THE EFFECT OF HYDROTHERMAL ALTERATION ON THE MECHANICAL AND PHYSICAL ROCK PROPERTIES

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ABSTRACT

This paper describes the relationship between hydrothermal alteration and physical/mechanical rock properties of selected formations from three geothermal fields in the Taupo Volcanic Zone, New Zealand. Our characterisation of hydrothermally altered rocks from geothermal reservoirs will lead to an improved understanding of rock mechanics in the geothermal environment, and subsequently support drilling optimization, wellbore stability studies and geomechanical modelling. To characterise the physical and mechanical rock properties of selected formations, samples were prepared from intact core for non-destructive and destructive laboratory testing. The hydrothermal alteration assemblages were characterised using optical mineralogy and existing petrography reports. All samples exhibited secondary mineralisation, but the type and occurrence varied depending on where in the system the sample was collected. The samples from the geothermal fields show a wide variety of physical rock properties. Samples of the same formation that originate from different wells across a field have a spread of uniaxial compressive strength and porosity because of differences in the alteration zones, primary rock properties and depth. Where this data spread exists, we have been able to derive trends for this specific data set and subsequently have an improved understanding of how hydrothermal alteration affects physical/mechanical properties.

1. INTRODUCTION

Alteration is an unavoidable process that produces significant changes in almost all of the mineralogical, chemical and physical properties of rocks (Pola et al. 2012), and two types of alteration are observed in volcanic environments: weathering and hydrothermal. The influence of secondary mineralization on the strength and durability of rock is of particular interest to the conventional geothermal industry because few rocks in a hot, dynamic, liquid and/or steam filled reservoir are fresh. Various petrographic and weathering indices have been proposed to identify alteration impacts on lithologies. These mainly relate to chemical, petrological and mechanical rock properties (Rigopoulos et al. 2010). In the Brady Hot Springs, Nevada, observations of rock strength found that quartz dominated lithologies had higher rock strengths (uniaxial compressive strength) than argillaceous lithologies because the high crystal content in the quartz dominated samples supports the rock against compression (Lutz et al. 2011). Tools that predict mechanical and physical rock properties are useful for reservoir development, management and prospect evaluation during exploration because there is usually very limited or no borehole-based rock property data (Ameen et al. 2009; Tamrakar et al. 2007). Relationships between strength and porosity, density or mineralogy for a specific rock formation are established based on laboratory tests on rock core from a given field or lithology. This is in order to acquire empirical relationships that can be used to derive the mechanical properties. Although the most accurate method of developing these relationships utilises direct measurement on core samples, the small volume of material available from geothermal drilling is a drawback to this method. Furthermore, testing techniques are expensive, leading to only limited numbers of samples tested in a given field. It follows that many researchers and industry practitioners commonly apply empirical strength relationships to geophysical wireline data or limited laboratory data (Cobanoglu & Celik, 2008; Dincer et al. 2004). Chang et al. (2006) reviewed thirty-two empirical relationships for sedimentary rocks where physical rock properties were derived from geophysical wireline tools. Their review made clear that a few of the empirical correlations appeared to work fairly well for some subsets of the rocks studied but only fitted to the formations the empirical correlations where designed. We have previously assessed the applicability of selected criteria to our formations and found that the relations did a poor job fitting the data (Wyering et al. 2012). The downfall of these empirical relationships is that they are only applicable to the particular lithologies being studied, and do not necessarily correlate for all rock types, especially silicic volcanic rocks affected by secondary mineralisation. Whilst the equations presented in the Chang et al. (2006) review paper may be useful to a practitioner in the geothermal industry as a first order approximation, they are focused on sedimentary rocks with no high temperature secondary mineralisation.

The present paper will address effects of the physical and mechanical rock properties of the hydrothermal alteration from selected formations from Ngatamariki, Rotokawa and Kawerau geothermal fields.

2. GEOLOGY OF THE TVZ AND GEOTHERMAL FIELDS

The Taupo Volcanic Zone (TVZ) is located in the central North Island of New Zealand in a 300 km long and 60 km wide belt, and is defined by caldera structural boundaries and vent positions (Wilson et al. 1995). It formed on a Mesozoic basement assemblage of metasedimentary rocks that have been reached by drillholes in Kawerau, Ohaaki, Rotokawa and Ngatamariki geothermal developments (Browne, 1989). Over the last 2 Ma the TVZ has erupted between 15,000 - 20,000 km^3 of volcanic rocks, with 80% being rhyolitic pyroclastic and subordinate lava flows from several caldera centres (Cole & Spinks, 2009). At present, a few andesitic volcanoes are located in the northeast and southwest of a predominantly rhyolitic volcanism section, where very high rates of magma generation and eruptions are associated with high temperature geothermal activity (Cole & Spinks, 2009). However, a number of andesite deposits have been intersected at depth in geothermal systems within the TVZ.

