# A STRUCTURAL MODEL FOR THE ROTOKAWA GEOTHERMAL FIELD, NEW ZEALAND

Irene C. Wallis[1], Candice J. Bardsley[1], Tom S. Powell[2], Julie V. Rowland[3] and Jeremy M. O'Brien[1]

[1]Mighty River Power, 283 Vaughan Road, Rotorua, 3010

[2]Powell Geoscience, 17 Pryce Road, RD5, Rotorua, 3076

[3]School of Environment, University of Auckland, Private Bag 92019, Auckland

irene.wallis@mightyriver.co.nz

**Keywords:** *Rotokawa Geothermal Field, structural model, acoustic image, fault and fracture distribution, uncertainty analysis, Aratiatia Fault Zone*

## ABSTRACT

Developing a structural model is a key part of exploring and developing a geothermal resource. Along with the impact structure has on a field's stratigraphy, faults are commonly evoked as permeability conduits and barriers. Subsequently their likely location is a key input into the reservoir conceptual model, well planning activities, reservoir numerical simulations and, in some cases, reservoir pressure distribution and well transient analysis. Developing a structural model for a volcanic-hosted geothermal system is a challenging undertaking because: (1) surface geophysical techniques typically used in other sectors of the resources industry, particularly reflection seismics, are limited by the highly attenuating clay cap and, if present, two-phase zones; (2) volcanic deposits are challenging to accurately identify because textures are difficult to identify in small drill cuttings where hydrothermal overprinting can be extensive and deposits commonly have complicated paleo-topography ; and (3) in contrast with mineral developments in epithermal environments, stratigraphy is often poorly constrained as geothermal developments typically comprise few wells, recovery of geologic material is commonly impoverished and wireline logging is rarely employed to correct/reconstruct well stratigraphy. It follows that, along with offering a simple and defensible fit to available data, structural models developed under these conditions need to articulate the associated uncertainty.

The present paper describes the most recent iteration of the Rotokawa structural model. This model comprises three large north-northeast striking structures and a deep, narrow NE-SW orientated depression, here interpreted as a paleo-valley. The Rotokawa structural model has been developed to fit the geology below the Wairakei Ignimbrite (around 1400 mVD), as this is the depth interval of greatest interest to the developer. Each fault in the Rotokawa structural model has an associated uncertainty derived by combining factors which account for our confidence in whether the fault is present at all, as well as the degree that the strike and dip magnitudes can be changed. Overall confidence in the present model is increased by its consistency with the regional structural setting, local micro-seismicity (Sewell et al. 2013) and available image log data.

## 1. INTRODUCTION

Understanding the geologic structure of a geothermal system is a key piece of geoscience required to successfully develop the resource because it underpins the conceptual model and commonly guides well targeting. As a field is developed and new data comes to hand, the geologic and structural models are updated, along with the conceptual model at times. Together these provide frameworks for interpreting and predicting (modelling) well behaviours as part of prudent reservoir management.

The interaction between structures and the reservoir, however, is not fixed though time – faults that at one time were across-strike barriers to fluid flow can become leaky and conversely zones of large-scale flow can plug with mineral precipitates (Rowland & Simmons 2012 and references therein). These dynamic processes are evidenced by both well behaviour changes and the distribution of micro-seismicity in the reservoir. For example, Quinao & Sirad-Azwar (2012) observed a significant change in mass-supply in two wells (RK14 & RK5). One proposed explanation is a change in the permeability structure of the reservoir volume adjacent these wells, possibly due to changes in the pressure conditions resulting in an across-strike barrier to fluid flow to leak. The next step to understanding phenomena like these is to synthesise the structural model, our understanding of the stress conditions within the reservoir (Davidson et al. 2012) and our reservoir monitoring (micro-seismic and well condition) into a single integrated model.

The present paper describes the current iteration of the Rotokawa structural model and how this model relates to acoustic image logs from two Rotokawa wells. It also discusses issues of uncertainty in these kinds of models and proposes one method of articulating that uncertainty.

### 1.2 Geologic and Structural Setting of the Rotokawa Geothermal Field

The ca. 2 Ma Taupo Volcanic Zone (TVZ) is an actively rifting volcano-tectonic depression, formed within a Mesozoic metasedimentary basement (Wilson et al., 1995). The active rifting of the TVZ is the result of oblique subduction of the Pacific Plate under the North Island. Quaternary basins comprising andesitic, dacitic and rhyolitic lavas, airfall deposits, and lake sediments, are cut by numerous subparallel northeast-southwest striking normal faults, which presumably root onto inherited structures within the basement. Rotokawa is located in the east-central part of the TVZ, about 12 km northwest of the town of Taupo (Figure 1). The Aratiatia Fault Zone is located to the north of the field and is the dominant known site of active faulting in the area. It forms the eastern boundary of the active Taupo Fault Belt (Villamor and Berryman 2001, Figure 2). Numerous geothermal resources occur nearby including Tauhara, Wairakei and Ngatamariki geothermal fields (Fig. 1).

