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Insights into Geothermal Systems from U-Pb Dating of Zircons in Hydrothermally Altered Rocks: the New Zealand Experience

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ABSTRACT

A key element in optimal exploration and utilisation of geothermal systems is an accurate picture of their geological and structural history. Siting of wells for extraction or reinjection, and strategies for exploration and reservoir management depend on understanding the location and duration of magmatic and tectonic events through geochronology. At several New Zealand geothermal fields, unique constraints on these events have been achieved by U-Pb dating of magmatic zircon in rocks penetrated by geothermal drillholes using secondary ion mass spectrometry (SIMS) techniques on the SHRIMP-RG instruments at Stanford University and The Australian National University. As well as underpinning magmatic and structural chronologies, the data have constrained the likely timing of heat and fluid contributions, the creation and disruption of permeability, and provided, verified or disproved stratigraphic correlations. New Zealand's high-temperature (>250 °C fluid) geothermal systems lie within the Taupo Volcanic Zone (TVZ), a rifting arc system active since ~2 Ma. Most systems are located in the central TVZ, and are hosted by the products of prolific rhyolitic and subordinate andesitic volcanism which unconformably overlie a faulted Mesozoic metasedimentary (greywacke) basement. Tectonic controls on geothermal system location and hydrology linked to caldera boundaries and fault systems of TVZ are understood on a regional scale. Many system-scale studies have provided insights through integration of geological and geophysical datasets, but until recently these have lacked a quantitative time scale. We highlight here four case studies where age data has proved to be critical in understanding the geology at New Zealand geothermal fields. At *Mangakino*, age data served to demonstrate that the rocks in the lowest two-thirds (~1.8 km) of the drilled stratigraphy were the intracaldera products of a linked pair of eruptions at ~1.0 Ma, indicating that the basement greywacke was at unreachable depths. At *Kawerau*, age data have led to a complete revision of the geological and structural history, leading to creation of a new geological model for field management. At *Ngatamariki*, the age data have demonstrated the minimum age for the earliest andesites (>1.9 Ma) and the onset of TVZ rifting and silicic volcanism in its present-day position, and provided reliable intrusion ages of the Ngatamariki intrusive complex. At *Wairakei*/*Tauhara*, the age data have demonstrated a major hiatus in activity from ~0.95 to ~0.35 Ma, and the extraordinarily rapid subsidence and infilling rates (~1 cm/yr) associated with rocks in the production area.

1. INTRODUCTION

The exploration and management of high-temperature (>250 °C fluid) geothermal systems for direct heat usage and electrical power generation requires an understanding of the geological structure and permeability pathways (including faults) within each system. Such understanding is fundamentally dependent on dating and correlating key marker horizons, in order to correlate laterally permeable formations and estimate the timing and rates of fault movements. Correlation of hydrothermally altered rocks is challenging, due to similarities in the lithologies, and the destruction by hydrothermal alteration of distinctive chemical, mineralogical and groundmass textural characteristics. Although correlations can be and are typically made on the basis of petrographic characteristics (rock type, crystal content, presence and abundance of recognisable mineral phases), such relationships may be ambiguous. However, if the ages of the lithologies can be established reliably, they can be used to differentiate or correlate between units within and beyond the geothermal field (e.g., Wilson et al., 2008, 2010).

Many intermediate to evolved volcanic rock compositions, particularly rhyolites, contain zircons that crystallised in the magma prior to quenching by eruption (Hoskin and Schaltegger, 2003, for review). Zircons are valuable repositories of age information due to their high concentrations of radiogenic elements (notably U and Th), exceptionally low uptake of background Pb, and resistance to hydrothermal alteration, replacement or recrystallisation that partially or completely affects the other minerals and groundmass in the rocks. The zircons (or parts of crystals) dated by U-Th disequilibrium or U-Pb techniques (Schmitt, 2011, for review) provide a spectrum of crystallisation ages for primary magmatic material in these rocks. The peak of zircon crystallisation provides an effective maximum age limit on the eruption(s) concerned, or provides an approximation to the emplacement age for intrusive rocks, while the youngest zircons provide a close approximation to eruption age (e.g. Dalrymple et al., 1999; Schmitt et al., 2003a; Milicich et al., 2013a). A combination of the age data and geological studies then permits the thermal and structural history of geothermal fields to be inferred (e.g. Norton and Hulen, 2001; Stimac et al., 2001; Schmitt et al., 2003b; Milicich et al., 2013b; Chambefort et al., 2014).

Interpretation of the age spectra obtained from zircons in hydrothermally altered rocks can be complicated by the nature of the material available for sampling and its inferred history. Ideally, zircons are extracted from coherent rock which represents 'pure' primary magmatic material (e.g. a piece of lava or intrusive rock, or single juvenile pyroclasts), where any spread in ages represents magmatic inheritance. However, since much of the primary volcanic material in volcanic-hosted geothermal systems is pyroclastic in origin, samples of bulk tuff are used which may contain fragments of accidental lithic material or intermixed ash-sized material from older rocks. Care is needed in separating out ages that may have come from the older accidentally included rocks or crystals. In addition, the nature of the downhole-sampled material is important. If core is used, then the sample is derived from a known depth in a given lithology, and downhole contamination can be eliminated as a source of any diversity in the zircon age spectra. If only cuttings are available, however, then not only may it be difficult to establish the nature of the rock host, but the possibility of contamination arises, from two sources. First, if a sedimentary unit is sampled, then the zircon population in those sediments may be derived from a great variety of sources, most or all of which may lie outside the geothermal field area. Second, downhole contamination from the open-hole section above the drill bit is inevitable, although this can be mitigated substantially by sampling cuttings samples from a narrow interval directly below well casing points. The use of cathodoluminescence (CL) imaging and petrography prior to dating can reduce the uncertainty introduced by non-ideal samples.

