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A 3D MULTI-DISCIPLINARY INTERPRETATION OF THE BASEMENT OF THE TAUPO VOLCANIC ZONE, NEW ZEALAND

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ABSTRACT

The Taupo Volcanic Zone (TVZ, New Zealand) is a NE-SW fault controlled volcano-tectonic depression, about 350 km long and 60 km wide, infilled by Quaternary volcano-sedimentary rocks with underlying faulted Mesozoic greywacke basement.

The depth of the basement is constrained by drillholes in several geothermal fields, including at Ohaaki, Kawerau, Rotokawa, Ngatamariki and Tauhara. At Wairakei, Mokai and Mangakino geothermal fields, the basement has not yet been encountered, although deep wells of more than 2.5 km vertical depth provide insights on the depth of the basement at these locations, and constraints on major structures (e.g. faults, caldera) affecting the TVZ.

The new capabilities of Leapfrog Geothermal allow complex geological and structural frameworks to be modelled. Here, regional and field specific geology, structural measurements, and gravity data interpretations are combined with historical and new geothermal drillhole data to model the surface of the greywacke basement in 3D.

The ability to model the greywacke basement in a 3D interface provides new insights regarding the geological and structural framework of the TVZ, and information that impacts our understanding of its rheology and controls on deep-seated permeability. The model provides an integrated and innovative tool to support future development of New Zealand's high enthalpy (>250°C) geothermal resources.

INTRODUCTION

The Taupo Volcanic Zone (TVZ) is a complex fault controlled volcano-tectonic depression, about 350 km long and 60 km wide, extending from Mount Ruapehu to the Bay of Plenty (North Island, New Zealand; Figure 1). It is a region characterised by intense volcanism, rapid extension and high heat output.

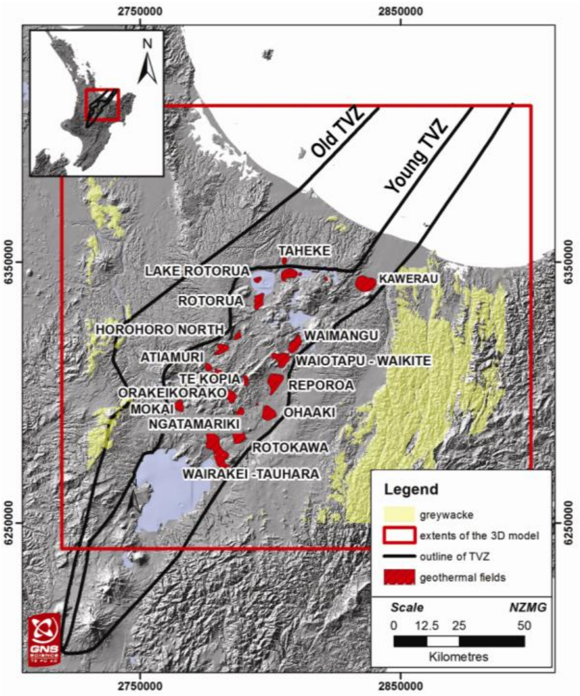

Figure 1: Map showing the location of the TVZ geothermal systems, and extent of the 3D basement model. Outcrops of the greywacke basement as per the QMAP Rotorua geological map are highlighted in yellow.

The modern TVZ began forming <2 Ma ago in response to regional crustal extension above the Hikurangi subduction zone. Past and active faulting, associated with major rhyolitic eruptions that prompted the formation of major caldera collapses, have deepened the TVZ depression which infilled by volcano-sedimentary rocks up to 3 km thick. The underlying basement rocks are complexly deformed and faulted Mesozoic volcaniclastic sandstones of the Torlesse and Waipapa terranes (Adams et al., 2009). In the last 5 years, numerous deep geothermal wells (>1500 m) have been drilled which provide new information on the geology and structure of the TVZ, and its geothermal fields. New information include revised stratigraphy and structure of Wairakei-Tauhara (Rosenberg et al., 2009; Bignall et al., 2010; Alcaraz et al., 2010), Ohaaki (Milicich et al., 2008; Milicich et al., 2010b), Kawerau (Milicich et al., 2010a; Alcaraz, 2010), Rotokawa (Rae, 2007) and Ngatamariki (Bignall, 2009).

