<table>
<thead>
<tr>
<th><strong>Title</strong></th>
<th>A review of the Rotokawa Geothermal Field, New Zealand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author(s)</strong></td>
<td>McNamara, David Daniel; Sewell, Steven; Buscarlet, Etienne; Wallis, Irene C.</td>
</tr>
<tr>
<td><strong>Publication Date</strong></td>
<td>2015-07-29</td>
</tr>
<tr>
<td><strong>Publisher</strong></td>
<td>Elsevier</td>
</tr>
<tr>
<td><strong>Link to publisher's version</strong></td>
<td><a href="https://doi.org/10.1016/j.geothermics.2015.07.007">https://doi.org/10.1016/j.geothermics.2015.07.007</a></td>
</tr>
<tr>
<td><strong>Item record</strong></td>
<td><a href="http://hdl.handle.net/10379/6725">http://hdl.handle.net/10379/6725</a></td>
</tr>
<tr>
<td><strong>DOI</strong></td>
<td><a href="http://dx.doi.org/10.1016/j.geothermics.2015.07.007">http://dx.doi.org/10.1016/j.geothermics.2015.07.007</a></td>
</tr>
</tbody>
</table>
A review of the Rotokawa Geothermal Field, New Zealand

David Daniel McNamara\textsuperscript{1}, Steven Sewell\textsuperscript{2}, Etienne Buscarlet\textsuperscript{2}, Irene C. Wallis\textsuperscript{2}

\textsuperscript{1} GNS Science, 1 Fairway Drive, Avalon, Lower Hutt, 5040, New Zealand

\textsuperscript{2} Mighty River Power Ltd., 283 Vaughan Road, Rotorua, 3040, New Zealand

Corresponding author: D.D. McNamara, mcnamadd@gmail.com, +6421844205
1. Abstract

The Rotokawa Geothermal Field of New Zealand has seen significant development over the last twenty years and has been the study site for new and innovative geological and geothermal research. This includes the one of the first direct data acquisition and characterisation of subsurface structure and stress properties via borehole image logs, a robust study of the magneto-telluric and microseismicity of the field, and the establishment of a comprehensive mode of the field’s variable fluid chemistry. This paper reviews published material on the geology, geophysics, and fluid chemistry of this field, as well as summarises the development history and sustainability of this nationally important energy resource.

2. Introduction

The Rotokawa Geothermal Field is one of twenty-five geothermal localities located within the volcano-tectonic setting known as the Taupo Volcanic Zone (TVZ) (Wilson et al., 1995, Wilson and Rowland, 2011, see Wilson and Rowland, 2015 this volume). The TVZ is an actively rifting, intra-arc basin associated with the Hikurangi subduction system, where the Pacific Plate subducts beneath the eastern side of the North Island (Cole and Spinks, 2009; Rowland and Simmons, 2012; Wilson et al., 1995). Rifting, which is thought to have begun ~2 Ma (Wilson et al., 1995), occurs at varying rates along the ~NE-SW rift axis, from ≤5 mm/year at the southern-most limit of rifting extension to 13-19 mm/year in offshore Bay of Plenty (Begg and Mouslopoulou, 2010; Seebeck et al., 2014; Villamor and Berryman, 2001; 2006). The
Rotokawa geostructural system itself has been suggested to be up to twenty thousand
years old based on knowledge of timing of hydrothermal eruptions (Krupp and
Seward, 1987; Vucetich and Howorth, 1976). The TVZ is segmented both
volcanically and tectonically. The Rotokawa Geothermal Field is located in the
central volcanic zone of the TVZ, which is associated with voluminous rhyolitic
volcanism (producing an estimated ≥6000 km$^3$ of magma at rates of ~3.8-12.8
km$^3$/year) (Wilson et al., 2009). Relative to the tectonic subdivision of the TVZ, the
Rotokawa Geothermal Field is located within the Whakamaru 2 Subdomain (Rowland
and Sibson, 2001), ~150 km from the inferred, NE-SW striking, rift axis of this sub-
division, and ~5 km to the eastern margin of the TVZ, on the downthrown block of
the Kaingaroa Border Fault (Rowland and Sibson, 2001).

The Rotokawa Geothermal Field is an important New Zealand resource as it is
one of seven geothermal fields utilised for power generation (174MW$_e$ capacity)
(Hernandez et al., 2015). The field occupies ~28 km$^2$, as defined by shallow
resistivity mapping (Risk, 2000), is located ~10 km northeast of the Taupo Township,
lies over the Waikato River, and encompasses Lake Rotokawa at its southern end
(Fig. 1). Two other significant TVZ geothermal fields are located near to the
Rotokawa field: the Wairakei-Taupara geothermal system to the southwest, and the
Ngatamariki Geothermal Field to the north (Hernandez et al., 2015). As an important
power producing field, Rotokawa has seen a high level of development over the past
couple of decades and has received significant attention from researchers. This paper
aims to: 1) provide a comprehensive literature review of the published research and
information that has assisted the development of this geothermal resource into a
nationally important resource, and 2) highlight novel and key research aspects at
Rotokawa in terms of impact on field development and lessons to be learned for future research at Rotokawa and for other New Zealand geothermal resources.

Development History

Exploratory drilling from 1965 to 1986 was carried out by the New Zealand government and confirmed the presence of a large, high temperature (>300°C) resource (Cole, 1998). In 1993, the Tauhara North No.2 Trust, Taupo Electricity Ltd, and WORKS Geothermal Ltd were granted resource consents from the Waikato Regional Council to extract 110 tonnes/hour of steam from the Rotokawa Geothermal Field for electricity generation (Bloomer, 1995; Taylor, 1995). In 1997, under the now joint venture of Tauhara North No.2 Trust and Power New Zealand, electricity generation began with the installation of ORMAT’s Geothermal Combined Cycle technology which utilises a steam turbine and binary plant (Legmann and Sullivan, 2003). This plant, referred to as ‘RGEN’, produced 24 MWe with production originally from two wells, RK5 and RK9, and shallow reinjection occurring in wells RK11 and RK12. Apart from the loss of non-condensable gases, all of the produced fluid was re-injected into the field. From 1997 to 2003 fluid withdrawal from the reservoir was ~300-330 kilotonnes/month which rose to ~400 kilotonnes/month in 2003 to support an additional 10 MWe of generation from the RGEN plant (34 MWe) (Milicich and Hunt, 2007; Sewell et al., 2012).

