U-Pb DATING OF ZIRCON IN HYDROTHERMALLY ALTERED ROCKS AS A CORRELATION TOOL: A CASE STUDY FROM THE KAWERAU GEOTHERMAL FIELD, NEW ZEALAND

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ABSTRACT

The exploration and successful management of high-temperature geothermal systems for electrical power generation and direct heat usage require an understanding of its geological structure and permeability pathways within the system. Central to sound interpretation of the geological structure is dating and correlating key marker horizons in order to correlate laterally permeable formations and estimate the timing and rates of movements across faults.

The correlation of Taupo Volcanic Zone (TVZ) hydrothermally altered rocks is challenging, due to similarities in the lithologies, and effects of hydrothermal alteration that alter distinctive chemical, mineralogical and textural characteristics. Although correlations can be made on the basis of petrographic characteristics, such relationships may be made ambiguous by overprinting alteration. Zircons from evolved (dacite to rhyolite) rocks can be dated by U-Pb techniques, supplying a spectrum of crystallisation ages for primary magmatic material in these rocks. The spectrum places a maximum age limit on the eruption(s), or can provide an estimate of the emplacement/cooling age for intrusive rocks. A combination of age data and geological studies then permits the structural history of geothermal field to be more confidently inferred.

In this paper we report new U–Pb age data from a sequence of hydrothermally altered rocks sampled from wells in the Kawerau Geothermal Field. We show how model-age data from zircons can be used to constrain interpretations of stratigraphy where conventional petrographic information might be ambiguous. The U-Pb age data have proved decisive when used with petrographic observations in deciding on an overall stratigraphic sequence. Comparisons of zircon crystallisation spectra are used to demonstrate how these correlations can be extended to regional studies.

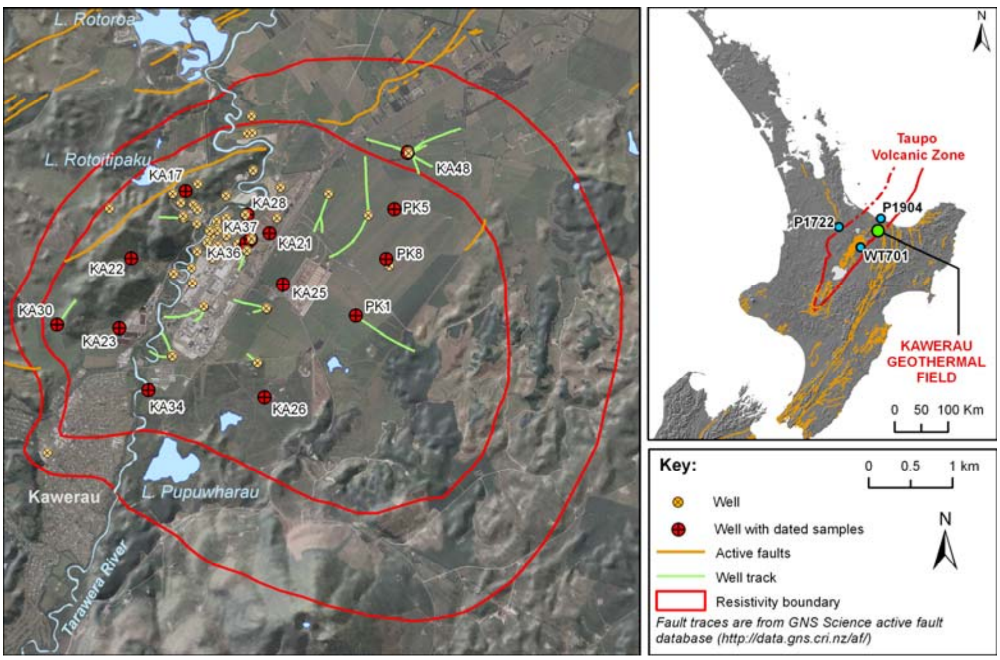

Figure 1: Location map of Kawerau Geothermal Field, with location of wells with dated samples. Locations of samples P1722, P1904 and WT701 are indicated on the right.