3. METHODOLOGY

Physical and mechanical rock property laboratory tests were conducted on selected core samples collected from Ngatamariki, Rotokawa and Kawerau. Our analysis evaluated ten lithological formations (Figure 1). Ngatamariki samples came from nine wells and consisted of three selected formations. Rotokawa samples came from three wells and all comprised one formation – the Rotokawa Andesite. Kawerau samples came from seven wells and consisted of the six different formations. The stratigraphic succession of these three fields and those sampled formations are displayed in Figure 1.

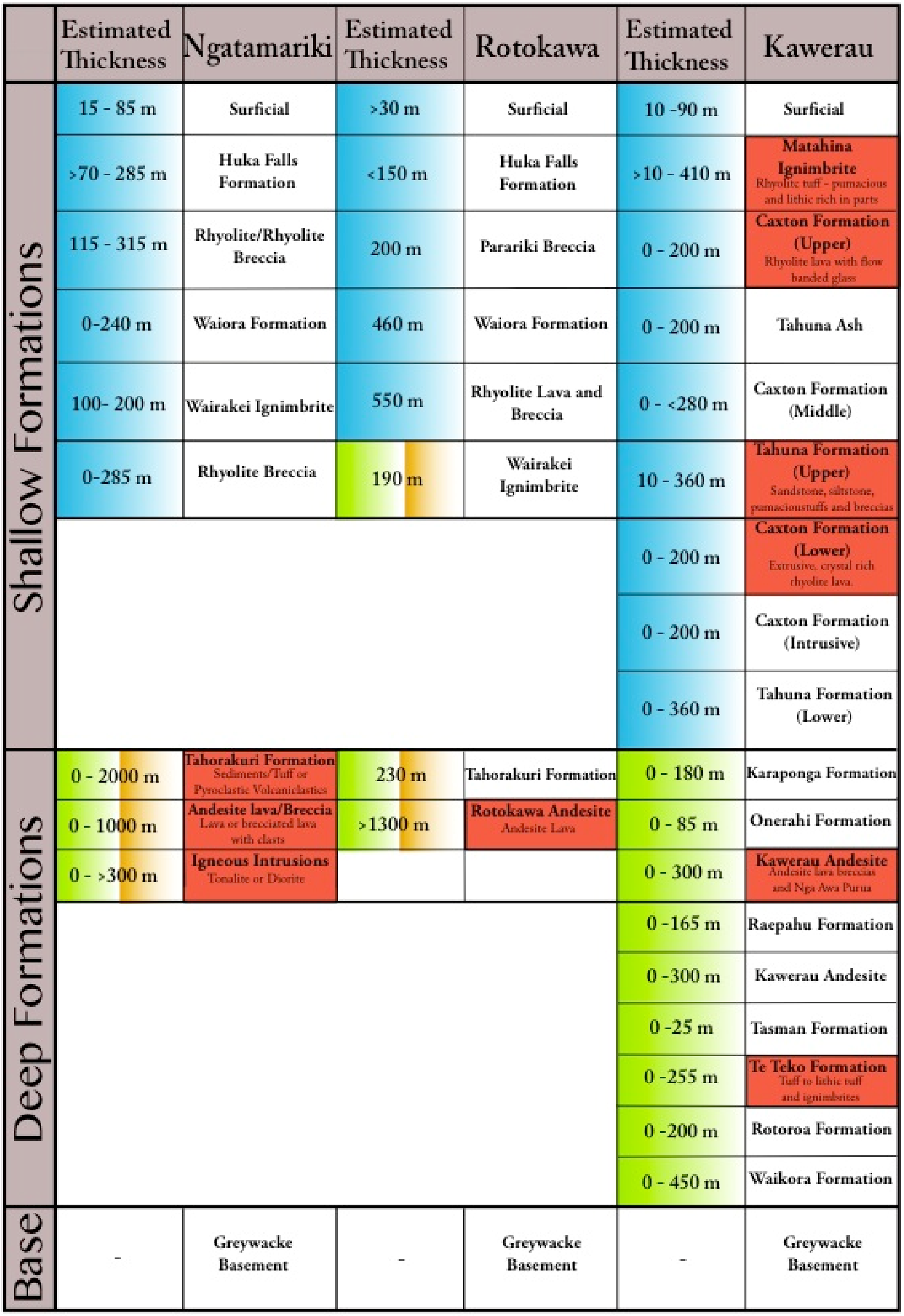

Figure 1: Generalised stratigraphy of the three geothermal fields and known thicknesses with the approximate alteration zones (Smectite – blue, green – illite and orange – epidote); red highlighted units were tested in this study (stratigraphy adapted from Rae et al, 2009; Chambefort & Bignall, 2011; Milicich et al. 2012)