In 2000, Mighty River Power Ltd acquired an interest in the Rotokawa Geothermal Field, combining with Tauhara North No.2 Trust to form the Rotokawa
Joint Venture (RJV) (Bowyer et al., 2008). The joint venture approach to development of the Rotokawa Geothermal Field is an excellent working example of a state owned power company working closely with indigenous, Maori landowners (Legmann and Sullivan, 2003). In 2005, due to increasing pressure in the shallow injection area, injection was moved to deeper levels on the field margin (wells RK16 and RK18) which was successfully identified from 1D analyses of magnetotelluric data (MT) (Hunt and Bowyer, 2007). Further development of the field was begun in 2007, when resource consents were awarded based on conceptual and numerical modeling of the field based on previous production and injection data, well results up to and including RK18 (Bowyer and Holt, 2010), and 1D and 3D analyses of MT data (Heise et al., 2008). The Nga Awa Purua (NAP) development began in 2008 including drilling of new wells (RK19 – RK33) and the construction of a 140 MWe, triple-flash plant in 2010 (McLoughlin et al., 2010). Together with the existing RGEN plant this brought the total field capacity to 174 MWe supplied by ~60000 - 65000 t/d of fluid from the reservoir.

Since this most recent development of the field, progress has concentrated on geological, conceptual, and numerical modeling of the field (Bardsley et al., 2012; Quino and Azwar, 2012; Quino et al., 2013; Sewell et al., 2012). This has utilised research into the geological nature and properties of the field (Anderson, 2011; Davidson et al., 2012; McNamara et al., 2014; Rae et al., 2011; Siratovich et al., 2014; Wallis et al., 2013), and detailed monitoring of reservoir pressure, temperature and chemistry along with other monitoring (e.g. tracer testing, microgravity, microseismic, levelling, thermal feature and groundwater) (Hunt and Bowyer., 2007; Sewell et al., 2013b; 2015; Sherburn et al., 2015; Winick, et al., 2015). These datasets
have been used to adaptively manage and model the evolution of the Rotokawa reservoir over time to ensure continued operation and possible further development.

3. Geology

The surface geology, hydrothermal features, and subsurface stratigraphy and petrology of the Rotokawa Geothermal Field are detailed in numerous works and have been refined with subsequent field development and drilling stages (Anderson, 2011; Arehart et al., 2002; Browne, 1989; Browne et al., 1992; Browne and Lawless, 2001; Collar and Browne, 1985; Eastwood et al., 2013; Grindley et al., 1985; Krupp and Seward, 1987; Leonard et al., 2010; Milicich and Hunt, 2007; Pochee, 2010; Price et al., 2011; Rae, 2007; Rae et al., 2010; 2011; Ramirez and Hitchcock, 2010; Schinteie et al., 2004; Siratovich et al., 2012; 2014; Wallis et al., 2013; Wyering et al., 2014).

Surface Geology and Features

There is a diverse array of thermal manifestations at the Rotokawa Geothermal Field including hot springs and seeps with associated acid-sulphate-chloride and chloride-bicarbonate derived sinters, a fumarole (the Rotokawa Fumarole), several areas of steaming ground, and hydrothermal eruption craters (Fig. 1) (Milicich and Hunt, 2007). Lake Rotokawa is a large acid-sulphate (pH~2) feature which is likely a hydrothermal eruption crater (Browne and Lawless, 2001; Collar & Browne, 1985).
Surface features are generally located in two areas of the Rotokawa Geothermal Field (Milicich and Hunt, 2007; Price et al., 2011). The southern area includes the lagoon on the NE shore of Lake Rotokawa, the acid-sulphate-chloride springs on the Parariki Stream, and the flood plain of the Parariki stream which hosts a rare setting where silica rich, acid fluid discharge forms sinters in a number of microbially mediated facies (Schinteie et al., 2009). The northern area contains a group of chloride-bicarbonate springs on the banks of the Waikato River, and a small area of steaming ground north of the Waikato River, near well RK8 (Fig. 1).

In the north of the field, surface geology is dominated by the Oruahineawe and Kaimanawa rhyolite domes and surrounding pumice breccias (Anderson, 2011; Downs et al., 2014). In the east, it is dominated by the 0.71 Ma andesites of Rolles Peak (Wilson et al., 1995), and in the west by rhyolite lavas exposed at the Aratiatia Dam and Rapids (Rae, 2007). Elsewhere, alluvium derived from Taupo Pumice forms terraces near the Waikato River, and exposures of Wairakei breccia can be found between the Waikato River and Lake Rotokawa (Rae, 2007). The area around Lake Rotokawa is covered with hydrothermal explosion breccias and tephra (Browne and Lawless, 2001; Collar and Browne, 1985). Lake Rotokawa together with a number of hydrothermal eruption craters (up to 1.5 km in diameter), eruption deposits, and hydrothermal eruption vents across the field indicate hydrothermal eruptive activity since the deposition of the Oruanui Foramtion (~ 20000 years; Collar and Browne, 1985; Vucetich and Howorth, 1976). Hydrothermal eruption craters are mainly filled and are located by examining clast sizes in hydrothermal eruption breccia deposits (Browne and Lawless, 2001). Deposits of Parariki breccia, erupted from depths <450 m, cover much of the south of the field (Rae, 2007). Breccias from the largest
hydrothermal eruption (~6060 years ago) cover an area of ~12 km$^2$ with a thickness of ~11m and are thought to have originated from the Lake Rotokawa area (Browne & Lawless, 2001; Collar & Browne, 1985).

Subsurface Stratigraphy

Drill cuttings and core from thirty-five wells, with vertical depths from ~500 to 3065 m, provide information on the subsurface stratigraphy of the Rotokawa Geothermal Field (Fig. 2) (Winick et al., 2011). Basement rock within the Rotokawa Geothermal Field is composed of Late-Palaeozoic to Late-Mesozoic, fine, silty, greywacke sandstone and argillite rocks of the Torlesse Supergroup (Grindley et al., 1985; Rae, 2007; Wallis et al., 2013). The basement has been encountered in wells in the injection area of the field (wells RK19-24), and in the bottom of well RK16 in the production area.

Overlying the basement is a laterally extensive, thick (up to 2200 m), andesite unit, the Rotokawa Andesite (Browne et al., 1992; Grindley et al., 1985; Rae, 2007; Rae et al., 2011; Wyering, 2015). Regional geological modeling of the Taupo-Reporoa Basin suggests that the Rotokawa Andesite complex is centred on the Rotokawa Geothermal Field, with limited lateral extent to both the north and south (Downs et al., 2014; Eastwood et al., 2013). The initial andesitic volcanism would have involved magmas migrating through faults and fractures to the surface >~1.9 Ma, constructing a large volcano under Rotokawa, potentially centred along the western border of the Rotokawa Geothermal Field based on lateral variation in
thickness of the andesite (Anderson, 2011; Browne et al., 1992; Chambefort et al., 2014). A thick andesite unit overlying greywacke basement in the Ngatamariki Geothermal Field is likely to be part of the Rotokawa andesite complex (Chambefort et al. 2014; Downs et al., 2014), but petrographical and geochemical comparison of these two units indicates possible separate eruptive centres, with basaltic andesite present at Rotokawa, and more dacite/andesite composition volcanism at Ngatamariki (Anderson, 2011; Browne et al., 1992). The classification of the samples used to define the dacitic composition in these studies as andesites is refuted however by Chambefort et al. (2014) who reclassify them as younger reworked breccias or conglomerates.