2. DATING OF ZIRCONS USING SIMS TECHNIQUES

In conventional K-Ar or ^{40}Ar/^{39}Ar age dating, the age of the host rock is estimated from accumulation of radiogenic argon since the minerals were quenched on eruption. In contrast, zircons yield age estimates based on methods, depending on the length of time since crystallisation, that measure the deficit of ^{230}Th or accumulation of Pb isotopes by radioactive decay in the U and Th decay series (Williams, 1998; Condomines et al., 2003). For young volcanic rocks the crystallisation age is generally measured by utilising the disequilibrium caused in the ^{238}U to ^{206}Pb decay chain because of the preferential uptake of U over Th in zircons, creating a deficiency in ^{230}Th that then decays back to the equilibrium value. The disequilibrium in ^{230}Th is measurable at most over a period of ~5 half-lives of ^{230}Th (i.e., ~350 kyr), but typically is applied to rocks that are of ages <200 ka. Model ages for individual analytical spots are then calculated as two-point isochrons on a plot of (^{230}Th/^{232}Th) versus (^{238}U/^{232}Th) (where values in brackets denote activity ratios) between a single (separately measured) value for the whole-rock and individual analyses of the zircon crystals (e.g., Charlier et al., 2005). For older rocks (i.e. usually older than 300 ka, but see the examples described below) the abundances of the Pb isotopes are measured directly and the ages of the analytical spots for our studies are estimated on the basis of the accumulated amounts of radiogenic ^{206}Pb relative to the source ^{238}U source isotope. However, allowance has then to be made for the initial disequilibrium in the ^{238}U to ^{206}Pb decay chain, caused by the preferential partitioning of U over Th into the zircons (Schärer, 1984) that is utilised, as described above, for the dating of very young volcanic rocks.

In order to measure the relevant isotopic ratios, two contrasting techniques can be used. The first involves dissolving single or (more commonly) multiple zircon crystals, and undertaking the isotopic measurements using Isotope-Dilution Thermal Ionization Mass Spectrometry (ID-TIMS). The resulting data are generally exceptionally precise (1 s.d. uncertainty values of <0.1 % or better), but lack context within the crystals (if, for example, there is inheritance of older cores within grains) and are technically demanding to undertake. The second technique involves measuring the relevant isotopes using Secondary Ion Mass Spectrometry (SIMS) techniques. SIMS instruments use a beam of charged ions (typically oxygen for dating purposes) to sputter a small volume of material from the surface of individual crystals that is then sent through a mass spectrometer. The technique is much less precise than ID-TIMS (1 s.d. uncertainties on single analyses typically of >1.5 % or worse), but is much quicker (14-22 minutes per analysis, depending on count times for each isotope measured), analyses a small spot (~25-35 microns across) in a pre-determined part of the crystal, and many more analyses can be accomplished in a given time period. In addition, the SIMS methods we have used involve the analysis of grains that have been polished down to approximately half way through their depth, so that internal structures and zones within each crystal can be seen in CL imagery. Analytical spot locations can thus be chosen accordingly to obtain ages for different parts of the crystal, such as rims (i.e. the youngest parts of the grains), or inherited cores, thus yielding better precision from aggregated suites of ages.

All of the examples discussed in this paper have utilised U-Pb dating of polished mounts by SIMS. In all the case studies, for various reasons we have utilised the Sensitive High Resolution Ion Microprobe-Reverse Geometry (SHRIMP-RG) instruments at Stanford University and The Australian National University (see Ireland et al., 2008). The primary decay system utilised is that of ^{238}U to ^{206}Pb because of it providing the best age-resolving power for the very young rocks dealt with in these studies. For further details of the specific techniques used in each study, see the relevant references cited in the case studies below.

Individual analyses include the raw ^{206}Pb/^{238}U ratio determinations, measurements of ^{204}Pb and ^{207}Pb to determine the proportion of the ^{206}Pb measured that represents contamination by common-Pb, plus measurements of the concentrations of ^{238}U and ^{232}Th in order to calculate the correction for the initial ^{230}Th disequilibrium. Individual analyses are culled if the proportions of the ^{206}Pb attributable to common-Pb exceeds a set amount, as the resulting age determinations are usually too imprecise (although often still accurate) to be of value. For the freshest young volcanic rocks, this cut-off might be as low as 10 % (e.g. Chamberlain et al., 2014), whereas for zircons from hydrothermally altered rocks, values of up to 70 % have had to be considered acceptable in order to retain enough analyses (e.g., Milicich et al., 2013a). The age determinations ages are then taken and a probability distribution function (PDF) calculated using Isoplot (Ludwig, 2008). The PDF considers all the values and their uncertainties to create a curve which reflects the age modes within the sample. The age spectrum obtained can be interpreted in several ways, depending on the sample characteristics and the nature of the material. Because U-Pb age systematics are essentially unaffected at magmatic temperatures, there can be a spread in ages due to a prolonged growth history in the magma, or inheritance of older crystals from earlier, related magmatic episodes (antecrysts) or foreign lithologies (xenocrysts: Charlier et al., 2005). For volcanic rocks, the peak of the PDF curve (which can be quantified by taken a weighted mean value in Isoplot) can be up to about 100,000 years prior to the eruption age where the latter can be independently determined (e.g. Simon et al., 2008, but see also Chamberlain et al., 2014). A maximum age for volcanic rocks can thus be assigned in the absence of other information. We have, however, found that a better approximation to the eruption age can be given from the weighted means of either rim ages only (Chamberlain et al., 2014; Cooper et al., 2014), or from the youngest ~1/3 of the age determinations (e.g. Milicich et al., 2013a). For plutonic rocks, the peak of the PDF curve (which can be quantified by taking a weighted mean value in Isoplot) gives a best estimate of the crystallization age (e.g. see the ages for the Ngatamariki intrusions in Chambefort et al., 2014; Fig. 1).

