dipping ( $68^\circ - 85^\circ$  to the SE) normal faults, and NW-SE striking faults that intersect them (Grindley, 1965). These NW-SE oriented faults were inferred to be concurrent with the development of the NE-SW striking faults, rather than being reactivations of inherited older basement structures. Mordriniak and Studt (1959) postulated a NW-SE trending graben (Maroa Graben) to the north of the WGF by linking strong, negative Bouguer anomalies with the SW boundary fault passing through the WGF. One of the NW-SE striking basement faults inferred by Cochrane and Tianfeng (1983) (the Mangakino Wairakei-Ahimanawa Fault) spatially intersected the Wairakei and Tauhara geothermal fields. However, the presence of these NW-SE structures is unsupported by drilling data (Grindley, 1965; 1982). Based on rift axes locations it is inferred that the WGF lies within a TVZ accommodation zone (Figure 1B), where the rift axis is offset to the northwest (Rowland and Sibson, 2001; 2004). The presence of an accommodation

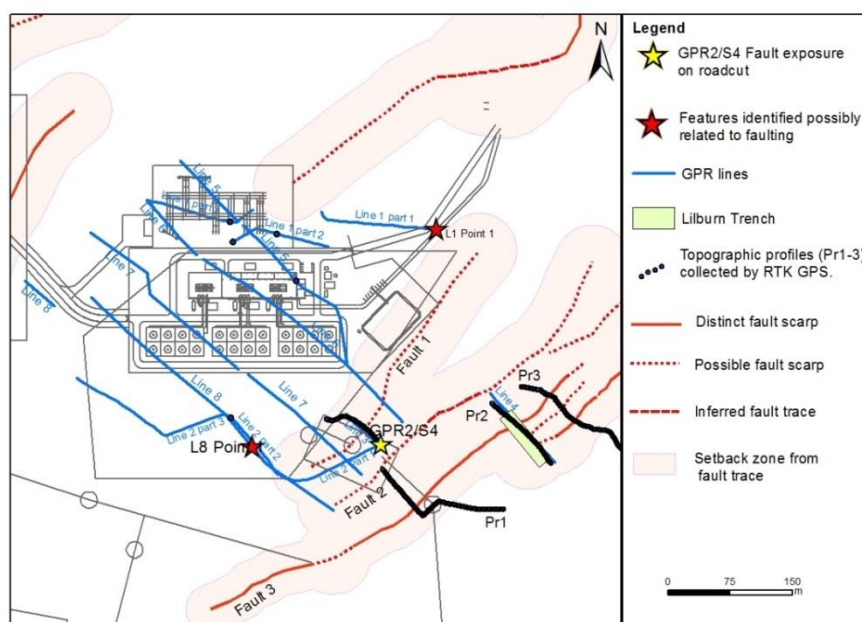
zone at the location of the WGF is correlated with the presence of the inferred NW-SE oriented basement faults (Rowland and Sibson, 2001).

### 3. RECENT STRUCTURAL STUDIES

#### 3.1 Surface Structures and Active Faulting

The faults comprising the TFB at the latitude of the WGF comprise, from east to west, the Rotokawa, Aratitia, Karapiti, Kaiapo, Whakaipo, Nagagiho and Whangamata faults (Figure 1B). Some of these structures were first described by Grindley and Hull (1986) and were added and updated into subsequent versions of the New Zealand active fault database (Langridge et al., 2015) and into modern geological maps (Leonard et al., 2010). Some faults such as the Kaiapo and Whakaipo faults have undergone partial fault rupture (over only a few kms of their lengths) in association with earthquake swarms e.g. during the 1922 earthquake swarm (Grindley and Hull, 1986).

