Natural subsidence at the Rotokawa Geothermal Field and implications for permeability development

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ABSTRACT

Levelling surveys of the Waikato River, running through the Rotokawa Geothermal Field and dating back to 1950 show that the field underwent significant subsidence prior to exploitation in 1997. This natural state subsidence can be related to mass removal from the reservoir by hydrothermal alteration. Pochee (2010) shows that altered Rotokawa reservoir andesite is depleted in silica by as much as 15% relative to unaltered reservoir andesite. This depletion is manifested as porosity enhancement due mostly to plagioclase feldspar phenocryst dissolution, similar to that found by Stimac et al (2004) for reservoir rock at the Tiwi field, Philippines. The natural subsidence at Rotokawa is inferred to be due to the gradual collapse of this pore space.

Long term natural subsidence within the reservoir is expected to create strain similar to that experienced in producing oil field reservoirs. Well damage due to subsidence commonly occurs due to horizontal thrust strain along hard-soft bedding plane boundaries and due to reactivation of fault structures. Similar processes may occur within the Rotokawa geothermal reservoir due to alteration-induced compaction, although a lesser strain rate coupled with softer, altered rock material, suggest that the effect may be more subtle. The rocks most susceptible to fracturing due to alteration-induced compaction would be those hardened by silicification surrounding softer reservoir rock. In this way, progressive alteration compaction would lead to fracturing of silicified rocks and reactivation of encompassing vein networks, leading to a positive feedback between alteration and permeability. As these rocks fracture, they increase in permeability which leads to greater access by hydrothermal fluids and more alteration. At a minimum, alteration compaction would play a role in providing incremental rock stress to fracturing due to local tectonic stress and periodic hydraulic pressure changes.

Alteration induced subsidence, such as inferred for Rotokawa, suggests that hidden geothermal resources might be expressed at the surface by geologic evidence of long term subsidence or be observed by modern measurements of surface deformation, such as historic geodetic measurements, precision GPS and satellite interferometry.

1. INTRODUCTION

The Rotokawa Geothermal Field is located on the North Island of New Zealand, approximately 10 km northeast of the town of Taupo on Lake Taupo's northern shore (Figure 1). Rotokawa is a high temperature (>330°C), boiling neutral alkali-chloride system developed in a reservoir of rift-faulted andesite and overlying ignimbrite at the southeastern margin of the the Taupo Volcanic Zone. The southern margin of the field contains a crater lake (Lake Rotokawa) and a series of extensive hydrothermal eruption deposits extending northeast of the lake along the Parariki stream (Collar & Browne, 1985). The Lake Rotokawa area is the site of numerous active fumaroles and boiling acid-chloride hot springs and was the site of surface sulphur mining in past. A field map is presented in Figure 2.

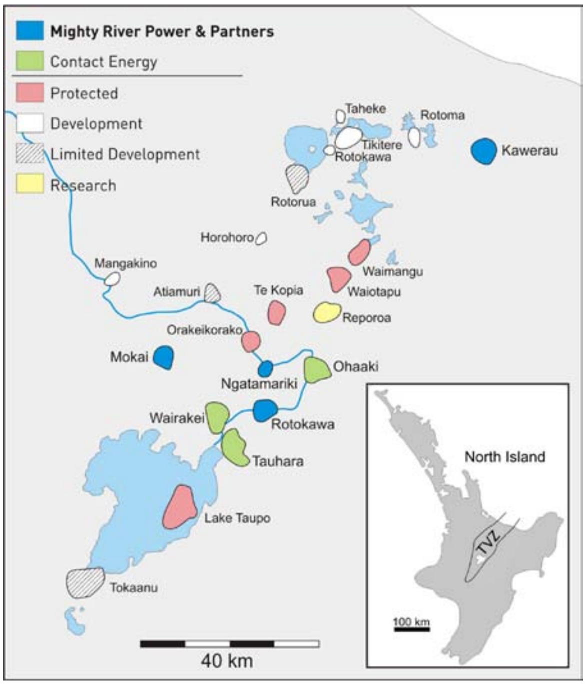

Figure 1: Geothermal fields in the Taupo Volcanic Zone of the North Island of New Zealand. Colours show the development classification of the regional councils

The field was discovered by deep drilling by the New Zealand Ministry of Works and Department of Science and Industrial Research (DSIR) in the 1980's. Generation at a 24 MW combined cycle binary plant began in 1997. Following a number of minor expansions in the first decade of production, the Nga Awa Purua 145 MW triple flash conventional evaporative cooling plant was commissioned in early 2010. The field now generates approximately 180 MW, fed by 12 production wells in the central part of the field south of the Waikato River and backed by 5 deep injection wells along the field's southeastern margin. A limited amount of spent water is injected into a thermal aquifer above the reservoir to mitigate acid carbonate corrosion to production well casings.

