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The development and application of the alteration strength index equation

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ABSTRACT

We have developed an alteration strength index (ASI) equation to address the effect of hydrothermal alteration on mechanical rock properties. This equation can be used to estimate a range of rock strengths, comparable to uniaxial compressive strength (UCS), based on rapid analysis of mineralogy and microstructure. We used rock samples from three geothermal fields in the Taupo Volcanic Zone (TVZ) to represent a range of alteration types. These are sedimentary, intrusive and extrusive rocks, typical of geothermal systems, from shallow and deep boreholes (72 measured Depth (mD) to 3280 mD). The parameters used in ASI were selected based on literature relating these aspects of mineralogy and microstructure to rock strength. The parameters in ASI define the geological characteristics of the rock, such as proportions of primary and secondary mineralogy, individual mineral hardness, porosity and fracture number. We calibrated the ASI against measured UCS for our samples from the TVZ to produce a strong correlation (R^2 of 0.86), and from this correlation we were able to derive an equation to convert ASI to UCS. Because the ASI–UCS relationship is based on an empirical fit, the UCS value that is obtained from conversion of the ASI includes an error of 7 MPa for the 50th percentile and 25 MPa for the 90th percentile with a mean error of 11 MPa. A sensitivity analysis showed that the mineralogy parameter is the dominant characteristic in this equation, and the ASI equation using only mineralogy can be used to provide an estimated UCS range, although the error (or uncertainty) becomes greater. This provides the ability to estimate strength even when either fracture or porosity information are not available, for example in the case of logging drill cuttings. This research has also allowed us to provide ranges of rock strengths based solely on the alteration zones, mineralogy, and depth of lithologies found in a typical geothermal field that can be used to update conceptual models of geothermal fields.

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1. Introduction

Rock strength is necessary for geothermal reservoir development, management and prospect evaluation because it controls rock behaviour during drilling, stimulation and resource extraction. Tools that predict rock properties are critical because there are usually limited or no borehole-based rock property data (Gunsallus and Kulhawy, 1984; Edlmann et al., 1998; Ameen and Smart, 2009). Relationships between strength and porosity, density or mineralogy for a specific rock formation have been widely developed based on laboratory tests on rock core from a given field or lithology (Chang et al., 2006; Tamrakar et al., 2007; Rigopoulos et al., 2010; Singh et al., 2012; Karakul and Ulusay, 2013). These relationships, however, were developed using mainly sedimentary, granitic and metamorphic rock samples and cannot be applied ubiquitously to all lithologies, especially hydrothermally altered volcanic rocks. Only recently have studies investigated the physical and mechanical properties of volcanic rocks (Ladygin et al., 2000; Frolova et al., 2005; Vinciquerra et al., 2005; Smith et al., 2009; Frolova et al., 2010; Nara et al., 2011; Pola et al., 2012; Heap et al., 2014a; Pola et al., 2014; Wyering et al., 2014; Heap et al., 2015) with reference to how different rock properties impact the strength of the material.

Recovering core to test is expensive and, owing to the fractures in the rocks, recovery can be poor leading to only a limited number of samples tested in a given geothermal field. Therefore, many researchers and industry practitioners apply empirical strength relations to borehole geophysics data or limited laboratory data (Edlmann et al., 1998; Koncagül and Santi, 1999; Dinçer et al., 2004; Entwisle et al., 2005; Çobanoğlu and Çelik, 2008; Binal, 2009). Chang et al. (2006) reviewed thirty-two empirical relationships for sedimentary rocks where physical rock properties were derived from borehole geophysics. Their review made clear that a few of the empirical relationships appeared to work fairly well for some subsets of the rocks studied. Wyering et al., 2012 assessed the applicability of selected empirical equations for predicting uniaxial compressive strength (UCS) for geothermally altered lithologies and found that the correlations between predicted UCS and measured UCS were poor. 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

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volcanic rocks affected by secondary mineralisation. Whilst the equations presented in Chang et al. (2006) 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 and therefore have limited utility (Yagiz, 2009).

Research has shown that several rock properties (mineral hardness, secondary minerals, microstructural damage that includes the presence of microfractures and pores) can influence the predicted rock strength of material (Tuğrul and Zarif, 1999; Ameen and Smart, 2009; Rigopoulos et al., 2010; Coggan et al., 2013; Heap et al., 2014a). Several petrographic and weathering indices related to chemical, petrological and mechanical properties, have been suggested to identify the impact of alteration on rock properties in different lithologies (Ulusay et al., 1994; Tamrakar et al., 2007; Ceryan et al., 2008; Yildiz et al., 2010; Pola et al., 2012, 2014).

This paper describes the development of a strength prediction equation that can be used to calculate a strength range comparable to UCS using descriptions of hydrothermal alteration, secondary mineralisation, porosity and bulk rock structural damage. The core samples used are sourced from the Ngatamariki, Rotokawa and Kawerau geothermal fields from the Taupo Volcanic Zone (TVZ), New Zealand, allowing the equation to be adapted for geothermal fields located in the TVZ. It encompasses a variety of lithologies that are found in the TVZ and the differing geothermal environments they are exposed to. The equation could be used in other geothermal systems worldwide with similar geothermal conditions or adapted easily to suit. We will show that development of this equation has improved understanding of how alteration mineralogy and physical properties control rock strength. We will demonstrate how a variant of the equation could be used in the field to optimize drilling of geothermal reservoirs through improved drill bit selection.