Within the Rotokawa geothermal field, Lake Rotokawa is the major geothermal manifestation. This lake occupies a young (6060 ybp, Collar and Browne 1985), large (~1 sq.

km) hydrothermal eruption crater, which is the southwestern example of several such features that form a NE-SW alignment through the middle of the field. A fumarole is also associated with this vent alignment (Figure 2). Hydrothermal eruption deposits encountered during drilling suggest that associated eruptions at Rotokawa predate the 26,500 yBP Oruanui eruption from Lake Taupo and the deposition of the Huka Falls Formation which is at least 190 ka old (Bignall et.al 2010). It follows that geothermal activity in the field is likely older than 200 ka.

Rotokawa is located on the southern edge of the 340 ka Whakamaru Caldera (Figure 1) which is the source of a thick layer of Wairakei Ignimbrite within the field. The Wairakei Ignimbrite forms the upper reservoir rock of the geothermal resource and at the scale sufficient for recognition using drill-hole stratigraphy (10's of meters), it appears largely uncut by faulting. Therefore, this formation, which lies at approximately 1400 mVD, is the upper extent of the structural model presented here. The Wairakei ignimbrite overlies a faulted and somewhat variable sequence consisting of the Nga Awa Purua Andesite, Tahorakuri Formation ignimbrite, Waikora Formation sediments, Rotokawa Andesite and Torlesse greywacke basement. Prior to 2012 the Nga Awa Purua Andesite was included in the Rotokawa Andesite. It has been separated out because of its stratigraphic position and further work on the geochemistry of this unit is required to confirm it as a separate eruptive episode. Silicic tuffs grouped into the Tahorakuri Formation are found both above and below the Waikora Formation sediments, suggesting that they represent a number of different eruptive events. The Wairakei ignimbrite is overlain by a thick (≤800 m) sequence of Waiora Formation ignimbrite and rhyolite lava, which is in turn overlain by locally derived Parariki hydrothermal eruption breccias, Huka Falls Formation tuffs and sediments and 26 ka Oruanui Formation tuff.

A structural model for the Rotokawa field has been described previously based upon the results of 17 wells (Figure 2: Bannister et al. 2008, Boyer & Holt 2010). The addition of 18 new well penetrations since 2008 has resulted in a revision of this model. Revision included the identification of an additional rock unit (the Nga Awa Purua Andesite), the relocation of faults and the proposition that a paleo-valley is present. The model presented here represents the best-fit to currently available data and, as in the case in any active sub-surface development, it will be redressed with new data that comes to hand.

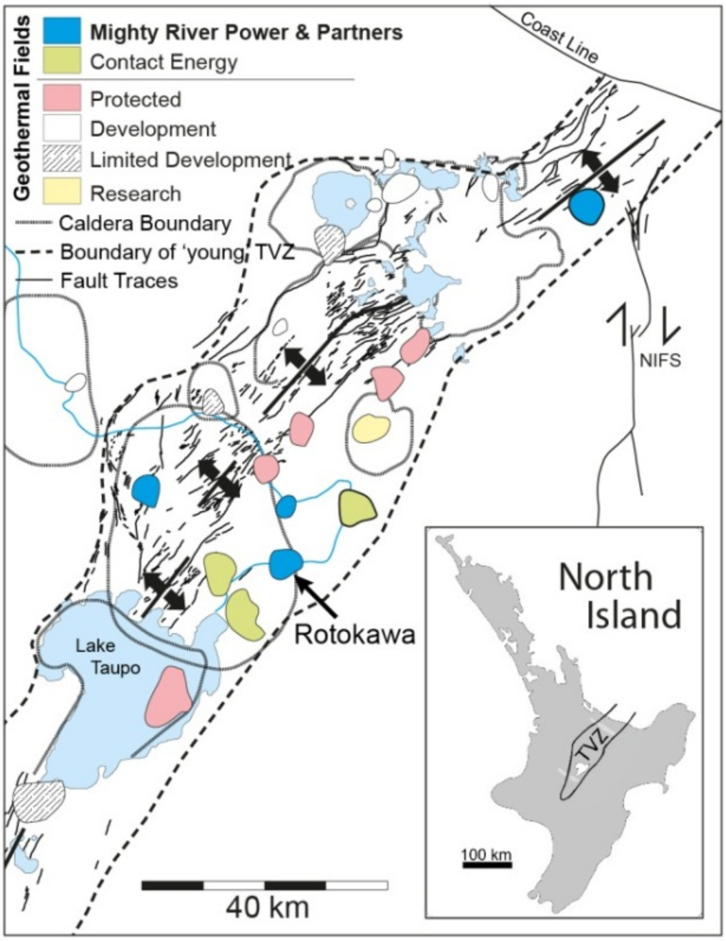


**Figure 1: Rotokawa location within the TVZ geologic and structural setting. Geothermal system locations as defined by Bibby et al. (1995). The centers of spreading for the TVZ rift segments are included to indicate the over-all structural trend. Structural features on this map are after Rowland and Sibson (2004). Fault traces from the GNS Active Fault Database.**