Most of the high temperature geothermal systems in the TVZ have reservoirs at 1500 – 2500 m depth, with several developed for electricity generation. Now, the New Zealand geothermal community is considering the potential of drilling hotter and deeper resources (Bignall and Carey, 2011), including reservoirs hosted in greywacke basement. At Kawerau, the high temperature reservoir is hosted in fractured-greywacke as shallow as 660 m below ground level, while at Ohaaki geothermal drilling encountered poor permeability in greywacke at 2 km depth (Wood, 1996). Clearly, there are technical challenges for development of deep-seated resources, as extraction becomes more difficult as rocks are less porous at high pressures and temperatures, thus reducing fluid flow, even though temperatures may be high. It is acknowledged that greywacke below known TVZ geothermal fields is saturated by hot fluids and are highly prospective resources for future deep production, and our 3D basement model provides a tool for targeting its deep-seated structural and stratigraphic permeability.

We are using the new structural capabilities of the 3D software Leapfrog Geothermal to integrate drillhole data, recent geological surface mapping and geophysical datasets to model the upper surface of the basement across the entire TVZ (Alcaraz et al., 2011a). This revised 3D model improves our understanding of the evolution and structure of the TVZ, but will also provide the New Zealand geothermal industry with a higher level of confidence to advance deeper exploration where greywacke occurs at (currently) unknown depth.

GREYWACKE DISTRIBUTION

Geological evidence

The volcaniclastic sandstones and argillites of the Waipapa Terrane and the Torlesse Terrane (collectively referred to as “greywacke” in this paper) occur at the ground surface in ranges to the west and east of the TVZ, respectively (Grindley, 1960; Healy et al., 1964; Leonard et al., 2010). The transition between the two terranes is buried beneath the young volcano-sedimentary infill of the TVZ (Leonard et al., 2010). For the purpose of this model, we consider the two terranes as one entity (Figure 1).

Within the TVZ, greywacke has been drilled in 69 drillholes in several geothermal fields, mainly towards the eastern margin of the volcano-tectonic depression. At Kawerau, 32 wells intersect the greywacke basement, as shallow as -666 mRL in KA29, and as deep as -1389 mRL in KA28. At Ohaaki, 26 wells intersect the basement, between -670 mRL (in BR29) and -2031 mRL (BR60). At Rotokawa 9 wells have intersected the basement between -1612 mRL (RK23) and -2720 mRL (RK16). One well intersected greywacke in Tauhara at -1793 mRL (TH17) and one well at Ngatamariki at -3012 mRL (NM6). This Ngatamariki well intersection with basement is the deepest in the TVZ, and is located less than 10 km from its eastern boundary. The greywacke has yet to be intersected at Wairakei, or other western fields such as Mokai and Mangakino, even though the deepest well in Mangakino reaches ~-2920 mRL (Fagan et al., 2006).

Geophysical evidences

The TVZ residual gravity signature is characterised by a broad region of low gravity anomalies, interpreted as the low density volcanic infill materials overlying basement denser rocks (Soengkono, 2011). Early interpretations assumed a constant density contrast of 0.5 Mg/m^3 between greywacke basement and volcaniclastic infill, and estimated the basement depth to 1 to 2.5 km in the central TVZ (Modriniak and Studt, 1959; Rogan, 1982; Soengkono, 1995). On the eastern margin of the TVZ, steep gravity gradients coincide with downfaulting of the basement towards the west (Modriniak and Studt, 1959; Hochstein and Hunt, 1970). The western margin, west of the Mangakino caldera, is not associated with a clearly defined gravity gradient (Bibby et al., 1995), and provides no clear insights on basement geometry.

Within the regional low gravity region of the TVZ, some areas have even lower gravity signatures, coincident with the location of known or inferred (major) caldera structures (Stern, 1982; Rogan, 1982).

Resistivity studies also provide an indication of the depth to the basement surface, as the greywacke is more resistive than overlying volcano sedimentary sequences. 2D Magnetotelluric profiles point to the low-resistivity infill of caldera collapse structures to 3km depth (Ogawa et al., 1999; Bibby et al, 1995).

