AN INTEGRATED APPROACH TO CORRELATION OF GEOLOGY IN GEOTHERMAL SYSTEMS: A CASE STUDY FROM THE KAWERAU GEOTHERMAL FIELD, NEW ZEALAND

S.D. Milicich[1,2], C.J.N. Wilson[1], G. Bignall[2], B. Pezaro[3], C. Bardsley[4]

[1]School of Geography, Environment and Earth Sciences, Victoria University, Wellington 6140, New Zealand

[2]GNS Science, Wairakei Research Centre, Taupo, 3377, New Zealand

[3]Mighty River Power Ltd., PO Box 90399, Auckland 1142, New Zealand

[4]Mighty River Power Ltd. PO Box 245, Rotorua 3040, New Zealand

s.milicich@gns.cri.nz

Keywords: *zircon, U-Pb dating, Kawerau Geothermal Field, Taupo Volcanic Zone, stratigraphy, correlation.*

ABSTRACT

The utilisation of geothermal systems benefits from understanding the host rock geology, locations/controls on permeability pathways, and the source/timing of heat input into the system. Using an integrated approach, i.e., combining age dating with systematic petrographic examination of relevant rock units, researchers can obtain greater insights into the geological and hydrological structure of a geothermal system, and hence its successful exploration and development at reduced risk. Here we present a revised geological framework for the Kawerau geothermal system, as a case study that outlines the structural and thermal history of the system.

The oldest definable event at Kawerau is faulting of basement greywacke along NW-SE orientated, dominantly strike-slip structures, which progressively generated half-grabens that were filled with sediments (and two ignimbrites, U-PB zircon-dated at 2.38±0.05 and 2.17±0.05 Ma, respectively). By the time the 1.46±0.01 Ma ignimbrite (Te Teko Formation) was deposited across the field, any local topographic relief was subdued. Subsequent deposition of ignimbrites occurred at about 1.0, 0.55-0.6, and 0.32 Ma, interspersed with sedimentary sequences that accumulated at average rates of 0.06 mm/yr. 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, with dikes and domes that are still exposed emplaced at 0.138 ± 0.007 Ma and a series of domes, sills and associated tuffs that were emplaced at 0.36 ± 0.03 Ma. The andesitic Putauaki