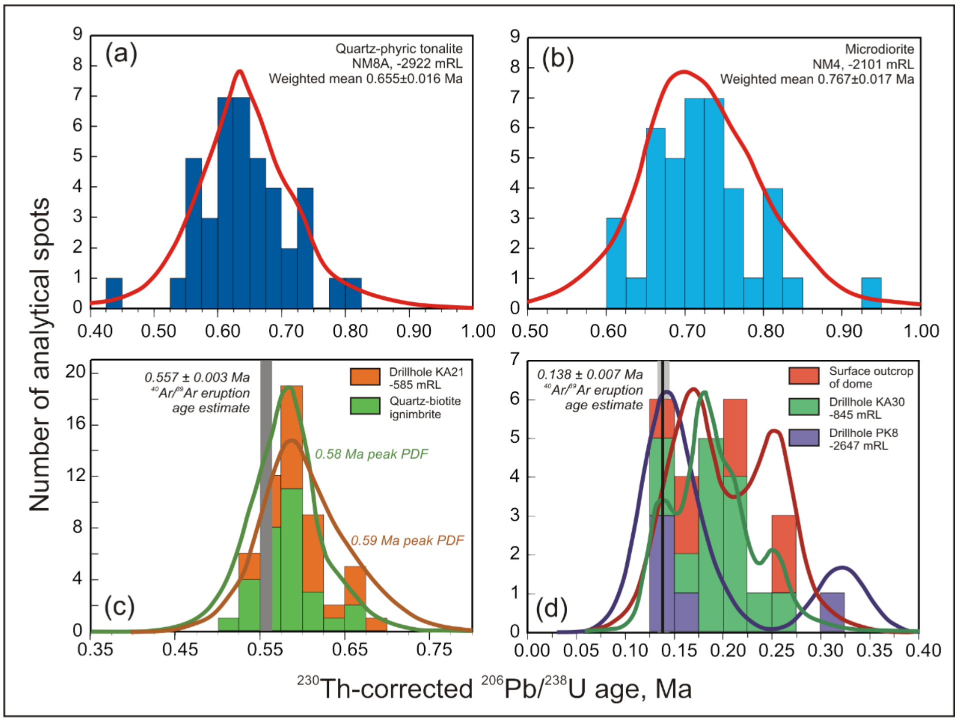

Figure 1: Four examples of results from U-Pb age determinations on zircons. All uncertainties given are 2 s.d. Histograms are shown of the age data (grouped into 25 kyr bins) and the associated probability distribution function (PDF) curves generated in Isoplot (Ludwig, 2008). Panels (a) and (b) are from altered intrusive rocks of the Ngatamariki Intrusive Complex (Chambefort et al., 2014). In these examples, the weighted means give estimates of the crystallization age to 95 % confidence to within 2-2.5 %, and allow the order of the intrusions to be accurately bracketed. Panel (c), from Milicich et al. (2013a), shows the age distributions of zircons from a subaerial, fresh volcanic deposit compared with those of its petrographically linked, hydrothermally altered subsurface equivalent in the Kawerau Geothermal Field. Note that the peaks in the PDF curves closely match, and that both are 20-30 kyr younger than the $^{40}Ar/^{39}Ar$ age determination on feldspar from fresh pumice (Leonard et al., 2010). Panel (d), from Milicich et al. (2013a), shows the viable age data (<70 % of the ^{206}Pb attributable to common-Pb) from three samples of the Onepu rhyodacite at Kawerau; one from the fresh surficial dome (dated by $^{40}Ar/^{39}Ar$ techniques: B.F. Houghton and M. McWilliams, unpublished data, cited in Milicich et al., 2013a), and two others from hydrothermally altered rocks that were inferred to be the feeder intrusions. The age data confirmed and reinforced the petrographic inferences of correlation, and showed that accurate estimates of eruption/intrusion age can be obtained from the average age of the youngest 20 % of the grains. These results are some of the youngest U-Pb age determinations ever reported on fresh or altered silicic rocks. See papers cited for more details.

3. CASE STUDIES

3.1 Mangakino Geothermal Field

Mangakino is the westernmost geothermal field identified in the TVZ (Fig. 2: Bibby et al., 1995, for overview). It is geographically contained within a caldera structure inferred to be the source for several members of an ignimbrite succession that range in age from ~1.6 Ma to 0.95 ± 0.03 Ma (Houghton et al., 1995). The Mangakino Geothermal Field was first investigated as a geothermal prospect in 1986. Results of geophysical surveys indicated that an area of low resistivity, similar to other geothermal fields within the TVZ, occurred within the Mangakino basin, with hot springs also present, prior to their flooding by the filling of Lake Maraetai. The first well (MA1) was drilled to 607 m vertical depth in 1986. In 2004 Mighty River Power undertook four drillholes: MA2 which was vertical and reached 3192 m below ground surface; MA2a, which occupied the same site as MA2 but was deviated, to reach 1759 m vertical depth; MA3, deviated and reaching 1840 m vertical depth; and MA4, deviated and reaching 1574 m vertical depth.

The stratigraphy of shallower parts of the field, down to the top of what was later identified as the 0.95 ± 0.03 Ma Marshall ignimbrites (Fagan, 2007), was established from studies of samples from drillhole MA1 (Wood, 1987). Identification of the deeper lithologies was made on the basis of petrographic identification and changes in phenocryst abundance and types (Fagan et al., 2006;

Fagan, 2007). From these observations, the ~1 Ma Rocky Hill ignimbrite was identified below the Marshall ignimbrites. As quartz was obvious in all cutting samples down to the deepest levels reached (in MA2), it was concluded by Fagan (2007) that the base of the Ongatiti ignimbrite had not been penetrated in any drillholes. Two lithologies, labelled A and B were therefore tentatively linked on the basis of petrography with the 1.18 Ma Ahuroa and 1.21 Ma Ongatiti ignimbrites, respectively.