3.1 Porosity and Density

In this study we are addressing the impacts of hydrothermal alteration on physical rock properties from the Ngatamariki, Rotokawa and Kawerau geothermal fields. Rock porosity and density impact mechanical strength, so these parameters were defined for each sample. Effective porosity (η_e) and density testing was carried out according to the saturation and caliper techniques (ISRM, 1978), which involves calculating dry density (Υ_{dry}) and saturated density (Υ_{wet}) of the cylindrical core samples submerged in distilled water under a constant air vacuum pressure. Determining effective porosity (η_e) of a hydrothermally altered rock sampled from below ~150°C reservoir is challenging as they commonly contain swelling clays; therefore dichloromethane was used to determine the saturated density as a non-polar saturation fluid would avoid activating the swelling clays.

3.2 Ultrasonic Wave Velocities

The ultrasonic wave velocities were determined in this study to address how different degrees of hydrothermal alteration impacts compressional and shear wave velocities. There are two basic types of elastic waves: body waves which travel through the interior of the rock body, and surface waves which can only travel along the surface of the rocks. In this study we have used ultrasonic pulse method to determine the body waves. Body waves are divided into two modes: compressional or primary waves (*P*) and shear or secondary waves (*S*). *P*-waves travel in any direction in a sample that resists compression, but since *S*-waves depend upon the ability of the transmitting material to resist changes in shape, they can only exist in the rock. The sample was set up and the height (mm), diameter (mm), mass (g) and density (g/mm^3) were input into the software C.A.T.S. Good acoustic coupling between the platens and the sample surface is necessary to ensure accuracy of transit time measurement, so petroleum jelly was used as a coupling agent. The compressional wave was sent through the rock sample, the first arrival was manually picked, and compressional wave velocity calculated (m/s). The testing was then repeated in shear wave mode. The selected compressional and shear wave velocities were used to derive the dynamic Poisson's ratio, Young's, Bulk and Shear moduli for each sample. This test process was then repeated for the samples after (1) oven drying at 105°C for 24 hours and (2) saturation in a vacuum chamber with deionized water for 24 hours. Every test was repeated 3-5 times in each respective saturation state to produce a range of compressional and shear wave velocities from which to draw an average.

3.3 Uniaxial Compressive Strength Testing

Uniaxial compressive strength tests, the key variable of our present study, were conducted using the ASTM (2010) and ISRM (1979) standards. Electrical resistance strain gauges were placed on each of the subsamples to measure axial and radial deformation of the sample during uniaxial loading.

4. RESULTS

4.1 Petrological Analysis

A wide variety of hydrothermal minerals have been recognized in active and extinct geothermal systems. Establishment of a many mineral species is highly dependent on temperature, and some minerals only occur over a specific temperature range that, in a given system, can be approximately correlated to specific depth ranges (Browne, 1978). Pressure is an important variable because it controls the distribution of two-phase (boiling) zones, which are often characterised by the occurrence of bladed calcite and vein minerals. Permeability, both by its extent and nature, plays a role in determining which alteration minerals form by controlling the amount of contact between fluids and reservoir rocks (Cox & Browne, 1998). We undertook petrological analysis using a polarized light microscope to characterise the primary and secondary mineral assemblage. This included identifying veining, microfractures, and natural planes of weakness on the core samples. The primary and secondary textures in the samples were also noted where they could be identified.

4.1.1 Ngatamariki Thin Section mineralogy

The Andesite Breccia is an intensely altered pale green to dark green clast supported breccia. In the polarized light microscope studies it was observed that the breccia contains clasts of greywacke, granite, andesitic lava, rhyolite lava and siltstone. The main alteration assemblage of the rock consists of epidote, chlorite and quartz, with minor calcite, pyrite, albite, adularia, and titanium oxide. The breccia contains small veins (<1-2 mm) with calcite, epidote, and quartz fills.

The Tahorakuri Formation core from Ngatamariki is strongly altered light greenish/greyish grey-white ignimbrites; though one core is an intensely altered, light grey breccia with abundant cream-whiteish clay. All of the Tahorakuri Formation samples were predominately altered to clay and fine-grained quartz. However, one core only contains these two minerals along with quartz – pyrite veins. The common alteration products in the samples are quartz, calcite, and chlorite with minor albite, adularia, wairakite, pyrite and rare titanium oxide. The veining in the samples mainly contain quartz, pyrite and some rare smaller calcite or illite (<0.2-0.3 mm).

4.1.2 Rotokawa Thin Section Mineralogy

The Rotokawa Andesite is a moderately to intensely altered lava/breccia. In the polarized light microscope studies it was observed that the samples matrix and primary minerals have been altered predominately to calcite, chlorite, quartz and minor epidote or hematite with the small amounts of albite, adularia, titanium oxide and pyrite.

