Journal of Volcanology and Geothermal Research 262 (2013) 7–24

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Reconstructing the geological and structural history of an active geothermal field: A case study from New Zealand

S.D. Milicich [a,b,*], C.J.N. Wilson [a], G. Bignall [b], B. Pezaro [c], C. Bardsley [d]

[a] School of Geography, Environment and Earth Sciences, Victoria University, Wellington 6140, New Zealand
[b] GNS Science, Wairakei Research Centre, Taupo 3384, New Zealand
[c] Mighty River Power Ltd., PO Box 90399, Auckland 1142, New Zealand
[d] Mighty River Power Ltd., PO Box 245, Rotorua 3040, New Zealand

ARTICLE INFO

Article history:
Received 8 March 2013
Accepted 15 June 2013
Available online 26 June 2013

Keywords:
Kawerau Geothermal Field
Kawerau geothermal system
Stratigraphy
Taupo Volcanic Zone
Correlation
U–Pb dating
Heat source
Magma

ABSTRACT

The utilisation of geothermal systems benefits from an understanding of the host-rock geology, locations and controls of permeability pathways, and the nature and timing of magmatic sources providing thermal energy. Kawerau Geothermal Field in the central Taupo Volcanic Zone (TVZ) of New Zealand is currently developed for electricity generation and direct uses of high-temperature steam to ~200 MW electrical output. The Kawerau geothermal system is hosted in a sequence of volcanic lithologies (tuffs, lavas and intrusive bodies) and sediments that overlie faulted Mesozoic metasedimentary (greywacke) basement. Identification of lithologies in the volcanic/sedimentary sequence is challenging due to the levels of hydrothermal alteration and lithological similarities. A combination of detailed petrological investigations, consideration of the emplacement processes and greater certainty of crystallisation or eruption ages through U–Pb age determinations on zircons is used to reconstruct the depositional and faulting evolution of the rocks hosting the currently active hydrothermal system. The oldest event inferred is faulting of the greywacke along northwest–southeast orientated, dominantly strike-slip structures to generate half-grabens that were filled with sediments, incorporating two dated ignimbrites (2.38 ± 0.05 and 2.17 ± 0.05 Ma). A 1.46 ± 0.01 Ma ignimbrite was deposited relatively evenly across the field, implying that any topographic relief was subdued at that time. Subsequent deposition of ignimbrites occurred in episodes around 1.0, 0.55–0.6, and 0.32 Ma, interspersed with thin sedimentary sequences that accumulated at average rates of 0.06 mm yr^{-1}. Andesite lavas from a buried composite cone occur as a conformable package between units dated at 1.0 and 0.6 Ma. Bodies of coherent rhyolite occur at multiple stratigraphic levels: two magma types with associated tuffs were emplaced as domes and sills at 0.36 ± 0.03 Ma, and a third type at 0.138 ± 0.007 Ma as dikes, and domes that are exposed at surface. The andesitic Putauaki composite cone southwest of the field first erupted around 8 ka, but earlier hydrothermal eruption breccias imply that magma was intruded to shallow depths as early as ~16 ka.

Age data and associated correlations show that post-1.5 Ma normal faulting has accompanied episodic subsidence of the Kawerau area, with fault movement focused between northeast–southwest structures (associated with the geometry of the modern TVZ) and the reactivated northwest–southeast structures associated with most displacement in the area prior to 1.5 Ma. Contrasts between emplacement of coherent rhyolite as sills at 0.36 Ma and a dike at 0.138 Ma reflect a shift in orientation of the principal stress axes in response to initiation of the modern TVZ rifting regime. Most volcanic rocks at Kawerau are distally sourced from elsewhere in the TVZ but form local marker horizons that delineate topographic relief within the field, and additionally constrain past subsidence rates. Current rates of subsidence and thermal output at Kawerau are geologically recent features associated with latest Quaternary rifting processes (<~50 ka) and emplacement of the magmatic system for Putauaki volcano (~16 ka) respectively.

1. Introduction

The geological framework of geothermal systems is challenging to quantify and interpret because of the extensive hydrothermal alteration. The high-temperature fluids that make a geothermal system attractive for utilisation and justify industry drilling programmes at low risk also serve to obscure its geological history through hydrothermal

* Corresponding author at: School of Geography, Environment and Earth Sciences, Victoria University, Wellington 6140, New Zealand. Tel.: +64 7 376 1460; fax: +64 7 374 8199.
E-mail address: s.milicich@gns.cri.nz (S.D. Milicich).

0377-0273/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jvolgeores.2013.06.004

alteration. The Taupo Volcanic Zone (TVZ) in New Zealand is one of the world's premier locations for water-dominated geothermal systems with a >50 year history of drilling and resource utilisation (Grant and Southon, 1986; Mongillo, 1986; Hotson, 1994; Spinks et al., 2010). Despite a long history of studying geothermal system geology in the TVZ, there is much still to learn about the geology, absolute ages and structure of geothermal systems in the overall volcano-tectonic history of this area, primarily because of a paucity of direct age data for rock units. In New Zealand and globally, the subsurface stratigraphy in geothermal systems is most often reconstructed from petrographic correlations with independently dated surficial units (e.g., Grindley, 1965; Browne, 1978; Stimac et al., 2008; Rosenberg et al., 2009). Surprisingly, there have been only limited numbers of dating studies of active hydrothermal systems, with those studies designed to resolve the source of heat that drives the system, e.g., at The Geysers, California (Dalrymple et al., 1999; Schmitt et al., 2003a,b) and Ngatamariki, New Zealand (Arehart et al., 2002), but more recently the value of dating has become apparent as a correlation tool (Wilson et al., 2008, 2010). Milicich et al. (2013) used U–Pb dating of zircons to date marker units in the Kawerau geothermal system. In this paper we use these data along with summary lithological observations to present a more reliable 3-D geological architecture, and structural and thermal history of the Kawerau system as a demonstration of the value of combined geological and dating studies in geothermal systems.