1. INTRODUCTION

The Kawerau Geothermal Field is located in the northern TVZ, near its eastern boundary (Fig. 1). Geothermal activity occurs at the southern end of the NE-trending Whakatane Graben, in an area where the NE-striking active rift of the TVZ intersects the N-trending strike-slip faults of the North Island Shear Belt (Nairn and Beanland, 1989; Mouslopoulou et al., 2007). This graben structure is evident east of the Kawerau Geothermal Field, where the 320 ka Matahina ignimbrite (Bailey and Carr, 1994; Leonard et al., 2010) is exposed at the ground surface, but occurs at 10 to 130 m depth beneath the field itself. During the Quaternary, Mesozoic basement greywacke within the Whakatane Graben has been downfaulted to 1-2 km below sea level, with the resulting structural depression infilled by volcanic rocks and sediments. More than 70 wells used for geothermal production, injection and monitoring have been drilled in the field since the 1950's. The geology of these wells provides the foundation of a substantially revised stratigraphy (Milicich et al., 2012a,b)

Here we use U-Pb age data from zircons from units within the Kawerau Geothermal Field to demonstrate how geochronology can be used to constrain interpretations of stratigraphy where conventional petrographic information may be ambiguous or inaccurate. Comparisons of zircon crystallisation age spectra are used to demonstrate how these correlations can be extended outside of the study area.

2. DATING

Hydrothermal alteration of rock within geothermal fields can obscure primary mineralogy and lithological textures, and may preclude direct dating by radiometric techniques. Magmatic zircons are commonly present in silicic volcanic rocks, and generally crystallise up to the point of eruption in magmas where zircon saturation was achieved. Zircons are resistant to hydrothermal alteration and can yield a record of their crystallisation ages.

Zircon crystallization-age spectra have been obtained from 27 samples of core and cuttings from ignimbrites, tuffs and rhyolite across the field by SIMS techniques (SHRIMP-RG instruments at the joint USGS-Stanford University facility and at the Australian National University).

Age determinations were made using the techniques described in Wilson et al. (2010). The presence of common Pb was evaluated by monitoring for ^{204}Pb, and a correction applied using the recorded ^{207}Pb/^{206}Pb values and an average common Pb isotopic composition for the modern Earth's crust (^{207}Pb/^{206}Pb = 0.8357; Stacey and Kramers, 1975). Raw ages were corrected for initial ^{230}Th disequilibrium using the U and Th concentrations in the zircon from the SIMS analysis and a whole-rock Th/U value of 4.4 (Wilson and Charlier, 2009).

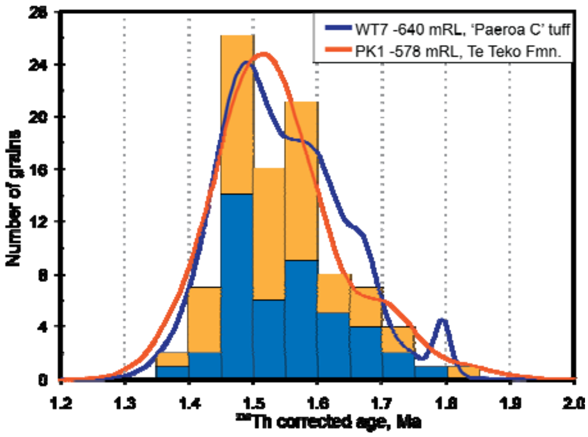

Figure 2: Histogram and relative probabilities (given by the probability density function in Isoplot: after Ludwig, 2008) for samples PK1 -578 mRL within the Te Teko Formation at Kawerau and WT7 -640 mRL from the 'Paeroa C' tuff at Waiotapu. In all cases, grains with >30 % common-Pb were omitted.

Summary histograms with associated probability density function (pdf) curves from Isoplot (Ludwig, 2003) are given for 3 representative samples and their regional correlatives in Figs. 2 to 4. The full suite of Kawerau age data is reported in Milicich et al. (2012a).

