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## Rock Properties of Greywacke Basement Hosting Geothermal Reservoirs, New Zealand: Preliminary Results

David D. McNamara, Daniel Faulkner, Evan McCarney

Department of Geothermal Sciences, GNS Science

1 Fairway Drive, Avalon, Lower Hutt, 5010, New Zealand

E-mail: d.mcnamara@gns.cri.nz

**Keywords:** Greywacke basement, geothermal reservoir, rock properties, permeability.

### ABSTRACT

Geothermal resources in New Zealand are known to be hosted in greywacke basement rocks. Fluid flow in these reservoirs and the wells that access them is controlled by fracture networks. As such it is of vital importance to understand how these structures are impacted by the mechanical and thermal properties of this basement rock, and how these in turn are affected by changing temperature and pressure conditions at depth.

This paper details the results of an initial set of laboratory tests of two New Zealand greywacke basement terranes, in which geothermal reservoirs are known to be hosted. The aim of the study was to provide an initial understanding of the rocks mechanical properties so that further, more refined testing could be applied. Low permeability and porosity measurements are consistent with the current understanding that fractures control fluid flow in the basement. Preliminary mechanical testing suggests a systematic difference between greywacke from the Waipapa and Torlesse Terranes, with the Waipapa Terrane being mechanically stronger, potentially as a result of a coarser grain size and/or composition differences. Tensile strength testing of whole rock and fractures in Waipapa greywacke rock show lower tensile strengths for the fractures. This indicates that geothermal fluid flow makes use of existing fracture networks via crack-seal mechanisms rather than through the generation of new fractures.

Further work, including mechanical testing at high temperature conditions, variable grain size, and variable composition will provide us with a better insight into the role increasing pressure and temperature conditions play in fracture controlled geothermal fluid flow as we approach the change from brittle to ductile deformation. This in combination with a rigorous investigation of the effects of the character and heterogeneity of greywacke basement in New Zealand will inform us on how best New Zealand can explore for and utilize deep (>3km), fracture dominated, geothermal resources.

### 1. INTRODUCTION

Utilization of geothermal energy is expanding worldwide in both electricity generation and direct use (Bertani, 2011). This trend is marked particularly in New Zealand electricity production which has seen an increase in supply from geothermal resources from ~7% in 2000 to ~14% in 2012 (Ministry of Business, Innovation and Employment, 2013) and more recent developments such as the completion of the 82MW Ngatamariki power station (Mighty River Power, 2013). Current geothermal development for electricity production in New Zealand accesses reservoirs at depths of  $\leq 3$ km delimiting what is known as the 'conventional' resource. As science and the industry seek to progress the development of geothermal power in New Zealand the focus shifts to deeper (>3km) potential reservoirs including a potential deep (4-5 km) drilling project (Bignall, 2011).

There are a number of scientific challenges associated with the utilization of both New Zealand's 'conventional' and 'deeper' geothermal reservoirs, the most critical of which is determining the nature of their permeability. Reservoir hosting lithologies in currently producing fields are volcanic or of a greywacke basement type (Bignall et al., 2010) and greywacke basement and intrusive lithologies are likely to compose any reservoir rock found at depths greater than 3km. In such lithologies fluid flow is thought to be dominated by structures such as faults and fractures (Bayrante and Sörli, 1989; Wood et al., 2001; McLean and McNamara, 2011; Wallis et al., 2012). Current knowledge of the depth extent of brittle deformation (faults and fractures) in the basement rocks of the TVZ comes from seismicity studies which suggest a potential convective geothermal regime to depths of ~6-8km (Bibby et al., 1995; Bryan et al., 1999). It becomes important to understand the effects changing pressures and temperatures will have at these depths for the penetration of geothermal fluids through the crust via a brittle pathway (i.e. cracks).

Key to understanding the contributions made to a reservoir's permeability by structure is knowledge of the rock properties and how these properties respond with depth as conditions (pressure and temperature) change from facilitating brittle deformation to ductile deformation (brittle-ductile transition, where deformation mechanisms change from brittle behavior to crystal plasticity and diffusion creep). A study by Violay et al. (2012) on the brittle-ductile deformation response of basalt showed that brittle deformation occurs up to 650°C and that hydrothermal fluids could circulate in the basaltic crust under Iceland to depths of 4-6 km. This is significantly higher than 300-450°C values determined for the brittle-ductile transition of quartzo-feldspathic rocks (Scholz, 1988 and references therein). It is likely that the brittle-ductile transition is sensitive to lithological variation and as such should be explored independently for a given area of geological interest.