East of the TVZ, Risk et al. (1993) identified the Torlesse greywacke resistivity signature below the Kaingaroa Plateau, a few hundred metres beneath young ignimbrites. Westward of the Kaingaroa Fault zone, the high resistivity structure is inferred dipping to 2 km depth below the low resistivity signature of the eastern geothermal systems (Risk et al., 1993; Bibby et al., 1995). Further west, the resistivity signature changes and cannot be traced. Assuming the greywacke is continuous at depth, variation in resistivity values is best attributed to mineralogical alteration of the rocks (Bibby et al., 1995; Heise et al., 2007).

BASEMENT MODELLING

Leapfrog Geothermal 2.2

Leapfrog Geothermal is a 3D modelling and visualisation software package developed by ARANZ Geo (Christchurch, New Zealand) with geoscientific input from GNS Science (Wairakei, New Zealand). It is an integrated interface that allows the development of conceptual and quantitative geological models. Version 2.2 of the software was released in October 2011, and provides improved tools and capabilities to answer the growing needs of the geothermal industry (Alcaraz et al., 2011b). Leapfrog Geothermal is being adopted within the geothermal industry, both in New Zealand and internationally, as an innovative resource management tool.

The new release of Leapfrog Geothermal 2.2 enhances the structural geological modelling capabilities of the software, in particular the modelling of faults and fault blocks. These are now processed using a chronological table which has enabled the modelling of complex geometries such as the TVZ's faulted greywacke basement.

Input data

The 3D model of the TVZ basement presented in this paper has been constructed using geothermal and mineral borehole data, and information from recent 1:250,000 geological mapping (Leonard et al., 2010) and the GNS Science's Active Faults database (GNS Science, 2011). Geophysical data, including inferred residual gravity anomalies surfaces (Soengkono, 2011) and MT sections (Heise et al., 2007) have been used as complementary information to constrain the geometry of the greywacke basement.

- Borehole data from TVZ geothermal fields were used to constrain the model: e.g., Kawerau, Waiotapu, Orakeikorako, Te Kopia, Ngatamariki, Mokai, Ohaaki, Rotokawa and Wairakei-Tauhara. Currently, the model incorporates data from 441 wells. Boreholes location, survey and geology datasets have been collected from public sources, or provided by courtesy of Mighty River Power Ltd. and Contact Energy Ltd.
- The latest geological map (QMAP Rotorua 1:250,000; Leonard et al., 2010) has also been used to help constrain the basement surface (Figure 2a). The QMAP Geographic Information System (GIS) dataset consists of numerous information layers, such as geological map units, fault locations, structural measurements and caldera outlines, which were used as primary input in the design of the model. The published geological map also provides four subsurface geology cross sections that were incorporated into the 3D model as georeferenced images and used as guidelines to model the basement surface.
- The GNS Science New Zealand Active Faults Database (GNS Science, 2011) was used to complement QMAP data. The Active Faults database contains detailed information compiled from field measurement of offset features, trenching and dating. The database also contains interpretation in the form of recurrence interval, slip rate and date of last movement. This database greatly assisted in the selection of the principal faults to be integrated into the model.
- Residual gravity data was incorporated into the geological model as an interpreted 3D depth to basement surface (Soengkono, 2011; Figure 2b). It was created using a density contrast of -470 kg/m^3, representing the average density difference between TVZ Quaternary volcanic infill and greywacke basement.
- Magnetotelluric 2D profile across the TVZ were also integrated in the model (Figure 2b, Heise et al., 2007).

Workflow

The TVZ basement model has been built following a standard workflow within Leapfrog Geothermal.

1. Definition of the region of interest: For this model, we have focused on the central and northern parts of the TVZ. The model coincides with the extent of the 1:250,000 QMAP, Rotorua geological map (Leonard et al., 2010). The model is constrained vertically by the topography (we used the GNS's Digital Terrain Model of New Zealand).

2. Importing data: we introduced numerous GIS datasets within Leapfrog Geothermal, including the known occurrences of greywacke at the ground surface, fault trace and caldera collapse outlines (from Graham et al., 2010). Maps and cross-sections were appropriately georeferenced and borehole data imported. The gravity surface was interpolated in Leapfrog Geothermal from imported ascii points and the MT profile was imported and geo-referenced as a cross-section.