3. U-PB AGE DETERMINATIONS AS A CORRELATION TOOL

The initial Kawerau Geothermal Field stratigraphy was established from lithology and petrography by Nairn (1977, 1981, 1982, 1986), Browne (1978), Grindley (1986), Christenson (1987), Tulloch (1990) and Allis et al. (1995), and summarised in Bignall and Harvey (2005). The problematic framework presented by Bignall and Harvey (2005) applied stratigraphic names inconsistently across the

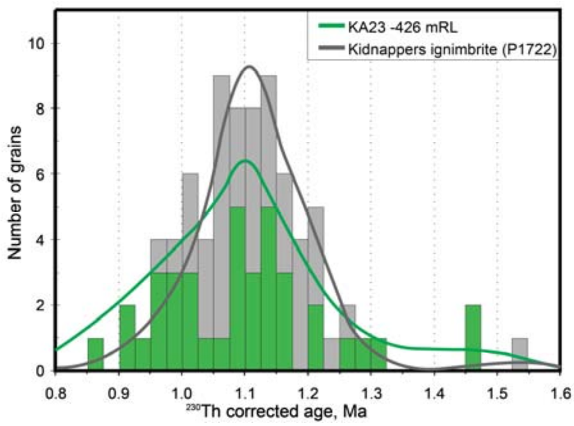

Figure 3: Histogram and relative probabilities (given by the probability density function in Isoplot: after Ludwig, 2008) for samples KA23 -426 mRL within the Raepahu Formation at Kawerau and P1722 from a surficial sample of the Kidnappers ignimbrite (data from Wilson et al., 2008). In all cases, grains with >20 % common-Pb were omitted.

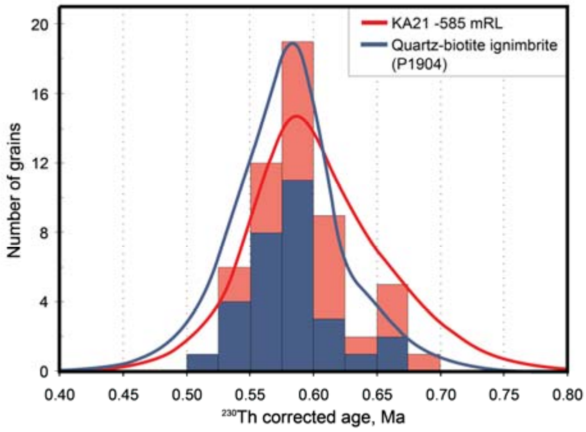

Figure 4: Histogram and relative probabilities (given by the probability density function in Isoplot: after Ludwig, 2008) for samples KA21 -585 mRL within the Karaponga Formation at Kawerau and P1904 from pumice in outwash fluvial sediments from the Quartz-biotite Ignimbrite of Nairn (2002). In all cases, grains with >30 % common-Pb were omitted.

Table 1 Summary of the main stratigraphic units in the Kawerau Geothermal Field (from Milicich et al., 2012a).

Formation	Lithology	Thickness
Surficial deposits	Peat deposits; sands and gravels; unconsolidated pyroclastics (incl. Whakamana Breccia, Rotoiti Breccia)	10 – 90 m
Onepu Formation	Twin surficial domes of rhyodacite (pl, qtz, py, hb, bt) and intrusive (porphyritic crystal-rich; corroded qtz, pl, mafics)	~200 m
Matahina ignimbrite	Partly welded grey-brown lenticulite & vitric tuff (pl, qtz, py)	10 – 410 m
Tahuna Formation	Crystal-rich, fine sandstone, siltstone, muddy lithic-breccia and unwelded pumice-rhyolite lapilli tuff	0 – 360 m
Caxton Formation	Buried domes of spherulitic and banded rhyolite (corroded and fractured qtz and pl) and intrusive (corroded and fractured qtz and pl, ± bt ± amp)	0 – 450 m
Karaponga Formation	Partly welded crystal-lithic tuffs (pl, qtz ± bt)	0 – 180 m
Onerahi Formation	Tuffaceous to muddy breccias and coarse tuffaceous sandstone	0 – 85 m
Kawerau Andesite	Augite-plagioclase andesite flows, breccias and tuff (in south)	0 – 300 m
Raepahu Formation	Partly welded crystal-vitric tuffs (qtz, pl, bt, lithic-poor and qtz, pl, bt, ferromagnesians, lithic-rich)	0 – 165 m
Tasman Formation	Muddy breccia, sandstone and siltstone, but widely represented by reddish brown siltstone	0 – 25 m
Te Teko Formation	Partly welded grey crystal-vitric tuff (corroded qtz, pl, bt)	0 – 255 m
Rotoroa Formation	Tuffaceous sandstone, poorly sorted crystal and vitric, water-laid tuff, siltstone	0 – 200 m
Waikora Formation	Greywacke pebble conglomerate and minor intercalated tuff and siltstone	0 – 450 m
Greywacke basement	Weathered, sheared greywacke and argillite	-