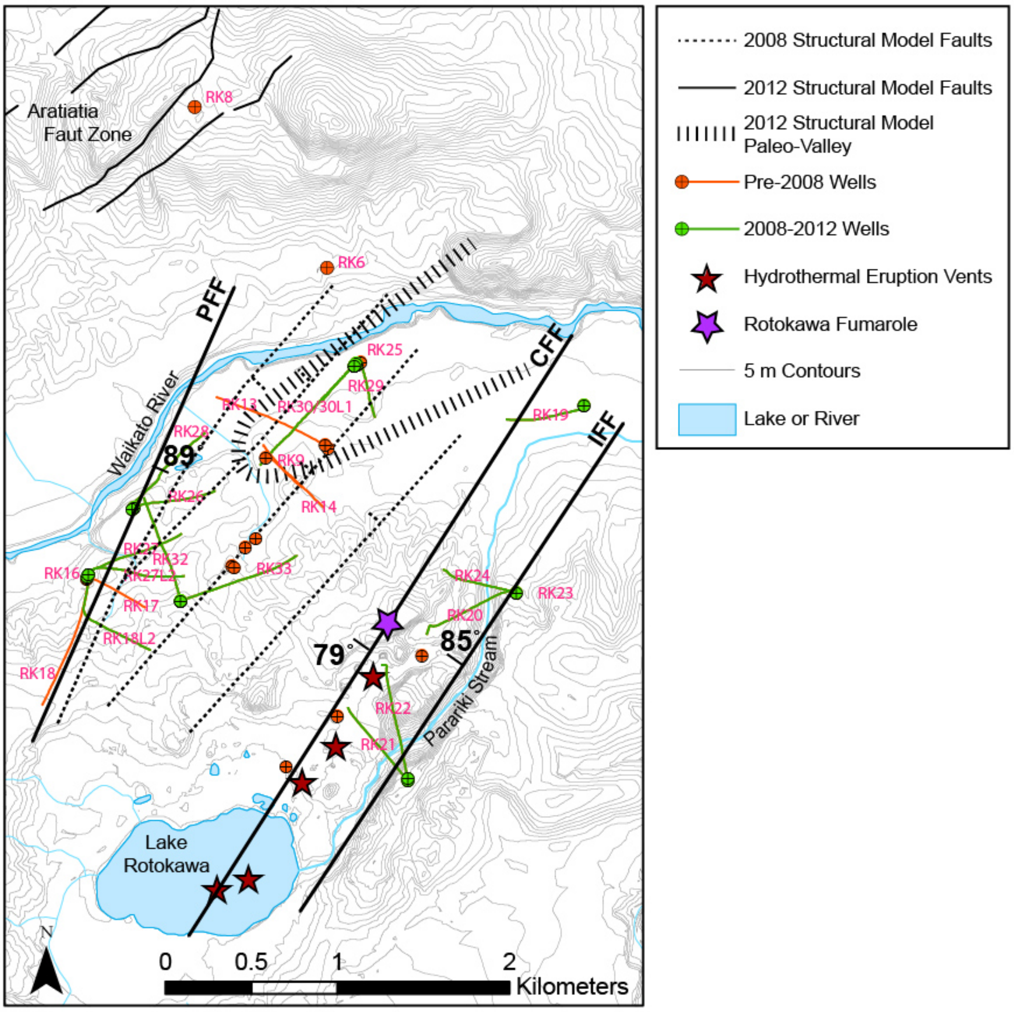


**Figure 2: Map of the Rotokawa field showing the 2008 model (Boyer & Holt 2008) and this study. The outer extent of the paleo-valley inferred to be present in the top of the Rotokawa Andesite is indicated.**

## 2. KEY ELEMENTS OF THE ROTOKAWA STRUCTURAL MODEL

The current iteration of the Rotokawa structural model comprises four major features; three faults and a paleo-valley (Figures 2 & 3). These features were located based on formation offsets between geothermal wells and they are aligned with the northeast-southwest regional structural trend. Figure 2 shows these faults as expressed at the top of the Rotokawa Andesite (2008 model) and terminating in the Wairakei ignimbrite (2012 model). None of the faults included in the present Rotokawa structural model project above the Wairakei ignimbrite because there is insufficient stratigraphic offset to warrant doing so. However, it is likely that these features do propagate up into the shallow sub-surface in some manner, most likely as more complex structures, due to the lower confining stress, with smaller offsets. The key reservoir interval of interest to the developer is below the Wairakei ignimbrite, so the authors do not consider termination of modelled faults at this depth a major limitation of the present model.

Surface expressions of structures are scarce at Rotokawa, and many other reservoirs in the TVZ, because of the cover created by the large volume silicic eruptive deposits that dominate the shallow geology of the region. However, a NE-SW alignment of eruption craters extends across the field and is indicative of structural control (Collar & Browne, 1985: Rowland & Simmons, 2012). Lithologies encountered during drilling suggest that these craters predate the Oruanui eruption from Taupo Caldera 26,500 yBP and the Huka Falls Formation which is at least 190 ka old (Bignal et al. 2010).