3. Building the structural network: Fault surfaces were generated using the QMAP GIS layers and Active Faults database as guidelines. Surface trace and attribute data (dip direction, dip angle, offset), were used to constrain the geometry of the faults. Calderas were modeled as closed and cylinder shape faults. Hierarchy and relationships between faults and calderas structures were designed to create a geologically consistent and realistic structural framework in conformity with the QMAP and Active Faults datasets (Figure 3).

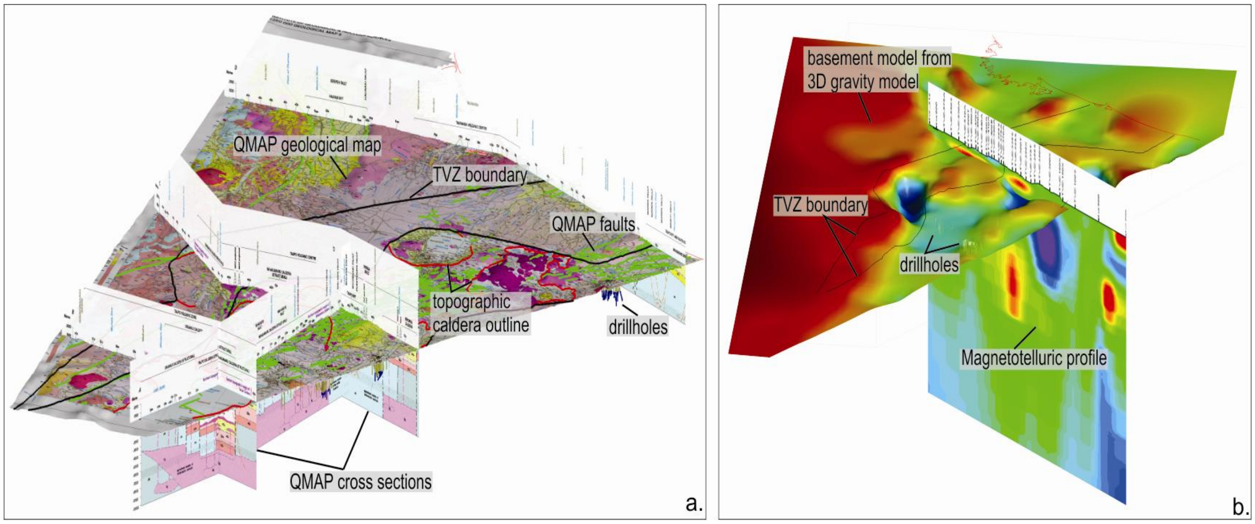

Figure 2: Input data imported in Leapfrog Geothermal. a: QMAP datasets include surface geology, cross sections and GIS layers such as faults and caldera outline. b: Basement model from 3D gravity interpretation (Soengkono, 2011) and MT 2D profile (Heise et al., 2007).