Abbreviations used are pl = plagioclase; qtz = quartz; py = pyroxene; hb = hornblende; bt = biotite; amp = amphibole.

field. A review of the Kawerau Geothermal Field stratigraphy was deemed necessary, and has resulted in a complete revision, with stratigraphic correlations undertaken by a combination of U-Pb age determinations and petrography. A summary of this stratigraphy is given in Table 1 and Figure 5 and discussed in detail by Milicich et al. (2012a,b).

As an example of the value U-Pb dating has for correlation altered rocks, there are three ignimbrite packages of substantial thickness which extend across the Kawerau field. The petrography of these ignimbrites is similar all contain primary quartz, plagioclase and biotite crystals and have variable lithic content. Due to the ambiguity of the petrography, samples these formations had been previously correlated with the Rangitaiki ignimbrite, which is $^{40}Ar/^{39}Ar$ dated (not at Kawerau) at 350 ± 3 ka (Leonard et al., 2010). New U-Pb zircon ages from these units fall into packages that have ages overlapping within the uncertainties of pooled ages. These clusters lie around 1.45-1.35 Ma (Te Teko Formation; Fig. 2), 1.0 Ma (Raepahu Formation; Fig. 3) and 0.6-0.5 Ma (Karaponga Formation; Fig. 4). This result has implications in the understanding of faulting and development of permeability pathways within the field.

An additional benefit in the use of U-Pb zircon age determinations is the ability to extend stratigraphic correlations beyond the localised area of study. The ignimbrites of the Te Teko Formation have here been correlated with the deepest of the major tuff units ('Paeroa C') intersected in drillhole WT7 (WT701; Fig. 1) in the Waiotapu Geothermal Field (Fig. 2). The Raepahu Formation (Edbrooke, 2005) was defined as a mapping term for surficial deposits of two major eruptions; the Kidnappers fall deposit and ignimbrite (Wilson et al., 1995; Cooper et al., 2012), and the Rocky Hill ignimbrite (Martin, 1961), both of which are exposed together west of the TVZ. These two deposits have $^{40}Ar/^{39}Ar$ ages that overlap within uncertainty around 1 Ma (Houghton et al., 1995; Wilson et al.,