The Rotokawa Andesite varies laterally and vertically, and is comprised of several eruptive flows of massive to slightly flow-banded, calc-alkaline, medium-to-low K-type, andesite lavas, pseudo-breccias, and breccias (Anderson, 2011; Browne et al., 1992; Rae, 2007). The lavas are porphyritic containing phenocrysts (average size of 1–2 mm) of plagioclase (30-40%, mainly labradorite composition), augite, orthopyroxene and minor hornblende, primary biotite, quartz, and Fe-Ti oxide in an intersertal groundmass of plagioclase microlites, primary magnetite, disseminated Fe-Ti oxides, interstitial pyroxenes, and occasional tuff and greywacke lithics set in volcanic glass (Anderson, 2011; Browne et al., 1992; Siratovich et al., 2014). Despite the high level of variation within the Rotokawa Andesite, it forms a geochemically coherent group (Anderson, 2011; Brown et al. 1992). The breccias units of the Rotokawa Andesite, which have been recovered by spot coring, contain clasts of sub-rounded, pebble-cobble sized, porphyritic volcanics in a heavily altered

Above the Rotokawa Andesite sequence lie the volcanioclastic and sedimentary deposits of the Reporoa Group (Tahorakuri and Waikora Formations) and, in places, an andesite of limited extent (Nga Awa Purua Andesite), and a stratigraphically younger ignimbrite of the Whakamaru Group, currently known as the Wairakei Ignimbrite (Browne et al., 1992; Gravley et al., 2006; Wallis et al., 2011; Wyering, 2014). The Waikora Formation is a rounded to sub-rounded pebble conglomerate (up to 250 m thick) that is largely comprised of eroded greywacke sandstone and argillite siltstone deposited in a fluvial environment (Anderson, 2011; Rae, 2007). The Tahorakuri Formation at the Rotokawa Geothermal Field consists of a white, crystal-vitric-lithic tuff, or ignimbrite of variable thickness (up to 250 m), which can contain pumice fiamme, greywacke and andesite lithics, and minor sedimentary deposits (Anderson et al., 2011; Rae, 2007; Wyering et al., 2014). The oldest samples of Tahorakuri Formation, which overly basement rock or andesites at the Rotokawa and Ngatamariki Geothermal Fields are dated (U-Pb on zircon) at 1.89, 1.84 and 1.87 Ma (Chambefort et al., 2014; Eastwood et al., 2013). A single age (1.89±0.03 Ma) has been determined from a sample of an ignimbrite of the Tahorakuri Formation that lies above the Rotokawa Andesite in the Rotokawa Geothermal Field (Eastwood et al., 2013). These ages, in addition to the fact that intervals of the Tahorakuri Formation can be found both above and below the Waikora Formation (Wallis et al., 2013), suggests it was deposited by a number of separate, eruptive events, and highlights the probability of a highly complex and reworked paleotopography for this unit over a large span of time. The Nga Awa Purua Andesite, an eruptive andesite unit originally
grouped with the Rotokawa Andesite, was recently redefined due to its stratigraphic position within the deposits of the Reporoa Group (Wallis et al., 2013). The Wairakei Ignimbrite is part of the Whakamaru Group, a sequence of erupted ignimbrites of 330-340 ka (Wilson et al., 1986). At Rotokawa this ignimbrite has a white appearance, is ~200-390 m thick in places, can appear as a non-welded to densely welded ignimbrite or pumice-vitric-tuff, is crystal-rich (embayed quartz, plagioclase, minor biotite), and contains small lithic fragments of rhyolite, andesite and argillite (Anderson, 2011; Grindley et al., 1985; Rae, 2007).

The Reporoa Group and Whakamaru Group ignimbrite (Wairakei Ignimbrite) are overlain by the volcano-sedimentary Waiora Formation intermixed with rhyolite lavas, breccias and domes of the Haparangi Rhyolite Group (Bowyer and Holt, 2010; Rae, 2007; Winick et al., 2011). The units of the Haparangi Rhyolite Group are reported to be anywhere between 450 - 800 m thick (Anderson, 2011; Grindley, 1985; Rae, 2007; Wallis et al., 2013), with thicker units occurring at shallower depths towards the north (Rae, 2007). This northwards thickening indicates these rhyolites may be part of the Oruahineawe-Kaimanawa dome complex which lies northeast of the Rotokawa Geothermal Field (Grindley, 1985; Rae, 2007). The rhyolites are reported as slightly banded and porphyritic, and crystal-poor with phenocrysts of quartz, plagioclase and minor ferromagnesians (only as relicts) in a perlitic or spherulitic groundmass (Anderson, 2011; Grindley et al., 1985). Rhyolite breccias are coarse and form a carapace to the lava flows and separate flows within a sequence (Grindley, 1985). In the Rotokawa Geothermal Field, the Waiora Formation consists interbedded layers of pumice, lithic (rhyolite, andesite, greywacke), crystal-
rich (hornblende, quartz, plagioclase), vitric tuffs, ashes and breccias that can be up to 550 m thick (Anderson, 2011; Rae, 2007).

The Waiora Formation is overlain by locally derived Parariki hydrothermal eruption breccias (consisting of quartz-feldspar rich, tuffaceous breccia in a silty-clay matrix) and finely laminated mudstones, siltstones, and pumiceous sandstone, lacustrine deposits of the Huka Falls Formation (Anderson, 2011; Wallis et al., 2013).

Intercalation of the Parariki hydrothermal eruption breccias and Huka Falls Formation deposits occurs on the southern side of the Waikato River in the Rotokawa Geothermal Field (Rae, 2007). These units are in turn overlain by the 26-27 ka Oruanui Formation (20-50 m thick) comprised of pumice tuff containing rhyolite lava lithic clasts and quartz and feldspar crystals (Rae, 2007).

Structure

The structure of the Rotokawa Geothermal Field is documented in a number of publications (Anderson, 2011; Bannister et al., 2008; Bowyer and Holt, Collar and Browne, 1985; 2010; Davidson et al., 2012; Downs et al., 2014; Grindley, 1961; Grindley et al., 1985; Krupp and Seward, 1987; Massiot et al., 2012; 2015; McNamara et al., 2014; Rae, 2007; Wallis et al., 2013). The surface geology at Rotokawa contains ample evidence of an active structural environment. For instance, active NE-SW striking, fault traces are observed in the northwest (Aratiatia Fault Zone), northeast, and to the west of Lake Rotokawa (Litchfield et al., 2014; GNS Science Active Fault Database, 2014) (Fig. 3). In addition, a NE-SW alignment of
hydrothermal eruption vents (including Lake Rotokawa) and the Rotokawa Fumarole is present inferring a NE-SW structural alignment control (Wallis et al., 2013).