Through analysis of aerial photographs and field studies (ground penetrating radar and paleoseismic trenching), Villamor et al. (2015) mapped a number of active faults in the Te Mihi area of the WGF (Figure 4). These faults were mapped on the basis that they display geomorphic fault scarps on the Oruanui ignimbrite constructional surface (~25 ka), such that they displace that surface and thus have been active at least in the last ~ 25 ka. These active fault traces in the WGF show a dominant NE-SW strike orientation with some minor E-W strike orientations. Based on their geomorphic expression, both fault sets are normal faults (with clear vertical displacements) with no geomorphic expression of lateral displacement (no strike-slip component). However, to date, only exposures of the NE-SW trending faults have been studied (Villamor et al., 2015). No other fault orientations with geomorphic expression of recent surface rupture are observed. Rosenberg et al. (2009), using this active fault mapping, show NE-SW striking faults in various concentrations across the WGF. Faulting is dense in the NW (Te Mihi area) of the field and only a few faults appear to the SE of the field. Subsurface offsets observed in the Wairakei Ignimbrite imply displacement on a fault zone that may be an extension of the Kaiapo Fault in the Te Mihi area.

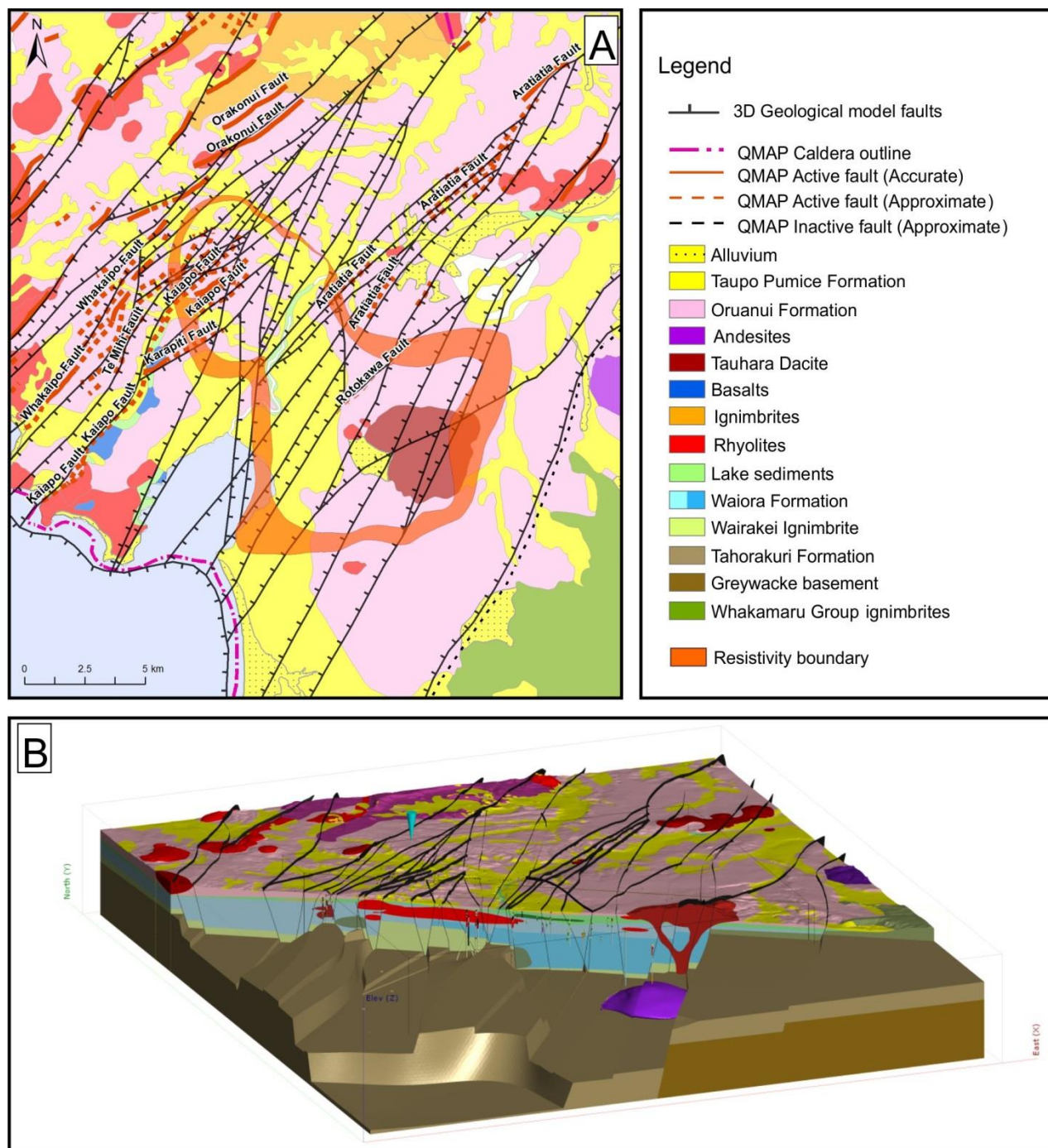


**Figure 4: Location of GPR lines, paleoseismic trench and logged outcrop around the proposed site of the Te Mihi Power Plant infrastructure. The classification of fault scarps is as per initial mapping prior to excavation of trenches and GPR survey (from Villamor et al., 2015).**

#### 3.2 Subsurface Structure

##### 3.2.1 Structures Determined from 3-D Geological Modeling

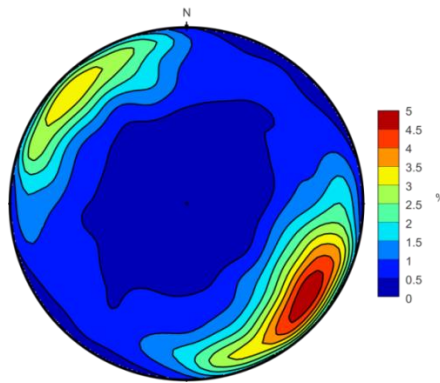
Recent 3-D modeling of the geology of the WGF (shown here and from Alcaraz et al. (2010)), integrating fault surface traces and major subsurface offsets in stratigraphic units between boreholes, displays dominant NE-SW, and rare N-S fault strike orientations (Figure 5). The geological model, being one interpretation of the data, is built using geological information from 261 wells, including recent deep wells in the Te Mihi area. Offsets of the deepest, oldest formations, used to infer faults at depth, are correlated to their most likely surface traces. Key stratigraphic units, including regionally extensive ignimbrites and localized lavas, can show subsurface offsets of up to 250 m in the Te Mihi area. In areas of the Wairakei-Tauhara geothermal system where no surface faults have been identified, particularly in the southeast, 3-D geological modeling has helped identify potential buried faults. 3-D geological modeling illustrates that even in areas where direct observation for faulting is lacking (from surface or borehole measurements); structural complexity may still be present at depth.



**Figure 5: A. Geological map of the Wairakei-Tauhara area (Leonard et al., 2010) with superimposed fault traces from 3-D geological modeling. B. 3-D geological model, looking approximately NE, of the Wairakei-Tauhara area, partially sliced NW-SE across the geothermal systems to show a cross-section. Faults are represented by black lines on the model.**