### 2.1 The Injection Field Fault

The Injection Field Fault (IFF) offsets the top of the Rotokawa Andesite between RK23 and the rest of the southern wells by a vertical separation of 250-350 m. The NE and SW extents of this structure are not constrained by well data. However, it is possible that the IFF relates to the surface lineament in topography along the Parariki Stream (Figure 2). The fault coincides with a steep decrease in temperature and an increase in pressure in the adjacent wells, perhaps suggesting that it marks the edge of a permeable compartment within the geothermal field. There is also very few micro-seismic events recorded south-east of this structure.

### 2.2 The Central Field Fault

The Central Field Fault (CFF) is identified by a large offset in the top of the Rotokawa Andesite between RK20, RK21, RK22 and RK24 in the southern part of the field (injection area) and the wells in the production borefield to the northwest (RK18L2, RK33, RK14 etc.). The vertical offset in the CFF is large, and greater than either the production field fault (PFF) or IFF. This fault zone creates a vertical offset the top of the Rotokawa Andesite of nearly 400 m. No well penetration between the CFF and PFF has intersected greywacke - the formation which directly underlies the Rotokawa Andesite in the injection area and in RK16 (NW of the PFF). Taking into account the deepest well penetration between the CFF and PFF with drill cutting returns, the minimum vertical offset in the top of the greywacke across the CFF is around 500 m. The CFF aligns with the boundary of micro earthquake locations (Sewell et al. this volume) and the alignment of hydrothermal eruption craters at the surface. Reservoir pressure monitoring, tracer returns and distribution of micro-seismicity indicate that the CFF plays a key role in the permeability structure of the Rotokawa reservoir – such that it appears to be an across strike barrier and along/up dip conduit for geothermal fluids. Due to its large offset, it is possible that the CFF is a fault zone (rather than a single structure) comprising a number of related fault rupture surfaces and associated damage zones. However, due to the resolution of the data available for construction of the present model, we have selected to represent it as a single structure.

### 2.3 The Paleo-valley

The NW part of the field hosts a >700 m deep ENE-WSW oriented canyon or paleo-valley feature, filled with Tahorakuri Formation ignimbrite and Waiora Formation greywacke gravels. This feature is defined by only two drill hole penetrations, RK30L1 and RK30L2, because cutting returns from nearby wells are incomplete. We therefore treat the interpretation of a paleo-valley as speculative and are undertaking further work to refine its morphology.

The paleo-valley has high relief on an otherwise fairly flat Rotokawa Andesite surface, making it a difficult feature to reconcile with the geology of the field. Powell et al. (2011) proposed that this feature is a fissure formed during subsidence related to an eruption of Tahorakuri Formation ignimbrite in the Ngatamariki area, adjacent to the north. Although a little deeper, the Rotokawa paleo-valley is of similar scale to those on the flanks of the Tongariro complex, as can be seen in a digital elevation models created from 20 m contours. Regardless of whether this feature is an erosional or depositional feature, the formation of the Rotokawa paleo-valley was likely influenced by structure; the surface of the Rotokawa Andesite is between 140 and 270 m deeper on the NW side of the canyon, perhaps suggesting that it is aligned along a fault or series of faults. Faults with orientations consistent with this paleo-valley are common within the TVZ (e.g., Aratiatia Fault Zone: Fig. 2), particularly in the vicinity of inferred transfer zones (Rowland et al., 2004).

### 2.4 The Production Field Fault

The Production Field Fault (PFF) was first proposed by Rosenberg et.al (2005). They identified an apparent repeated stratigraphic sequence in well RK17 (see Figure 4 in Bowyer and Holt, 2010). The magnitude of throw on this fault was later revised downward after the identification of the Nga Awa Purua Andesite which lies above the Tahorakuri Formation in this part of the field and was previously included in the Rotokawa Andesite. The identification of this unit was based on stratigraphic relationships and further geochemical work is required to assess its relationship to other andesites at Rotokawa. The only two wells located in the foot-wall block of this structure are RK16 and RK18L1, and the fault is also intersected by RK32 at around 2350 mVD. The orientation of the PFF in the present model is tightly constrained by offset in the Rotokawa andesite between those wells in the foot wall and RK18L2, RK17, RK27L2, RK27, RK26 and RK28 – wells interpreted as intersecting the PFF at around 1300-1400 mVD on the footwall and terminating in the hanging wall block. The presence of the PFF is also constrained by the absence of Waikora Formation and Tahorakuri Formation in the footwall, two formations that are absent from the hanging wall.

