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U–Pb dating of zircon in hydrothermally altered rocks of the Kawerau Geothermal Field, Taupo Volcanic Zone, New Zealand

S.D. Milicich [a,b,*], C.J.N. Wilson [a], G. Bignall [b], B. Pezaro [c], B.L.A. Charlier [d], J.L. Wooden [e], T.R. Ireland [f]

[a] School of Geography, Environment and Earth Sciences, Victoria University, Wellington 6140, New Zealand
[b] GNS Science, Wairakei Research Centre, Taupo 3377, New Zealand
[c] Mighty River Power Ltd., PO Box 90399, Auckland 1142, New Zealand
[d] CEPSAR, The Open University, Walton Hall, Milton Keynes MK7 6AA, United Kingdom
[e] SUMAC, Stanford University, Stanford, CA 94305-2220, USA
[f] Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

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ABSTRACT

Crystallisation-age spectra have been obtained by SIMS techniques (SHRIMP-RG) on zircons from altered volcanic units penetrated by drillholes at Kawerau Geothermal Field in the central Taupo Volcanic Zone (TVZ), New Zealand. Drillholes penetrate 700–1300 m of volcanic rocks and sediments before reaching the basement Mesozoic greywacke. Twenty-seven samples of altered volcanic lithologies and two surficial, fresh rock units have been studied in order to constrain ages of the major stratigraphic units. Within the volcanic/sedimentary pile the oldest in-situ ignimbrites that can be widely correlated have ages of ~1.45 Ma. Between them and the basement greywacke is a variable thickness of sediments, mostly greywacke gravels and minor volcaniclastic units, reflecting localised basinal deposition associated with strike–slip faulting. Two ignimbrites within this sequence yield age estimates of c. 2.4 and 2.1 Ma, consistent with these being distal southern Coromandel Volcanic Zone deposits, pre-dating TVZ activity. Below the regional marker plane of the 0.32 Ma Matahina ignimbrite, three main ignimbrite groups occur, with ages around 1.45 Ma, 1.0 Ma and 0.6–0.5 Ma, which are separated by sediment-dominated intervals and andesite volcanics. All of these ignimbrites represent marker horizons from other volcanic centres and do not reflect the presence of local magmatic heat sources.

Numerous bodies of coherent rhyolite, previous labelled as Caxton and Onepu rhyolites, have been intersected at all pre-Matahina ignimbrite levels (including within the basement greywacke) and reflect earlier local magmatic heat sources. Our geochronological data resolve these rock bodies into three packages. The youngest is represented by the surficial rhyodacite Onepu domes, $^{40}Ar/^{39}Ar$ dated at 0.138 ± 0.007 Ma. U–Pb ages on zircons from dome material yield a spectrum that can be matched (consistent with petrography) with two dikes intersected at 880 m and 2.67 km depth, and with an estimated age of 0.15 ± 0.01 Ma (Onepu Formation). The older two packages consist of older crystal rich (~15%) and younger crystal-poor (~5%) rhyolite, here grouped as Caxton Formation and with eruption/intrusion age of 0.36 ± 0.03 Ma. The shallowest Caxton rhyolite bodies are interpreted to be domes, whilst deeper intersections are inferred to be sills based on the lateral extents relative to thicknesses.

Net subsidence rates inferred from depths to key units do not reflect the present-day situation. Modern rates of subsidence (2 ± 1 mm/yr) associated with TVZ rifting processes can have been active for no more than ~50,000 years, based on elevation differences of the Matahina ignimbrite top surface. An inferred change in intrusion geometry from sill (Caxton) to dike (Onepu) indicates a change in principal stress orientations reflecting onset of the modern Whakatane Graben. This change is dated at ~0.37 Ma in coastal sedimentary sequences 23 km to the north of Kawerau, consistent with our age data. Although previously interpreted to be a long-lived system, the modern Kawerau Geothermal Field is a Holocene entity reflecting the rejuvenation of magmatic heat flux associated with Putauaki volcano superimposed on an area of multiple reactivated fault structures, sporadic magmatism and variable rates of subsidence.

1. Introduction

The successful exploration and management of high-temperature geothermal systems for electrical power generation and direct heat

* Corresponding author at: School of Geography, Environment and Earth Sciences, Victoria University, Wellington 6140, New Zealand. Tel.: +64 7 374 8211; fax: +64 7 374 8199.
E-mail address: s.milicich@gns.cri.nz (S.D. Milicich).

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usage requires an understanding of the geological structure and permeability pathways (including faults) 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 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. A further complexity in volcanic terrains is that the original depositional surface may not be flat, so apparent offsets of the same units between drillholes may not be due to later displacement but instead reflect primary topographic relief. Although correlations can be made on the basis of petrographic characteristics (rock type, crystal content, presence and abundance of recognisable mineral phases), such relationships may be made ambiguous by overprinting hydrothermal alteration. In order to establish a sound chronostratigraphic sequence in a geothermal field, key information is the ages of the lithologies, especially when these 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 as a trace mineral phase zircons that crystallised in the magma prior to quenching by eruption (Hoskin and Schaltegger, 2003). The zircons (or portions within the crystals) can be dated by U–Th disequilibrium or U–Pb techniques (Schmitt, 2011, for review) to give insight into the age patterns of crystallisation within the parental magma. Zircons are valuable repositories of age information due to their resistance to hydrothermal alteration, replacement or recrystallisation that partially or completely affects the other minerals and groundmass in the rocks. Dating individual zircons provides a spectrum of crystallisation ages for primary magmatic material in these rocks. The peak of zircon crystallisation provides a maximum age limit on the eruption(s) concerned, or provides an approximation to the emplacement age for intrusive rocks, whilst the youngest zircons provide a close approximation to eruption age (e.g. Dalrymple et al., 1999; Schmitt et al., 2003a). A combination of 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).

