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Combining scanning electron microscopy and compressibility measurement to understand subsurface processes leading to subsidence at Tauhara Geothermal Field, New Zealand

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ABSTRACT

The Tauhara geothermal field is located within the Taupo Volcanic Zone, New Zealand and has undergone subsidence in three localized areas referred to as the Crown, Rakaunui and Spa Sights bowls, with measured subsidences of 0.9, 2.4 and 2.9 m, respectively. These subsidence bowls are situated close to Taupo township and are of concern to the public and for geothermal developers. Therefore, an intensive subsidence study at the Tauhara field was undertaken to better understand and mitigate further subsidence. Tauhara and Wairakei are often referred to as one system as a shallow, low resistivity anomaly extends continuously across both fields. However, they are two individual fields with separate up-flows. Tauhara is located in the south of the system, while Wairakei is located in the northern area. The Wairakei field also has subsidence bowls that reach up to 15 m in localized areas. Extraction of fluids from the Wairakei field began in 1958 (currently 171 MWe) but did not begin at Tauhara until 2010 (currently 23 MWe). At Wairakei, initial fluid withdrawal was from the Waiora Formation which extends under both the Wairakei and Tauhara fields. Since 1958, fluid pressure in the Waiora Formation has dropped and this pressure decline extends under both the Wairakei and Tauhara fields. A pressure drop has also been detected in the Mid Huka Falls Formation which is a permeable stratigraphic unit present at shallower depth (relative to the Waiora Formation) in both fields. The Tauhara subsidence investigation included drilling, with continuous core recovery, at selected sites located inside (THM 16), outside (THM 13, THM 14) and on the periphery (THM 12) of known subsidence bowls. Cored samples representative of the seven formations encountered were analyzed to establish their stiffness by determining their constrained modulus (CM) value. On the same samples, the effect of hydrothermal alteration was established using scanning electron microscopy (SEM), electron dispersive spectroscopy (EDS), petrography and X-ray diffraction (XRD). Key findings include the following: (1) CM values ranged from 20 to 1800 MPa; (2) THM 16 revealed the lowest CM values of the study (<100 MPa) at 50 to 100 m of depth, where there has been a change in the subsurface to more acidic conditions; (3) Samples that revealed no clay minerals attached to crystal surfaces produced significantly higher CM values (THM 13, CM = 1730 MPa), than those samples where clay minerals were attached to and altering the crystals (THM 12, CM = 84 MPa); (4) Fracturing of crystals was observed in some samples from drillholes THM 12 and THM 13 located on the periphery and outside the Rakaunui subsidence bowl respectively, which may be a response to localized stress induced by subsurface compaction; (5) No crystal fracturing was observed in THM 14 located outside all subsidence bowls. The pressure drop across both the Tauhara and Wairakei geothermal fields has resulted in compaction of the Huka Falls Formation at depth with consequent subsidence at the surface. At Tauhara, compaction of the Huka Falls Formation at 130 to 400 m of depth occurs within the Rakaunui subsidence bowl. Furthermore, intense hydrothermal alteration at the Crown subsidence bowl (THM 16) has weakened a hydrothermal breccia deposit where compaction occurs at 35 to 200 m of depth. The combination of techniques used in this study proved a useful tool for unraveling complex geothermal processes altering the subsurface rocks. By establishing the hydrothermal alteration processes and coupling them with CM values we gained insights into rock stiffness and fluid–rock interactions within the Tauhara geothermal field.

1. Introduction

The Wairakei–Tauhara geothermal system is located within the Taupo Volcanic Zone (TVZ), New Zealand (Figure 1). Wairakei and Tauhara are

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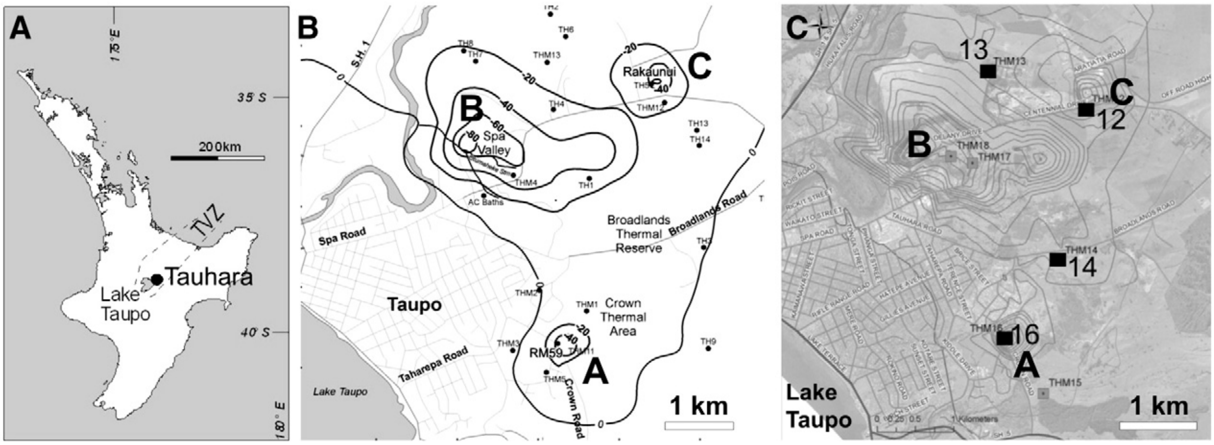