Sub-surface structure is mainly known from geological data from drilling (including observations of repeated stratigraphic units), 3D modelling of the field, and geophysical observations including borehole image logging and microseismic data. Though there have been several revisions of the structural model over the years they all comprise NE-SW striking structures which define a graben within the greywacke basement which is in-filled by Rotokawa Andesite and subsequent volcanics and sediments (Bowyer and Holt, 2010; Wallis et al., 2013). All models point to the presence of topography in the greywacke basement before andesite deposition. A subsurface structural model was defined by Bowyer and Holt (2010) using geologic data from the 17 wells completed at the time. The 2010 model defined a series of four NE-SW striking, normal faults that significantly offset the greywacke basement and Rotokawa Andesite, forming a narrow graben structure (Fig. 3).

This 2010 model was revised using data from a further 18 wells drilled between 2010 and 2012 and employing 3D geologic modelling techniques (Wallis et al., 2013) (Fig. 3). In this revised model the graben was widened and a new structure was defined in the south east of the field (Injection Field Fault - IFF) whose near-surface trace is coincident with the Parariki Stream and the Rotokawa Fault Zone (Grindley, 1961). A paleo-valley in the top surface of the Rotokawa Andesite (Fig. 3) is also hypothesized to account for the geologic complexity in the NE of the graben, but this feature is poorly constrained due to sparse geologic data in this area. The widened
graben is bound to the NW by the SE dipping Production Field Fault (PFF) and to the SE by the NW dipping Central Field Fault (CFF), the latter of which displays significant offset at depth >400 m. The PFF, CFF, and IFF are modeled as continuous through the greywacke basement, Rotokawa Andesites, and other units older than the Wairakei Ignimbrite. However, relatively small differences in elevation of the top of the Wairakei Ignimbrite between wells across the field suggests only small, if any, reactivation of these structures since deposition of the ignimbrite.

Interpretation of structure and stress data from borehole image logs (collected mainly within the andesite units) show fracture orientations are dominated by NE-SW strikes with either NW or SE dip directions (Davidson et al., 2012; Massiot et al., 2012; 2015; McNamara et al., 2014). Observations of fracture dip direction patterns revealed heterogeneity such that; 1) some of the imaged wells have a predominant fracture dip direction thought to be influenced by their proximity to the larger fault structures (from the 2013 structural model), and 2) depth intervals within individual wells displayed zonation of fracture dip directions (alternating zones of SE and NW dipping fractures) suggesting antithetic faulting in the subsurface, a feature typical of normal faulting environments. Data from borehole image logs also show that the in-situ horizontal stress field orientations are heterogeneous. The horizontal maximum stress direction (SHmax) has an average NE-SW (035°/215°) orientation but this can vary across the field by up to 14° (range is 025°/205° to 049°/229°). In addition stress field orientation is heterogeneous within the vicinity of a well as indicated by rotations in the SHmax directions in individual wells (largest rotation recorded over a 10 m depth interval in a well is 30°). Field scale stress field perturbations are related to activity on the large faults that make up the graben structure under the geothermal
field. More localised stress field rotations are attributed to slip on fracture planes with the larger perturbations inferred to indicate the presence of a nearby, large scale, active fault. Overall, *in-situ* stress field orientation measurements are consistent with an extensional tectonic regime in the Rotokawa Geothermal Field, and with previous studies of stress orientations in the TVZ (Hurst et al., 2002; Massiot et al., 2013; McLean and McNamara, 2011; Seebeck et al., 2014; Townend et al., 2012; Wallis et al., 2012) and with preliminary determinations of *in-situ* stress magnitudes for the Rotokawa Geothermal Field (Davidson et al., 2012).

**Hydrothermal Alteration**

A number of works have documented the hydrothermal alteration of the Rotokawa Geothermal Field (Anderson, 2011; Chambefort et al., 2011; Grindley et al., 1985; Hedenquist et al., 1988; Price et al., 2011; Rae et al., 2010; 2011; Siratovich et al., 2014; Wyering et al., 2013; 2014). At the surface, and in the shallow subsurface (< ~500 m, Bowyer et al., 2008), there is extensive, steam heated, acid-sulphate alteration, including large amounts of native sulfur in addition to kaolinite, smectite, silica residue, alunite and other sulphates, cinnabar, and arsenic precipitates (Chambefort et al., 2011; Price et al., 2011; Rae, 2010). Areas of extinct neutral chloride-style surface alteration, including silicification and silica sinter float, are restricted to the banks of the Waikato River (Collar and Browne, 1985).

Beneath the near-surface acid alteration zone, to ~1000 m depth, a propylitic mineral assemblage is found including mordenite, wairakite, epidote, clinozoisite,
quartz, illite, adularia, chlorite, calcite (and bladed calcite), albite, leucoxene, and accessory pyrite and hematite (Anderson, 2011; Rae, 2010). Supergene, or steam-heated acid-sulphate, alteration (containing rare, anhydrite, alunite, and kaolinite) is sporadically encountered up to depths of ~1600mVD (Chambefort et al., 2011; Hedenquist et al., 1988). Anhydrite has however also been noted in alteration mineral assemblages at depths >2000 mVD. Stable isotope studies also show that some sulphate has formed via SO$_2$ disproportionation, similarly to hypogene sulphate formation associated with magmatic-hydrothermal fluids in high-sulphidation epithermal environments (Chambefort et al., 2011). The dominant chlorite-epidote alteration assemblage overprints this deep, higher temperature, magmatic-hydrothermal anhydrite assemblage.

Many early studies of the deeper stratigraphic units (Torlesse Greywacke and Rotokawa Andesite) reported overall weak alteration with greater alteration intensity restricted to fractures (Grindley et al., 1985; Rae, 2010). However, recent investigation of drill-core and cuttings show that, at least in some locations, the Rotokawa Andesite can be intensely altered (Rae et al., 2011; Siratovitch et al., 2014; Wyering et al., 2013; 2014). In addition, hydrothermal alteration within the Rotokawa Andesite is generally more intense in the pseudo-breccias and breccias than the massive lavas, likely due to greater fluid-rock interactions (Anderson, 2011). Within the lavas, alteration is more intense in the groundmass, and is dominated by chlorite/epidote, illite, and quartz (Siratovich et al., 2014; Wyering et al., 2014). Phenocrysts are commonly replaced (plagioclase by albite, adularia, calcite and pyrite, and ferromagnesiants by chlorite, quartz, calcite, secondary biotite, and epidote) and often only recognisable as relict shapes (Wyering et al., 2014). Pochee
(2010) shows that hydrothermally altered Rotokawa Andesite is depleted in silica by as much as 15% compared to its unaltered form. This depletion is associated with porosity enhancement due mainly to dissolution of plagioclase phenocrysts. Amygdales (average size 1-1.5 mm) are commonly filled with chlorite, calcite, haematite, pyrite, and chalcedony with quartz rims, and fractures in the lava are typically mineralised with quartz, calcite (including bladed calcite), anhydrite, and epidote (Anderson, 2011; Wyering et al., 2014). Rare samples of Rotokawa Andesite have also reported high temperature alteration minerals actinolite and tremolite (Rae et al., 2011).