Relief on the Rotokawa Andesite across the PFF is greatest in the southwest (> 288 vertical meters). However, the actual vertical displacement on the fault may be greater if the footwall block was subject to appreciable erosion prior to the deposition of the Nga Awa Purua Andesite. The magnitude of offset in this structure is reduced toward the northeast until there is near negligible offset in the top of the Rotokawa Andesite between RK6 and RK8 (<10 m – small enough to be accounted for by uncertainty in the stratigraphy or topography).We infer from this that the fault terminated prior to reaching these wells, thus giving the foot-wall a ramp geometry (Figure 4). Variation in the distribution of displacement is not uncommon and typically the magnitude of displacement on a fault is greatest in the centre of the structure and decreases towards the tips (Fossen 2010). The current iteration of the Rotokawa structural model does not project beyond the reservoir itself, but it is likely that this fault continues to the southwest.

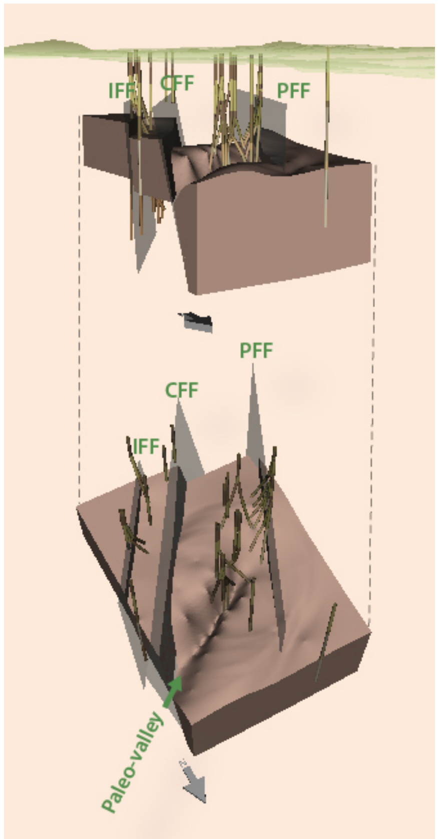


**Figure 3: Views into the MVS earth model of Rotokawa depicting fault offsets in the top of the Rotokawa Andesite (PFF, CFF & IFF) and the inferred morphology of the inferred paleo-valley.**

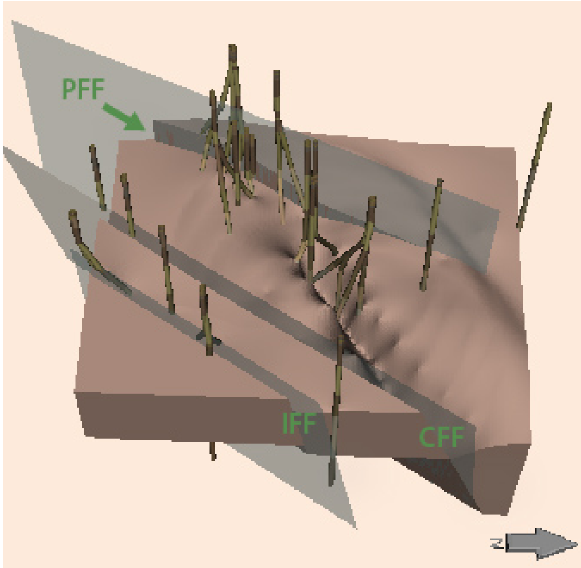


**Figure 4. View into the earth model showing the variation in the distribution of displacement along the PFF.**

### 2.5 Parallels between the Structural Model and Wellbore Images

Acoustic images were acquired in RK32 and RK18L2, two wells in the northern sector of the field proximal to the PFF, as well as in RK30L1 which is located within the inferred paleo-valley (Figure 5 & 2). The images detected a number of features interpreted as open or clay-filled fractures and faults (for further discussion of imaging technologies c.f. Davatzes & Hickman 2005 or Halwa et al. 2013). Overall the fractures interpreted from the acoustic logs have lower dips than the modeled faults.

RK32 is deviated to the north-northwest and is interpreted as intersecting the PFF at depth. The orientation of most fractures imaged in this well strike between 010 and 080, with a mean of 043. The PFF, which was modelled based on well offset data independent of these image log data, strikes 020. The apprent miss-match between these orentations could be explained by: (A) orentation bias because the log data presented here have been corrected for measurement bias such as the undersampling of fractures sub-parallel to the borehole axis (Barton & Zoback, 1992: Massiot et al. 2012); (B) all fractures from a 1077 m logged interval have been compressed here onto a single plot to represent an overvall trend thus disgusing local varation which could be related to the PFF; and (C) faults are not typically planar along strike as we model them, and subsequently there may be local variation in strike.

Aside from the slight miss-match in strike mentioned above, the dominant attitude of fractures interpeted from the RK32 acoustic log is generally consistant with the attitude of the PFF. In contrast, the dominant dip of fractures interpreted from the RK18L2 acoustic log, a well that terminates in the hanging wall of the PFF and is deviated southeast away from this structure, is opposite to the PFF. Following the reasoning that the attitude of smaller fractures are likely to be influenced by a proximal larger structure, the dip of fractures imaged in RK18L2 may indicate the presence of an antithetic fault related to the southwestern extent of the PFF.