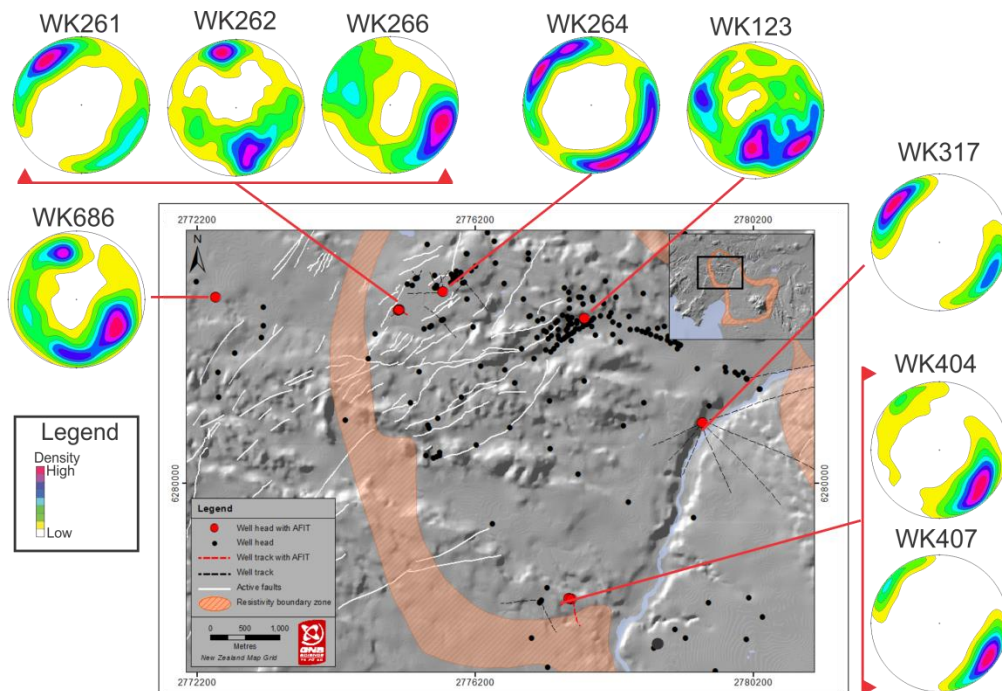
### 3.2.2 Borehole Televiewer Log Data

Since 2009 a number of BHTV logs have been acquired in the WGF; WK686, WK123, WK317, WK404, WK407, WK261, WK262, WK266, and WK264 (Figure 7). Structure and stress patterns from the initial interpretation of portions of these BHTV logs (4077 m from a total of 6258 m acquired BHTV log) is reported by Massiot et al. (2013). From the current interpretation of the WGF BHTV logs, 5595 structural features have been identified. Fractures with a low acoustic amplitude constitute ~99% of the data with the final 1% having high acoustic amplitude. Only three features displayed observable offsets or truncations of other natural features and are classified as faults. Fractures identified with low confidence (poorly resolved on the BHTV log) make up 14% of the dataset but are interpreted with enough confidence to be of geological origin rather than BHTV image or drilling artifacts. Structure orientation measurements (from the entire dataset) show a dominant NE-SW strike orientation with a dominant dip direction to the NW (27% of fractures; 15% dip to the SE). Subordinate populations of the fracture dataset strike N-S (26%; 16% dip W, 10% dip E), strike E-W (21%; 12% dip N, 9% dip S), and strike NW-SE (10%; 5% dip NE, 5% dip SW). Most fractures (75%) have dip magnitudes  $\geq 60^\circ$ .

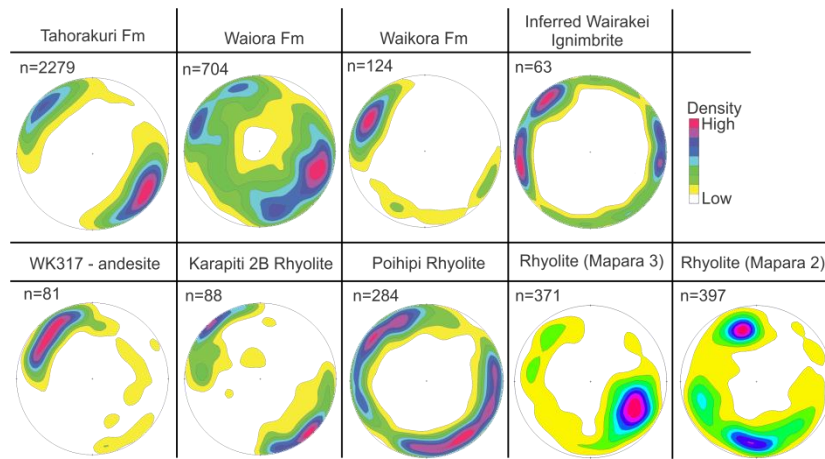


**Figure 6: Fisher contoured, lower hemisphere stereonet of poles to planes of all structures identified from all BHTV logs acquired in the WGF.**