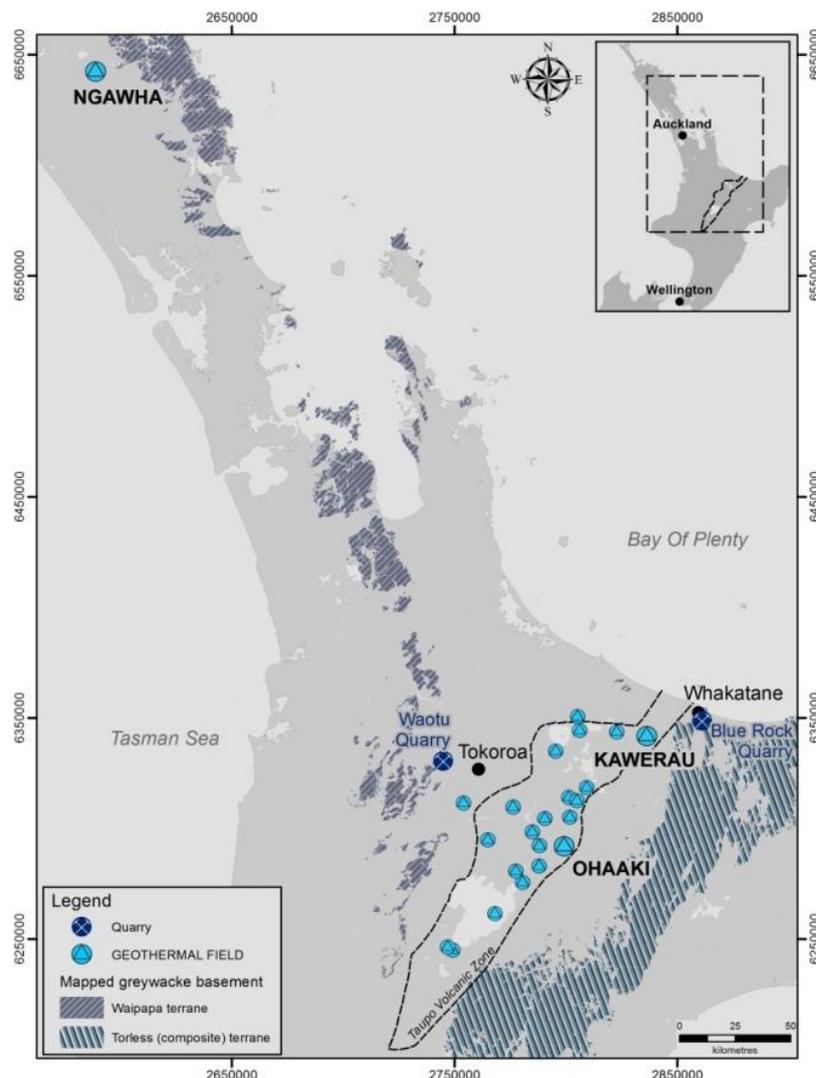
This work presents preliminary data exploring the properties of New Zealand greywacke basement type rocks at experimental conditions and what this may mean for the extent of circulation geothermal fluid flow in New Zealand's crust and future geothermal development in New Zealand.

## 2. GEOLOGICAL CONTEXT

The majority of geothermal development in New Zealand occurs within a geological region known as the Taupo Volcanic Zone (TVZ) with only one producing field located outside of it, the Ngawha Geothermal Field (Figure 1). The TVZ represents the active, southern portion of the Lau-Havre-Taupo extensional back arc basin formed as a result of subduction of the Pacific Plate beneath the North Island of New Zealand (Rowland et al., 2012). The Ngawha Geothermal Field is located on the Northland peninsula in a structural depression that lies above a shallow rhyolite body thought to be the heat source for the field (Bayrante and Sörli, 1989). These areas are underlain by two distinct Late Permian to Early Cretaceous basement greywacke terranes, the Waipapa and Torlesse Terranes (Mortimer, 2004; Adams et al., 2009).

Three geothermal fields in the North Island of New Zealand produce power from geothermal reservoirs hosted in these greywacke basement lithologies, the Ngawha, Ohaaki and Kawerau Geothermal Fields. The Ngawha geothermal reservoir is hosted within Waipapa Terrane basement composed of grey-green argillites and massive, quartzo-feldspathic sandstones strongly altered and veined with common fault breccia textures (Bayrante and Sörli, 1989; Cox et al., 1998). The geothermal reservoirs of the Ohaaki field are hosted in Torlesse Terrane greywacke rocks of ‘granite-rhyolite’ provenance and are down-faulted toward the NW (Wood et al., 2001). This terrane is dominated by interbedded, medium-fine grained, fractured, greywacke sandstones with thin argillite partings and common hydrothermal veining.