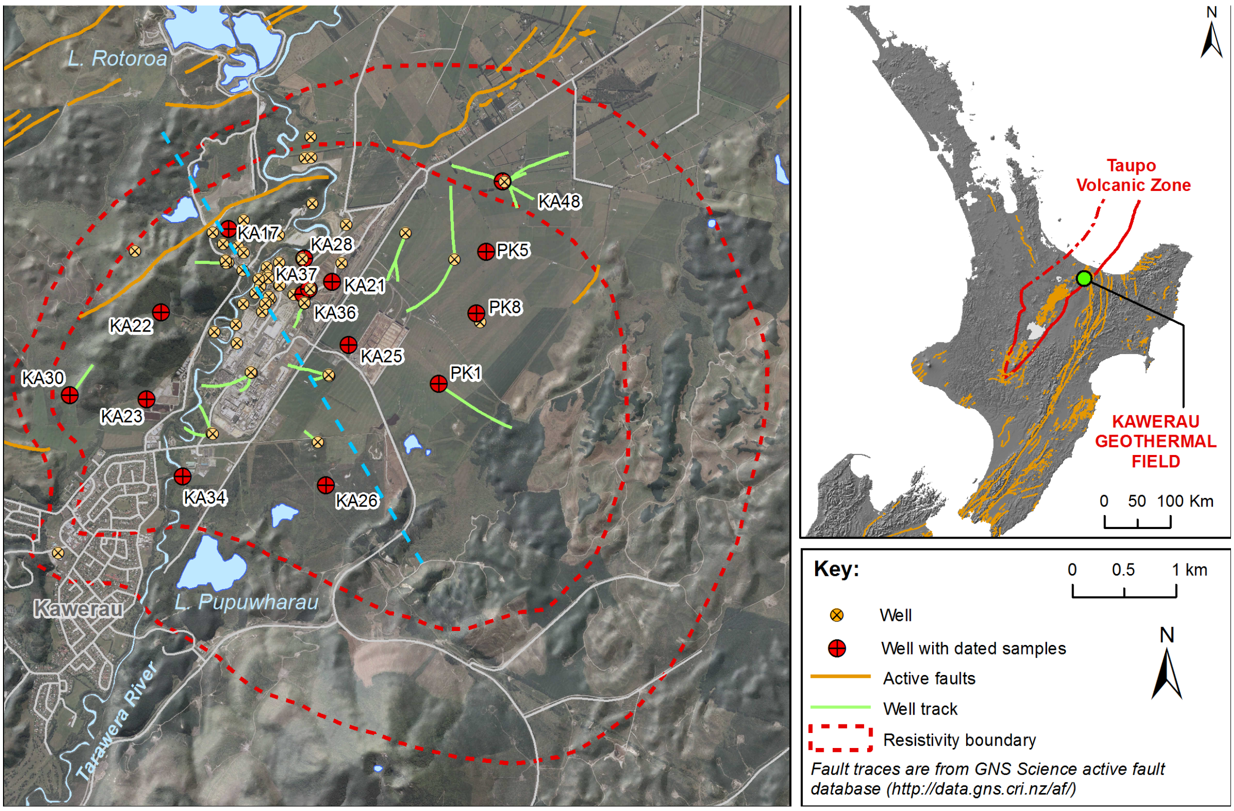


Figure 1: Location map of Kawerau Geothermal Field, with location of wells with dated samples, and approximate resistivity boundary zone at ~500 m depth (after Allis, 1997). Cross section line of Fig. 2 is indicated with the dashed blue line.

composite cone first erupted around 8 ka, but evidence of hydrothermal eruption breccias point to magma being intruded to shallow depths as early as ~16 ka. Current rates of regional tectonic subsidence (2±1 mm/yr) and thermal output at Kawerau are geologically recent, and are associated with latest Quaternary rifting processes (<~50 ka) and emplacement of the Putauaki volcano-magmatic system (~16 ka).

1. INTRODUCTION

The geological framework of geothermal systems is often challenging to quantify and interpret due to extensive hydrothermal alteration. Despite a long history of studying the geology of geothermal systems in the Taupo Volcanic Zone (TVZ), there is much still to learn about the geology, ages and structure of geothermal systems in the overall volcano-tectonic history of the area. Typically, the subsurface stratigraphy in geothermal systems is reconstructed from petrographic correlations with independently dated surficial units (e.g., Grindley, 1965; Browne, 1978, Stimac et al., 2008; Rosenberg et al., 2009). There have been only a limited number of dating studies of active hydrothermal systems, primarily designed to resolve the source of heat driving 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). More recently the value of dating has become apparent as a correlation tool (Wilson et al., 2008, 2010). Milicich et al. (2013a) used U-Pb dating of zircons to characterise marker units in the Kawerau geothermal system. In this paper we use these data along with summary lithological observations to present a revised geological framework for the Kawerau Geothermal Field, as a case study that outlines the structural and thermal history of the geothermal system.

Kawerau is the northeastern most 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). 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., 1995; Nairn, 2002). The Kawerau geothermal system occurs in the southern part of the Whakatane Graben, 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). More than 70 wells used for geothermal production, injection and monitoring have been drilled in the field since the 1950s. The geology of these wells provides the foundation of a substantially revised stratigraphy (Milicich et al., 2013a,b), summarised here in Table 1.

Table 1 Summary of the main stratigraphic units in the Kawerau Geothermal Field (from Milicich et al., 2013a).

Formation	Lithology	Thickness (m)	Age (Ma)	Type Section (mRL)
Recent Alluvium	Peat deposits; sands and gravels; unconsolidated pyroclastic deposits (incl. Whakamana Breccia, Rotoiti Breccia)	10 – 50		
Hydrothermal Eruption Breccias	Hydrothermal eruption deposits, from 16,000 and 9,000 yr BP	1 - 10		
Unconsolidated pyroclastics	Unwelded pumiceous pyroclastic flow and airfall tuffs	0 – 80		KA27 (25 to -55)
Onepu Formation#	Twin surficial domes of rhyodacite (pl, qz, px, hb, bt) and intrusive (porphyritic crystal-rich; corroded qz, pl, mafics)	2 – 200	0.138	KA30 (-739 to -849)
Matahina Formation	Partly welded grey-brown ignimbrite & vitric tuff (pl, qz, px)	10 – 410	0.32*	PK3 (-11 to -244)
Tahuna Formation#	Crystal-rich, fine sandstone, siltstone, muddy lithic-breccia and unwelded pumice-rhyolite lapilli tuff	0 – 360	0.44	KA21 (-477 to -570)
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	0.36	KA17 (-167 to -307)
Karaponga Formation#	Partly welded crystal-lithic tuffs (pl, qz ± bt)	0 – 180	0.51-0.60	KA21 (-570 to -624)
Onerahi Formation#	Tuffaceous to muddy breccias and coarse tuffaceous sandstone	0 – 85		KA17 (-563 to -630)
Kawerau Andesite	Augite-plagioclase andesite flows, breccias and tuff (in south)	0 – 300		KA48 (-507 to -644)
Raepahu Formation	Partly welded crystal-vitric tuffs (qz,pl,bt, lithic-poor and qz,pl,bt, ferromagnesians, lithic-rich)	0 – 165	1	KA23 (-400 to -564)
Tasman Formation#	Muddy breccia, sandstone and siltstone, but widely represented by reddish brown siltstone	0 – 25		KA48 (-781 to -786)
Te Teko Formation#	Partly welded grey crystal-vitric ignimbrite (corroded qz, pl, bt)	0 – 255	1.34-1.46	KA23 (-583 to -839)
Rotoroa Formation#	Tuffaceous sandstone, poorly sorted crystal and vitric-rich, water-laid tuff, siltstone	0 – 200	2.17-2.4	KA25 (-706 to -898)
Waikora Formation	Greywacke pebble conglomerate and minor intercalated tuff and siltstone	0 – 450		KA48 (-820 to -1285)
Greywacke basement	Weathered, sheared greywacke and argillite	-		