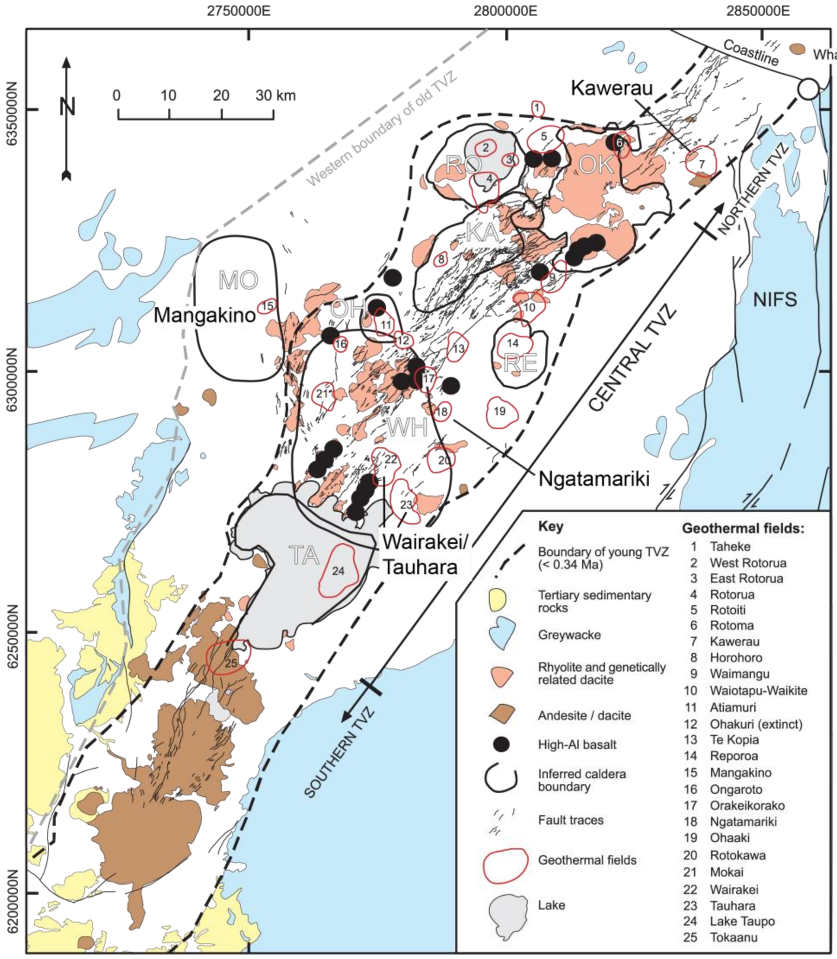

Figure 2: Geology of the TVZ showing the setting of the main high-temperature geothermal systems (figure courtesy of Julie Rowland, University of Auckland). Major rock units and faults are simplified after the 1:250,000 QMap series (Edbrooke, 2005; Townsend et al., 2008; Leonard et al., 2010; Lee et al., 2011). White regions represent rock types other than those indicated (i.e., volcaniclastic rocks, lake sediments, reworked materials). Caldera boundaries are after Wilson et al. (2009). Boundaries of the TVZ are modified after Wilson et al. (1995) and Villamor and Berryman (2001, 2006); 'old TVZ' is the envelope around vents active from 2.0 to 0.35 Ma. The 'young TVZ' boundary (active since 0.34 Ma, and including virtually all of the major modern hydrothermal areas) is a composite of that defined on volcanic grounds (Wilson et al., 1995) and that defined on structural grounds (Villamor and Berryman, 2001, 2006). NIFS = North Island Fault System (after Beanland, 1995). Low-resistivity zones were used to delimit the geothermal fields (after Bibby et al., 1995).

Four samples were taken for U-Pb age dating on zircons, in order of increasing depth. (a) Cuttings from drillhole MA4 at nominal depth 1480-1530 m, in material interpreted to be the Rocky Hill ignimbrite. (b) Drill core sample from the deviated drillhole MA2A at nominal depth 2087 m, equivalent to a nominal vertical depth of 1755 m. This material was representative of ignimbrite lithology A. (c) Cuttings samples from drillhole MA2 at nominal depth 2040-2050 m below ground level, again taken as representative of lithology A. (d) Cuttings samples from drillhole MA2 at nominal depth 2800-2840 m below ground level, representative of lithology B. For comparative purposes samples were also collected from surface exposures of the ~1 Ma Kidnappers ignimbrite (which underlies the Rocky Hill ignimbrite with a geologically short time break, expressed by an erosion surface) and the Ongatiti ignimbrite.

Despite the differences in petrography that led to the diverse labelling of lithologies below the Rocky Hill ignimbrite, the zircon age spectra obtained from the four drillhole samples (Fig. 3) demonstrate that all the materials sampled have a common younger PDF peak and hence the same dominant crystallization age. By comparison with the age spectra from the surface lithologies, we infer that all the drillhole material labelled lithologies A and B has an eruption age analytically indistinguishable from that of the Rocky Hill and closely-linked Kidnappers eruptive units. The subsurface material attributed to the Rocky Hill and Kidnappers eruptions amounts to at least 1.8 km of intracaldera tuff. The lack of intense welding in the core cut from lithology A in MA2A is consistent with Kidnappers tuff, as this eruption was phreatomagmatic and only one exposure is known of (incipiently) welded ignimbrite from this event.

There were three outcomes of the zircon age dating work at Mangakino. (a) An unequivocal correlation could be established between the subsurface altered caldera-filling pyroclastic rocks and their fresh equivalents in outflow deposits. (b) This study proved that a substantial volume of intracaldera material for both the Kidnappers and Rocky Hill eruptions existed. The implication from the age data is that any rocks that would be a target for geothermal production (i.e., with high fracture permeability: dense-welded tuff or greywacke) lay at depths beyond the reach of current drilling technology. (c) The similarities in the age spectra between samples from drillhole core versus cuttings showed that the latter were usable of age dating work, provided that the effects of downhole mixing were minimised. At Mangakino circulation losses were minimal, and samples were taken from within but towards the base of zones of homogeneous rock where any influx from other lithologies was minimized, despite not being able to sample directly below casing.

3.2 Kawerau Geothermal Field

Kawerau is situated near the northeastern limit of the central TVZ where sources of voluminous silicic volcanism and associated magmatism to the SW merge into the andesite-dacite northern TVZ arc (Wilson et al., 1995; Fig. 2). Structurally, the Kawerau Geothermal Field lies within the southern part of the NE-trending Whakatane Graben, in a zone where the active TVZ rift structures intersect the N- trending strike-slip faults of the North Island Fault system (e.g. Mouslopoulou et al., 2007). The TVZ graben structure is well expressed at Kawerau, where the 0.322 ±0.007 Ma Matahina ignimbrite (Leonard et al., 2010) is exposed at the surface east of the field, but occurs at 10 to 410 m depth beneath the field itself. The Matahina ignimbrite and pre-0.322 Ma volcanic rocks crop out W and NW of the field, and are extensively faulted and uplifted to form the western shoulder of the modern Whakatane Graben. During the Quaternary, greywacke within the Whakatane Graben has been downfaulted to 1-2 km below sea level, with the resulting structural depression infilled continuously by the Quaternary volcanic rocks and sediments. The greywacke has been penetrated by numerous wells within the field and the lower limits of the volcanic and sedimentary sequence are clearly defined.

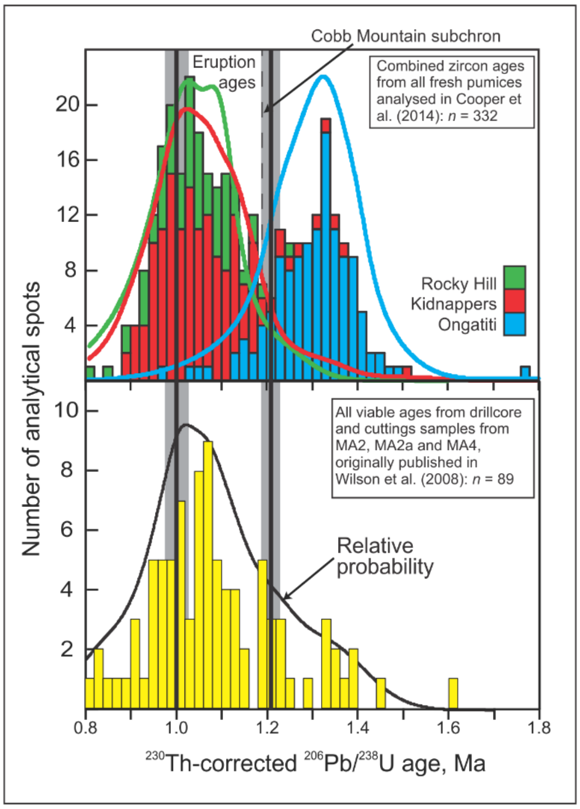

Figure 3: Compilation histograms and probability density curves from (upper panel) all Mangakino zircons analysed by Cooper et al. (2014) and (lower panel) all ages with <20 % of the 206Pb attributable to common Pb from Mangakino drillcore and cutting samples, originally published by Wilson et al. (2008) and recalculated using the same procedures as in Cooper et al. (2014). Eruption ages (black lines) with uncertainties (light grey- shaded areas) are shown for the Kidnappers/Rocky Hill and Ongatiti eruptions from 40Ar/39Ar age determinations (Houghton et al. (1995). Dark grey-shaded area marks the Cobb Mountain Subchron, during which the intervening Ahuroa ignimbrite was erupted (Houghton et al., 1995). Note that the Mangakino zircon age spectrum has subsidiary modes around the eruption ages of the Ahuroa and Ongatiti, plus the peak of crystallisation ages in the Ongatiti, reflecting inherited grains in the samples.

