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Mechanical and physical properties of hydrothermally altered rocks, Taupo Volcanic Zone, New Zealand

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ABSTRACT

Mechanical characterization of hydrothermally altered rocks from geothermal reservoirs will lead to an improved understanding of rock mechanics in a geothermal environment. To characterize rock properties of the selected formations, we prepared samples from intact core for non-destructive (porosity, density and ultrasonic wave velocities) and destructive laboratory testing (uniaxial compressive strength). We characterised the hydrothermal alteration assemblage using optical mineralogy and existing petrography reports and showed that lithologies had a spread of secondary mineralisation that occurred across the smectite, argillic and propylitic alteration zones. The results from the three geothermal fields show a wide variety of physical rock properties. The testing results for the non-destructive testing shows that samples that originated from the shallow and low temperature section of the geothermal field had higher porosity (15 – 56%), lower density (1222 – 2114 kg/m^3) and slower ultrasonic waves (1925 – 3512 m/s (v_p) and 818 – 1980 m/s (v_s)), than the samples from a deeper and higher temperature section of the field (1.5 – 20%, 2072 – 2837 kg/m^3, 2639 – 4593 m/s (v_p) and 1476 – 2752 m/s (v_s), respectively). The shallow lithologies had uniaxial compressive strengths of 2 – 75 MPa, and the deep lithologies had strengths of 16 – 211 MPa. Typically samples of the same lithologies that originate from multiple wells across a field have variable rock properties because of the different alteration zones from which each sample originates. However, in addition to the alteration zones, the primary rock properties and burial depth of the samples also have an impact on the physical and mechanical properties of the rock. Where this data spread exists, we have been able to derive trends for this specific dataset and subsequently have gained an improved understanding of how hydrothermal alteration affects physical and mechanical properties.

1. Introduction

Alteration produces significant changes in almost all the mineralogical, chemical and physical properties of rocks (Lumb, 1983; Arel and Tugrul, 2001; Begonha and Sequeira Braga, 2002; Arikan et al., 2007). Two types of alteration are observed in volcanic environments: weathering and hydrothermal (Ceryan et al., 2008; Yıldız et al., 2010; Pola et al., 2012). Weathering occurs when the Earth's atmosphere and waters interact with the rock system; while in a hydrothermal context alteration is caused by the movement of hot, dissolved-ion rich fluids through reservoir rocks causing dissolution, mineral deposition, clay mineral formation producing secondary mineralisation (Frank, 1995; Finizola et al., 2002; Hurwitz et al., 2002; Hase et al., 2005; Pola et al., 2012, 2014). Several factors, in a geothermal field, affect the formation of alteration minerals; pressure, permeability, rock type, temperature, duration, and these minerals vary in relative abundance both within a system and between systems (Browne, 1978, 1989; Mehegan et al., 1982; Cox and Browne, 1998; Robb, 2005; Pola et al., 2012).

Relationships between strength and porosity, density or mineralogy for a specific rock formation (Chang et al., 2006), and the influence of secondary mineralisation on the physical and mechanical properties of rock has been studied by many authors (Ulusay et al., 1994; Kahraman et al., 2005; Sousa et al., 2005; Chang et al., 2006; Tamrakar et al., 2007; Ceryan et al., 2008; Yıldız et al., 2010; Rajesh Kumar et al., 2011; Pola et al., 2012, 2014). Studies to this extent are of limited interest to the conventional geothermal industry because few rocks in a hot, dynamic, liquid and/or steam filled reservoir are unaltered or exposed at the surface. However, the results/relationships developed are mainly for sedimentary, granitic and metamorphic rocks and cannot be applied ubiquitously to all lithologies, especially hydrothermally altered volcanic rocks at depth. Only recently have studies investigated the physical and mechanical properties of volcanic rocks (Vinciguerra et al., 2005; Smith et al., 2009; Nara et al., 2011; Pola et al., 2012, 2014; Heap et al., 2014). However, these studies are focused on site-specific lithologies and on rock properties that are not directly relevant to the sub-surface reservoir rocks of the Taupo Volcanic Zone (TVZ) geothermal fields, which are examined in this study. Mass transfer resulting primarily