4.1.3 Kawerau Thin Section Mineralogy

The Matahina Ignimbrite is a moderately altered light brown to light greyish cream ignimbrite. The primary minerals of plagioclase and quartz have been altered to abundant clay, quartz, titanium oxide, calcite, albite and pyrite. Glass shards are still evident in the sample.

The Caxton Formation (Upper) is white and yellow altered rhyolite lava that is predominately clay, quartz, anhydrite, wairakite and titanium oxide.

The Tahuna Formation is a dark grey moderate to intensely altered mudstone that is made of clay, calcite and quartz. No veining is present. All the grains in the sample are all aligned in the same direction.

The Caxton Formation (Lower) consists of quartz and plagioclase as its primary minerals that have been strongly altered to clay, quartz, calcite, albite, adularia and titanium oxide. The Kawerau Andesite is a moderately to intense pale to dark green altered andesitic lava that has been altered to chlorite, calcite, albite, illite, titanium oxide and quartz. A high level of calcite veining and vugs in-filled with calcite, quartz and chlorite are seen in the sample.

The Te-Teko formation has two distinctive lithologies: Crystal lithic tuff and tuffaceous pebbly sandstone. Both the lithologies have undergone intense alteration. The crystal lithic tuff is a pale cream with spicks of green. In the polarized light microscope studies it was observed that the primary minerals (plagioclase, ferromagnesian minerals and quartz) have been replaced by chlorite, clay, calcite, pyrite quartz albite, wairakite and titanium oxide. The samples contain strong veining of clay and a few calcite veins. The tuffaceous pebbly sandstone primary minerals plagioclase and quartz has been altered to calcite, pyrite, chlorite, titanium oxide, illite, quartz and albite.

4.2 Physical and Mechanical Properties – Laboratory Testing

The testing results for the effective porosity varied between 1 and 56%, the bulk density varied between 1000 and 2900kg/m^3 and the results varied between 1800 and 4600m/s for compressional wave velocities and 800 and 2700m/s for shear wave velocities between all the formations. The results in Figure 2 show that the effective porosity and density of the formations can be similar as seen with the Rotokawa Andesite (purple), or variable as seen with the Matahina Ignimbrite (blue) where the effective porosity varies from 5 and 13% and 15 and 50% respectively.

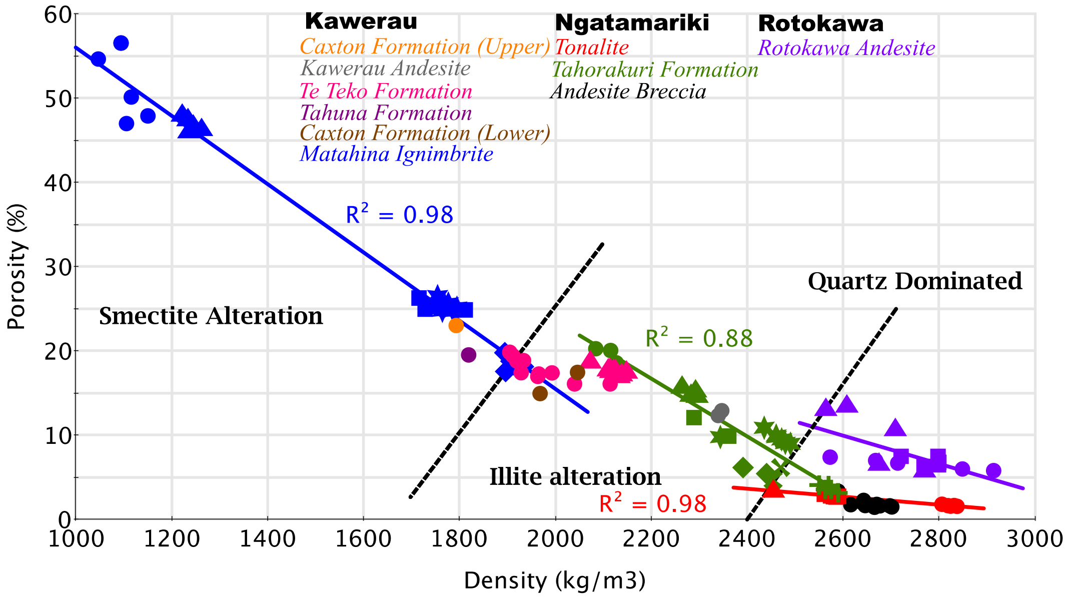

Figure 2: Plot of effective porosity and density from the three geothermal fields. Symbology differentiates samples taken from different wells. Plot is split into three alteration zones based on observed mineralogy which are key for this study.