More than 70 wells (Fig. 2) have been drilled in the field for various purposes. The stratigraphy encountered during drilling at Kawerau and reported by many workers is summarised by Bignall and Harvey (2005). The pre-existing stratigraphic framework used by these workers was inconsistent, however, with many of the stratigraphic names incorrectly applied across the field. A re-examination of the rocks in the field was accomplished at the same time as a programme of U-Pb dating of zircons (Fig. 4: Milicich et al., 2013a, 2013b).

The age determinations from at Kawerau were central in establishing the chronology of key marker horizons and the tectono-magmatic evolution of the field. The age spectra obtained from the Kawerau samples, and inferred correlations with three surficial units dated by $^{40}Ar/^{39}Ar$ techniques suggested that the weighted mean of the youngest 20-30 % of the grains analysed provides a close approximation to the eruption age of the unit concerned (see Fig. 1c,d). The weighted average applied to all age data was in some cases skewed by incorporation of older, unrelated grains, but the age at the peak of the pdf curve provided a reliable maximum age even where there was a tail of older grains. A cut-off of 70 % common-Pb still yielded acceptable age estimates for fingerprinting rocks that could not be dated by any other means, and acceptable age estimates could be obtained for one unit that returned a $^{40}Ar/^{39}Ar$ age of 138±7 ka (Fig. 1d).

The new age data also yielded insights into the geological history of the area (Milicich et al., 2013a, 2013b). The Mesozoic greywacke basement was strike-slip faulted to form pull-apart basinal structures prior to 1.5 Ma. Basinal structures were infilled with greywacke gravels with minor intercalated tuffs and finer sediments, the latter including tuffs with ages of 2.38 and 2.17 Ma. The geometry of the basinal infill sediments and lack of net contemporaneous displacement of greywacke across the field suggest that the faulting was strike-slip dominated, and that by the time of deposition of ignimbrites around 1.45 Ma the area had limited topographic relief. Thick ignimbrite units newly recognisable across much of the field are clustered in time, with bursts of activity at 1.45-1.35 Ma, ~1.0 Ma and 0.5-0.6 Ma. Only two sub-surface ignimbrites could be correlated with surface-mapped units at ~1.0 Ma (Kidnappers ignimbrite; cf. Mangakino, Fig. 3) and 0.56 Ma (Quartz-biotite ignimbrite: Fig. 1c). Long-term average tectonic subsidence rates derived from the depths to the top contacts of dated units are generally <1 mm/yr, and it could be inferred that the 2 ± 1 mm modern rates of (pre-utilisation) subsidence cannot have been active for more than ~50,000 years. Numerous bodies of coherent rhyolite to rhyodacite previously mapped in the field could be shown from geochronology and petrography to represent a combination of dome extrusions and intrusions, rather than domes extruded on many different occasions through the history of the field. The Caxton Formation rhyolites, erupted at 0.36 Ma, are represented by crystal-richer and crystal-poorer lithologies, each of which is represented by domes and sill intrusions. The 0.138 Ma Onepu Formation rhyodacite is represented by surficial domes and four dike intersections at depth. The corresponding inferred change in orientation of the minimum principal stress axis (σ_3) from vertical at 0.36 Ma to horizontal by 0.138 Ma reflects the onset of the modern stress regime associated with TVZ rifting.

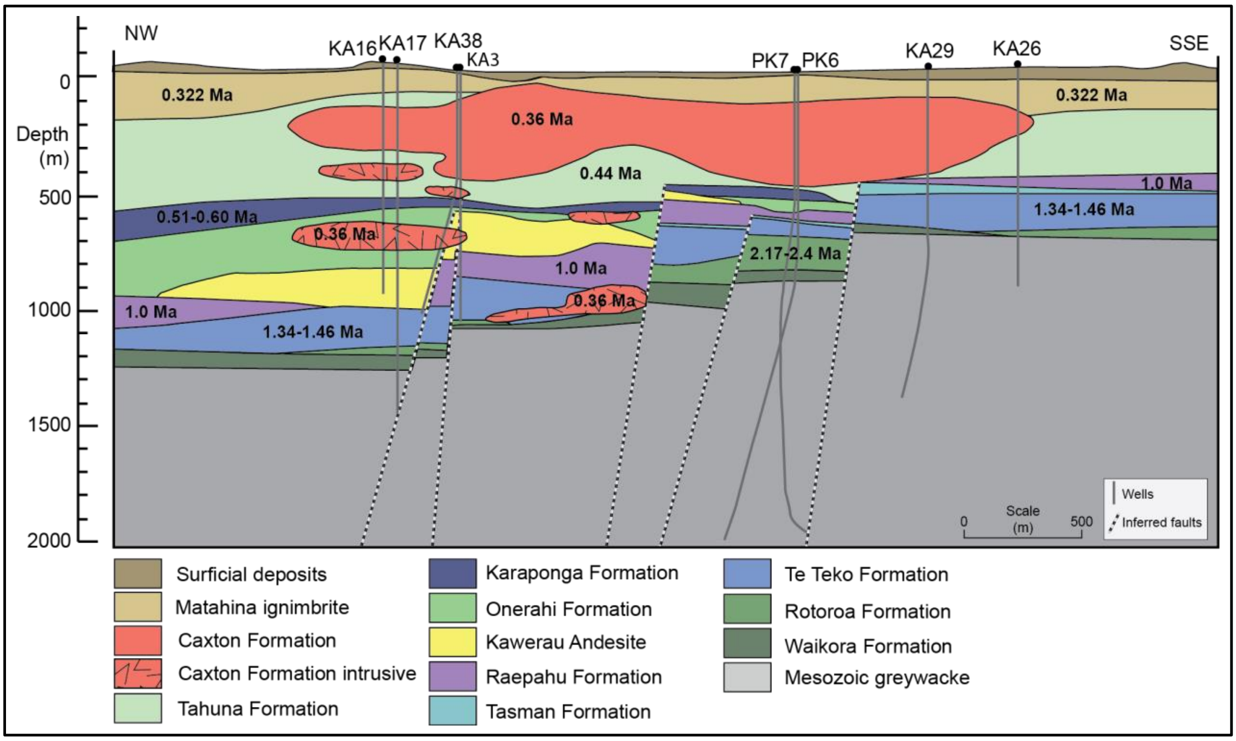

Figure 4. Cross section across the Kawerau Geothermal Field, with the major formations and their stratigraphic relationships interpreted in light of the new U-Pb age data marked on the relevant formations (see Milicich et al., 2013a, 2013b for details). Wells are projected onto the section. Ages from Milicich et al. (2013a) except for Leonard et al. (2010) for the Matahina ignimbrite.