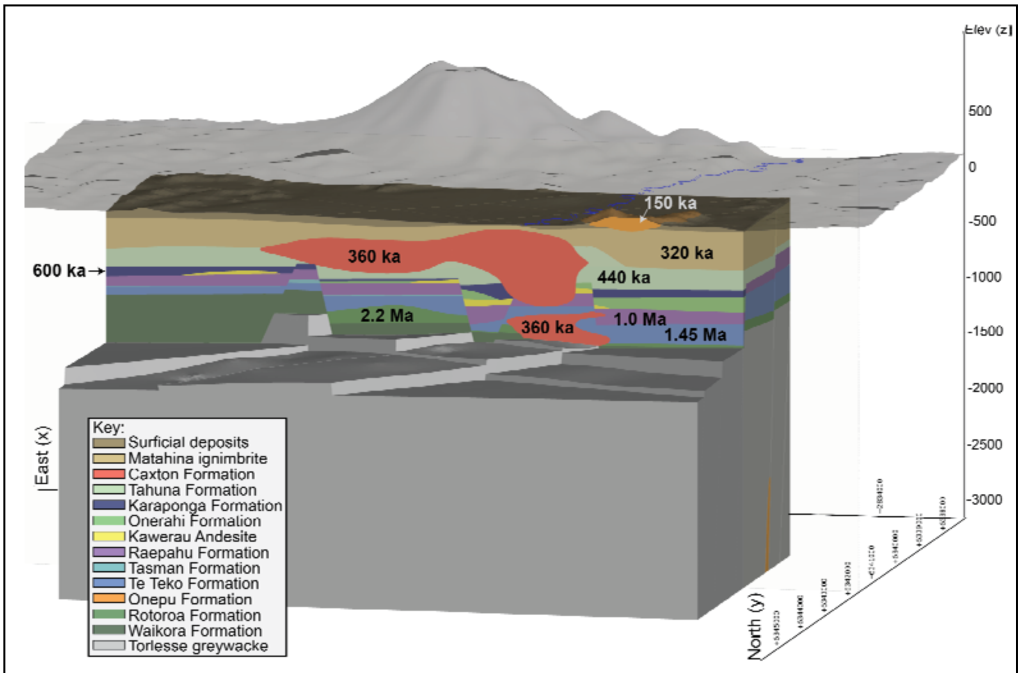

Figure 5: Geology of the Kawerau Geothermal Field with zircon U-Pb ages of the formations.

1995), but are inferred to represent separate eruptions, based on field evidence for an intervening short-lived period of erosion (Wilson, 1986). The lateral equivalent of the Raepahu Formation at Kawerau is inferred to be a series of ignimbrites with U-Pb ages clustered around 1.0 Ma. The age spectra from Kawerau and a surface sample from the Ngatira Rd (Putaruru) pumice pit (P1722; Fig. 1) show this correlation (Fig. 3). The age spectrum from an ignimbrite in the Karaponga Formation (Fig. 4) closely matches that from zircons extracted from crystal-rich, large-quartz and biotite-bearing pumices (P1904; Fig. 1) found in fluvial outwash deposits exposed on the Bay of Plenty coast (Hikuroa et al., 2006). These outwash deposits are correlated on the basis of bracketing unpublished $^{40}Ar/^{39}Ar$ age data (G.S. Leonard and A.T. Calvert, pers. comm.) with a large ignimbrite (the Quartz- biotite Ignimbrite of Nairn, 2002; Cole et al., 2010) which has also independently been $^{40}Ar/^{39}Ar$ dated at 557 ± 3 ka (Leonard et al., 2010).