Abbreviations used are pl = plagioclase; qz = quartz; px = pxroxene; hbl = hornblende; bt = biotite; amp = amphibole. *Leonard et al. (2010). # new stratigraphic names defined in Milicich et al. (2013b). The Rotoroa and Waikora Formations are part of the Tamurenui subgroup#.

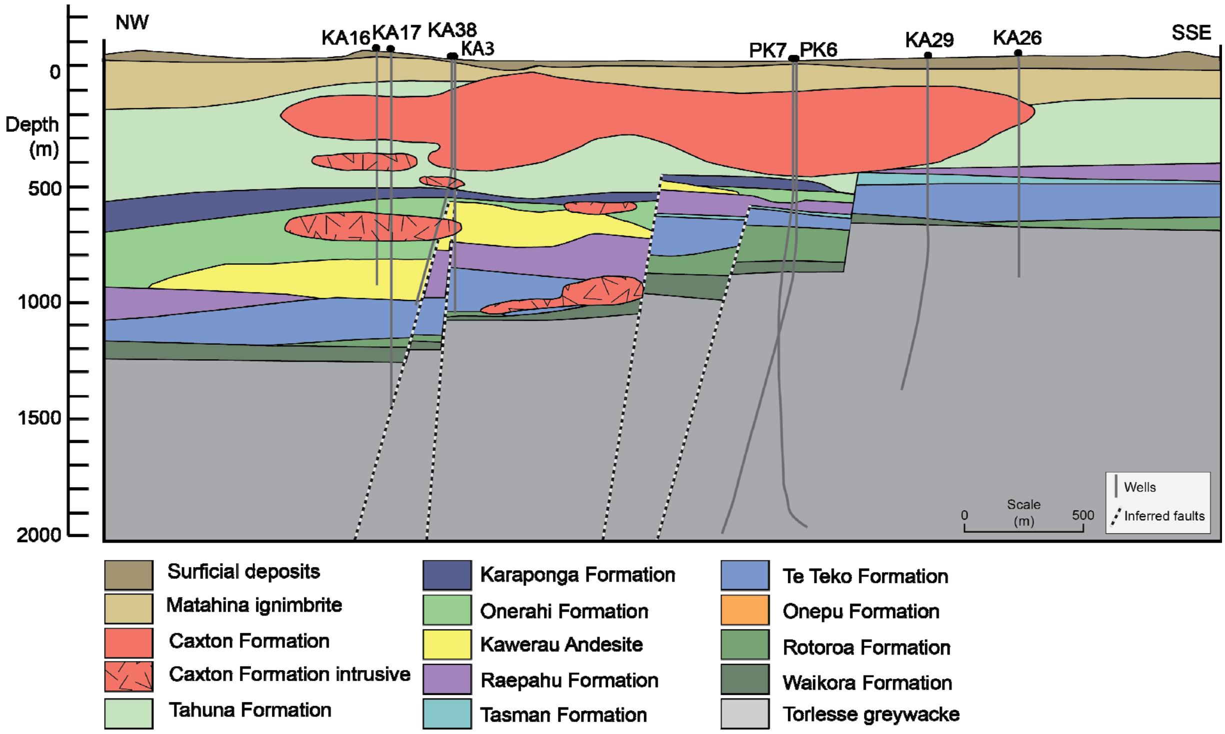


Figure 2: Cross section from NW to SSE across the Kawerau Geothermal Field (cross section line is indicated in Fig. 1). Wells are projected onto the section.