Fig. 1. Location maps of Tauhara geothermal field and study sites, Taupo Volcanic Zone (TVZ), New Zealand. (A) North Island of New Zealand showing the location of Tauhara geothermal field within the TVZ. (B) Location of three subsidence bowls within Tauhara. A = Crown bowl, B = Spa Sights bowl, C = Rakaunui bowl. (C) Location of cored drillholes from which samples in this study were analyzed. Contour lines shown in (B) and (C) represent subsidence rates in mm/year. Numbers represent drillhole number. A = Crown bowl, B = Spa Sights bowl, C = Rakaunui bowl.

separate geothermal fields with two distinct up-flows but are often referred to as the Wairakei–Tauhara field due to their close proximity. Power generation from Wairakei began in 1958 while Tauhara was not commissioned until 2010. At Wairakei, subsidence became evident shortly after production started with subsidence in the range of one to two meters over a 1 km^2 area, and locally reaching up to 15 m near Geyser Valley (Allis et al., 2009). Subsidence is a common surface effect in many geothermal fields of New Zealand following fluid extraction and pressures drops.

Subsidence at Tauhara is manifested in three smaller subsidence bowls: (1) Spa Sights bowl identified in the 1960s with subsidence of 2.9 m; (2) Rakaunui bowl also identified in the 1960s with subsidence of 2.4 m; and (3) Crown bowl identified in 2000 with 0.9 m of subsidence (Bromley et al., 2009; Figure 1). Because of the Tauhara geothermal field's proximity to Taupo township, subsidence at Tauhara is a concern for both the public and for geothermal developers. The Tauhara Subsidence Project (described below) was initiated by Contact Energy to better understand and mitigate further subsidence.

The intensive subsidence investigation undertaken at Tauhara involved drilling and recovering continuous cores from nine drillholes (157 to 804 m depth), located outside, on the margin and inside known subsidence bowls. Selected core samples from key stratigraphic units were tested to determine their mineralogical and mechanical properties. Specialized tests on core samples included pocket penetrometer, shear vane, Atterberg limits and constrained modulus (CM) tests (Bromley et al., 2010, 2013). The strength of the cored rock was indicated by point load testing and the CM value was obtained from K_o triaxial testing on selected cores. The CM is the fundamental parameter controlling land subsidence due to fluid withdrawal (Galloway et al., 1998; Gambolati et al., 1999; Teatini et al., 2006; Phillips and Galloway, 2008). Full details on the mechanical properties of Tauhara cored rocks are given in Pender et al. (2013).

In this study, we characterize the hydrothermal alteration of selected cored rocks reported in Pender et al. (2013), enabling a direct comparison of hydrothermal alteration and rock strength. Work undertaken in this study also complimented data analyzed and presented in Bromley et al. (2010). Specifically, this study involved examination of cores from four drillholes, namely, THM12 (peripheral to Rakaunui subsidence bowl), THM 13 (outside subsidence area), THM 14 (outside subsidence area), and THM16 (inside Crown subsidence bowl; Figure 1). The mineralogy and physical properties of the cored samples were characterized using X-ray diffraction (XRD), scanning electron microscopy (SEM) analyses and imagery, electron diffraction spectroscopy (EDS) and thin section petrography. Specifically SEM revealed the fine-scale details of the hydrothermal alteration taking place in the subsurface affecting the strength of the various lithologies. Furthermore, SEM established the subsurface conditions both past and present, enabling a temporal sequence of hydrothermal alteration and changing subsurface conditions to be established. Such changes have an impact on fluid–rock interactions at depth and these changes can either stiffen or soften the lithologic units. Therefore, coupling these observations with CM measurements provided qualitative information on fluid–rock interactions, as well as quantitative measurements of rock stiffness.

2. Overview

2.1. Development history

Wairakei and Tauhara are two separate geothermal fields with separate up-flows and different fluid characteristics. Wairakei is located in the northern part of the system while Tauhara is located in the southern section. The two fields are often referred to as the Wairakei–Tauhara geothermal system as the shallow resistivity determined by geophysical surveys shows a low resistivity anomaly extending continuously across Wairakei and Tauhara (Risk, 1984). The shallow resistivity is used to interpret the distribution of smectite and illite–smectite clay minerals, which are electrically conductive and originated from hydrothermal fluids under 200 °C. In agreement with the continuity of the shallow clay cap inferred from resistivity, monitoring wells in both the Wairakei and Tauhara areas show a mutual pressure response to production and injection indicating that the two fields are hydrologically connected (e.g. Milloy and Wei Lim, 2012). The Wairakei geothermal power plant began production in 1958. In 2007, Contact Energy obtained resource consent for future production at the Wairakei geothermal field and is close to commissioning the Te Mihi Power Station (scheduled for the second half of 2013), which will bring total generation from the Wairakei geothermal field close to 333 MWe.

At present, the Tauhara geothermal reservoir is used for electricity generation through the Te Huka Binary Power Station (commissioned in 2010 with a 23 MWe installed capacity). During the early stages in the development of Wairakei, production fluids were mostly extracted from the Waiora Formation which extends under both the Wairakei and Tauhara fields. Presently, production is from the Waiora Formation and deeper (e.g., Tahorahuri Formation; Bignall et al., 2010). Since 1958, the fluid pressure in the Waiora Formation has dropped approximately 2000 kPa (Bixley et al., 2009). This pressure decrease extends under both Wairakei and Tauhara. A pressure drop has also been detected in