The distribution of fractures interpreted from the RK30L1 acoustic image log show a similar attitude as the CFF, but the orentation of the inferred paleo-valley, a valley which is possibly a fault-controlled feature, is not strongly reflected in these data. The orientation of the paleo-valley is simiar to the deviation direction of RK30L1, such that the well deviation azimuth is ~045° and the north and south ridges of the paleo-valley lie approximatly 054° and 064° respectivily. If the acoustic image undersampled those fractures which lie sub-parallel to the RK30L1 welltrack, it is likely the population of features associated with the inferred paleo-valley are under-represented in the image. Consequenlty the fracture distribution interpreted from the RK30L1 acoustic image does not rule out the possibility that a fault zone oriented between 054 and 064° is the mechanism which created this valley in the Rotokawa Andesite.

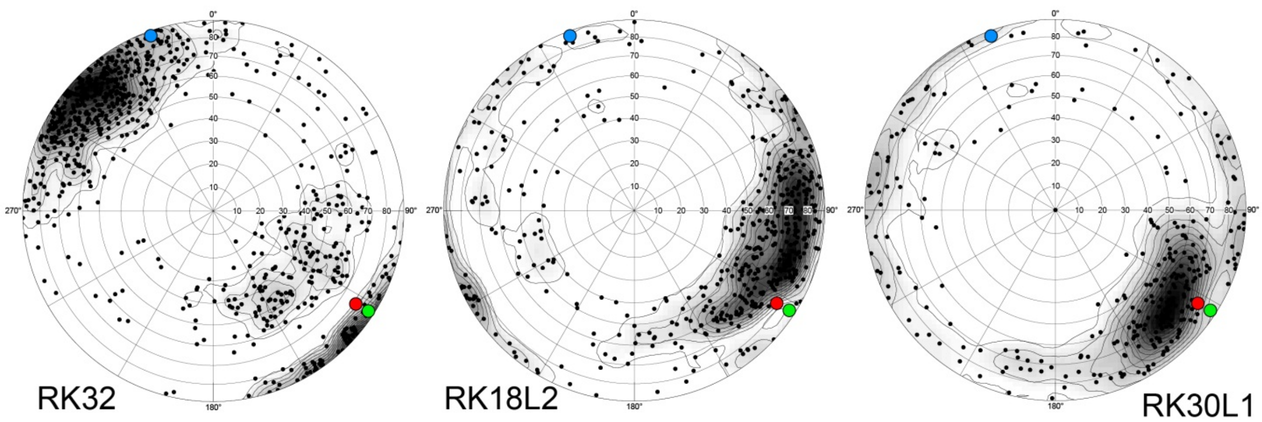


**Figure 5. Schmidt lower hemisphere stereonet with the distribution of attenuative fractures (and possibly also faults) interpreted from acoustic images in RK18L2, RK32 and RK30L1 plotted as black poles to plane (Massiot & McNamara 2010, 2011 and McNamara 2010) with Kamb contours overlaid to highlight key areas of clustering. The attitude of the PFF (blue), CFF (red) and IFF (green) are also plotted.**

## 3. ARTICULATING UNCERTAINTY

Structural models of the sub-surface are commonly produced for geothermal fields. However, rarely do such models convey the uncertainty associated with the interpretation beyond a few scattered question marks and dashed lines. As computer power and 3D modeling software improves, it is likely that geoscientists will be able to build and test multiple geologic-structural models, test the level of confidence associated with each model's fit to geologic and reservoir data, and assess down-stream impact of model alternatives on components of the conceptual model. We see the first step in this process is being able to identify, articulate and, where possible, quantify geologic uncertainty.

The first issue contributing to the total uncertainty associated with a structural model is one of confidence in the well stratigraphy, which is the primary data set on which the model is based. Hydrothermal alteration commonly obscures diagnostic features (composition and texture) that a geologist uses to identify a rock. In addition, drill cuttings typically have poor depth control (if they are returned at all) and wireline logs have not traditionally been utilised in the geothermal industry to aid reconstruction lithological variation at depth. Recent experience at the adjacent Ngatamariki geothermal field has taught us that identification of stratigraphic contacts based on cuttings alone can be off-depth by anywhere from a few meters to up to 100 m. Furthermore, small sizes, poor condition and mixing of cuttings can result in smaller units not being located at all (c.f., Wallis et al. 2012 & Halwa et al. 2013). It follows that the application of wireline technologies can significantly reduce this uncertainty if deployed before a liner is run and the well completed. In the absence of these data, we must accept this uncertainty and account for it as required.

The second issue of uncertainty is associated with reconstructing the space between wells. Compared to minerals developments in epithermal environments, geothermal developments typically comprise relatively few reservoir penetrations between which the geoscientist must interpolate strata and structure. This uncertainty is amplified by two factors. First, the high tempo of TVZ landscape forming processes (volcanic eruption, deposition, lake formation, catastrophic flooding events, tectonic faulting, erosion, etc.) results in a heterogeneous crustal assemblage, with few markers of original horizontality. Second, traditional tools for imaging the sub-surface stratigraphy, such as reflection seismics have limited application in geothermal because of the attenuative properties of clay caps, poorly consolidated volcanic deposits near-surface, two-phase conditions and the rarity of flat-lying reflectors. Magnetotellurics, the staple tool of a geothermal geophysicist, may provide some clues about the locations of particular geologic units or structures, but these interpretations are commonly tenuous. In a geothermal field with re-injection, clouds of micro-seismicity may image major faults (Sewell et al. 2013), but an absence of seismicity cannot be correlated with an absence of structure.