Interpretation of the age spectra obtained from zircons in hydrothermally altered rocks depends, however, on the nature of the material available for sampling and its inferred history. Ideally, zircons are extracted from coherent rock which represents an aliquot of magmatic material (hand specimen of lava or intrusive material, or single juvenile pyroclasts). However, since much of the primary volcanic material in volcanic-hosted geothermal systems is pyroclastic in origin, samples of tuff tend to be used, which may contain fragments of accidental lithic material or intermixed ash-sized material from older rocks. Secondly, 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 diversity in the zircon age spectra. If only cuttings are available, then not only may it be difficult to establish the nature of the rock host, but the possibility of downhole contamination from the open-hole section above the drill bit becomes an issue. Cuttings samples are ideally collected from directly below well casing points to minimise this issue. The use of cathodoluminescence (CL) and petrography can be used to reduce the uncertainty introduced by non-ideal samples.

In this paper we report U–Pb age data obtained from a sequence of strongly hydrothermally altered rocks sampled as mostly core and some cuttings from wells in the Kawerau Geothermal Field in New Zealand. Despite extensive alteration of the primary volcanic mineral assemblages in the samples, the zircon crystals appear almost entirely unaffected by the hydrothermal activity (either in the form of dissolution or by overgrowths visible under cathodoluminescence). We show how age data from the zircons can be used to constrain interpretations of stratigraphy where conventional petrographic information might be ambiguous or inaccurate. A challenge correlating stratigraphy at Kawerau is the absence of a marker horizon that is present across all wells in the field. Consequently, U–Pb age data have proved valuable, balanced with petrographic observations, in deciding on an overall stratigraphic sequence. The new chronology established here is then used in a companion paper (Milicich et al., in preparation) to revise the stratigraphic and structural history of the Kawerau Geothermal Field.

2. Kawerau Geothermal Field

Kawerau Geothermal Field is one of 23 active high-temperature geothermal fields in the Taupo Volcanic Zone (TVZ) of New Zealand (Fig. 1; Bibby et al., 1995; Rowland and Sibson, 2004; Kissling and Weir, 2005; Rowland and Simmons, 2012). The onshore TVZ is a rifted arc that is segmented into three parts (Healy, 1962; Wilson et al., 1995a). The central portion is dominated by exceptionally vigorous rhyolitic caldera volcanism, and also contains most of the high-temperature geothermal systems, whilst the northern and southern segments are dominated by andesite–dacite composite-cone volcanism with localised geothermal systems (Bibby et al., 1995; Wilson et al., 1995a; Fig. 1). Kawerau is situated at 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 (Nairn, 2002). Structurally, the Kawerau 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 Shear Belt (Nairn and Beanland, 1989; Mouslopoulou et al., 2007; Begg and Mouslopoulou, 2010; Villamor et al., 2011). The TVZ graben structure is well expressed at Kawerau, where the 0.322 ± 0.007 Ma Matahina ignimbrite (Bailey and Carr, 1994; Leonard et al., 2010) is exposed at the surface east of the field, but occurs at 10 to 130 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.

The Quaternary volcanic rocks of the TVZ, and earlier Miocene–Pliocene volcanic rocks of the Coromandel–Kaimai area to the NW (see Booden et al., 2012 for a review), rest on indurated metasediments ('greywacke') accreted to the margin of Gondwanaland during the Mesozoic (Mortimer, 2004; Adams et al., 2009; Leonard et al., 2010). 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 sequences are clearly defined.

3. Surface and subsurface stratigraphy at Kawerau

The 0.322 ± 0.007 Ma Matahina ignimbrite is the oldest surficial unit in the Kawerau area (Fig. 2), exposed to the southeast of the field and intersected by many drillholes in the field. The rhyodacitic Onepu domes on the western margin of the field are bracketed in age between the Matahina and overlying 61 ka Rotoiti ignimbrites (Wilson et al., 2007; Cole et al., 2010). A $^{40}Ar/^{39}Ar$ age of 0.138 ± 0.007 Ma determined by M.A. Lanphere (U.S. Geological Survey) and B.F. Houghton on material from the Onepu domes is recorded in unpublished files held by GNS Science and has been cited (without uncertainty) by Christenson (1997). The modern volcanic landscape at Kawerau is dominated by Putauaki (Mt. Edgecumbe), a Holocene, multiple vent dacite–andesite volcano (Nairn, 2002), which last erupted at 2400 ^{14}C years B.P. (Carroll et al., 1997). Other geological units exposed in the area are young pyroclastic deposits from Okataina Volcanic Centre,