4. Fluid Properties

Fluid temperature and chemistry of the Rotokawa Geothermal Field, in both the pre and post production states, has been reported in many publications (Bloomberg et al., 2012; Bowyer et al., 2008; Chambefort et al., 2011; Collar and Browne, 1985; Giggenbach, 1995; Hedenquist et al., 1988; Henley and Middendorf, 1985; Khabar et al., 1986; Krupp and Seward, 1987; 1990; Price et al., 2011; Rae et al., 2011; Reyes et al., 2002; Ward et al., 2006; Winick et al., 2011), resource consents documentation (e.g. Milicich and Hunt, 2007) and by internal industry reporting (e.g. Sewell et al., 2013a).

The Rotokawa Geothermal Field can be vertically divided into three geochemically distinct aquifers; a deep, high temperature (>300 °C), convecting, geothermal reservoir; an intermediate aquifer containing mixed, hot, two-phase
geothermal fluid, and cold groundwater; and an unconfined, near surface, shallow aquifer, containing single-phase liquid with local areas of boiling (Sewell et al., 2012; Winick et al., 2011). Each aquifer is largely separated by intervening low permeability layers with local zones of interconnection between aquifers. Overall, the Rotokawa Geothermal Field is classified as an arc-type geothermal system with fluid derived from andesitic rock as suggested by its Cl, B and Cs content, and containing a high (~ up to 15%) magmatic component determined from its isotopic composition (Giggenbach, 1995). The Rotokawa Geothermal Field is a high gas flux (CO₂ emission rate of 633 ± 16 t/d, minimum H₂S emission from the reservoir of 80 t/d, based on the CO₂/H₂S ratio of the Rotokawa fumarole) field with the N₂, He, and Ar composition of the gases falling on a magmatic-groundwater trend (Bloomberg et al., 2012; Hedenquist et al., 1988; Reyes et al., 2003).

The Shallow and Intermediate Aquifers

The shallow groundwater aquifer is hosted mainly within the Oruanui Formation and is underlain by the Parariki Breccia and Huka Falls Formation, which act as an impermeable aquitard (Winick et al., 2011). The aquifer is characterised by a mixture of three fluid types. Steam-heated, acidic (pH = 2.1-2.8), chloride-sulphate waters (chloride and sulphate concentrations from ~300 to 900 mg/kg), discharge from springs on the shore of Lake Rotokawa, and are also found in shallow, groundwater monitor wells (Milicich and Hunt, 2007; Winick et al., 2011). Bicarbonate-rich waters (from ~150 to 300 mg/kg HCO₃⁻) of steam-heated origin are found in the central part of the field and discharge from springs along the Waikato River (Khabar et al., 1986;
Milicich and Hunt, 2007). Cold groundwater, with low concentrations of geothermal components (e.g. Cl $< 65 \text{mg/kg}$, B $< 1.5 \text{mg/kg}$ in the monitoring well of the National Equestrian Centre (RKNEC)), is found on the margins of the field. Water levels in shallow monitor wells show the hydraulic gradient drives northward flow of the shallow groundwater, from Lake Rotokawa toward the Waikato River, consistent with topography. This flow direction is also consistent with the spatial occurrence of water types across the field which suggest northward flow of hot, variably-acidic, chloride water at shallow depths from the south of the field toward the Waikato River with varying degrees of cooling, dilution and neutralisation occurring along the way (Winick et al., 2011).

The intermediate aquifer, hosted mainly within the Waiora Formation and Haparangi Rhyolite, is a complex mixture of downward migrating fluids from the shallow groundwater system, boiled, deep reservoir fluids migrating upward through an area of weakly developed reservoir clay cap, steam condensates, and heated, marginal groundwater (Bowyer et al., 2008; Winick et al., 2011). Rising, boiling reservoir fluids produces CO$_2$ and H$_2$S-rich steam condensates at the base of the Huka Falls Formation and Parariki Breccia. These condensates conductively heat and mix with descending, oxygenated groundwater, which oxidises and removes H$_2$S in the form of soluble SO$_4$ and releases H$^+$. This process leaves behind a highly acidic and corrosive fluid which has caused external casing corrosion for a number of wells in the Rotokawa Geothermal Field (Glover and Mroczek, 1995; Winick et al., 2011). The occurrence of these types of fluids is also evidenced in the presence of hydrothermal alteration minerals formed in acidic conditions (kaolinite, alunite,
dickite and goethite) in a number of wells across the field at intermediate aquifer depths (up to ~500 m) (Bowyer et al., 2008).

The Deep Aquifer: The Main Geothermal Reservoir

The deep reservoir is mainly hosted in the Rotokawa Andesite, the Waikora and Tahorakuri Formations and Torlesse greywacke and is capped by a smectite-rich clay zone hosted mainly within the Wairakei ignimbrite and basal layers of the Waiora Formation (Winick et al., 2011). Natural-state fluids in this reservoir displays chemical gradients across the field, with higher concentrations of Cl, B, Li, Cs and non-condensable gases (NCGs) in the south compared to the north (from south to north respectively; Cl from ~900 to ~450 mg/kg, B from ~50 mg/kg to ~10 mg/kg, Li from ~9 to 2 mg/kg, Cs from 1.6 to 0.3 mg/kg, NCGs from 1.8 to 0.4 wt%; Giggenbach, 1995; Price et al., 2001; Winick et al., 2011). In addition, CO$_2$/Cl and B/Cl ratios are also higher in the south than the north (Giggenbach, 1995; Winick et al., 2011). Isotope studies on alteration quartz, epidote and anhydrite in the Rotokawa Andesite show that oxygen and hydrogen isotopes are also heavier in the south of the field compared to the north (Chambefort et al., 2011). This south to north variation implies that the reservoir fluids are poorly mixed. Two main hypotheses for this have been proposed; the northern and southern sectors of the reservoir exist as separate systems each with its own geochemical parent; or progressive dilution occurs within the deep reservoir from a deep, heated groundwater from the north of the field (Winick et al., 2011).
Fluid temperature within the deep reservoir in the Rotokawa Geothermal field can be up to ~340 °C (Hedenquist et al., 1988; Winick et al., 2011). Early geothermometer measurements using Na-K-Ca and alkali ratio (Na/K, Na/Li) geothermometers determined high fluid temperatures up to 340 °C for the Rotokawa Geothermal Field at depths of ~1-2.5 km (Henley and Middendorf, 1985). Gas geothermometry (CO₂/Ar-H₂/Ar) of the Rotokawa Fumarole indicates a deep, >300 °C liquid reservoir source. Fumarole gas chemistries are similar in composition to gases (N₂-He-Ar) obtained from a flow test in well RK4 (Hedenquist et al., 1988) suggesting a direct deep reservoir source with no significant residence time for re-equilibration in the overlying intermediate aquifer (Winick et al., 2011).