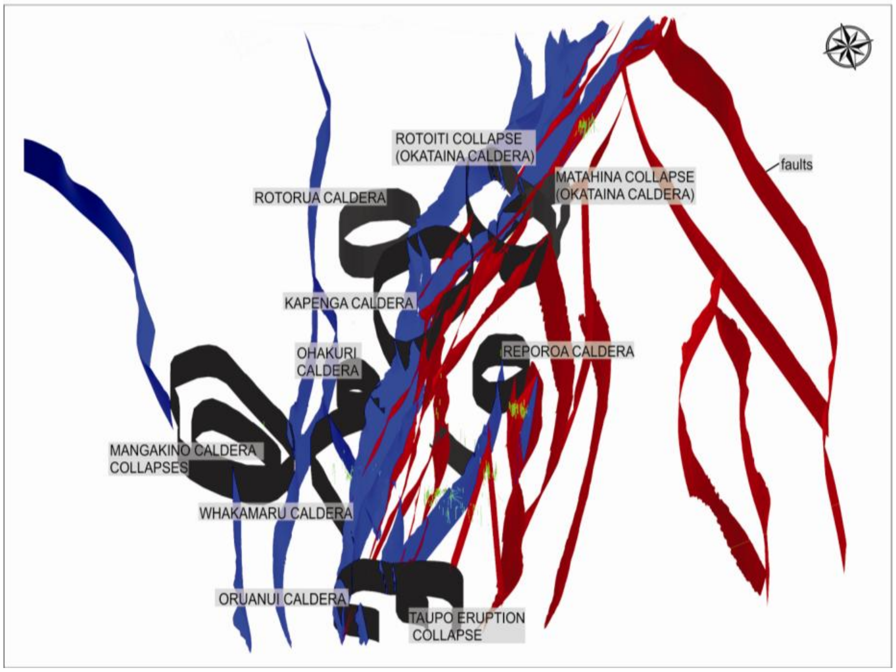

Figure 3: Structural framework created for the TVZ basement model. Faults are in red (dipping to the west) and blue (dipping to the east). Calderas are black cylinder shaped faults.

4. Building the greywacke basement surface (Figure 4): Leapfrog Geothermal honours all the stratigraphic contact points from the borehole data loaded in the software. This means that all the drillholes are used to generate the surfaces: i.e., if the basement is intersected in the drillhole, then it provides a factual depth to locally constrain the surface. If it is not intersecting the basement, then Leapfrog will automatically force the surface underneath the borehole maximum depth. The surfaces were also constrained using surface outcrops from the geological map.

5. Adjusting basement surfaces (Figure 4): in an area with no drillholes, the surfaces were manually edited using the QMAP interpretive geological cross-section as guidelines, digitising contacts between Quaternary volcano-sedimentary infill and greywacke basement. In areas having neither borehole data nor QMAP information, the gravity surface and MT cross section were used as complementary information to constrain the basement depth.

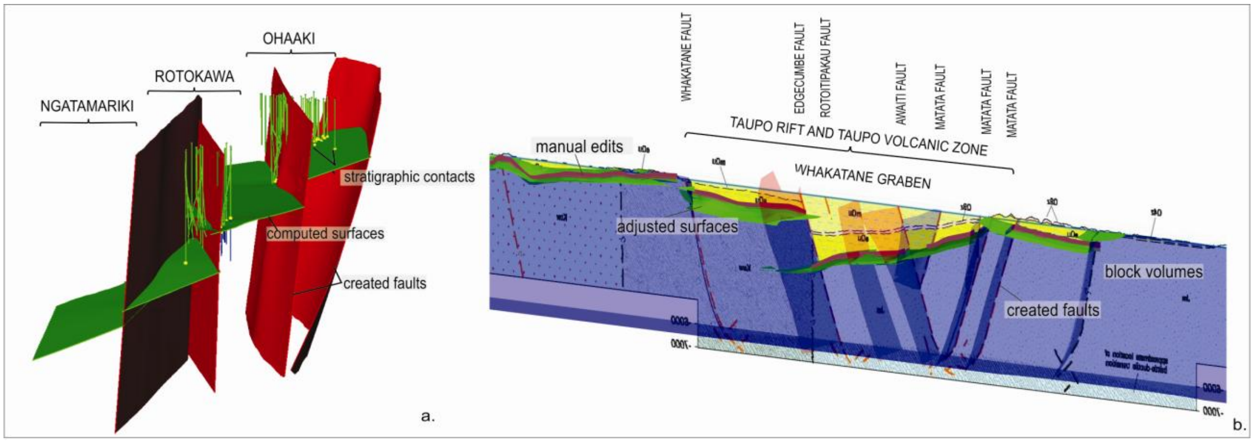

Figure 4: Illustration of surfaces built in Leapfrog Geothermal. a: surfaces are generated from lithological contact points. b: surfaces are created through manual edits of polylines, using the interpretive geological cross section as a guideline. These surfaces represent the upper surface of the basement and are computed by Leapfrog Geothermal to generate volumes.

DISCUSSION

The active extension in the TVZ is mostly accommodated through the Taupo Rift, with normal faulting dominantly striking NE-SW. In this model, more than 45 principal faults were selected based on their geographical extent, data confidence, and their activity. Local faults were added where detailed geological model have already been built (e.g. Alcaraz et al., 2011b; Alcaraz et al., 2010; Milicich et al., 2010b) and could be used as high resolution inputs into the regional model.