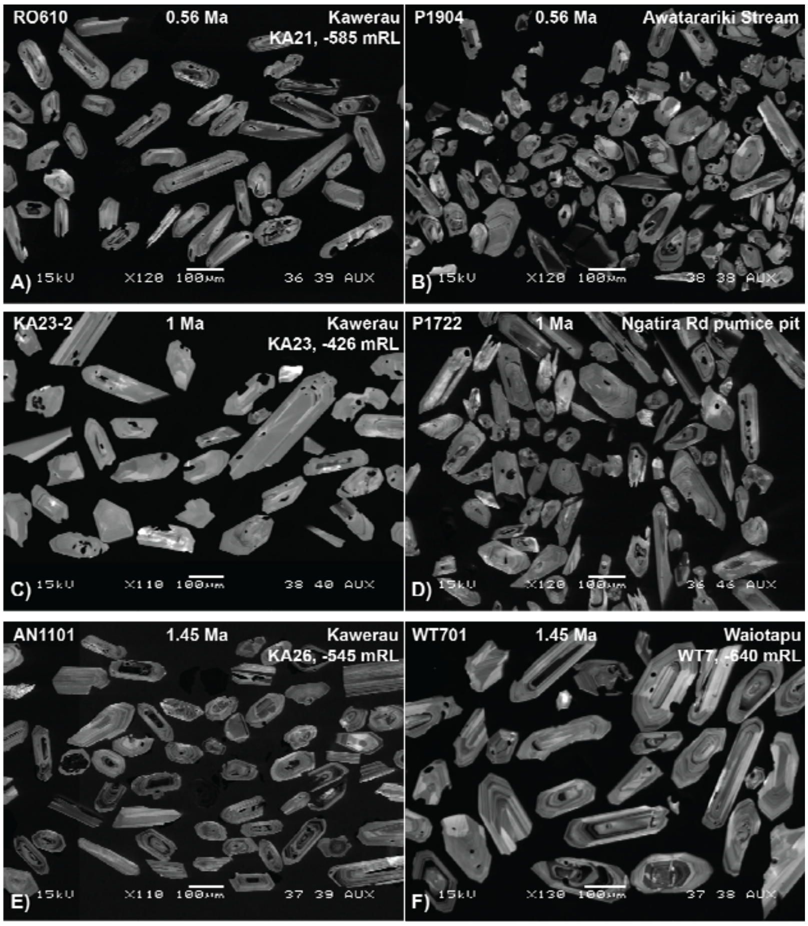

Figure 6: 0.56 Ma tuffs have zircon with moderately complex textures, with from Kawerau (A) and the Awatarariki Stream near Matata (B); 1 Ma zircons with simple zoning, from Kawerau (C) and the Ngatira Rd pumice pit (D); 1.45 Ma zircons with complex zoning, from Kawerau (E) and Waiotapu (F). The images are representative of zircon textures for all units in these age groupings.

4. ZIRCON TEXTURES AS A CORRELATIVE TOOL

In addition to U-Pb dates, zircon textures can be utilised as a broad correlation tool once initial correlation by dating has been achieved. Zircon textures reflect the geological history of the mineral, particularly episodes of magmatic crystallisation or resorption and changes in the uptake of trace elements, as seen in patterns of cathodoluminescence (CL) brightness (Corfu et al., 2003; Finch and Hanchar, 2003).

In this study, we have found zircon textures to be sufficiently different between age-grouped tuffs to distinguish them on CL imagery alone, although these differences do not serve to differentiate individual tuffs within these groupings. For example, zircons from the 0.5-0.6 Ma tuffs of the Karaponga Formation have zircons with moderately complex textures, including many with dark cores (Fig. 6 A & B). Zircons in the ~1.45 Ma tuffs of the Te Teko Formation display very complex zonations (Fig. 6 E & F), while zircons from the ~1Ma Raepahu Formation have very simple zoning, with thin, moderately dark-CL zones rich in trace elements such as the rare-earth elements, U and Th (Fig. 6 C & D).

These textural relationships can in principle be used to confirm correlation of tuffs from future drillhole sampling at Kawerau on the basis of imagery (coupled with stratigraphic and petrographic constraints), without the need to undertake further U-Pb dating. The textures also serve to confirm correlation with eruptive units elsewhere that show similar age spectra (Fig. 6). The deepest of the major tuff units (‘Paeroa C’) reached at Waiotapu Geothermal Field (45 km SW of Kawerau) has a U-Pb age of ~1.45 Ma from zircons (Wilson et al., 2010) that show similarly complex textures to those zircons in the Te Teko Formation ignimbrites at Kawerau. Similarly, the petrography and zircon age spectra and zircon textures from sample KA23_2 (Raepahu Formation) are closely matched by those from the surficial ~1 Ma Kidnappers ignimbrite (as well as its buried and altered equivalent in the Mangakino Geothermal Field: Wilson et al., 2008).

5. SUMMARY

The understanding of geological structure and permeability pathways is fundamental to the exploration and management of high-temperature geothermal systems. Key to geo-hydrological interpretation is the correlating of marker horizons across the field so that permeable connections and the timing and rates of movements across faults may be inferred. At Kawerau Geothermal Field, we have overcome the obstacles of correlating intensely altered rocks by combining petrographic descriptions with zircon U-Pb dating to produce a strong stratigraphic framework and field-wide correlations of many units. This has greatly advanced the understanding of the geology of the Whakatane Graben, the key points of this study being:

- The main deep ignimbrites in the field are clustered in age around 0.5-0.6 Ma (Karaponga

Formation), 1 Ma (Raepahu Formation) and 1.45 Ma (Te Teko Formation). Long periods of local volcaniclastic and sedimentary deposition occurred between these major volcanic episodes.

- The Rangitaiki ignimbrite, which has previously been reported in wells in the field, is absent. Strata previously ascribed to this unit have now been re-assigned variously to the Karaponga Formation, Raepahu Formation and Te Teko Formation.
- Using zircon U-Pb age spectra, correlations can be extended over wide geographic areas. Units from within the Kawerau Geothermal Field have been correlated with units at Waiotapu, Matata and in the Waikato region.