The TVZ lies geographically between the mapped occurrences of these terranes (Waipapa Terrane to the west and north and Torlesse Terrane to the east and south). Though the transition from one terrane into the next is nowhere exposed it is thought to be close to or under the Kawerau Geothermal Field (Adams et al., 2009; Milicich et al., 2013). The geothermal reservoir hosting greywacke basement at Kawerau is mainly composed of medium-grained sandstone sourced mainly from ‘andesite-dacite’ rocks, with minor argillite and chert and is down-faulted to the NW (Milicich et al., 2013). This greywacke basement is difficult to characterize in terms of terrane and has been ascribed to both the Torlesse (Wood et al., 2011) and the Waipapa (Adams et al., 2009). While both the Kawerau and Ohaaki geothermal reservoirs are hosted in greywacke-type rocks only the Kawerau field displays significant production (Wood et al., 2001). This is attributed to compositional differences affecting the range of temperature at which brittle deformation can occur.



**Figure 1: Map of the North Island of New Zealand showing the location of the geothermal fields, the Taupo Volcanic Zone, the mapped exposure of both the Waipapa and Torlesse greywacke basement terranes, and the locations of the quarries used for sampling.**

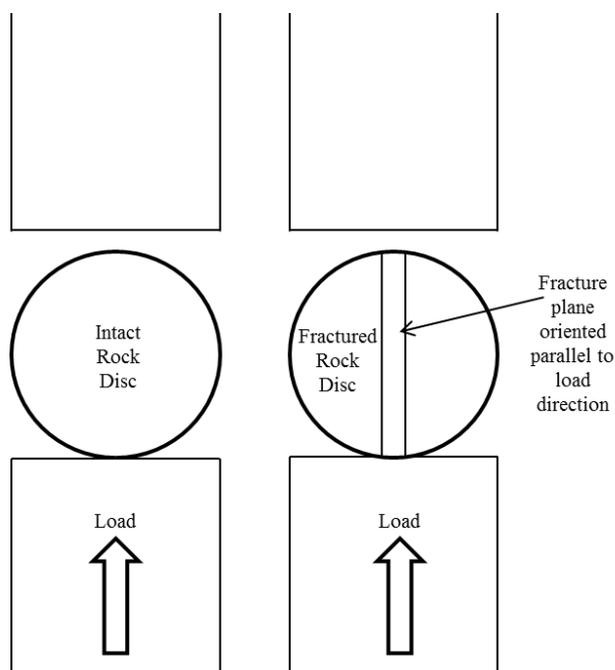
### 3. METHOD

Samples of both the Waipapa and Torlesse greywacke terranes were acquired from surface exposures in order to test their properties. These included both intact samples of the greywacke sandstone horizons and samples with hydrothermal veining. Waipapa samples are sourced from the Waotu Quarry located ~15km east from the town of Tokoroa and Torlesse samples were collected from Blue Rock Quarry located just south of Whakatane (Figure 1). A wide range of properties are examined in this work including mechanical properties such as compressive and tensile strength, Young's Modulus ( $E$ ), and Poisson's Ratio ( $\nu$ ), porosity, and permeability.

The majority of the data presented in this work was collected at the Rock Deformation Laboratory in the Department of Earth and Ocean Sciences, University of Liverpool. Unconfined compressive strength (UCS) tests were carried out on samples from both quarries. Cores (20 mm diameter) of greywacke were drilled from acquired samples and fitted with both axial and radial strain gauges to monitor the evolution of the elastic properties during deformation. Samples were then brought to failure using an ELE manufactured deformation apparatus with a modified hydraulic loading system capable of 150 tonne loading capacity in the absence of confining pressure.

This same apparatus was utilized for Brazilian Tests on 20mm diameter discs of greywacke basement rock. Brazilian Tests were performed on both 'intact' discs of greywacke and on discs that had been cored to contain a mineral-filled (sealed) fracture plane. Axial loading was carried out parallel to the fracture planes to determine the tensile strength of the fracture fill (Figure 2).

Triaxial compressive tests were carried out on 20mm diameter greywacke cores using a high pressure, high temperature triaxial deformation apparatus. The deformation rig is capable of performing triaxial deformation experiments at pressures up to 250 MPa (equivalent to ~10km depth) and temperatures up to 250°C. The rig utilizes a servo-controlled ball-screw driven actuator with a 30 tonne loading capacity. The internal force gauge design utilizes high performance materials (maraging steel with a ~2 GPa yield strength) to maximize the load measuring sensitivity. A balanced piston design allows the full 30 tonne capacity to be directly applied to the sample. Samples of greywacke sandstones from both terranes were brought to failure under confining pressures of 25, 50 and 75 MPa (equivalent to ~1, 2, and 3km depth respectively).