When assessing the fracture orientations in individual wells some, such as WK404 and WK407, display similar fracture orientation trends to that observed for the entire WGF dataset (dominantly dipping to the NW; Figure 6). Contrary to this, fractures observed in well WK317 show a dominant dip direction to the SE, antithetic to the dominant WGF dip direction (except for WK266). This variation between dominant NW and SE dipping fracture orientation may be related to proximity to faults with those same variations in dip direction across the WGF, forming conjugate fault sets. Three wells drilled from the same pad in the Te Mihi area (WK261, WK262, and WK266) also display different dominant fracture orientations. WK261 shows NE-SW strike orientations with a dominant SE dip direction, WK262 shows E-W fracture strike orientations dipping both north and south, and WK266 displays dominant NNE-SSW strike orientation with a prevailing WNW dip direction (Figure 7). The BHTV logs for these three wells only overlap the same depth intervals for ~90 m of their length (between WK262 and WK266). Thus, the observed variations in fracture strike orientation may be depth related. Current data indicates some structural orientation variation with depth may be related to lithology (Figure 8). BHTV logged intervals of Tahorakuri and Waiora formations from all wells show that there is a dominance of NW dipping fractures, while fractures observed in BHTV logged intervals from the Waikora Formation show dominant SE dip orientations. Some of the subordinate structural orientations observed from the BHTV data show particularly high densities in specific lithologies (e.g. the Mapara 2 Rhyolite contains numerous E-W striking fractures, and the Wairakei Ignimbrite has a high proportion of N-S striking fractures).



**Figure 7: Map of the WGF showing Fisher contoured, lower hemisphere stereonet of poles to planes of structures identified from well with an acquired BHTV log.**

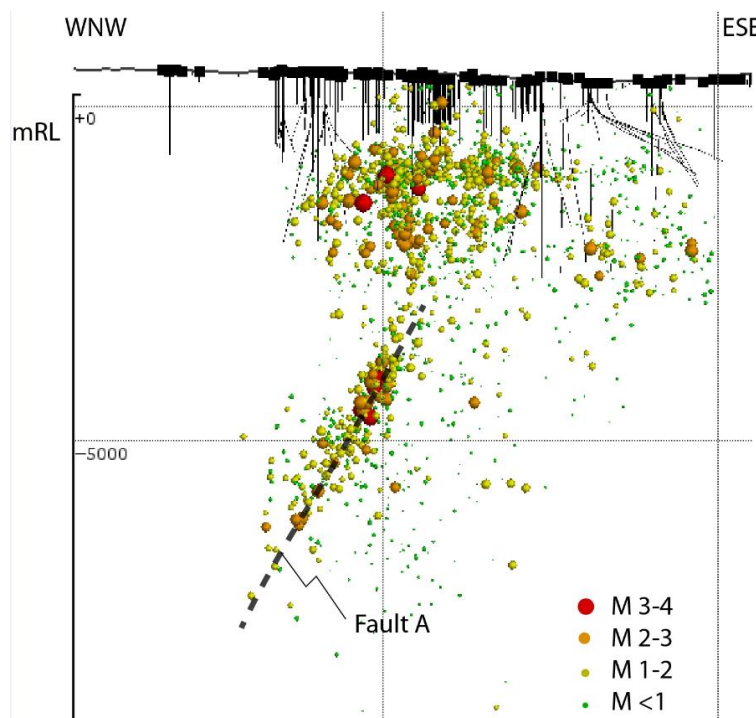


**Figure 8: Fisher contoured, lower hemisphere stereonet projections of poles to planes of structures identified within lithologies over which a BHTV log was acquired in the WGF.**

### 3.3 Structural Insights from Seismicity

Thirteen borehole seismometers, installed at depths ranging from 65 to ca. 1200 m, have been operational at the WGF since 2009 (Sepúlveda et al., 2013), providing unprecedented detail of the seismic structure of this geothermal system. Due to higher sensitivity of the local network relative to the regional GeoNet network (Boese et al., 2014), previously undocumented structural features could be recognized, at shallow (< 3 km) depths, including a ENE-WSW (Karapiti-Otupu Fault) and NE-SW (Alum Lakes Fault) trending seismic clusters (both dipping ~NW). The microearthquake hypocenter data also shows that, although the bulk of the shallow microseismicity (< 3 km depth) is within the shallow boundary of the WGF, there is also some deeper seismicity (3-7 km) offset to the NW of the field (Sepúlveda et al., 2013). The hypocenters of this deeper microseismicity define NE-SW (Te Mihi-Poihipi Fault (TM-PO), dipping NW), and NW-SE (Western and Central Faults) striking linear features (Figure 9).