The enthalpy-chloride diagram for the Rotokawa reservoir illustrates the various chemical processes that occur to produce the observed fluid types in the field (Figs. 2, 4; modified from Winick et al., 2011). A hot, possibly two-phase, deep (>4 km) upflow is inferred for the south of the field. As these waters rise up under Lake Rotokawa, they boil adiabatically. Steam then condenses in the shallow groundwater around the lake and then drains downward through permeable features in the vicinity of the Central Field Fault. The chemistry of the shallow groundwater wells and thermal features are an expression of boiled reservoir fluid as found in wells RK2 and RK3, mixed with steam-heated groundwater. Wells RK2 and RK3 were both completed at shallow depths (880 m and 910 m respectively) and show a weakly developed clay-cap, and boiling-point-for-depth natural state temperature profile. Deep reservoir fluids outflow toward the north and are progressively diluted with a conductively heated groundwater (up to 290 °C) to generate the variations of deep reservoir fluid (Winick et al., 2011). Given the difficulty in obtaining a conductively
heated reservoir fluid, the previous authors suggested an alternative hypothesis for the south to north dilution due to a short-lived down-flow of meteoric fluid after a series of large hydrothermal eruptions over the past 20,000 years.

Fluid Metal Concentrations

Many studies have explored the metal concentrations of the Rotokawa geothermal fluids by investigating the muds deposited around hot springs, and mineral deposits in parts of the geothermal plant and pipelines (Krupp and Seward, 1987; 1990; Reyes et al., 2002; Simmons and Brown, 2007; Ward et al., 2006;). Muds and silica precipitates around thermal manifestations contain ~250,000 tons of metal-rich material (e.g. gold, arsenic, antimony, tungsten, thallium, mercury, silver, germanium, gallium) and economic deposits of sulfur. Similar metals are noted in mineral precipitates within geothermal pipelines and areas of the geothermal power plant (sphalerite, wurtzite, pyrite, chalcopyrite, galena, rare tellurides such as hessite, altaite, and stibnite). Rotokawa geothermal fluids also carry silica as known from aggregate silica and quartz precipitations in geothermal pipelines. From the amount of metals contained in muds around hot springs and accompanying direct measurement, it was determined that deep geothermal fluids were saturated in native gold (~7-23 ppb) and silver (as the mineral argentite, ~1100-2400 ppb), antimony (180-230 ppb), arsenic (1200-1400 ppb), gallium (20-30 ppb), thallium (14 ppb), tungsten (30-60 ppb) (values are minimum estimates) (Krupp and Seward, 1987, 1990; Simmons and Brown, 2007). While mercury is not found in hot springs muds as it tends to partition into the vapour phase during fluid boiling, bright red cinnabar is noted to precipitate.
in a number of steam vents in Rotokawa, though most of it is likely still lost to the atmosphere. Due to their individual thermodynamics these metals precipitate out at various depths in the geothermal field as the fluid conditions change, leaving a zoned metal precipitation profile reflected in the zoning of well precipitates (Reyes et al., 2002).

5. Geophysics

Geophysics, including studies of microseismicity, magnetotellurics, electrical resistivity, gravity surveys, magnetic anomalies, and self-potential surveys, has been utilised extensively at Rotokawa for early exploration drilling through to field development and operations (Bannister et al., 2008; 2010; Bertrand et al., 2012; Bibby et al., 2005; Heise et al., 2008; Hochstein et al., 1990; Hunt and Harms, 1990; Hunt and Bowyer, 2007; Rawlinson, 2011; Risk, 2000; Sewell et al., 2013a; 2015; Sherburn et al., 2013; 2015; Soengkono et al., 1991).

Schlumberger resistivity surveys were first undertaken at Rotokawa in the 1960’s and used to assist well siting (Risk, 2000). Using an array spacing of AB/2 = 500 m and 1000 m, these surveys provided shallow (above ~500 m depth) apparent resistivities. In 2004, to assist siting deep injection wells on the field margins, magnetotelluric (MT) surveys were undertaken. Over 80 MT-TDEM stations across the Rotokawa field provided high resolution resistivity variation to depths of ~1-1.5 km (Sewell et al., 2012). Low resistivity at Rotokawa correlates well with higher smectite clay levels (~5-30 %) as determined from methylene blue tests of drill-
cuttings, as is observed in most high-temperature, volcanic geothermal fields (Cumming, 2009; Gunderson et al., 2000; Ussher et al., 2000). Correlation of these zones of low resistivity / high smectite clay content to natural state well temperature profiles, show they are related to low permeability, indicated by linear, or conductive, temperature profiles (Fig. 5). These zones of high smectite clay content represent altered rocks in the Rotokawa Geothermal Field that form low permeability caps for the various aquifers. Lowest resistivity values occur within the upper 300 m of the field, corresponding to high smectite clay abundances within the Huka Falls Formation and Parariki Breccia. Together, these units act as a shallow cap to the intermediate aquifer. Resistivity increases below this cap, associated with decreasing smectite clay content within the Haparangi Rhyolite lava and Waiora Formation, the geological units which form the intermediate aquifer.

Higher resistivities persist to depth (~2 - 3 km) within the centre of the field, associated with higher rank clay alteration (illite and chlorite) and near boiling-point-for-depth temperatures in an area found between wells RK1, RK2, RK3, RK4, and RK11. A deeper (~800-1200 m depth), low resistivity layer is observed at the margins of the field which is associated with low permeability, smectite-altered rock overlying the deep reservoir. The lateral transition from higher resistivity to lower resistivity at these depths appears to be associated with a lateral transition from the permeable, high temperature, convecting reservoir to lower temperature and lower bulk permeability where heat transfer is dominantly conductive (e.g. 330-340 °C and high permeability measured in well RK24 and ~200 °C and low permeability measured in well RK19). Bertrand et al. (2015; 2012) report a further deep low resistivity zone beneath Rotokawa at ~2-6 km depth centred in the south of the field interpreted to be
related to recent intrusions of magma. There is however little evidence for recent magmatic intrusions from the geology, geochemistry and alteration of the wells currently drilled at Rotokawa.

Microseismic monitoring has proven to be a valuable reservoir monitoring tool at Rotokawa (Bannister et al., 2008; Rawlinson, 2011; Sewell et al., 2013a; Sherburn et al., 2013). A network of ten surface seismometers has operated almost continuously at Rotokawa since 2008. The microseismicity is mostly located close to injection wells with magnitudes below 3.5, similar to other geothermal fields worldwide (e.g. Majer et al., 2007). Since deep injection was moved to the southeast of the field in October 2008, the bulk of the microseismicity has been located within a rectangular area between deep injection wells and production wells (Fig. 6). The microseismicity is sharply constrained within a NE-SW trending band, interpreted to represent a large scale field structure known as the Central Field Fault. This microseismicity pattern, together with tracer test results, suggests that injection flow is impeded across the Central Field Fault. Swarm-like seismic activity (>15 events per day) and larger magnitude seismic events (magnitudes 2 - 3.5) are also observed along this NE-SW trending structure. It appears that most of the observed microseismicity is due to thermal contraction of the rock associated with low-pressure injection of cooler (80-120 °C) fluid into the hotter (330-340 °C) reservoir although other inducing mechanisms are likely occurring (Sewell et al., 2013a; Sherburn et al., 2013; 2015).