2. Geothermal setting

The active Taupo Volcanic Zone (TVZ) is located at the southern end of the Tonga Kermadec arc in the central North Island of New Zealand, in a 300 km long (200 km on land) and 60 km wide belt, defined by caldera structural boundaries, volcanic vent positions and geothermal systems (Fig. 1: Cole, 1990; Wilson et al., 1995). The >20 geothermal systems in the TVZ, totaling ~4500 MW thermal output (Bibby et al., 1995), are related to magmatic heat generated at depth and shallow crustal structure that provides the permeability necessary for convective transport of hydrothermal fluids (Rowland and Sibson, 2004; Rowland and Simmons, 2012). These circulating fluids become rich in dissolved minerals, as they percolate through the stratigraphy (Henneberger and Browne, 1988) and precipitate minerals in the reservoir rocks producing the secondary mineralisation that are observed when the rocks are drilled and brought to the surface (Goff and Janik, 2000). The rock types we used in this study (described in detail in Wyering et al., 2014) were sourced from shallow formations – Rhyolitic ignimbrite, Rhyolitic lava, and Siltstone/Sandstone – and from deep formations – Rhyolitic ignimbrite, Andesite Lava/Breccia and Tonalite intrusive – from numerous geothermal fields in the TVZ.

3. Data source

All of the data used in this study are sourced from Wyering et al. (2014). They characterized the physical and mechanical properties of lithologies from the Ngatamariki, Rotokawa and Kawerau geothermal fields (Fig. 1), using non-destructive and destructive methods to determine porosity, density, ultrasonic wave velocities and uniaxial compressive strength (UCS). The samples were cored to a mean diameter of 39.6 mm and were cut and ground to within the length to diameter ratio of 2:1. Their study examined thin sections using a polarized light microscope, that utilized plane polarized light (PPL) and cross-polarized light (CPL) to identify primary and secondary minerals (that includes but is not limited to clays, quartz, epidote, chlorite, albite and pyrite), microfractures and bulk rock fractures in the lithologies. Although Wyering et al. (2014) did mention the textures of the samples, they were not used in this study because the samples were moderately to intensely altered. The textures within the samples were completely replaced and difficult to distinguish, reducing the ability to use the data.

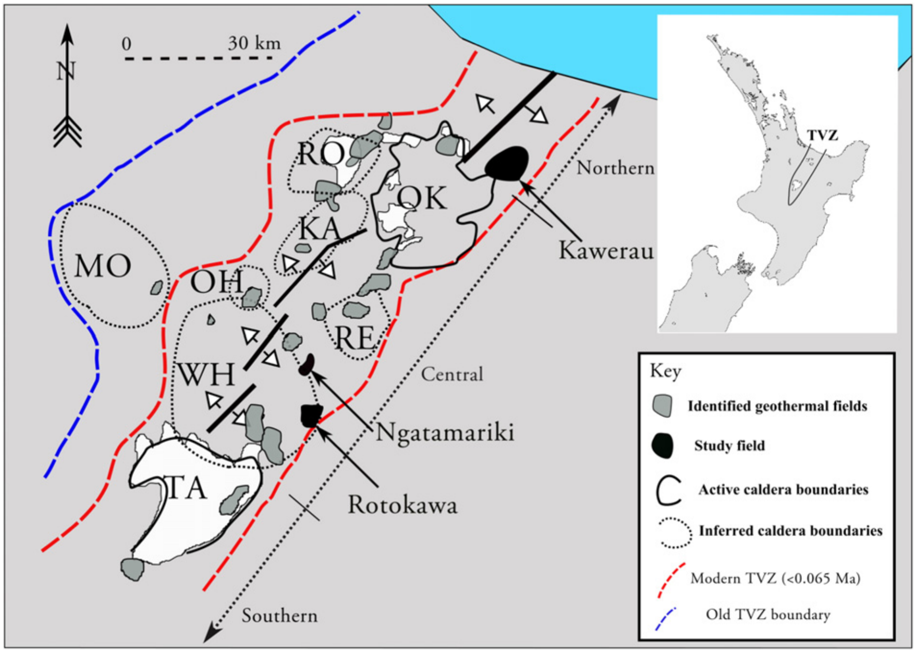

Fig. 1. A map of geothermal activity in the Taupo Volcanic Zone (TVZ), showing the positions of geothermal systems, the active and inferred caldera boundaries and the Taupo Rift (white lines with arrows). The geothermal fields used in this study are located. Abbreviations are named calderas: KA = Kapenga, MO = Mangakino, OH = Ohakuri, OK = Okataina, RE = Reporoa, RO = Rotorua, TA = Taupo, WH = Whakamaru. The map is split up into the main volcanic activity in the TVZ and outlined by the boundary of the young TVZ (<0.34 Ma) (Adapted from Wilson et al., 1995; Bibby et al., 1995; Rowland and Sibson, 2004; Kissling and Weir, 2005; Rowland and Simmons, 2012).

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