Shallower seismicity observed beneath the WGF show strong spatial-temporal characteristics, with clustered bursts of activity, for both production and reinjection areas. Increases in microseismicity have been noted in some areas following the onset of reinjection, while episodes of increased seismicity are also noted, associated with reduction in fluid extraction (Sepúlveda et al., 2015). Few moment-tensor mechanisms are available for earthquakes near the WGF (Kim et al., 2014). A moment-tensor solution for a 8 km deep,  $M_w$  3.7 earthquake (Geonet Event ID: 2015p495943) beneath the field shows strike-slip faulting on a N-S striking, sub-vertical plane (strike  $\sim 180^\circ$ , dip  $\sim 85^\circ$ ), but requiring 30% compensated linear vector dipole (CLVD), which suggests fluid-assisted faulting.



**Figure 9: WNW-ESE cross-section in the direction perpendicular to the NNE-SSW strike of deep TM-PO fault, interpreted from linear distribution of microseismicity (period 2009-2013; from Sepúlveda et al., 2013). Events colored and sized by magnitude.**

## 4. DISCUSSION

### 4.1 The Structural Nature of the Wairakei Geothermal Field

A variety of studies have presented structural data for the WGF which is located in a structurally complex and tectonically active area of the TVZ. The approximate horst and graben structure of the system is defined from geophysical methods and well geology, but a definitive 3D interpretation of this structure remains unresolved. Orientation trends in the active faulting (dominantly NE-SW, E-W, and N-S striking) are mirrored in the modeled fault orientations, structural trends identified from BHTV logging, and linear trends identified from seismicity in the WGF. This suggests that dominant structural patterns are consistent with the active, NE-SW tectonic trend observed across the TVZ.

Despite this observed consistency in structural orientation between the three different datasets, and the added detail they bring to the characterization of the WGF structural architecture, it remains unclear whether there is a link between the active faults we observe at surface and the shallow and deep seismicity patterns. This is mainly due to the uncertainty of the architecture of the larger structures in the subsurface and on how the active faulting at the surface connects to these with depth. In fact seismicity patterns seem to imply that faulting structure varies with depth, something that may be reflected by the inconsistent fracture orientations observed from BHTV logs. A further topic that warrants investigation is the triggering mechanisms for seismicity in the WGF. While some seismicity seems to delineate structural planes, the more diffuse hypocenter locations of seismicity may reflect processes such as thermal contraction (Sherburn et al., 2015).

Structural evidence for large scale NW-SE structures in the basement rock underlying the WGF is based upon interpretations of various types of geophysical mapping, and deep (>3 km) NW-SE linear trends in seismicity. The current model for the nature of these NW-SE structures is that it represents a regional scale fault or faults associated with an accommodation zones between TVZ rift segments. It is unclear whether the small proportion (10%) of NW-SE striking fractures observed from BHTV logs from 1-3 km deep in the WGF are related to these similarly oriented, deeper faults or whether this fracture set developed as part of a connected network concurrent with the dominant NE-SW tectonic trend. Similarly it is difficult to constrain the relationship of these inferred NW-SE striking faults to the dominant structural patterns observed in the upper few kilometers and surface of the WGF, which lack an observable NW-SE orientation trend.

### 4.2 The Role of Structure in the Permeability in the Wairakei Geothermal Field

The role of structure in permeability in the WGF is documented by a number of authors. Mordriniak and Studt (1959) suggested that their NW-SE trending, Maroa Graben boundary faults controlled hydrothermal expression, particularly where they intersected NE-SW striking structures. These boundary faults were thought to coincide with the Wairakei-Tauhara System to the SW, and to the Rotokawa, Ngatamariki, Orakei Korako, and Atiamuri on the NE side of the graben. Grindley (1965; 1982) had similar ideas, stating that the main structures identified in his work were the primary fluid flow pathways supplying the Waiora geothermal aquifer in the WGF. He also noted that major zones of heat loss occurred where NW-SE trending faults intersected NE-SW trending structures. This theory of intersecting orthogonal fault orientations relating to areas of enhanced permeability is expanded by Rowland and Sibson (2004) who show that 80% of the geothermal fields in the TVZ correlate with rift structures, and that 60% are located in the areas associated with the inferred locations of the accommodation zones. These accommodation zones are linked to inferred NW-SE striking structures in the basement at depth, and intersection of these structures with modern structural architecture (NE-SW striking faults) creates enhanced vertical permeability.