2. REVISED GEOLOGY

Three major groups of material form the rocks at Kawerau above the greywacke basement: (a) primary pyroclastic rocks and their resedimented equivalents, (b) intrusive and extrusive coherent rhyolite that was emplaced as magma, and (c) sediments plus paleosols.

Deposition of ignimbrite in the Kawerau area was distinctly episodic with periods of eruptive activity at 1.45-1.35 Ma (Te Teko Formation), ~1.0 Ma (Raepahu Formation), 0.5-0.6 Ma (Karaponga Formation) and 0.32 Ma (Matahina Formation) (Table 1, Fig. 2). The first and third of these periods fall into gaps in the onshore primary ignimbrite record (Houghton et al., 1995). These two time periods do, however, see rapid accumulation of distal ash deposits in the marine record east of the North Island (Carter et al., 2003, 2004; Allan et al., 2008) and in the Wanganui Basin (Pillans et al., 2005), although in general it is not possible with available data to correlate these with the specific units found at Kawerau. The second period is correlated with the combined products of the Kidnappers and Rocky Hill eruptions at ~1.0 Ma, mapped elsewhere as the landscape-forming Raepahu Formation (Edbrooke, 2005; Leonard et al., 2010), and with thinner deposits reported widely as the Potaka Tephra (e.g. Shane 1994; Carter et al, 2004). Intervals of ignimbrite previously labelled as Rangitaiki Ignimbrite (ca. 350 ka, where dated in its primary surface outcrop: Leonard et al., 2010) have been shown to be much older, and the intervals have now been redistributed within the formations mentioned above.

Numerous bodies of coherent rhyolite to rhyodacite previously mapped in drill core and cuttings in the field (Browne, 1978) can 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 (Fig. 2), 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 (Fig. 2) is represented by surficial domes and two dike intersections at depth.

3. STRUCTURAL DEVELOPMENT

Using the ignimbrite units (initially emplaced subhorizontal) as marker horizons, the progression of faulting structures can be followed through the development of the area. This progression can be followed in 3-D images in Fig. 3.

- NW-SE fault structures (i.e. those orientated at a high angle with respect to the modern TVZ structural grain) predate 1.5 Ma and are related to deposition of the Waikora and Rotoroa formation sediments in half-grabens generated by strike-slip faulting.

- Prior to emplacement of the Te Teko Formation (1.46 Ma) there was little remaining topographic relief as this formation is relatively uniform in thickness across the field. The subsequent development of Tasman Formation sediments and paleosols occurred over about a 0.35 Myr period after the emplacement of the Te Teko Formation ignimbrites, but only in the SE part of the Kawerau field.

- The Raepahu Formation was deposited at ~1 Ma. Its thickness is controlled by faulting structures, mostly in the northwest part of the field, that roughly align to the modern NE-SW TVZ grain. The Raepahu Formation is also not a uniform thickness across the field, indicating it has infilled topographic relief created either by faulting or erosion. Following emplacement of the Raepahu Formation ignimbrites, these early NE-SW rift related faults became the dominant structural control in the Kawerau area, and probably controlled the position of the Kawerau Andesite feeder zone. The sediments of the 1.0-0.6 Ma Onerahi Formation thicken to the northwest, infilling down-faulted structures in this direction. During this time the flows of the Kawerau Andesite were also emplaced.

- By 0.6 Ma (emplacement of the Karaponga Formation), the dominant rifting-related northeast-southwest structures of the TVZ were no longer active. It is possible that this was due to a more general cessation of rifting in the TVZ, as indicated by the general lack of regionally distributed large ignimbrites erupted between 0.71 and 0.35 Ma (Houghton et al., 1995; Leonard et al., 2010). By ~0.4 Ma (emplacement of the Tahuna and Caxton formations) thorough to the present day, the only known active faults in the area are the Onepu and Rotoitipaku Faults, and the main locus of rifting lies just NW of the field. Accompanying the apparent lack of active rifting, magma generation under the field resulted in emplacement of sills and domes of the Caxton Formation.