**Figure 2: Schematic showing the arrangement of intact and fractured samples used in a compression rig for Brazilian Tests.**

Permeability tests were carried out using the pulse-transient technique (Brace et al., 1968) in a high pressure, hydrostatic fluid flow apparatus with servo-controlled pore fluid pumps connected to both the 'upstream' and 'downstream' ends of the sample. Argon gas was used as the fluid. Permeability was measured in samples of both greywacke terranes at confining pressures of 20MPa on cores of 20mm diameter. Upstream and downstream pressure are set at 10MPa  $\pm$  0.5MPa (creating a differential stress of ~10MPa) such that a ~1MPa difference is created across the sample (Figure 3). Upstream and downstream pressures are then monitored over time as they equilibrate over the sample. Unconfined samples of greywacke rock were heated to 200°C and 400°C at a rate of 0.25°C/min in a conventional oven and then cooled at the same rate. The same permeability tests described above were carried out to investigate potential thermal effects on the rock fluid flow properties. This same sample rig was used to obtain S and P wave velocities of greywacke core over a range of confining pressures (0-100MPa) both under increasing and decreasing confining pressure paths.

Nuclear magnetic resonance (NMR) core measurements were made at Magritek Ltd., Wellington, New Zealand to provide porosity and permeability estimates for comparison with the laboratory measurements. NMR directly detects fluid within a rock core while the matrix remains undetected. The sample is placed in a magnetic field and then excited using a series of radio frequency (RF) pulses. After each pulse a small RF signal (echo) is generated by the nuclei within the fluid which is recorded as a train of echoes with a defined spacing, the echo time (TE) (Meiboom and Gill, 1958). The signal amplitude that makes up the echo train decays away with one or more characteristic relaxation times ( $T_2$ ) (Bloembergen et al., 1948). The initial amplitude of the signal gives an

indication of the total fluid in the sample. A pore volume value must be combined with a bulk volume measurement (often made with calipers) to obtain porosity and the instrument must be calibrated against a known volume of the saturation fluid. A sample of Waipapa greywacke was measured using the Magritek 2MHz Rock Core Analyzer calibrated with 4.6g of MnCl<sub>2</sub> doped water with a T<sub>2</sub> of 50ms and a T<sub>1</sub> of 100ms. The Carr-Purcell-Meiboom-Gill (CPMG) sequence was used to measure T<sub>2</sub>, with 60µs echo times and a signal-to-noise ratio of 200. The CPMG decay was fit using a Lawson and Hanson (1974) inverse-Laplace algorithm. A T<sub>1</sub> inversion recovery pulse sequence was used with a 3 second wait time between each scan. The T<sub>1</sub> data was also fit with the Lawson and Hanson inverse-Laplace algorithm.

**4. RESULTS**

**4.1 Mechanical Properties**

Table 1 contains preliminary values for a range of mechanical properties for both the Waipapa and Torlesse Terrane greywacke rocks. The Waipapa Terrane greywacke rocks display higher density values (median = 2.71 g/cm<sup>3</sup>) than the Torlesse Terrane (median = 2.62 g/cm<sup>3</sup>), higher UCS, and ν and E values.

| Property                     | Waipapa Terrane Greywacke | # of Tests | Torlesse Terrane Greywacke | # of Tests |
|------------------------------|---------------------------|------------|----------------------------|------------|
| Tensile Strength (MPa)       | 20.3 - 35.7               | 8          | -                          | -          |
| UCS (MPa)                    | 301 - 310                 | 2          | 164 - 255                  | 2          |
| Density (g/cm <sup>3</sup> ) | 2.42 - 2.74               | 12         | 2.51 - 2.66                | 9          |
| Poisson's Ratio (ν)          | 0.28 - 0.29               | 2          | 0.11 - 0.17                | 2          |
| Young's Modulus (E)(GPa)     | 6.5 - 7                   | 2          | 2.3 - 6                    | 2          |

**Table 1: Ranges of values for mechanical properties of samples of greywacke sandstone from the Waipapa and Torlesse Terranes.**

Triaxial failure values at confining pressures of 25, 50 and 75 MPa for greywacke rocks from both terranes are shown on Figure 3. Taking into account gathered data the Mohr-Coulomb parameters, friction angle (φ) and the cohesion of intact rock (c) are calculated producing Mohr-Coulomb Failure Criterion for both the Waipapa Terrane (equation 1) and the Torlesse Terrane (equation 2):

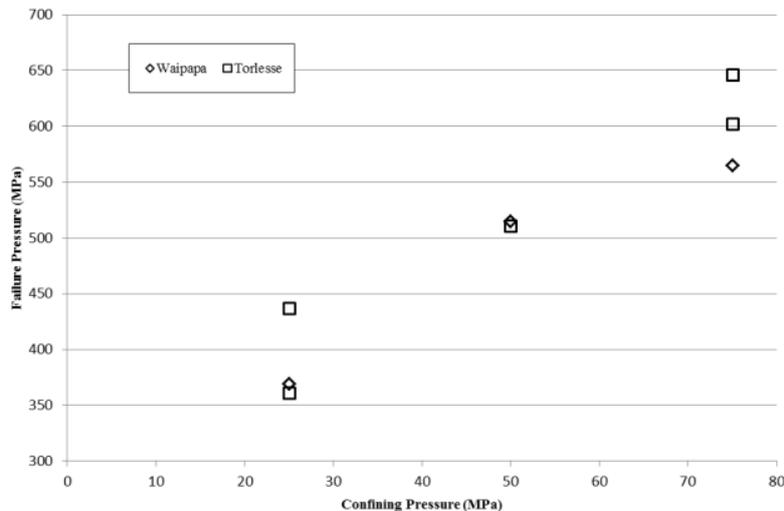
$$\tau = \sigma \tan(43) + 51 \tag{1}$$

where τ is shear strength, σ is the normal stress, 43 is the internal angle of friction in degrees, and 51 MPa is the cohesive strength.