In addition to rifting, the history of the TVZ has been affected by large, caldera-forming rhyolitic eruptions. More than 15,000km^3 of materials have been erupted in the last 1.6 Ma (Wilson et al., 1995). These calderas are major collapse zones and affect the basement surfaces at depth. Eight calderas have been included in the model: Mangakino, Kapenga, Whakamaru, Reporoa, Rotorua, Ohakuri, Okataina and Oruanui calderas. We chose to model the inferred structural collapses zones, (cf. figure 32 in Leonard et al., 2010), instead of using the topographic expressions (as presented in the geological map itself). Precisely representing the complexity of caldera collapse zone was not the purpose of this work, nonetheless an attempt has been made to illustrate Mangakino, Okataina and Oruanui/Taupo calderas as composite collapse zones. The Kapenga, Whakamaru and Okataina calderas are cross cut by recent faulting, adding to the complexity of the structural network in those areas.

The model we present here (Figure 5) provides a coherent 3-dimensional geometry of the greywacke basement across the central and northern (onshore) part of the TVZ. It honours drillhole data, surface geology and follows the geological cross-sections interpretation. Minor discrepancies can be identified between model and cross-sections at the junctions of some calderas: Whakamaru/Taupo eruption collapse zones and Mangakino/ Whakamaru/ Ohakuri calderas. The caldera margins used in the QMAP geological cross sections are linked to the topographic margins, while in our model we used inferred structural collapse zones at depth, leading to minor differences between the 3D and 2D views.

The interpreted gravity surface has been used as a regional indicator of the basement depth and provides useful insights where there is no surface or available downhole data. A strong correlation is indicated between inferred caldera locations and low gravity anomalies, especially for the Mangakino, Rotorua, Kapenga and Okataina calderas. The inferred location of the Whakamaru collapse zone is not as clear. Relationships between Mangakino, Ohakuri, Whakamaru calderas, and the Maroa Volcanic Centre must be clarified. The 2D MT cross–sections in this area point to a thick sequence of low-resistivity materials, indicating that the basement may be deeper than interpreted in our model. This suggests that the calderas may have crosscut each other, and mean that the extents of structural collapse zones used in the model are underestimated.

The gravity surface used in this model is generally consistent with the known depth (borehole data) of greywacke in the Kawerau area, but does not concur with drillhole data in the southern part of the TVZ. The interpreted gravity surface is shallower than the maximum depth of wells that do not intersect the basement. Consequently, this study concludes that the interpreted gravity surfaces will need some adjustment to account for factual drillhole data. This is expected to increase the gravity gradient that coincides with the Kaingaroa Fault, the major structure marking the eastern margin of the TVZ.