We have developed an approach to quantifying the uncertainty related to the space between wells which simply quantifies the amount of *wriggle room* that the inferred structure has. This approach results in an overall confidence percentage being allocated to each fault. The higher the percentage, the greater the confidence that the fault exists as constructed in the model. We believe that it is critical at this stage to take a simple approach so that it is replicable, matches the resolution of the currently available data/tools and can be communicated easily to collaborators, particularly numerical modelers, who have an interest in understanding the level of uncertainty of the geologic inputs to their own workflows.

In our approach, three ranking criteria are applied to each fault (Table 1). These three criteria were combined and averaged to give an overall confidence for that structure. The first criterion assesses the justification for creating the fault in the first place, such that it addresses if magnitude of geologic offset between wells is sufficiently great to warrant locating a fault between them or if there is a clear repeating sequence in the stratigraphy. Although the same uncertainty ranking process has been applied at Kawerau, Mokai and Rotokawa geothermal developments, the threshold in the first ranking criterion is specific to the field due in part to variations in well spacing. At Rotokawa, geological offset in the Rotokawa Andesite with a magnitude of at least 100m was the minimum criterion on which to justify placing fault between wells. Where offset between wells is greater, a higher confidence percentage is applied. This large minimum magnitude was chosen to avoid mistaking fault offset with the topographic relief which would be expected on the upper surface of an andesite lava deposit. Furthermore, the spacing between wells at Rotokawa is, in some instances, relativity great when compared to Kawerau and Mokai.

The second criterion describes the level of confidence in the map-view position of the fault, both in strike azimuth and lateral position. This combines the amount a fault could move laterally and in strike azimuth as constrained by wells, micro-seismicity distribution and the location of surface expressions interpreted as related to the structure. Criterion three was the final test applied and is based on the magnitude of the range of permissible dips. This ranking criterion is constrained by the same factors which constrain the map-view location. Micro-seismicity and alignment of surface features (e.g., the alignment of hydrothermal eruption vents) contributed to the constraining of the CFF and therefore the high confidence percentage applied in both criterion two and three (Table 1).

**Table 1: Results of the uncertainty analysis for faults in the 2012 Rotokawa structural model. Refer to text for definitions of ranking criteria 1, 2 and 3.**

| Fault | Fault Confidence Ranking Criteria | | | Sum Confidence Factor |
|---|---|---|---|---|
| | (1) Existence of Offset | (2) Map-view Location | (3) Dip Magnitude | |
| IFF | 70% | 65% | 80% | 71% |
| CFF | 80% | 95% | 95% | 85% |
| PFF | 80% | 80% | 80% | 80% |

## 2. CONCLUSIONS

Structural models are utilised to inform the development of a geothermal resource by underpinning conceptual models, guiding well targeting and supporting the interpretation of well and reservoir behaviour. The present paper describes the most recent iteration of the Rotokawa structural model. This model comprises three large north-northeast striking structures and a northeast striking paleo-valley.

- The Injection Field Fault (IFF) is constrained by few well penetrations, but may relate to surface topography and represent the edge of a permeable compartment.

- The Central Field Fault (CFF) has been identified though large stratigraphic offset and the distribution of micro-seismicity (Sewell et al., 2013). It may also relate to an alignment of hydrothermal eruption vents at surface and it plays a key role in the permeability structure of the reservoir.

- We have speculated that there is a paleo-valley in the Rotokawa Andesite, filled with ignimbrites and greywacke gravels. Although we are yet to confirm the mechanism that created this feature, its morphology is reasonable when compared with surface analogues. Interpretation of the acoustic image collected within this the inferred paleo-valley has neither confirmed nor ruled out the presence of a fault zone aligned with this feature as presently modelled.

- The Production Field Fault (PFF) has variation in displacement magnitude along its length and terminates prior to reaching RK6 and RK8, giving the foot-wall a ramp-like geometry. The PFF, which is constrained in the structural model by a number of well penetrations in both the hanging and footwall, has an attitude which is similar to fractures interpreted from acoustic image of RK32 – a well that interests the PFF at depth. In contrast those fractures interpreted from an acoustic log in a well deviated southeast away from the PFF hints to complexity not captured in the present Rotokawa structural model and the possible presence of an antithetic fault related to the south-western extent of the PFF.