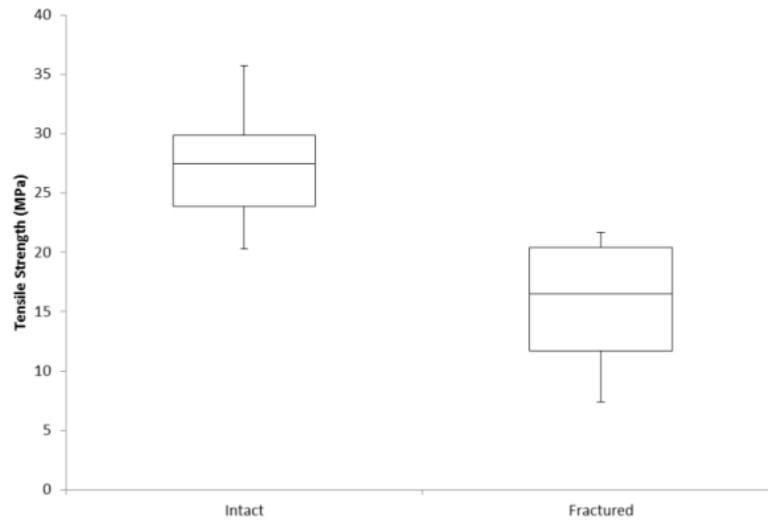
$$\tau = \sigma \tan(44) + 49 \tag{2}$$

where τ is shear strength, σ is the normal stress, 44 is the internal angle of friction, and 49 MPa is the cohesion.

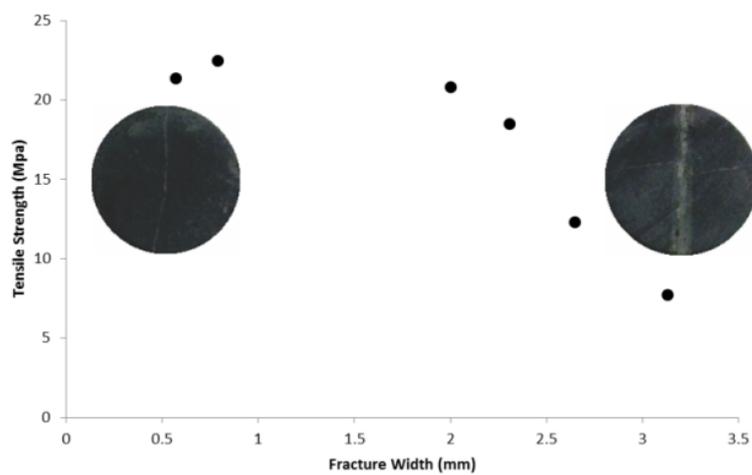
Figure 4 shows box and whisker plots of the tensile strength data gathered from 'intact' and 'fractured' samples of greywacke from the Waipapa Terrane. Intact greywacke rock has higher tensile strengths (~20-36MPa) than the quartz veins that run through it (~7-22MPa). A plot of quartz vein tensile strength against fracture width (Figure 5) shows that wider fractures have lower tensile strengths than narrow ones.



**Figure 3: Graph showing results of triaxial compression tests of greywacke rocks from both study terranes at various confining pressures.**



**Figure 4: Box and whisker plot showing the tensile strengths of Waipapa Terrance greywacke sandstones and of quartz filled fractures within them.**



**Figure 5: Graph showing tensile strength of fractures of variable width in Waipapa Terrane greywacke. Insets are photographs of the narrowest and widest fractures tested.**