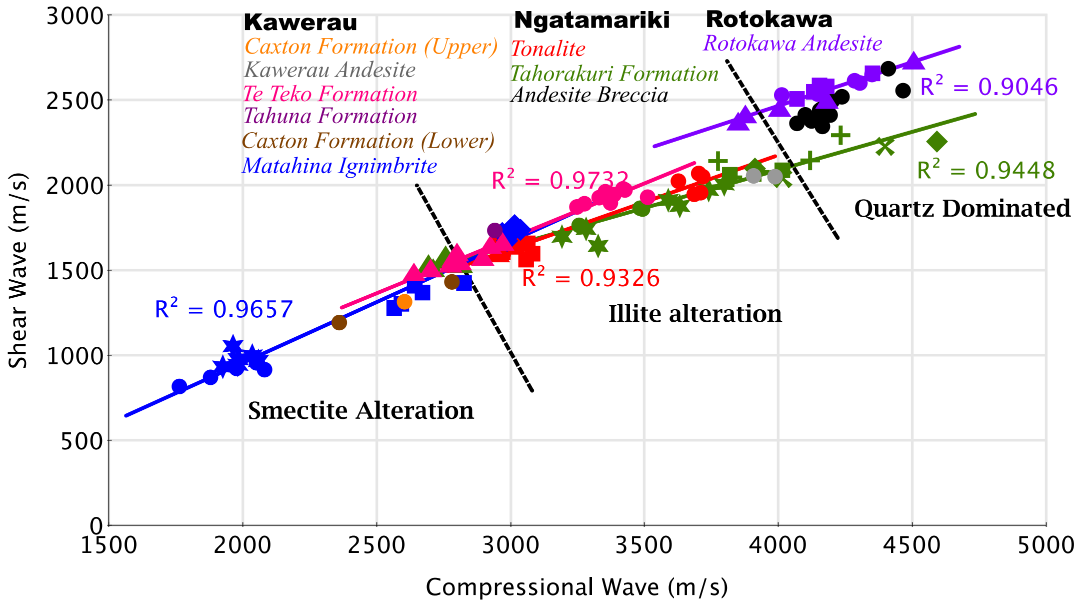

Figure 3: Plot of compressional wave velocities and shear wave velocities (ultrasonic wave velocities) from the three geothermal fields. Symbology differentiates samples taken from different wells. Plot is split into three alteration zones based on observed mineralogy which are key for this study.

The plot of effective porosity against density in Figure 2 shows a strong relationship between effective porosity and density; with the effective porosity increasing as the density decreases. The ultrasonic wave velocities in Figure 3 demonstrate that as the compressional (V_p) wave velocity increases the shear (V_s) wave velocity increases. The Tahorakuri Formation, Matahina Ignimbrite and Tonalite show strong formation-specific trends with R^2 values greater than 0.88 for effective porosity and density and R^2 values greater than 0.9 for ultrasonic wave velocities. However, they do fall within the broader trend defined by all formations.

The results from the uniaxial compressive strength testing are displayed in Table 1 with UCS ranging from 5 to 189 MPa.

Table 1: Measured minimum and maximum UCS in MPa for formations from Ngatamariki (NM), Rotokawa (RK) and Kawerau (KA).

Formation	Depth (mD)	Min UCS	Average UCS	Max UCS
Andesite Breccia (NM)	2181	37.7	128	189.2
Rotokawa Andesite (RK)	2121-2321	70.6	130	213.6
Te Teko Formation (KA)	758 - 1102	29.5	43	59.4
Matahina Ignimbrite (KA)	72 - 106	5.3	30	76.5
Caxton Formation (Upper) (KA)	155	24	24	24
Caxton Formation (Lower) (KA)	458	22.6	28	33.5

5. DISCUSSION

To determine the variation of physical and mechanical rock properties from the different geothermal fields, samples have been used from a number of wells that encounter the same formation. The Tahorakuri Formation, Tonalite, Rotokawa Andesite, Kawerau Andesite and Te Teko Formation samples came from deep, high temperature sections of a typical geothermal system, whereas the Matahina Ignimbrite, Caxton Formation (Upper and Lower) and Tahuna Formation come from shallow, low temperature sections of a typical geothermal system (Figure 1). All these formations therefore have undergone different types and intensities of hydrothermal alteration along with having different primary rock types and burial depths (overburden magnitude).