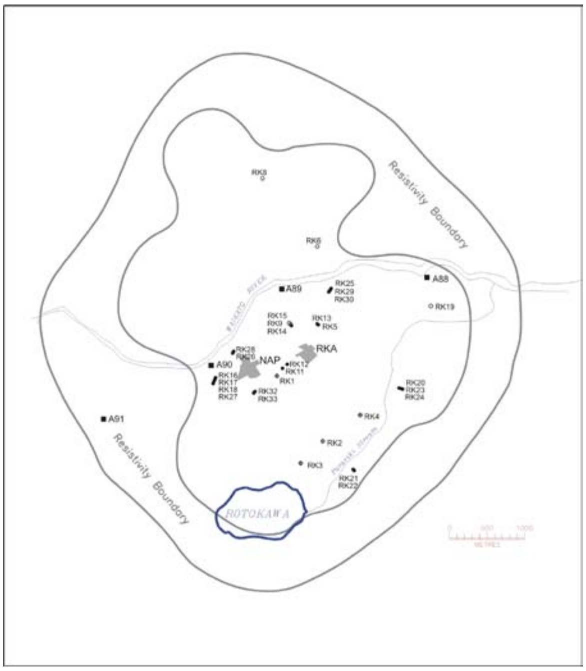

Figure 2: Rotokawa Geothermal Field showing surface locations of wells. Filled circles indicate production or injection wells, open indicate observation wells and circles with crosses abandoned. Wells RK1 through 8 were drilled in the 1980's by the Ministry of Works and DSIR. Present production wells located in the central sector of the field include RK5, 14-18 and RK25-33, deep injection wells at the southeast include RK20-24. RK11 & 12 are shallow injection wells. Locations of the two power plants at the field, the 34MW Rotokawa combined cycle binary plant (RKA) and 145MW Nga Awa Purua triple flash plant (NAP) are shown in gray. The field north of the river is undeveloped and two early Crown wells there are used for observation. Levelling benchmarks A88 through A91 are shown as squares.

2. LONG TERM SUBSIDENCE

Early levelling surveys show that the Rotokawa underwent significant natural subsidence prior to exploitation. Subsequent leveling surveys have shown significant regional deformation probably of tectonic origin, but here the deformation is localized to the just the few benchmarks across the field, consistent with local subsidence. Figure 3 shows elevation changes of early benchmarks along the Waikato River extending across the centre of the field. Benchmark locations are shown in Figure 2. Relative to A88, A89 has been dropping at about 2mm per year since 1950, without a noticeable change in rate following field startup in 1997. It is interesting that, other than local subsidence related to cooling at shallow injectors in the centre of the field, there has been little change in the subsidence rate over the field as of 2009.

3. ROCK VOLUME LOSS DUE TO ALTERATION

The cause for long term subsidence at Rotokawa appears to be metasomatic rock mass removal associated with hydrothermal alteration. Adam Pochee at the University of Auckland (Pochee, 2010) studied the change in rock mass and volume of altered and unaltered reservoir andesite drill core from Rotokawa. He found that increasing rank of propylitic hydrothermal alteration resulted in mass loss to the rock, as calibrated using the concentration of immobile elements titanium and aluminium. The major mass loss was in silica (SiO2) with variable and relatively minor losses (<5%) in most major cations (e.g., sodium, calcium potassium, magnesium and iron) and minor additions in sulphur and carbon (from magmatic gases). Silica loss was up to 15% by mass compared to unaltered samples.