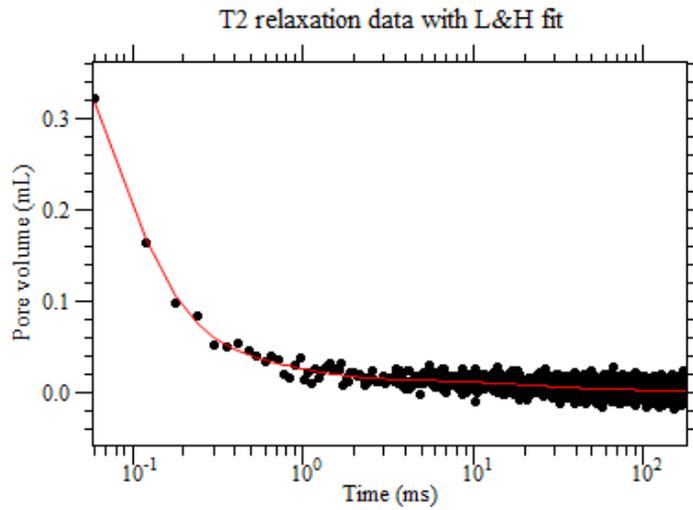
## 4.2 Permeability and Porosity

### 4.2.1 Fluid Flow Test

A fluid flow test done across a sample of Torlesse greywacke at a confining pressure of 20 MPa provided a very low permeability value of  $\sim 4.824 \times 10^{-22} \text{ m}^2$  ( $\sim 4.89 \times 10^{-7} \text{ mD}$ ).

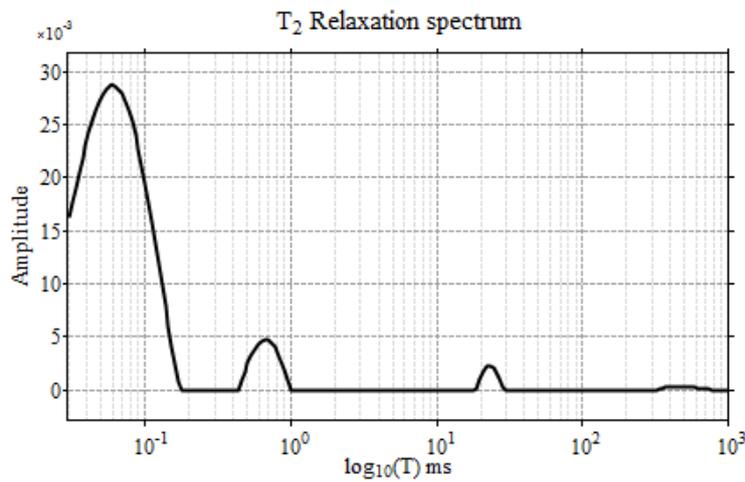
### 4.2.2 NMR Core Measurements

Both  $T_2$  and  $T_1$  experiments were carried out on a sample of Waipapa Terrane greywacke sandstone. The CPMG sequence was collected with linear spacing but is binned pseudo-logarithmically (Figure 6).



**Figure 6: Graph showing the fit of the CPMG sequence (red line).**

The data are noisy and the fit becomes poor at the beginning of the  $T_2$  decay. This provides a porosity measurement of 5% and a total fluid volume of  $\sim 0.75$  mL. However the  $T_2$  spectrum (Figure 7) shows that most of the signal has a relaxation rate on the order of the sampling rate suggesting this measurement of  $T_2$  relaxation is susceptible to errors.



**Figure 7: Graph showing the relaxation rates for the collected  $T_2$  spectrum.**

$T_1$  experiments acquire the signal after two RF pulses. In this experiment we acquire with an echo to minimize the impact of probe ringing. A comparison of the initial amplitude of the FID for the Waipapa greywacke experiment to the calibration sample (Figure 8) provides a porosity measurement of 2% (total fluid volume of  $\sim 0.3$  mL). Here the data is fit well throughout the data set compared to the  $T_2$  data.

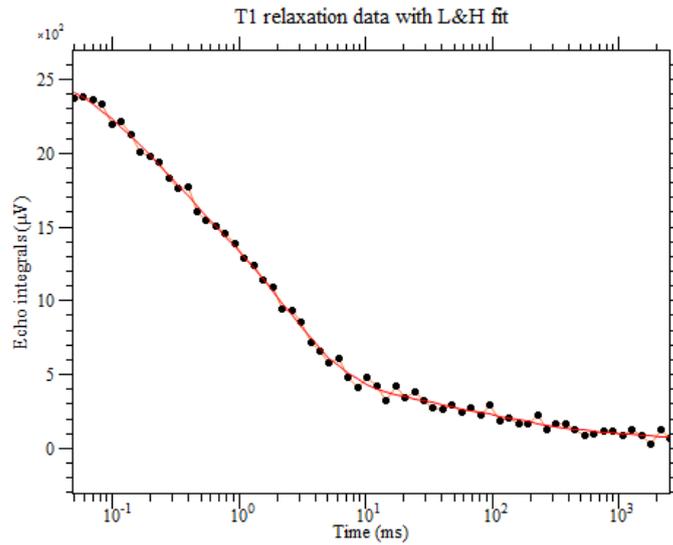


Figure 8: Graph showing the FID of the T1 measurement on the greywacke sample against the calibration sample.