5.1 Porosity and Density

Porosity and density are key physical characteristics of rocks, as they affect mechanical properties like strength, ultrasonic wave velocity and permeability. As an overall trend from the three geothermal fields, shallow/low-temperature formations have a higher porosity and lower density than rocks from deep/high-temperature formations. Volcanic rocks typically have a wide range of primary matrix porosity, due to the different primary lithologies, which can be enhanced or reduced by alteration (Rejeki et al. 2005). An example of this variation in properties is seen in Figure 2 with the Tahorakuri Formation – dominantly a variably welded sequence of tuffs and ignimbrites. The data for this formation are from seven different wells located across the Ngatamariki geothermal field. As individual wells the samples are closely related, which is illustrated by the samples from the same core plotting around similar porosities and densities. This demonstrates that samples obtained from the same section of well have closely related physical properties, which can be due to the samples originally having the same primary lithology, alteration intensity and originating from the same burial depth. The Andesite Breccia, Rotokawa Andesite and Te Teko Formation also demonstrate this tendency to cluster around the same porosity and density. In the case of the breccia this is probably more related to the fact that we have only sampled from one core because a formation of this kind is likely to have a wide range of porosities depending on clast arrangement, while the andesite is likely because it does have a low range of matrix porosities. Although the samples from the Te Teko Formation are of different primary lithology (fine sandstone and ignimbrite), the apparent clustering could be controlled by the secondary mineralisation, as the two different lithologies could have had different primary porosities.

In their study of porosity in the Darajat Geothermal Field, Indonesia, Rejeki et al. (2005) proposed that porosity is mainly controlled by rock type and alteration processes. Variations in original rock texture, grain size and fragment abundance, along with dissolution or replacement of primary minerals, leads to variation in porosity values. They also found that alteration mineral assemblage and clay type play a significant role in enhancing or reducing primary porosity; such that illite alteration produces a lower porosity compared to smectite alteration. The porosity and density plot (Figure 2) has been subdivided into smectite, illite and quartz dominated alteration based on the mineral assemblage seen in thin sections. It can be perceived that where formations contain clays, like smectite or illite, they tended to have a higher porosity and lower density than formations that have quartz dominated alteration. As an overall trend, in Figure 2, samples that have primary lithologies of ignimbrites or tuffs and contain smectite/illite alteration e.g. Matahina Ignimbrite, have a higher porosity (greater than 15%) and lower density (less than 1800 kg/m^3) than samples derived from lavas, breccias or intrusions with a quartz dominated alteration, e.g. Tonalite (less than 5% and greater than 2400 kg/m^3). The same trend can be seen at a formation trend scale. A well-defined example of is from the Tahorakuri Formation. When split into individual wells samples, as mentioned before, the samples tend to cluster around the same porosity and density. NM2, with an illite alteration assemblage has higher porosities and lower densities (~20% and 2100 kg/m^3) than samples from NM4 (~3% and 2600kg/m^3) with quartz dominated alteration. This variation may be related to the alteration because each sample from the different wells has undergone a different alteration history; however the Tahorakuri Formation does contain a number of different lithologies, and therefore the influence of primary lithology cannot be eliminated.

Stimac et al. (2004) found that in the Tiwi geothermal field the andesite sequence primary lithology plays a smaller role in influencing porosity rather than the process of compaction due to burial and reaction with fluids at elevated temperatures. Compaction by grain rotation/crushing, which can occur during faulting, and infilling of large primary voids by early-formed alteration minerals both work to reduce porosities. Figure 4 plots the porosity of the samples from the Ngatamariki, Rotokawa and Kawerau geothermal field against the depth range where the samples were collected. The data set compares with Stimac et al. (2004), showing that there maybe some compaction going on for the Rotokawa Andesite, Andesite Breccia and Kawerau Andesite. This is displayed in Figure 4 where the burial depth of these lithologies increases as the porosity of the sample decreases. However, it is important to note that the formations represented by deep sampling in our data set primarily have low primary porosities when deposited. A clear compaction/diagenesis trend can therefore not be applied to this dataset when taken together.

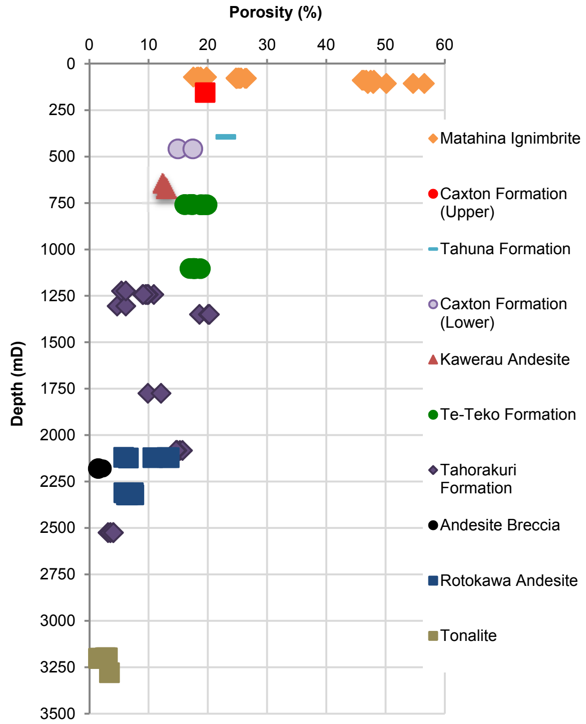

Figure 4: Porosity (%) vs. depth (mD) for all samples.