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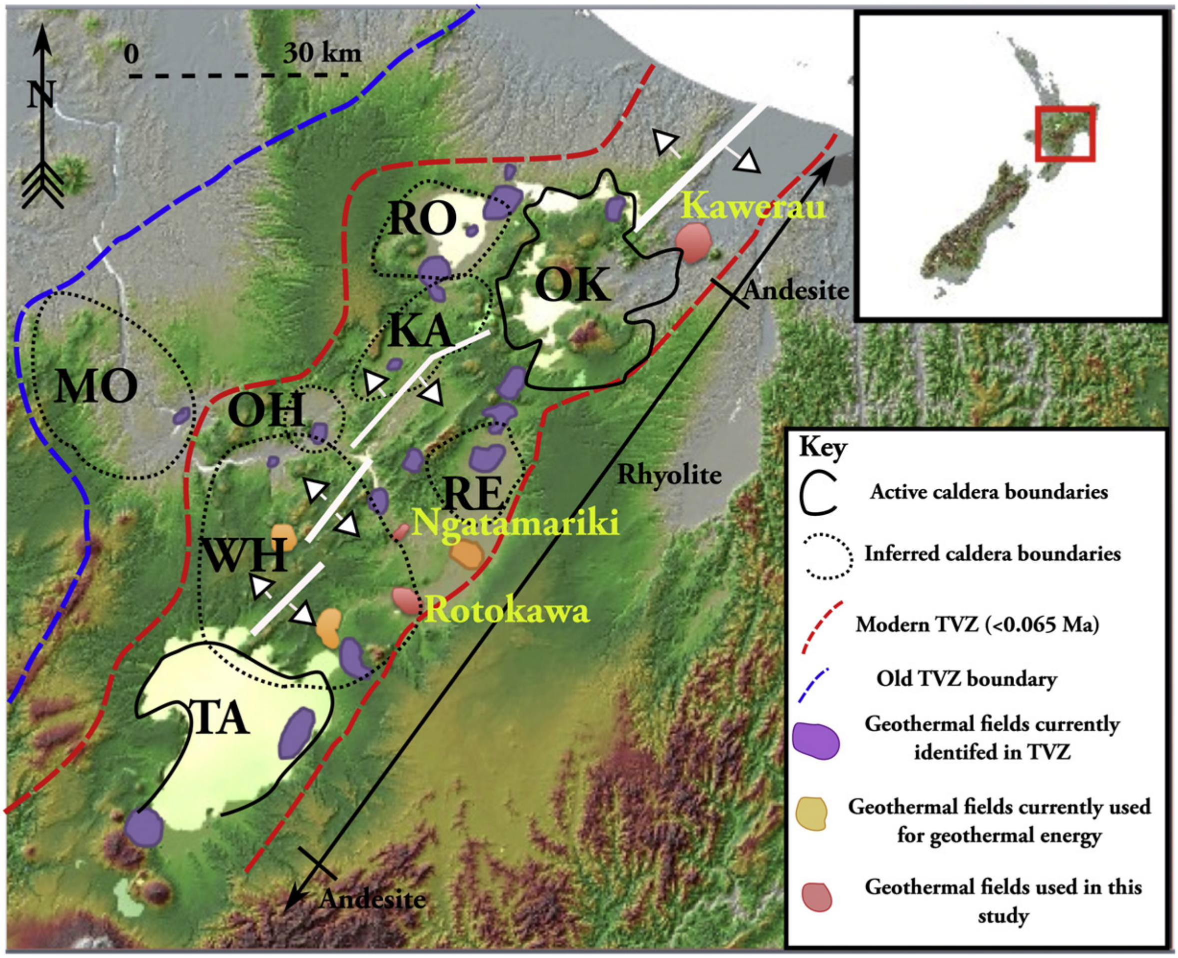

Fig. 1. Digital elevation map with the geologic setting of geothermal activity in the Taupo Volcanic Zone (TVZ), showing the positions of geothermal systems (red, purple, orange), the active and inferred caldera boundaries and the Taupo Rift. The yellow names represent the geothermal fields that are being addressed in this study. 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 is 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).

from dissolution of reservoir rocks minerals and precipitation of alteration products (Ferry, 1979; Giggenbach, 1984; Henneberger and Browne, 1988; Simmons and Browne, 2000; Pochee, 2010; Esmaeily et al., 2012) cause the bulk geochemistry and mineralogy of the reservoir rocks to differ from its initial primary rock mineralogy, leading to a partial or wholesale changes in the rock composition and subsequent physical and mechanical behaviour (Lumb, 1983; Arel and Tugrul, 2001; Begonha and Sequeira Braga, 2002; Robb, 2005; Arikan et al., 2007; Yıldız et al., 2010).

The aims of this paper are: to produce a detailed description of the altered lithologies used in this study and to physically and mechanically characterize hydrothermally altered volcanic rocks. We then examine the relationships between physical and mechanical properties and lithology to quantify the effect of hydrothermal alteration on these lithologies. The purpose of this analysis is to support on-going research into the development of a new geotechnical model to aid in the understanding of the primary controls of rock properties in a young igneous geothermal system, and how these properties may be utilised for bit selection in drilling (Wyering et al., in Preparation).

2. Geological Setting

The rocks in this study originate from the Taupo Volcanic Zone (TVZ), which 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, vent positions and geothermal fields (Fig. 1: Wilson et al., 1995; Rowland and Sibson, 2001), and in its modern form coincides with a structurally and magmatically segmented rift system (Taupo rift). The oblique subduction of oceanic crust from the Pacific plate beneath the Indian-Australian plate caused the back arc/arc basin producing the TVZ (Cole, 1990; Bibby et al., 1995, 2008; Darby et al., 2000; Rowland and Sibson, 2004; Cole and Spinks, 2009; Seebeck et al., 2010; Rowland et al., 2012).

The geothermal systems in the TVZ are developed by the transportation of meteoric waters, which percolate down through fractures, faults and textures in lithologies, and then rise when heated by deep magma or intrusive bodies (Henneberger and Browne, 1988; Hochstein, 1995; Rowland and Sibson, 2004; Rowland and Simmons, 2012). These circulating geothermal fluids become rich in dissolved minerals, as they percolate through the stratigraphy (Henneberger and Browne, 1988) and precipitate minerals in the reservoir rocks (Goff and Janik, 2000).

The samples were taken from core sourced from the Ngatamariki, Rotokawa and Kawerau geothermal fields. Ngatamariki and Rotokawa comprise volcanic and sedimentary lithologies overlying a Mesozoic metasedimentary (greywacke) basement. The shallow formations contain sediments, tuffs and tuffaceous breccias, siltstones, ignimbrites, and brecciated/tuffaceous rhyolite lava. Deeper formations contain the Tahorakuri Formation, which is divided into two sections: a mix of sedimentary layers, and tuff or pyroclastic volcaniclastics with andesitic lava or breccia on top of the basement rock. Ngatamariki also contains an intrusive material in the northern end of the field (Fig. 2: Krupp