In this study, we have found zircon textures to be sufficiently different between age groupings of tuffs to distinguish them on CL imagery alone, but these differences do not serve to differentiate individual tuffs within these groupings. This technique provides a potential correlation tool once the initial age determinations have been undertaken.

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REFERENCES

Allis, R.G., Christenson, B.W., Nairn, I.A., Risk, G.F., Sheppard, D.S. and White, S.P.: Kawerau geothermal field : its natural state and response to development. *Institute of Geological & Nuclear Sciences client report*. 72436C.10 (1995).

Bailey, R.A. and Carr, R.G.: Physical geology and eruptive history of the Matahina Ignimbrite, Taupo Volcanic Zone, North Island, New Zealand. *N.Z. J. Geol. Geophys*, 37, 319–344 (1994).

Bignall, G., Harvey, C.C.: Geoscientific review of the Kawerau Geothermal Field. *Institute of Geological & Nuclear Sciences client report*. 2005/20 (2005).

Browne, P.R.L.: Petrological logs of drillholes : Kawerau Geothermal Field. *New Zealand Geological Survey.. Report* 84 (1978).

Christenson, B.W.: Fluid-Mineral equilibria in the Kawerau hydrothermal system, Taupo Volcanic Zone, New Zealand. *Ph.D. thesis*, University of Auckland (1987).

Cole, J.W., Spinks, K.D., Deering, C.D., Nairn, I.A. and Leonard, G.S.: Volcanic and structural evolution of the Okataina Volcanic Centre; dominantly silicic volcanism associated with the Taupo Rift, New Zealand. *J. Volcanol. Geotherm. Res.*, 190, 123–135 (2010).

Cooper, G.F., Wilson, C.J.N., Millet, M.-A., Baker, J.A., Smith, E.G.C.: Systematic tapping of independent magma chambers during the 1 Ma Kidnappers supereruption. *Earth Planet. Sci. Lett.*, 313–314, 23–33 (2012).

Corfu, F., Hanchar, J.M., Hoskin, P.W.O., Kinny, P.: Atlas of zircon textures. *Rev. Mineral. Geochem.*, 53, 469–500 (2003).

Edbrooke, S.W. (compiler): Geology of the Waikato area: scale 1:250,000. Institute of Geological & Nuclear Sciences 1:250,000 geological map 4. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand (2005).

Finch, R.J. and Hanchar, J.M.: Structure and chemistry of zircon and zircon-group minerals. *Rev. Mineral. Geochem.* 53, 1–25 (2003).

Grindley, G.W.: Subsurface geology and structure of the Kawerau geothermal field. In: M.A. Mongillo (Editor), The Kawerau Geothermal Field : contributions from the 1982 seminar and other recent scientific investigations. *Department of Scientific and Industrial Research. Geothermal Report* 10, pp. 49–65 (1986).

Hikuroa, D.C.H., Gravley, D.M., Wilson, C.J.N., Browne, P.R.L., Olsen, A.W.: Recent stratigraphic studies at Matata: implications for Kawerau geothermal field modelling and subsurface interpretation. *Proceedings, 28th New Zealand Geothermal Workshop* (2006).

Houghton, B.F., Wilson, C.J.N., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M., Pringle, M.S.: Chronology and dynamics of a large silicic magmatic system: central Taupo Volcanic Zone, New Zealand. *Geology*, 23, 13–16 (1995).

Leonard, G.S.; Begg, J.G.; Wilson, C.J.N. (compilers): Geology of the Rotorua area: scale 1:250,000. Institute of Geological & Nuclear Sciences 1:250,000 geological map 5. 102 p. + 1 folded map. Lower Hutt: Institute of Geological & Nuclear Sciences Limited (2010).

Ludwig, K.R.: Isoplot/Ex version 3.41, A geochronological toolkit for Microsoft Excel. Berkeley, California, Berkeley Geochronology Center Special Publication 4 (2003).

Martin, R.C.: Stratigraphy and structural outline of the Taupo Volcanic Zone. *N.Z. J. Geol. Geophys.*, 4, 449–478 (1961).