3.3 Ngatamariki Geothermal Field

The Ngatamariki Geothermal Field is located in the southern part of the central TVZ, approximately 20 km NNE of Taupo (Fig. 2; Bibby et al., 1995). The New Zealand Government first explored the field in the 1980s, and four initial wells (NM1-NM4) were drilled. These wells were sited based on the presence of a shallow conductor detected by electrical resistivity surveys undertaken as part of a wider survey of the Taupo-Waiotapu region in 1963-1969. A later Schlumberger traverse survey delineated a 7 to 12 km^2 preliminary resource boundary (Boseley et al., 2010) in the vicinity of hot springs along the Waikato River and local streams. From 2004, Mighty River Power Ltd continued exploration, conducting surface geophysical surveys as well as drilling three deep exploration wells (NM5-NM7) to further delineate the extent of the resource and assess its capacity for future electricity generation. During this phase of exploration in 2005-2010, the stratigraphy at Ngatamariki was discussed in relation to development of a conceptual model of the Ngatamariki Geothermal Field by Urzúa-Monsalve (2008), Bignall (2009), and Boseley et al. (2010). In late 2011 the construction of an 82 MW_e ORMAT binary plant (commissioned mid-2013) at Ngatamariki commenced, along with the drilling of four additional wells (NM8-NM11) for production and injection. Results from the drilling of these wells have added significantly to our understanding of the stratigraphy at Ngatamariki.

In contrast to Kawerau, the stratigraphy at Ngatamariki is relatively simple, and is divided into two unequal parts by the crystal-rich welded ignimbrites of the 350 ka Whakamaru ignimbrite and the 340 ka Paeroa Subgroup ignimbrite. The older rocks are a thick succession (labelled the Tahorakuri Formation) of pyroclastic deposits plus minor lavas which rest on a large (Ruapehu-sized) andesite composite cone that sits in turn on the greywacke basement. The pre-350 ka rocks have been intruded by a composite plutonic body, termed the Ngatamariki Intrusive Complex, which represents the only truly plutonic body drilled in situ to date in the TVZ. This pluton contrasts with the minor hypabyssal (in rock texture and geological setting) dikes and sills seen at other fields (e.g. Kawerau). Age dates determined for the pre-350 ka rocks are reported in Eastwood et al. (2013), and ages for both pre- and post-350 ka rocks are reported in Chambefort et al. (2014) and summarised in Fig. 5.

Key results from the age dating at Ngatamariki are as follows. First, a reliable pair of bracketing ages has been obtained for the earliest and latest members of the Ngatamariki Intrusive Complex, between 0.716 and 0.655 Ma (Figs. 1a,b and 4). The previous, widely cited ages through $^{40}Ar/^{39}Ar$ techniques of 0.55 ± 0.09 Ma on amphibole and 0.55 ± 0.035 Ma on white mica associated with the intrusion hydrothermal alteration halo (Arehart et al., 2002) are now interpreted as cooling/hydrothermal ages. There can now be made an accurate reconstruction of the Ngatamariki 'palaeo-hydrothermal system' associated with this intrusion (Lewis et al., 2013), as dating and petrography has identified a volcanic equivalent and hence delineated the ground surface at the time of intrusion. In turn, reconstruction of the fossil system allows the alteration patterns and processes associated with the modern field to be discriminated. Second, the ages obtained from ignimbrites in the deeper parts of the Tahorakuri Formation are older than any previously linked to TVZ sources (Houghton et al., 1995). The thicknesses of these ignimbrites imply that they were sourced from the area outlined as the TVZ in Fig. 2, and not from the Kaimai area (northwest of the TVZ and which was active around this time: Briggs et al., 2005) and represent the earliest manifestation of large-scale TVZ silicic volcanism. Closely similar ages have also been obtained from deep parts of the Tahorakuri Formation at Rotokawa (Eastwood et al., 2013) and at Broadlands/Ohaaki