Repeat microgravity surveys have also been utilised to monitor mass changes across the field during operations (Hunt & Bowyer, 2007). The largest microgravity
changes measured (≤ +300 µgal) occurred between 1997 and 2003, and were centred on shallow injection wells. This positive mass increase has been inferred to be the result of an increase in fluid density associated with re-saturating steam to liquid during injection. It is also possible that temperature-related changes in rock density contributed to these observed microgravity changes.

6. Discussion

Insights Into the Thermal History of the Field

The Rotokawa reservoir history can, in part, be determined from its alteration mineral assemblage (Anderson, 2011; Chambefort et al., 2011; Siratovich et al., 2014; Wyering et al., 2014). For the most part, the alteration mineralogy encountered is consistent with the measured temperatures in wells (Rae et al., 2011). Observed epidote alteration supports high temperature fluids (>230-240 °C), rare occurrences of actinolite-tremolite infer temperatures of >300°C, illite suggests reservoir temperatures of >220°C, and mixed smectite-illite and smectite-chlorite in the shallower parts of the system, infer temperatures of <=200°C (Anderson, 2011, Pochee, 2010). Fluid inclusion temperatures are, for the most part, consistent with measured temperatures (Hedenquist et al., 1988; Rae et al., 2011), however some studies show that thermodynamic changes have occurred in parts of the hydrothermal system over time (Rae et al., 2011). Fluid inclusion temperatures (>300°C) from the northern-most well in the field, RK8, are significantly higher than current measured
temperatures (250-270°C). Alteration mineralogy in this well also shows evidence of cooling from textural relationships between alteration minerals (e.g. actinolite replaced by chlorite). As the measured temperature profile in RK8 is conductive, and the well has low measured permeability, it has been suggested that the inferred cooling in this part of the system resulted in reduced permeability. Clay mineralogy and fluid inclusion analyses in the southern part of the reservoir shows that it has heated over time by ~30-60°C (Hedenquist et al., 1988; Rae, 2007). It therefore appears from the current data that the heat source for the system may have migrated over time from north to south, however further study of the alteration is warranted to fully investigate this.

Structural Controls on Fluid Flow

Permeability in deep (>~1 km), high-temperature, geothermal reservoirs hosted in crystalline, volcanic and plutonic rocks is thought to be dominated by fractures and faults (Davatzes and Hickman, 2010). In the Rotokawa Geothermal Field, whose main reservoir is hosted predominantly within andesitic lava flows of the Rotokawa Andesite lithology, structure is thought to be a major component of its fluid flow pathways (McNamara et al., 2014; Sewell et al., 2015). The Rotokawa Andesite contains a number of volcanic facies from breccias to lava flows and therefore has a large range of measured matrix porosity ($\phi = 4.4 - 16.3$; Siratovich et al., 2014). A comprehensive study of the mechanical properties of the Rotokawa Andesite lavas reveals they are isotropically micro-fractured (Siratovich et al., 2014). From laboratory investigations the presence and intensity of these micro-fractures is thought
to be a controlling factor on the unit’s physical and mechanical properties, including a relationship between higher micro-crack density and higher matrix porosity and permeability values (Siratovich et al., 2014).

Observations from borehole images (McNamara et al., 2014) in the Rotokawa Andesite show that the majority of permeable zones contain wide fractures, fracture clusters, and fractures oriented along the NE-SW active tectonic trend. Similar fractures and fracture populations are however also observed outside of the andesite permeable zones implying that a lot of the fractures imaged are potentially sealed by hydrothermal minerals, and/or that there are further controls on which structures flow that is unresolvable at the borehole scale (e.g. fracture length, fracture connectivity) (Davidson, 2014; Massiot et al., 2015; McNamara et al., 2014).

At the kilometre scale, faults are thought to compartmentalise the deep Rotokawa reservoir (Heise et al., 2008; Hernandez et al., 2015; McNamara et al., 2014; Quinao and Sirad-Azwar, 2012; Quinao et al., 2013; Rae, 2007; Sewell et al., 2013a; Sherburn et al., 2015). Microseismic data shows a spatial correlation between seismic activity and the inferred location of the CFF such that events cluster along the SE (injection field) side of the structure, implying it acts as a barrier to cross-fault fluid flow which is consistent with tracer tests (Sewell et al., 2013a, 2015; Sherburn et al., 2015). Other data suggests the CFF is permeable along strike and up-dip, such as an alignment of surface geothermal expressions (e.g. Lake Rotokawa and the Rotokawa Fumarole), and boiling point for depth conditions in RK2, RK3 and RK4 (Sewell et al., 2012). Whilst injecting in wells RK16 and RK18 in the northwest of the field,
large and rapid returns of tracer from wells RK18 to RK17, along with microseismic
data, indicate that the PFF (or its associated damage zone) is a major, NE-SW
oriented, permeable zone. Furthermore, during injection in wells RK16 and RK18 in
the northwest of the field, northeast fluid flow directions were determined from
naphthalene sulfonate tracer tests, a pathway spatially coincident with the PFF
(Bannister et al., 2008). Production wells along the PFF are all in good hydraulic
communication, and the pressure drawdown since the start of NAP has also been
elongated along this structure (Quinao et al., 2013).

Conceptual Model and Sustainable Development

Knowledge of a geothermal field constantly evolves and therefore stepped
development of geothermal reservoirs over time can reduce the risk that installed
capacity exceeds the sustainable capacity of the resource. The stepped development
undertaken at Rotokawa (an initial 24 MWe in 1997, 34 MWe in 2003, and 174 MWe
in 2009) is a good example. Monitoring of the response of the reservoir to the initial
development from 1997 to 2009, as well as step-out drilling for deep injection
provided sufficient information to build a robust conceptual and numerical model of
the field. This was then used to assess the sustainability of the planned increased
production for the NAP development (Bowyer and Holt, 2010).

Following the NAP plant start-up in 2010, the conceptual and numerical models
of the field were updated. A large amount of information had been obtained since the
previous conceptual and numerical model update in 2007, most importantly the
information obtained from the drilling of new wells for the NAP development, and
the initial response of the reservoir to greatly increased production and injection. An
important lesson learned from the initial reservoir response to increased production
was that the reservoir is highly compartmentalized leading to highly variable pressure
drawdown across the field (Quinao et al., 2013). This reservoir compartmentalization
is an important factor in obtaining sustainable production and predicting reservoir
changes over time.