Kawerau is the most northeastern of the active high-temperature geothermal systems in the TVZ (Fig. 1; Bibby et al., 1995; Rowland and Sibson, 2004; Kissling and Weir, 2005; Rowland and Simmons, 2012). In regard to its volcano-magmatic setting, Kawerau is situated at the transition between rhyolite-dominated caldera-related activity that characterises the central TVZ and the northern TVZ arc of andesite–dacite composite cones (Wilson et al., 1995a; Nairn, 2002). The Kawerau geothermal system occurs in the southern part of the Whakatane Graben (Fig. 1), in an area where normal faulting of the TVZ rift interacts with the dominantly strike-slip faulting of the North Island Shear Belt (Nairn and Beanland, 1989; Mouslopoulou et al., 2007; Begg and Mouslopoulou, 2010; Villamor et al., 2011). In this paper, we use the term 'Kawerau geothermal system' to refer to the natural entity, and 'Kawerau Geothermal Field' to refer to the geothermal resource and the infrastructure and land boundaries associated with the geothermal power station.

2. Geological framework for the Kawerau geothermal system

Numerous wells used for geothermal production, injection and monitoring have been drilled at Kawerau (Fig. 2) and cores and cuttings from most of these have been re-examined (Milicich, 2013a,b) and combined with the U–Pb age controls (Milicich et al., 2013) to provide a new, consistent stratigraphic framework. Detailed stratigraphic logs and

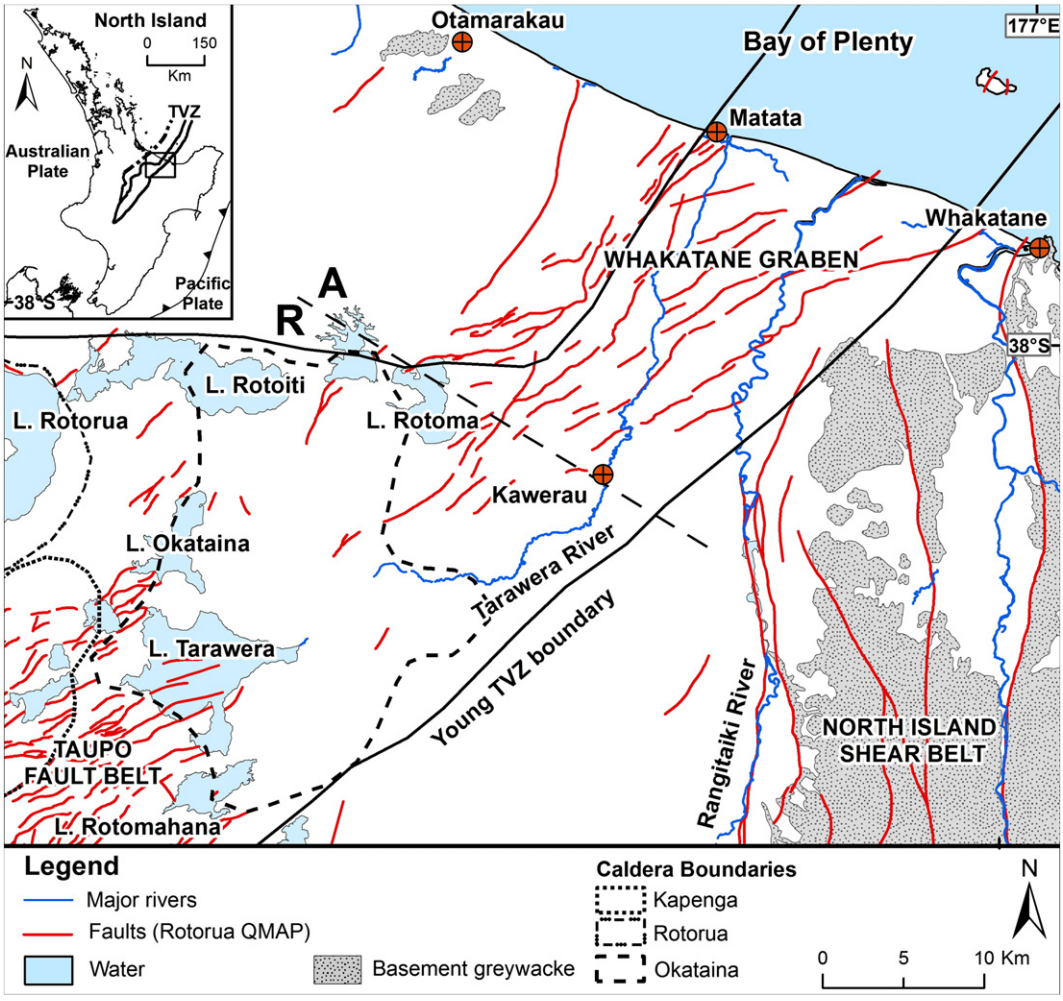

Fig. 1. Locality and structural map of the local Kawerau area. The young (350 ka to present) boundary to the TVZ is shown, with its subdivisions into andesite-dominated (A) northern segment and the rhyolite dominated (R) central segment.
Caldera boundaries from Wilson et al. (2009); faults and greywacke outcrop areas from Leonard et al. (2010).