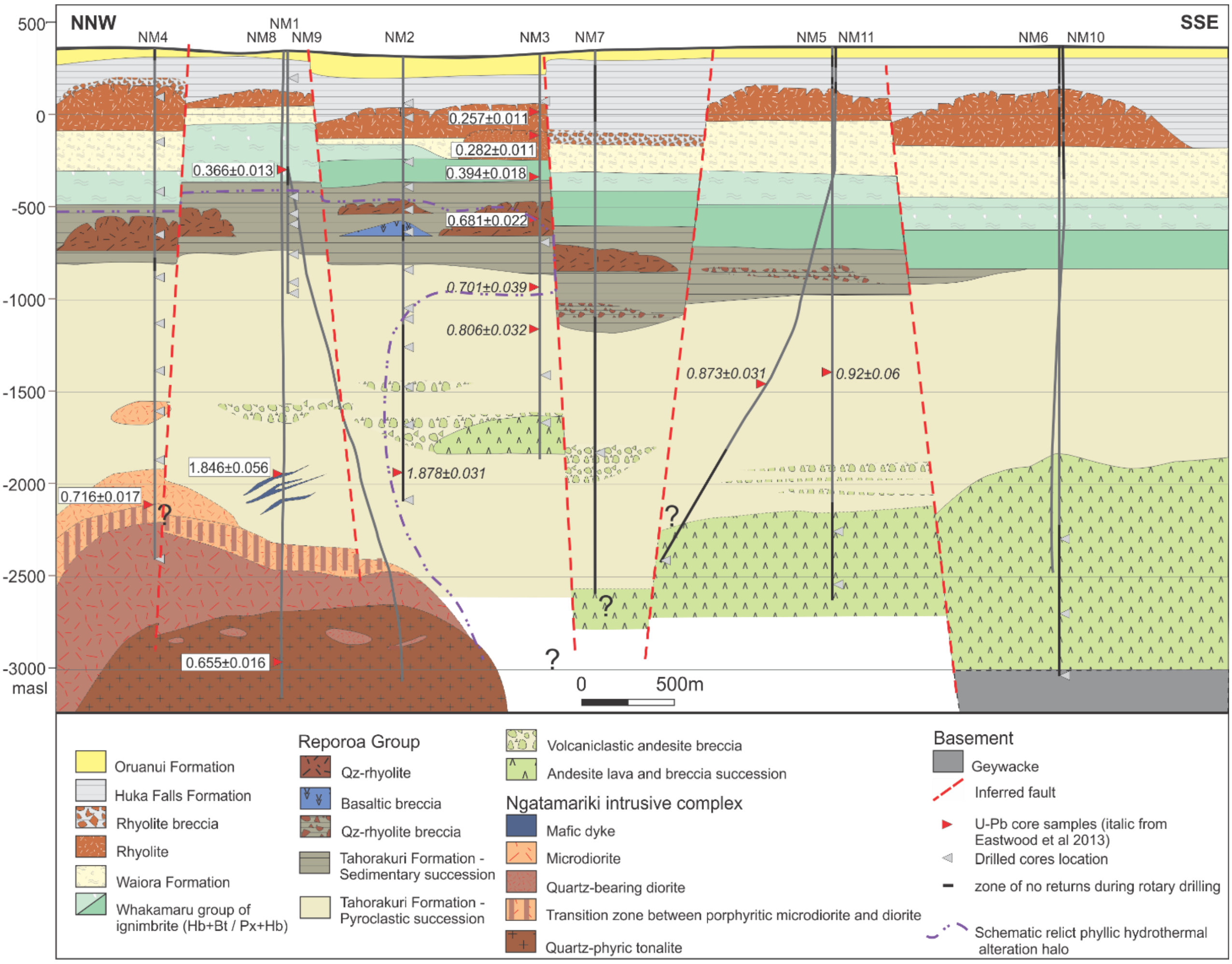

Figure 5: Summary cross section of the Ngatamariki Geothermal Field (from Chambefort et al., 2014), with the positions of boreholes marked or projected on to the line of section. The Whakamaru group of ignimbrites (including the Paeroa Subgroup units) has been 40Ar/39Ar dated at 350-340 ka (Downs et al., 2014a). Zircon U-Pb age determinations are shown, from Eastwood et al. (2013) and Chambefort et al. (2014). These ages represent the best estimate of eruption age on the basis of the youngest 20-30 % of analyses for volcanic rocks, or the weighted mean values for intrusion age for plutonic rocks of the Ngatamariki Intrusive Complex.

(Chambefort et al., 2014). Third, the andesite beneath the Tahorakuri Formation pyroclastic deposits occurs at broadly similar chronostratigraphic levels at Ngatamariki, Rotokawa and Broadlands/ Ohaaki. At Rotokawa, the andesite can be demonstrated to comprise a large (Ruapehu-sized) andesite composite cone with >2.2 km of material being present (Browne et al., 1992; Rae, 2007). The presence of this andesite demonstrates that the eastern front of the TVZ has been in its present position for >1.9 Myr and that the long-term migration of the arc has been episodic and not gradational (cf. Seebeck et al., 2014, and references therein).

3.4 Wairakei/Tauhara Geothermal Field

Wairakei (here including its co-joined neighbour Tauhara) is sited 7 km NE of Taupo, and is known worldwide for being only the second geothermal field globally to be developed for power generation. The geology and structure of the Wairakei-Tauhara geothermal system has been described and reviewed in many published documents and unpublished reports during the past 60 years of its utilisation for power generation (see Rosenberg et al., 2009; Bignall et al., 2010, for reviews). The geothermal system is defined in two dimensions (i.e., its geographic extent) by a single electrical resistivity boundary zone (Risk 1984) that encloses an area of approximately 75 km^2 of which the Tauhara part covers about 50 km^2 and the Wairakei part, approximately 25 km^2 (shown separately on Fig. 2). Drillhole and reservoir measurement data show that geological and hydrological (pressure) connections exist between the two parts of the system (Milloy and Wei Lim, 2012), although fluid chemistry clearly demonstrates that discrete Wairakei and Tauhara upflow regions are sustained (Henley and Stewart, 1983; Glover and Mroczek, 2009).

The unified resistivity boundary zone highlights the extent and connection (within about 500-700 m depth) of dispersed hot fluid and hydrothermally altered rock in the reservoir and cap-rock formations. The shape of the system boundary reflects upflow through the greywacke basement (>3 km depth) and shallower channelling of fluid flow within and between strata and along generally NE-trending fault zones.

The location of the system indicates the probable location of the primordial magmatic heat source(s) within the crust, but it also coincides with the location and likely effects of repeated magmatic episodes including those associated with ~27 ka Trig 9471 and Rubbish Tip rhyolite domes at the west side of Mt Tauhara (Sutton et al., 1995), the 25.4 ka Oruanui supereruption (Allan et al., 2012) and the ~11 ka Acacia Bay dome magma (Charlier et al., 2005). Some of the aims of ongoing research on the Wairakei system are to establish the ages of volcanism, and utilising the stratigraphic framework, to constrain periods of structural evolution potentially associated with the Whakamaru caldera (WH in Fig. 2) and the southern part of the Taupo-Reporoa basin.

The strata that host the Wairakei-Tauhara system are a ~3 km thickness of young and predominantly rhyolitic, pyroclastic rocks and lava bodies, and the fluvial and lacustrine deposits derived from them. Beneath this sequence is greywacke and argillite, probably of Jurassic-Cretaceous age. The strata revealed by drilling at Wairakei and Tauhara have been used to construct a geological model (Alcaraz et al., 2010) which reveals detail of a normal-faulted >3 km deep, NE-trending basin in the east-central region and a structural high beneath the Wairakei field. Key marker horizons, including Wairakei Ignimbrite (part of the 350 ka Whakamaru ignimbrite group) have been dated by their U-Pb zircon ages. The first outcome was to unequivocally correlate strongly altered yet texturally and petrographically distinctive Wairakei Ignimbrite with Whakamaru ignimbrite (previously dated by $^{40}Ar/^{39}Ar$ and U-Pb methods). Another achievement has been to recognise the **absence** of Wairakei Ignimbrite (Fig. 6) through the interval in several wells across the basin between Tauhara and Wairakei where it should have been intersected. The absence of this marker demonstrates that subsidence, erosion and sedimentation occurred in a central graben structure at a cumulative rate of 7-10 mm/year, while a structural high persisted in the west of the field.