5.2 Ultrasonic Wave Velocities

Ultrasonic wave velocities are one of the non-destructive geophysical methods used by engineers in varies fields (Martinez-Martinez et al. 2006). Our research is using ultrasonic wave velocities to determine a relationship between wave propagation and hydrothermal alteration. Lama & Vutukuri (1978) and Gardener et al (1974) found that various factors (e.g., rock type, texture, density, porosity, water content and temperature) affect the propagation velocity of ultrasonic waves. More recent studies have shown that pore structure, pore frequency, texture, fracturing, and severe mineralogical changes in a rock also affect the ultrasonic wave velocity (Pola et al. 2012). Hydrothermal alteration leading to secondary mineralisation has an impact on the velocity of ultrasonic waves due to mineralogical and pore/void geometry changes. Therefore, the plot of ultrasonic wave velocities has been divided into smectite, illite and quartz dominated alteration based on the minerals seen in thin sections (Figure 3). The overall trend of the data from all three geothermal fields shows that those rocks lead by quartz dominated alteration and lower porosity have faster compressional wave propagation, averaging between 4000 – 5000 m/s, compared to samples with smectite alteration, which fall between 1750 – 3000 m/s. A study by Ladygin et al. (2000) on three geothermal systems from the Kuril-Kamchatsky Region, Asia showed variations in ultrasonic velocities due to the secondary mineralisation and porosity. High temperature (350-260° C) alteration by a large variety of secondary minerals (e.g., chlorite, quartz, wairakite, albite and epidote) produced compressional wave velocities around 3000-4000 m/s with porosities around 15-20%, whereas the hydrothermal alteration containing low temperature clays (smectite) produced compressional wave velocities of around 2500-2000 m/s with porosities of >25%. An earlier study conducted by Han et al. 1986, found that a small amount of clay, even 1 or 2 % by volume, (e.g. smectite) could alter the matrix of sandstones leading to a reduction in the ultrasonic velocities. This trend can be seen in the Tahorakuri Formation as it ranges from 2300 – 4400 m/s for the compressional wave velocities, with some samples containing alteration that falls into the illite alteration zone (more clay rich) and others that fall into the quartz dominated alteration zone (more quartz, epidote and chlorite rich). From the Rotokawa Andesite it can be seen that the samples from one well fall just on the boundary between illite and quartz dominated alteration. Furthermore, Tonalite has two distinct clusters around the 3000 m/s and 3600 m/s compressional wave velocity that could be due to differing amount of secondary mineralisation.

Ultrasonic wave velocities generally decrease with increasing porosity and microfractures. Wyllie et al. (1958) determined from their research that if possible a wave would travel through intact rock avoiding fractures and voids. Gardner et al. (1974) found that microfractures and porosity influence the velocity of an ultrasonic wave as demonstrated with samples of gabbro. The tested gabbro had a P-wave velocity of 5699 m/s in a dry, non-fractured sample, and decreased in P-wave velocity (3352 m/s) as fractures formed. Figure 5 shows the same decreasing trend of compressional wave velocity as the porosity increases for all of the data from the Ngatamariki, Rotokawa and Kawerau geothermal fields. This agrees with Wyllie et al. (1958) and Gardner et al. (1974) where the compressional wave travelled through the core sample faster with lower porosity due to the wave being able to travel through the rock body faster than through the air in the voids. With the available sample set it is not possible to determine the primary controlling factor (alteration or porosity), but it is more likely to be porosity.

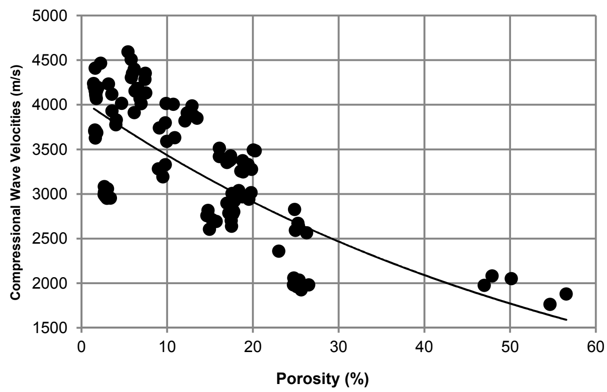

Figure 5: Porosity vs. compressional wave velocity.