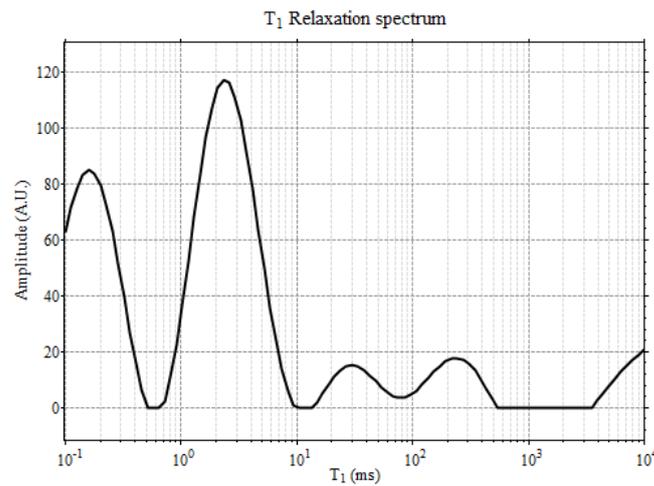


Figure 9: Graph showing the relaxation rates for the collected  $T_1$  spectrum.

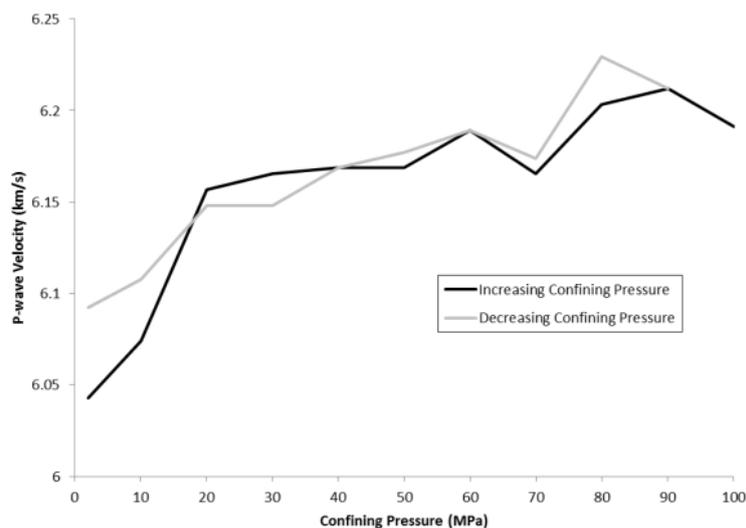
Permeability correlates well with porosity and NMR relaxation (Kenyon, 1997). The NMR data shows that the porosity is very low and the relaxation rates are very short (Figure 7 and 9). Using the standard constant of the Schlumberger permeability estimation equation:

$$k_{SDR} = A\phi^4 T_{LM}^2$$

where  $T_{LM}$  is the log mean value of the relaxation distribution,  $\phi$  is the porosity and A is 0.1 for  $T_1$  and 4.5 for  $T_2$ , we can estimate a permeability of around  $10^{-6}$  mD. This is a rough estimate because the model was developed for much more permeable sandstone samples.

#### 4.3 Acoustic Velocity

Figure 10 shows the acoustic velocities of P waves across a sample of Waipapa Terrane greywacke under first increasing confining pressure (2 – 100 MPa) and then decreasing confining pressure (90 – 2 MPa). From 2 – 20 MPa confining pressures there appears to be a sharp yet small increase in velocity followed by smaller increases as confining pressures increase to 100 MPa. This pattern is mirrored during decreasing confining pressure though the unconfined velocity (2 MPa) appears to be higher than when it was measured prior to pressurization.



**Figure 10: Graph showing change in P-wave velocities over a sample of Waipapa Terrane greywacke with changing increasing and decreasing confining pressure.**

## 5. DISCUSSION

### 5.1 Initial Implications

This study represents preliminary laboratory results and as such only describes data from a small number of samples. Further testing will be required before conclusions can be drawn from a statistically relevant dataset. Nevertheless these early results provide useful insight into the nature and behavior of greywacke basement hosting geothermal reservoirs.

The very low permeability and porosity measurements obtained in this study are consistent with the hypothesis that fluid flow in New Zealand's greywacke basement is not controlled by pore space, but rather by structures such as faults and fractures (Wood et al., 2001; Bertrand et al., 2012, Wallis et al., 2012). Thermo-mechanical behavior of the greywacke rocks is consequently an important consideration when assessing their geothermal resource potential as the amount and style of brittle deformation will be change as temperatures and pressures do.

Preliminary data on the tensile strength of greywacke samples suggest existing fault and fracture planes are more likely to be reactivated (at least under tensile conditions), compared to new tensile fractures being created in the intact rock. In addition, the wider the structures, the less stress required to reactivate them. We suggest the study of structural patterns from outcropping greywacke (i.e., greywacke quarries in the vicinity of geothermal areas, Bayrante et al., 1989; Rowland and Sibson, 1998; Zuquim and Rowland, 2013) will support advanced structural modeling of New Zealand's basement hosted geothermal fields, and can be used to resolve fracture network relationships and better understand reservoir fluid flow in New Zealand's deep-seated geothermal systems.