The WGF lies within a TVZ accommodation zone and thus intersecting, NE-SW and NW-SE striking, large scale, structures are inferred to control the permeability of this resource. To date no significant NW-SE structure has been directly identified in the WGF, though direct structural orientation observations (Massiot et al., 2013; Villamor et al., 2015) and modeled fault orientations (Alcaraz et al., 2010) are only available from the top three kilometers of the field where the basement greywacke, inferred to underlie the Tahorakuri Formation, has yet to be drilled. The NW-SE elongate shape of the Wairakei-Tauhara resistivity pattern (Risk et al., 1984) may be a result of a NW-SE oriented accommodation zone facilitated by a similarly oriented basement structures (Rowland and Sibson, 2004). However it has also been suggested that this resistivity pattern may represent a hydrological link controlled mainly by formation permeability (within the Wairakei Ignimbrite or brecciated zones of the Karapiti 2A Rhyolite) rather than structure (Rosenberg et al., 2009; Milloy and Lim, 2012). Recent studies of seismicity in and around the WGF however, offer support for the presence of deep NW-SE trending structures. Hypocenters of deep microseismicity (> 3km) under the WGF appear to define NW-SE trending linear features, which may indicate structurally-controlled up-flow (Sepúlveda et al., 2013).

Reservoir tracer tests in the WGF indicate that NE-SW oriented faults form important fluid flow pathways, channeling fluid from deep reinjection zones to the producing wells, along strike (Bixley et al., 1995; Bixley et al., 2009). In addition these studies also suggest little cross-fault flow occurs across NE-SW oriented structures. Correlation of structural data acquired from BHTV logs (from wells WK317, WK404, WK407) to pressure, temperature, and spinner (PTS) logging (McLean and McNamara, 2011) shows that wide aperture fractures (interpreted as zones of dense fracturing) correlate with feed zone locations in some wells. In other wells, individual, or groups of fractures, appear responsible for distinct changes in well temperature profiles. These studies indicate that structure plays an important role for permeability in the WGF, at least at depths from 1.5 to 3 km.

## 5. SUMMARY AND FUTURE WORK

While significant investigation into the structure of the WGF has occurred there are still important problems to resolve. The larger issues relevant to the study of the WGF, given its location within an inferred accommodation zone in a structurally complex rift, include; the nature of the NW-SE oriented structures inferred at depth (hard-linked or soft-linked, regional scale basement structures or local accommodation structures formed during the rifting process), determining the reason for a lack of NW-SE oriented structures in the shallow crust given their inferred presence at depth, determining the nature and cause of structural orientation heterogeneity across the field, and determining what role the interplay between structure and stress field orientation variability has on fluid flow.

To do this further data analysis is proposed to be carried out on a variety of structural datasets from the WGF. Detailed interpretation of existing and newly acquired BHTV logs in the WGF, and analysis of structure and stress trends is required to develop understanding of the nature of structural variability in the upper 3 km of the field, and what role lithology has to play in any observed variability. Additionally this data needs to be analyzed in comparison with well test logs that provide indications of permeability to gain a better understanding of the role of structure in fluid flow in the WGF. Furthermore, observed structural patterns from BHTV logs need to be related to the 3-D modeled macro-structural character, which in turn will provide a clearer understanding on whether surface and subsurface faults are linked and what the nature of this linkage may be.

New moment-tensor, full-waveform inversions of the deeper (3-7 km) microseismicity are underway, focused on examining the source mechanisms of  $M_l$  2-3 earthquakes near and beneath WGF. This includes analysis of deeper earthquakes occurring on the Te Mihi-Poihipi Fault inferred to be located NW of the WGF. This seismic moment analysis will primarily use seismic waveform data from the WGF borehole seismic network, complemented by waveform data from the GeoNet national seismograph network, and temporary broadband seismometers located just outside the WGF. We anticipate that the analysis will provide additional constraint on the orientation of deep faults in the proximity of the WGF, and provide information on the nature of these deeper seismic events.

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