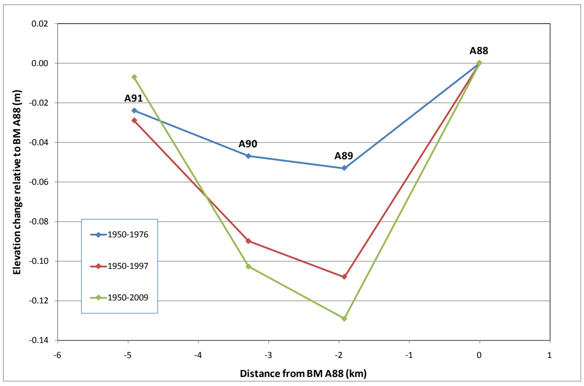

Figure 3: Elevation changes, in metres, at benchmarks in Figure 2 relative to Benchmark A88.

This mass loss was accompanied by a change in the volume of the rock. Figure 4, taken from Figure 29A in Pochee (2010), shows the relationship of net mass loss in rock samples to volume factor; the change in volume of rock material versus reference samples based upon concentrations of immobile elements. The figure shows as much as 10% change in rock volume in the samples, consistent with the samples which had experienced the greatest mass loss.

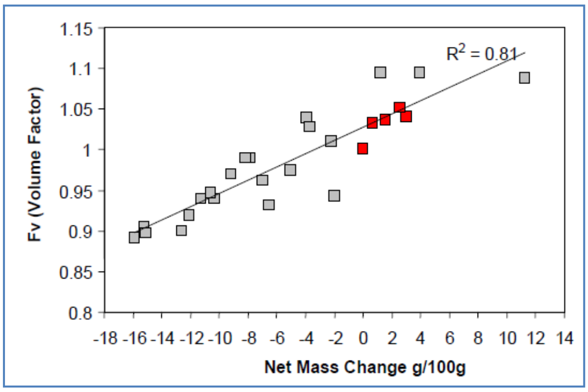

Figure 4: Figure 29a from Pochee (2010) showing the relationship between net mass loss in Rotokawa andesite due to hydrothermal alteration versus rock volume factor. Relatively unaltered samples are shown in red. Samples showing increased rock volume appear to affected by filling of primary porosity with alteration minerals.

The principal mechanism for rock removal due to alteration in these samples appears to be in the form of porosity development. Figure 5 from Pochee (2010) shows the relationship between mass loss and porosity. Relatively unaltered reference samples show low porosity (1-2%) and samples with mass loss show porosity up to 18%. Petrographic examination shows that the majority of this porosity is due to dissolution of plagioclase feldspar phenocrysts in the andesite rock matrix. This is similar to the nature of porosity observed in reservoir andesite at the Tiwi field, Philippines, reported by Stimac et al (2004).

Not all of the removed silica would be expected to leave the system. Some would be redeposited in veins and in zones of silicification. Surface and subsurface discharge of hydrothermal fluids to outside the system would be expected to account for significant net loss of silica over time, however

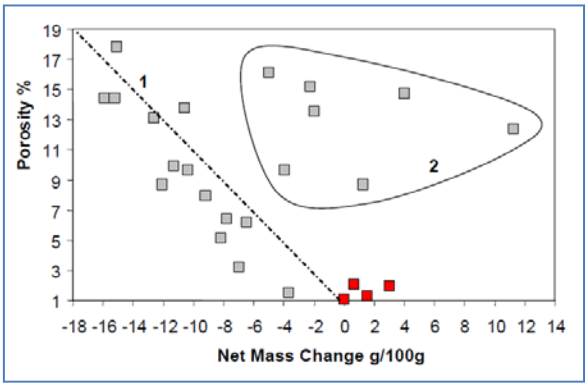

Figure 5: Figure 29b from Pochee (2010) showing the relationship between mass loss due to hydrothermal alteration of Rotokawa andesite cores, and rock porosity. Samples in red are least altered samples and uniformly show 1-2% porosity. Samples along trend 1 show increasing porosity with mass loss. Samples in area 2 are suspected as being affected by hidden veining, or were inhomogeneous samples (such as breccias), where samples taken for the separate analyses were of differing composition. During the study, an attempt was made to exclude samples with visible veining since these would show net mass gain unrelated to hydrothermal alteration of the rock matrix.