Tests on samples from both basement terranes have shown that intact greywacke sandstone is mechanically very strong, with a UCS of 164-310MPa and tensile strengths of ~20-36MPa. Compared to values determined for other crystalline lithologies, e.g. Westerly Granite (UCS = ~200MPa, Heap and Faulkner, 2008, tensile strength = ~10 MPa, Homand-Etienne and Houpert, 1989) and basalts and andesites (UCS = ~50-150MPa, tensile strength = 10-25 MPa, Dinçer et al., 2004; Siratovich et al., 2012) these rocks are on par or stronger. Other studies report UCS values of ~168-245MPa for Waipapa and Torlesse Terrane greywacke sandstone, (Stewart, 2007 and references therein) although reported tensile strengths are lower (~7-19MPa). Comparison of unconfined strength data between terranes indicate that the Waipapa greywacke is systematically stronger than the Torlesse greywacke, further evidenced by the higher densities, Poisson's ratio (i.e. less compressible), and Young's modulus (i.e. stiffer).

Heterogeneity in New Zealand greywacke grain size has previously been reported as a cause of variation in UCS values (Rowe, 1980; Cook, 2001), with finer-grained greywacke tending to have lower compressive strengths. From the samples tested in this study those representing the Torlesse Terrane had a finer grain size than those from the Waipapa Terrane, confirming this reported observation. Further work will explore the extent of this heterogeneity in grain size within and between terranes to determine fully the effect on mechanical behavior.

Triaxial deformation experiments undertaken on Torlesse and Waipapa terrane greywacke have provided cohesion ( $C$ ) and friction angle ( $\phi$ ) values similar to those reported from other exposures of this terrane (Cook, 2001). However, triaxial test results imply similar mechanical properties for both terranes as opposed to uniaxial tests which indicate the Waipapa Terrane rocks are mechanically stronger. Possible explanations for the mechanical responses of the Torlesse to the Waipapa rocks may be that the application of confining pressure reduces the effect inherent flaws or weaknesses (i.e. microcracks, etc.) have on rock failure. Further testing and performing seismic velocity tests on the Torlesse greywacke (similar to that reported here for the Waipapa Terrane) will shed more light on this.

From our preliminary results, we infer a systematic mechanical difference between greywacke from the Waipapa and Torlesse terrains. This will affect the way fracture development and reactivation occurs, is an important consideration for individually

managing and utilizing basement hosted reservoirs in each terrain, and may impact future exploration of New Zealand's deeper (>3 km) basement geothermal resources.

## 5.2 The Effect of Temperature

To date geothermal wells in New Zealand have rarely been drilled deeper than 3km. Temperatures experienced at these depths vary across the geothermal systems, with a typical maximum of ~300°C, which approximates the brittle-ductile transition temperature of quartzo-feldspathic / granite-type rocks. As already discussed, rock composition has a large bearing on the brittle-ductile transition temperature. In addition the fact that seismicity records indicate brittle failure to a depth of up to ~6-7km in the TVZ implies the thermo-mechanical behavior of New Zealand greywacke basement rocks is different to that of quartzo-feldspathic / granite-type rocks.

Greywacke composition has been inferred to impact the occurrence of brittle deformation in the TVZ (Wood et al., 2001), and may explain variations in permeability in geothermal reservoirs hosted by greywacke basement. Torlesse greywacke is sourced from granite-rhyolite while the Waipapa is derived from andesite-dacite. The difference between the assumed temperatures that allow brittle deformation to occur for these rocks (based on composition) may explain why the Ohaaki Geothermal Field (granite-rhyolite sourced) has no basement permeability while the andesite-dacite Torlesse does.

Future work to investigate the effect of composition will focus on the thermal effects on brittle failure of greywacke of variable composition. This in addition with measurements of the properties of fractures within greywacke rocks will aid in determining whether greywacke rock can support and sustain a permeable fracture network.

## 6. CONCLUSIONS

The preliminary results from this pilot study conclude that:

- a) The greywacke rocks that compose the basement terranes of geothermal systems in New Zealand are mechanically very strong.
- b) There is a systematic difference in the mechanical behavior of the Torlesse and Waipapa Terranes where the Waipapa Terrane appears to be mechanically stronger.
- c) This difference may be due to Waipapa greywacke having a coarser grain size and/or an andesite-dacite composition compared to Torlesse greywacke having a finer grain size and/or a granite-rhyolite composition.
- d) Both greywacke terranes have very low permeability and porosity confirming a dominant fracture control over fluid flow.
- e) Veins within these greywacke rocks have lower tensile strengths than the rocks themselves and this difference increases with increasing fracture width.
- f) This implies the existing fracture network (through crack-sealing processes) is likely to dominate fluid flow in the basement greywacke rather than by the continual generation of new fractures.

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