Milicich, S.D.; Wilson, C.J.N.; Bignall, G.; Pezaro, B.; Charlier, B.L.A.; Wooden, J.L.; Ireland, T.R.: U-Pb dating of zircon in hydrothermally altered rocks of the Kawerau Geothermal Field, Taupo Volcanic Zone, New Zealand. *J. Volcanol. Geotherm. Res.*, (submitted) (2012a).

Milicich, S.D.; Wilson, C.J.N.; Bignall, G.; Pezaro, B.; Bardsley, C.: Stratigraphy and structural evolution of

Kawerau Geothermal Field, Taupo Volcanic Zone, New Zealand. (2012b: in prep).

Mouslopoulou, V., Nicol, A., Little, T.A. and Walsh, J.J.: Displacement transfer between intersecting regional strike-slip and extensional fault systems. *J. Struct. Geol.*, 29, 100–116 (2007).

Nairn, I.A.: Geology of the Okataina Volcanic Centre: scale 1:50,000. Institute of Geological & Nuclear Sciences geological map 25. Institute of Geological & Nuclear Sciences Limited, Lower Hutt, New Zealand (2002).

Nairn, I.A.: Geology of Kawerau geothermal field : preliminary report on new data. *Geothermal circular*. Department of Industrial and Scientific Research (1977).

Nairn, I.A.: Some studies of the geology, volcanic history, and geothermal resources of the Okataina volcanic centre, Taupo Volcanic Zone, New Zealand. *Ph.D. thesis*, Victoria University, Wellington, New Zealand (1981).

Nairn, I.A.: Geology of Kawerau geothermal field (MK11): results of drilling, 1977-1982. *Geothermal circular*. Department of Industrial and Scientific Research, pp. 23 (1982).

Nairn, I.A.: Geology of Kawerau geothermal field - results of drilling, 1977-present. In: M.A. Mongillo (Editor), The Kawerau Geothermal Field : contributions from the 1982 seminar and other recent scientific investigations. *Department of Scientific and Industrial Research. Geothermal Report* 10., pp. 23–47 (1986).

Nairn, I.A. and Beanland, S.: Geological setting of the 1987 Edgecumbe earthquake, New Zealand. *N.Z. J. Geol. Geophys.*, 32, 1–13 (1989).

Stacey, J.S. and Kramers, J.D.: Approximation of terrestrial lead isotope evolution by a two-stage model. *Earth Planet. Sci. Lett.*, 26, 207–221 (1975).

Tulloch, A.: Petrological logs of drillholes KA 27-35 and KA 10, 17 (deepened), Kawerau Geothermal Field. *DSIR Geology and Geophysics contract report*. 1990/11 (1990).

Wilson, C.J.N.: Reconnaissance stratigraphy and volcanology of ignimbrites from Mangakino volcano. In: I.E.M. Smith (Ed.), Late Cenozoic Volcanism in New Zealand. *Royal Society of New Zealand Bulletin*, 23, 179–193 (1986).

Wilson, C.J.N. and Charlier, B.L.A.: Rapid rates of magma generation at contemporaneous magma systems, Taupo volcano, New Zealand: insights from U-Th model-age spectra in zircons. *J. Petrol*. 50, 875–907 (2009).

Wilson, C.J.N., Houghton, B.F., Kamp, P.J.J., McWilliams, M.O.: An exceptionally widespread ignimbrite with implications for pyroclastic flow emplacement. *Nature*, 378, 605–607 (1995).

Wilson, C.J.N., Charlier, B.L.A., Fagan, C.J., Spinks, K.D., Gravley, D.M., Simmons, S.F., Browne, P.R.L.: U-Pb dating of zircon in hydrothermally altered rocks as a correlation tool: application to the Mangakino geothermal field, *N.Z. J. Geol. Geophys.*, 176, 191–198 (2008).

Wilson, C.J.N., Charlier, B.L.A., Rowland, J.V. and Browne, P.R.L.: U-Pb dating of zircon in subsurface, hydrothermally altered pyroclastic deposits and implications for subsidence in a magmatically active rift: Taupo Volcanic Zone, New Zealand. *J. Volcanol. Geotherm. Res*., 191, 69–78 (2010).