The present iteration of the Rotokawa structural model is constrained primarily by offsets in geology between wells (particularly in the Rotokawa Andesite). These offsets are interpreted from drill cutting returns which have not been depth corrected with wireline logging. As such, there is an unquantifiable level of uncertainty associated with these stratigraphic data. Setting this initial uncertainty aside and accepting these well data, we were able to develop a process which articulated uncertainty in the remainder of the model development. This process comprised three ranking criteria which addressed levels of confidence in the likelihood that a modelled fault exists at the proposed location and attitude. By more clearly articulating uncertainty in a structural model we are better able to communicate with our technical collaborators, particularly numerical modellers, who utilise these models in their own workflow.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge Mighty River Power and Tauhara North #2 Trust (together the Rotokawa Joint Venture) for their support of and permission to publish this work.

## REFERENCES

Bibby, H.M., Cadwell, T.G., Davey, F.J., & Wenn, T.H., Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. *Journal of Volcanology and Geothermal Research* 68: 29-58 (1995)

Bannister, S., Sherburn, S. Powell, T. & Bowyer, D., Microearthquakes at the Rotokawa Geothermal Field, *New Zealand. Geothermal Resources Council Transactions* (2008)

Bignall G, Milicich S, Ramirez E, Rosenberg M, Kilgour G and Rae A 2010. Geology of the Wairakei-Tauhara Geothermal System, New Zealand. *Proceedings World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April 2010.

Bowyer, D and Holt, R., 2010, Case study: Development of a numerical model by a multi-disciplinary approach, Rotokawa Geothermal Field, New Zealand, *Proceedings World Geothermal Congress 2010*. Bali, Indonesia, 25-29 April 2010.

Collar RJ, Browne PRL 1985. Hydrothermal Eruptions at the Rotokawa Geothermal Field, Taupo Volcanic Zone, New Zealand. *Proceedings 7th NZ Geothermal Workshop* (1985).

Davidson, J., Siratovich, P., Wallis, I., Gravley, D., & McNamara, D., Quantifying the Stress Distribution at the Rotokawa Geothermal Field, *Proceedings of the New Zealand. New Zealand Geothermal Workshop*, Auckland (2012)

Davatzes, N.C. & Hickman, S., Comparison of acoustic and electrical image logs from the Coso Geothermal Field, CA. *13th Workshop on Geothermal Reservoir Engineering*, Stanford, CA (2005)

Fossen, H. *Structural Geology*. Cambridge University Press: Cambridge (2010)

GNS Active Fault Database: http://data.gns.cri.nz/af/index.jsp

Halwa, L. Image Interpretation Report (FMI & AFIT) NM10, *Schlumberger Data and Consulting Services Report* (2012)

Halwa, L., Wallis, I.C., & Torres Lozada, G., Geological analysis of the volcanic subsurface using resistivity-type borehole images in the Ngatamariki Geothermal Field, New Zealand. *This Volume* (2013)

Massiot, C. & McNamara, D. Structural Interpretation of Acoustic Borehole Images from Well RK18L2, Rotokawa Geothermal Field; *GNS Science Consultancy Report 2010/216* (2010)

Massiot, C. & McNamara, D. Structural Interpretation of Acoustic Borehole Images from Well RK32, Rotokawa Geothermal Field; *GNS Science Consultancy Report 2011/64* (2011)

Massiot, C., McNamara, D., Lewis, B., Price, L., & Bignall, G. Statistical Corrections of Fracture Sampling Bias in Boreholes from Acoustic Televiewer Logs. *New Zealand Geothermal Workshop 2012 Proceedings.* (2012)

McNamara, D. Structural Interpretation of Acoustic Borehole Images from Well RK30L1, Rotokawa Geothermal Field. *GNS Science Consultancy Report 2010/124.* (2010)

Powell, T., O'Brien, J. and Boseley, C., A Tahorakuri Formation caldera boundary at Ngatamariki; abstract and oral presentation, *Proceedings Geosciences Society of New Zealand*, Nelson, 1 Dec (2011).

Rosenberg MD, Kilgour GN, and Fraser HL. Geology of Wells RK16, RK17 and RK18 at Rotokawa Geothermal Field. *IGNS Client Report* 2005/45 (2005)

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, 427-457 (2012)

Rowland, J.V. and Sibson, R.H., Structural controls on hydrothermal flow in a segmented rift system, Taupo Volcanic Zone, New Zealand: *Geofluids*, v. 4, p. 259-283 (2004).

Sewell, S.M., Cumming, W., Bardsley, C., Quiano, J., Wallis, I.C., Shearburn, S., Bourguignon, S., Bannister, S. Interpretation of microearthquakes at the Rotokawa Geothermal Field 2008 to 2012. *This volume*. (2013).

Villamor P, Berryman K A Late Quaternary Extension Rate in the Taupo Volcanic Zone, New Zealand, Derived from Fault Slip data. *New Zealand Journal of Geology and Geophysics* 44: 243–269(2001).

Wallis, I., McCormick, S., Sewell, S. & Boseley, C., Formation assessment in geothermal using wireline tools – application and early results from the Ngatamariki Geothermal Field, New Zealand. *Proceedings of the New Zealand Geothermal Workshop*. Auckland (2012).

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D. & Briggs, R.M., Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. *Journal of Volcanology and Geothermal Research* 68:1-28 (1995)