5.3 Uniaxial Compressive Strength (UCS)

Hydrothermal fluid-rock interaction results in the development of secondary minerals that fill pores and cracks, substitute matrix and replace primary minerals. It can therefore result in part or complete changes in the rock composition and, consequently, mechanical behavior. The samples from the shallow, low temperature regions of the geothermal field had low UCS with an average of 28 MPa compared to samples from deep/high temperature regions that had an average of 129 MPa. This illustrates that samples from deeper in a geothermal system typically have higher strengths than samples from the shallow regions. This trend could mostly be due to lithology trends as samples from shallow depths are predominately ignimbrite/tuffs while deep depths comprise intrusive and extrusive lavas. As individual formations it is evident that hydrothermal alteration influences the rock strength as seen in the Rotokawa Andesite and Matahina Ignimbrite, where the secondary mineralogy is different between samples and the UCS varies from 70 – 213 MPa with an average of 128 MPa and 5 to 76 MPa with an average of 30 MPa, respectively. The Matahina Ignimbrite has a smectite alteration assemblage with large amounts of clay and calcite alteration. However, the variation in the data was due to the larger abundance of fresh rock (quartz and glass) in the later samples allowing for the samples with a higher percentage of quartz to retain their strength.

Strength and stiffness properties of intact rock under uniaxial compression are fundamental in geotechnical investigations. Studies have shown that only very subtle changes occur in rocks prior to failing in compression (Wawersik & Fairhurst 1970). A rock in uniaxial compression undergoes volumetric changes, by where the compressive load causes a decrease in volume as pore spaces are closed. However, dilation and an associated increase in rock volume may occur in the late stages of the test due to distance between grains increasing as a result of rock deformation. Bridgman (1949) observed this process in soapstone, marble and sandstone. Compressibility of rocks is dependent upon the ability of individual grains, pores and cracks to compress. Cracks in rocks are one of the major factors contributing to the compressibility, through the growth of macroscopic fractures generally taking place rapidly when the applied stress becomes equal to the compressive strength. Compressibility of porous rocks are greater than that of solid material of the same composition and for any pore shape or concentration (Lama and Vutukuri, 1978). This is illustrated in Figure 6 where the Youngs modulus is plotted against porosity, with a trend of high porosity samples having higher rock compressibility.

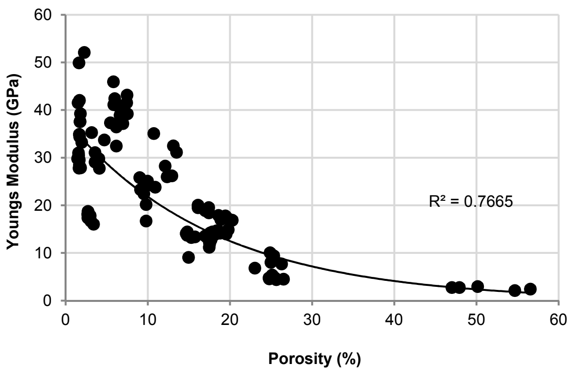

Figure 6: Plot of porosity (%) vs. Youngs modulus (GPa).

Walsh (1961) found that spherical pores are two or three times more effective than cracks at increasing rock strength because the sample compresses inwards closing the pores leading to a stiffer rock. He also found that the strength of a rock is more affected by a few long cracks than numerous microcracks. This is because the amount of energy required to fail along a large crack is less than the energy required to produce failure along numerous small cracks by expanding and connecting them. We also noted the impact of crack distribution during the UCS testing that had large fractures propagating through the rock. One sample in particular from the Andesite breccia failed at 37.7 MPa due to sliding along an obvious fracture (note that typical andesite breccia UCS > 100 MPa).

In summary, previous studies and our present results demonstrate that the ultimate failure of a rock sample is affected by changes in mineralogy, grain size, shape, orientation and distribution, microcracks density, orientation, length and distribution.

6. CONCLUSION

Samples from Ngatamariki, Rotokawa and Kawerau geothermal fields show a wide variety of physical and mechanical rock properties. The physical rock properties as shown by the porosity and density and ultrasonic wave velocities plots have an overall trend, in addition to the formation specific trends, as clearly shown in Figures 2 and 3. The formation-specific trends indicate the level of variability of physical parameters within each formation sample set, while the position of each grouping on the overall trends indicate the relationship between the two properties being analysed and gives an idea of the cross-field variability within a particular lithology.

The mechanical properties of a rock are significantly affected by the presence and geometry of fractures and porosity; highlighted in this case by two samples of andesite breccia with a measured UCS that differs by approximately 150 MPa. In addition, changes in mineralogy have also been observed to significantly affect the strength of a rock, as exemplified in the Matahina Ignimbrite ranging from 5 MPa to 76 MPa. The Matahina Ignimbrite is of smectite alteration assemblage with large amounts of clay and calcite alteration. However, the variation in the data was due to the larger abundance of fresh rock (quartz and glass) in the later samples allowing for the samples to retain strength.

Although noticeable variability of both physical and mechanical rock properties was encountered during testing, we have been able to derive trends from these results and develop an improved understanding of how hydrothermal alteration could affect physical/mechanical properties.

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