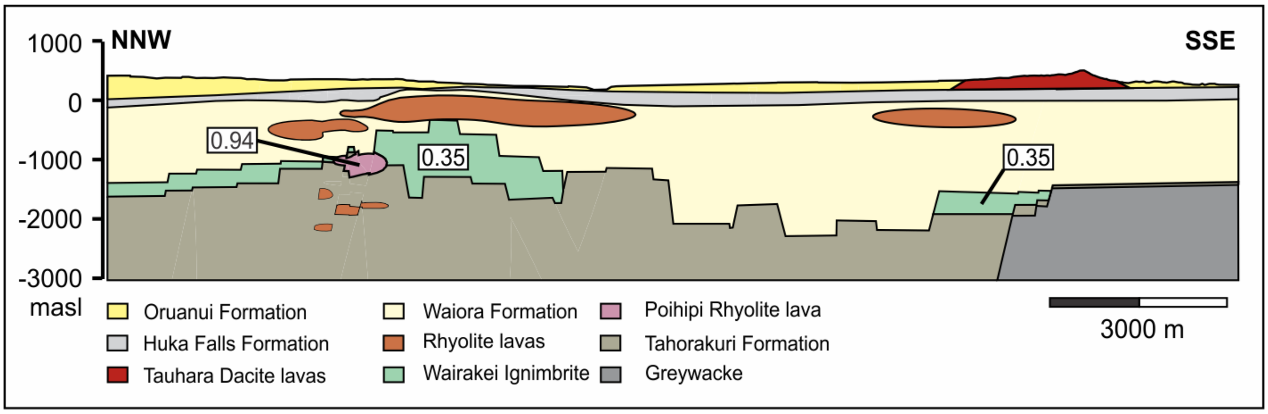

Figure 6: Summary geological cross section of the Wairakei and Tauhara geothermal fields, constructed from a Leapfrog 3-D geothermal model. For clarity, inferred faults and positions of boreholes are not shown. Indicative U-Pb ages determined from zircons in the Poihipi rhyolite lava (0.94 Ma) and Wairakei Ignimbrite (=Whakamaru group ignimbrite: 0.35 Ma) are highlighted. Late Mesozoic greywacke has been intersected by one eastern Tauhara well, but occurs beyond the limits of the deepest wells in the centre and west of the fields, which intersect only pyroclastic rocks and sediments (Tahorakuri Formation) at maximum depths.

Beneath the western side of Wairakei lie several rhyolite lava bodies. One of these, the Poihipi rhyolite, lies within Tahorakuri formation tuff and is intersected by drillholes <200 m beneath a partial cover of Wairakei Ignimbrite. A U-Pb zircon age of 0.94 Ma from this rhyolite provides strong evidence for a major hiatus in extrusive and explosive volcanism in the local area (in contrast to several episodes of activity at Ngatamariki) which would not otherwise be known or resolvable.

4. CONCLUSIONS

Given that there are many possible approaches to the exploration and modelling of hydrothermal systems globally, what are the key outcomes and benefits from U-Pb dating of zircons in hydrothermally altered rocks that have become apparent in the studies outlined here and others in the Taupo Volcanic Zone?

First, with the techniques that we have adopted, that is using SIMS techniques on polished cross-sections of grains, we have been able to obtain accurate, reasonably precise (uncertainties at the 1 s.d. level between 0.5 and 3%) ages for rock units that are consistent with stratigraphic ordering. By obtaining at least 20-30 analyses where possible, and taking weighted means of analytical spots that represent the same zones in crystals (i.e. rims versus cores) we have been able to discriminate the ages of rock units to within 10-20 kyr. All the age data we have obtained seem to not have been unaffected by hydrothermal alteration, except for a minor increase in the proportions of the ^{206}Pb signal that represents common-Pb. Any increases in common-Pb do not give rise to errors in ages, provided that the characteristics of the common-Pb overprint are accurately established (for these purposes, the value of the ^{207}Pb/^{206}Pb ratio for the common-Pb correction in data reduction). Large amounts of common-Pb (i.e. greater than the 10% or 20 % proportions that are used for the cut-off in studies of fresh, volcanic zircons: e.g. Chamberlain et al., 2014; Cooper et al., 2014) generally yield greater uncertainties on the age estimates, rather than systematic inaccuracies. The methods that we have adopted over multiple analytical sessions allow about 60-65 analyses to be run in a 24 hour period (utilising the automated running facilities on the SHRIMP-RG instruments), yielding about 50 values for unknowns (the other analyses being standards).

Second, the results that we have been able to obtain have been essential to clarifying stratigraphic successions within geothermal fields where petrographic correlations were ambiguous or impossible to justify. This has proved to be of importance particularly at fields like Kawerau, where drilling and core/cuttings examinations have occurred over a 35-40 year period by many different workers and led to inconsistent labelling of rock units within the field. In similar fashion, our work has been able to prove or disprove correlations between rock units in geothermal wells and their proposed surficially exposed units. The age data at Mangakino demonstrated unequivocally that the great thicknesses of tuff penetrated in MA2 correlated only with one surface unit, the products of the ~1 Ma Kidnappers eruption (Wilson et al., 2008; Cooper et al., 2014). We were able to unambiguously date the intrusion age of the Ngatamariki Intrusive Complex, establish the level of the former land surface and so provide a framework for ongoing work that is reconstructing the palaeo-Ngatamariki geothermal system. The accurate age data permit also the reconstruction of faulting and subsidence histories, thus allowing the effects of caldera collapse (at Mangakino) to be demarcated separately from the longer-term patterns of subsidence that control modern faulting and permeability pathways at fields like Kawerau (Milicich et al., 2013b).

Third, the age results for each field have allowed interpretations to be made of subsidence histories and geological structure that provides further insights into the setting of the TVZ in an active rift system (Villamor and Berryman, 2001; Rowland et al., 2010), and its overall volcanic history. Key correlations have been established between deeply buried and altered rocks in geothermal systems and their fresh subaerial equivalents. Several new major packages of ignimbrites have been discovered (especially in the >1.4 ma period) that have no analogues in the subaerial record, but likely relate to voluminous tephras in the deep-sea record (e.g. Carter et al., 2004). The presence of a major, long-lived horst structure down the axis of the central TVZ has been outlined (Rosenberg et al., 2009; Wilson et al., 2010), separating major basinal structures (Downs et al., 2014b) that have controlled the distribution of rock types that are important in controlling aquifers and aquitards in the geothermal systems like Wairakei (Rosenberg et al., 2009).

In these case studies, the ages obtained allowed significant refining in the understanding of the geological framework hosting the geothermal systems. The results have directly influenced the development and management of these fields through input into 3-D geological and numerical models of the geothermal systems and been utilised in various resource consents. In conclusion, it is apparent that the dating of hydrothermally altered rocks in geothermal fields has great potential to be applied elsewhere, not just to unravel the immediate complexities of stratigraphy and faulting timings, but also to link geothermal fields into their regional geological, volcanological and tectonic settings.

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