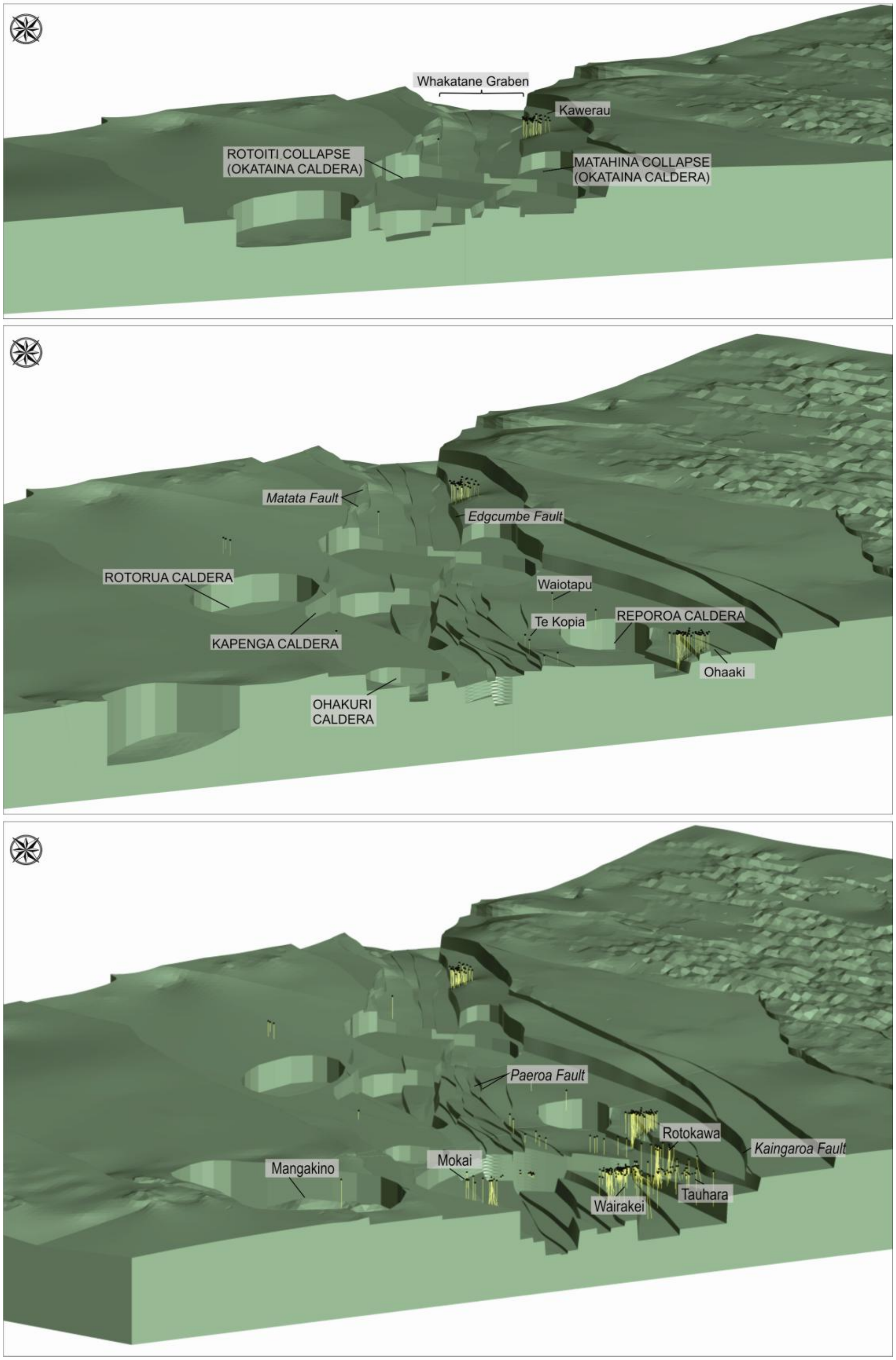

Figure 5: 3D model of the Taupo Volcanic Zone greywacke basement. 3D perspective views from NE (top) to SW(bottom).

CONCLUSIONS

The geological model presented in this paper is a new 3D interpretation of the upper surface of the greywacke basement in the TVZ, and has been built using Leapfrog Geothermal version 2.2. The ability of the software to handle the TVZ's complex structural framework has enabled a realistic 3D model to be constructed. It is a major advancement on past 2D interpretations, and illustrates a geologically plausible 3-dimentional view of the basement surface at depth, in accord with factual and current interpretive (e.g. geophysical) data.

The model is expected to foster discussion, and will promote new research initiatives. Improved geoscientific knowledge, including insights on the basement structure and evolution of the Taupo Volcanic Zone, will help to resolve the permeability structure of deep geothermal resources in the region, and reduce uncertainties and technical barriers to sustainable development.

In the future, Leapfrog Geothermal will continue to be used to correlate new scientific findings and test possible TVZ geological framework and hydrological scenarios, including structural and stratigraphic controls on heat and fluid flow. The 3D model will be used in collaborative work to develop a time-series reconstruction of TVZ depression evolution, and to model the modern strain distribution across the TVZ.

The 3D greywacke basement model, presented here, will provide an important tool in deciding the location of the future deep geoscience well in the proposed industry- / ICDP-supported, international deep geoscience TVZ-Deep Geothermal Drilling Project. The findings of TVZ-DGDP, and drilling / engineering experience gained, will be invaluable to the international EGS research and development community.

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