The current conceptual model of the Rotokawa Geothermal Field is summarised
in Hernandez et al. (2015) (Fig. 2). The model combines information from the
geological and structural model, as detailed in Wallis et al. (2013), and the conceptual
fluid flow pathways, as described in Winick et al. (2011), both of which has been
described earlier in this paper. The field is broadly divided into the current production
and injection areas, separated by the NE-SW trending CFF. Well responses and
pressure drawdown observations across the field show that the permeability is highly
heterogeneous within the field and that there are semi-isolated compartments. This is
supported by observations of fluid mixing patterns (Winick et al., 2011), stress
orientation heterogeneity across the field (McNamara et al., 2014), structural variation
across the field (Massiot et al., 2015; McNamara et al., 2014; Wallis et al., 2013) and
spatial observations of microseismicity during injection (Sewell et al., 2015; Sherburn
et al., 2015). The current conceptual model (Hernandez et al., 2015) contains a
laterally extensive, permeable, mixed, thermal-groundwater aquifer (constrained from
temperature profiles), which overlies much of the deep reservoir from around +100 to
-450 mRL in most wells. This aquifer is thought to be connected to the deep reservoir
somewhere between wells RK4, RK3, and RK1 (Fig. 2). The top of the deep reservoir
lies between -500 to -750 mRL (constrained from natural state temperature and permeability distribution) and its base at no deeper than -3000 to -4000 mRL (constrained from microearthquake data).

The current conceptual and numerical models of the reservoir continue to be updated and are integral to the adaptive management of the Rotokawa Geothermal Field and therefore the long-term sustainability of the resource (Hernandez et al., 2015). Detailed reservoir monitoring, particularly of pressure, temperature and chemistry, has been essential to build robust conceptual and numerical models, and enable the adaptive reservoir management needed in order to ensure sustainable development and operation. Changes in the injection strategy at Rotokawa over time provide a good example of this. Initially injection was relatively shallow (~300-500 m) which resulted in increased pressure within the intermediate aquifer (Hunt and Bowyer, 2007). To alleviate these shallow pressures, and provide pressure support to the reservoir, deep injection wells were drilled on the western edge of the reservoir to target a deepening reservoir and decreasing permeability, evidenced by a deepening smectite clay cap interpreted from MT surveys (Sewell et al., 2012). An injection tracer test was performed that showed fast returns of injection fluid back to production wells in a NE-SW oriented pathway, interpreted as structurally controlled fluid flow pathways (Sewell et al., 2015). This work resulted in injection moving to the south of the field, so that production and injection were across rather than along the NE-SW structural axis, decreasing the risk of injection cooling of the production field. Recent tracer injection tests confirm that this injection location provides some pressure support to the reservoir whilst ensuring injection fluid travel times are long.
enough to allow full re-heating of the fluid prior to production (Hernandez et al., 2015; Mountain and Winick, 2012).

Environmental effects of the development of the resource have been minimal (e.g. Price et al., 2012; Sewell et al., 2013b). Deep production and injection means that changes in pressure and temperature occur mostly in the deep reservoir and this minimises the risk of near-surface impacts. Regular monitoring of the temperature, flow, and chemistry of the main surface thermal features at Rotokawa has shown that there has not been any impact on these features from development (Sewell et al., 2013b). Effects on local groundwater have also been minor (Sewell et al., 2013b). Repeat levelling surveys since 1997 have shown that ground subsidence has been relatively minor, with the maximum total subsidence measured from 1997 to 2013 being ~200 mm (Abele and Currie, 2013). The increase in deep injection has resulted in increased induced seismicity since the development and operation of the NAP plant in 2010 (Sherburn et al., 2013, 2015). Event magnitudes of \( \leq 3.5 \) have been recorded, and although some events have been reported as felt, none have caused serious concern or damage (Sherburn et al., 2013; 2015).

7. **Acknowledgements**

Acknowledgements go to the Geothermal Resources of New Zealand research program at GNS Science for funding this review paper, and the Rotokawa Joint Venture Ltd. (Mighty River Power Ltd. and Tauhara North No. 2 Trust) for providing comment.
8. References


(Tahorakuri Formation) at Ngatamariki and Rotokawa Geothermal Fields, 35th New Zealand Geothermal Workshop 2013 Proceedings, Rotorua, New Zealand.


Hurst, A. W., Bibby H. M., Robinson, R. R., 2002. Earthquake focal mechanisms in the central Taupo Volcanic Zone and their relation to faulting and


Rae, A.J., O'Brien, J., Ramirez, E., Bignall, G., 2011. The application of chlorite geothermometry to hydrothermally altered Rotokawa Andesite, Rotokawa


reservoir numerical modelling and well targeting at the Rotokawa Geothermal Field, New Zealand, Proceedings Thirty-Seventh Workshop on Geothermal Reservoir engineering, Stanford University, Stanford, California, SGP-TR-194.


Figure 1  Map of the Rotokawa Geothermal Field showing key features including the resistivity boundary (Risk, 2000), locations of geothermal springs and water features of variable chemistry, and hydrothermal eruption vent locations. Inset shows location of the Rotokawa Geothermal Field in the North Island, New Zealand. 1 = West Pool, 2 = Lagoon Out, 3 = Paraiki Stream Lake Rotokawa Outlet, 4 = Paraiki Stream Seep, 5 = Explosion Crater, 6 = Rotokawa Fumarole, 7 = Ed’s Spring, 8 = Paddock Seeps, 9 = Waikato River Seep, 10 = Paraiki Stream Waikato River Confluence.
Figure 2  Cross-section of the Rotokawa Geothermal Field (A – A’ as shown on Figure 3) showing geological units, well locations (Rk1, Rk1x, Rk2, Rk3, Rk4, Rk5, Rk6, Rk9, Rk13, Rk14), clay cap, isotherms (120°C, 160°C, 200°C, 240°C, 280°C, 320°C), the Central Field Fault, and geochemical processes in the reservoir (1 = hot two-phase upflow, 2 = deep conductively heated groundwater (up to 290°C), 3 = dilution and mixing with the deep conductively heated groundwater, 4 = adiabatic boiling, 5 = steam heated groundwater). Adapted from Winick et al. (2011).
Figure 3 Map of the Rotokawa Geothermal Field showing active faults from GNS Active Fault Database (2014), modelled structures from Bowyer and Holt (2008), and modelled structures from Wallis et al. (2013) (1 = Production Field Fault, 2 = Central Field Fault, 3 = Injection Field Fault).
Figure 4  Plot of enthalpy (corresponding to the quartz geothermometer temperature) versus reservoir chloride for the Rotokawa production wells, monitoring wells, and thermal features. Modified from Hedenquist (1988), and Winick et al. (2011).
Figure 5  SW – NE MT cross-section (B – B’ as shown on Figure 3). Grey lines represent isotherms, black lines represent well tracks, and blue lines either side of well tracks are MeB smectite logs. Modified from Sewell et al., (2012).
Figure 6  a) Map showing microseismic events post the NAP development (February, 2010) to the end of 2012. b) A 3D view, looking Northwest, of the seismicity (green spheres) and the Central Field Fault. Production wells on the left and injection wells on the right. Well tracks are coloured for geology and for feed zone locations. Modified from Sewell et al., (2013a).