4. SUBSIDENCE MODEL

Under lithostatic load, porosity developed by hydrothermal alteration would be expected to gradually collapse, resulting in long term compaction of the reservoir. The rate of long term subsidence over the field can be related to compaction of reservoir rock using the analytical model for a deep, disk-shaped compacting aquifer, developed by Geertsma (1973):

$$U = -2\,Cm\,(1\text{-}v)\,\Delta p\,H\,[1 - (D/R) / (1 + (D/R)^2)^{1/2}]$$

Where:
U = maximum elevation change due to subsidence
Cm = uniaxial compression (calculated to be 0.62 of bulk compressibility)
v = Poisson's ratio (assumed to be 0.3)
Δp = pressure change
H = aquifer thickness
D = aquifer depth
R= aquifer radius

In this model, the maximum subsidence observed at the surface can be calculated for a buried aquifer of given diameter and given uniaxial compressibility and change in pore pressure. For Rotokawa, bulk compressibility is assumed to be analogous to compaction of porosity due to lithostatic load. Assuming representative values for Rotokawa (H = 2 km, D = 2 km, R = 1.8 km), the 2 mm/year natural subsidence, the model predicts a bulk volume change of $4.5\text{X}10^{-6}$ per year for the Rotokawa reservoir, or 0.45% volume change per 1000 years. This seems to be a reasonable alteration rate for a geothermal system; assuming that the process of porosity development is in steady state with compaction, the maximum porosity observed in the Rotokawa andesite cores (18%) would take approximately 20,000 years to develop.

5. DISCUSSION

Subsidence due to petroleum extraction is known to induce deformation within and around a compacting reservoir (Bruno, 1990). This phenomena is reasonably well studied because subsidence-induced deformation often leads to widespread well damage and well failure. Deformation is predominantly in two forms: sub-horizontal shear thrusts above the compacting reservoir and high angle normal faulting along the reservoir margins. Thrust faulting above the reservoir is often along bedding planes, exploiting mechanically weak formations, such as shale. Normal faulting is often in the form of re-activated pre-existing faults within the reservoir.

A similar style of deformation may accompany natural alteration induced compaction, as at Rotokawa. There are significant differences in the geothermal environment, however, that would hinder fault and fracture development. For one, the strain rate of reservoir rock due to alteration-induced compaction is much slower than in a producing oil and gas reservoir. Rock temperature is also higher, favouring ductile rather than brittle failure. Lastly, hydrothermal alteration tends to weaken rocks, again favouring ductile rather than brittle failure. The major rock matrix alteration mineral at Rotokawa is chlorite mica, which is a far weaker material than the matrix of unaltered andesite lava. The strength and strain rate of hydrothermally altered rock at reservoir conditions is under further study.

Taken together, these factors suggest that only the most hard and brittle of rock features would be susceptible to fracturing due to alteration-induced compaction. It would also require that these brittle features exist as interconnected networks within compacting rock rather than as isolated bodies. Deformation would be expected to favour ductile failure in softer material surrounding any isolated patches of harder rock rather than brittle fracture of the hard patches. Therefore, the most likely geologic features to be fractured solely by alteration induced compaction would be pre-existing networks of hard rock, such as quartz veins and zones of silicification, and perhaps layers of very hard primary rock, such as welded ignimbrite. In this way, progressive hydrothermal alteration may enhance local permeability by repeatedly fracturing a surrounding network of hard vein material, leading to a positive feedback between alteration and permeability development, as greater local permeability promotes further alteration.

At a minimum, stress induced by alteration compaction would probably play a supporting role to tectonic stress and varying hydraulic pressure in the development of fractures in a geothermal reservoir.

The alteration compaction process inferred here for Rotokawa has implications for the exploration of hidden geothermal systems (those without a surface discharge to guide exploration). These might be observed at the surface by their subsidence signature, such as by geologic or geomorphic evidence of land subsidence over the previous few thousand years. The fact that the Waikato River fully bisects four large geothermal systems in the Taupo Volcanic Zone and passes close to a number of others is perhaps due to this process.

Alternatively, modern measurements of surface deformation, such as from historical geodetic measurements, like those at

Rotokawa, or by satellite measurements, such as precision GPS or synthetic aperture interferometry, might be useful in exploring for hidden resources.

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