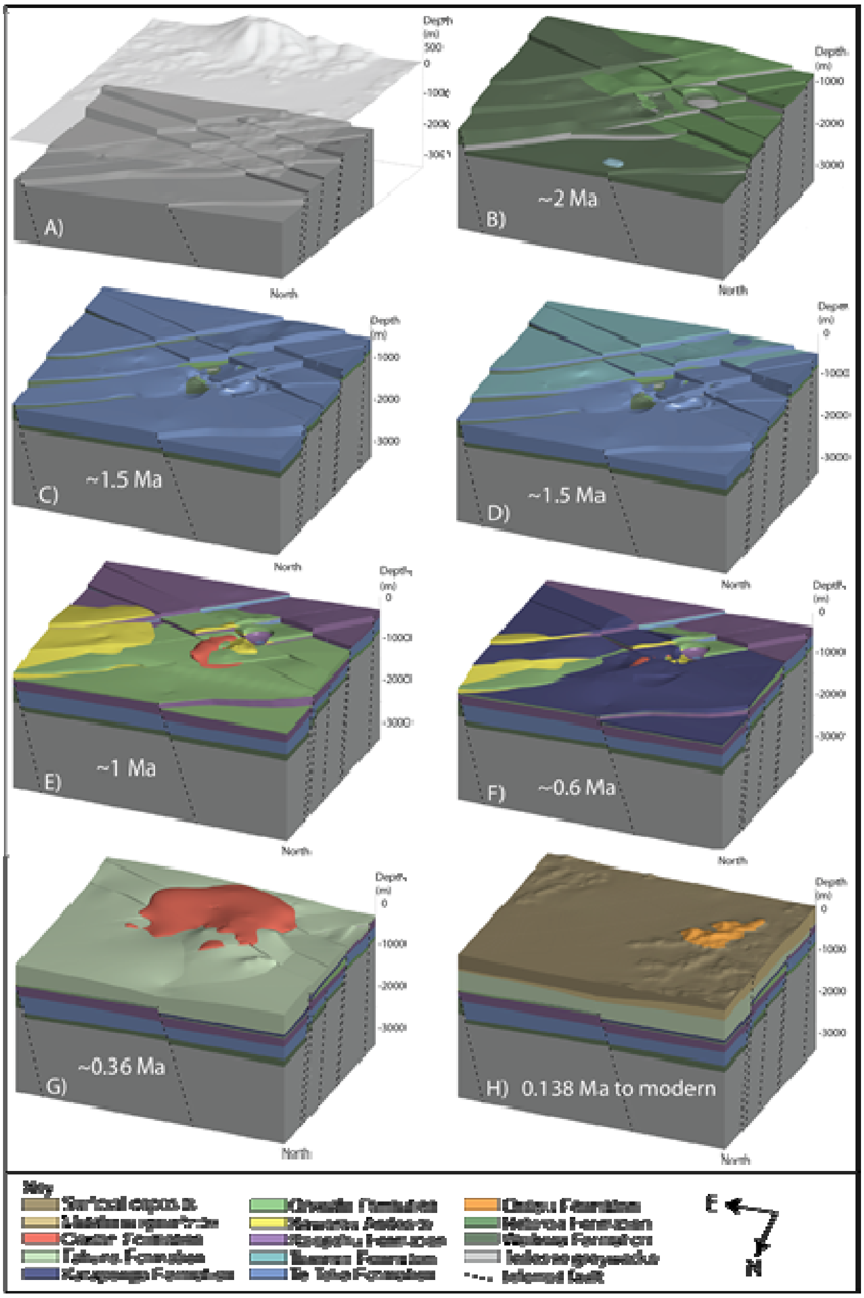


Figure 3:3-D geological representation of the Kawerau geothermal system, with the development of structure and stratigraphy through time. Note, this is stripping back the stratigraphy, not an indication of landscape at that time. A) NW-SE and NE-SW TVZ structural grain and are evident in the greywacke basement. B) Deposition of the Waikora and Rotoroa formation sediments is related to the NW-SE structures. C) Uniform thickness of the Te Teko Formation indicates little topographic relief was present at the time of deposition. D) The Tasman Formation sediments and paleosols occur only in the southeast of the field. E) The Raepahu Formation was deposited along structures mostly in the NW part of the field, roughly aligning with the modern NE-SW TVZ grain, infilling topographic relief. The Onerahi Formation sediments thicken to the NW, infilling down-faulted structures in this direction. F) By the time of emplacement of the Karaponga Formation, the dominant rifting NE-SW structures of the TVZ have mostly been buried. G)-H) By emplacement of the Tahuna and Caxton formations, through to the modern situation, the only remaining active faults in the area are the Onepu and Rotoitipaku Faults in the NW of the area

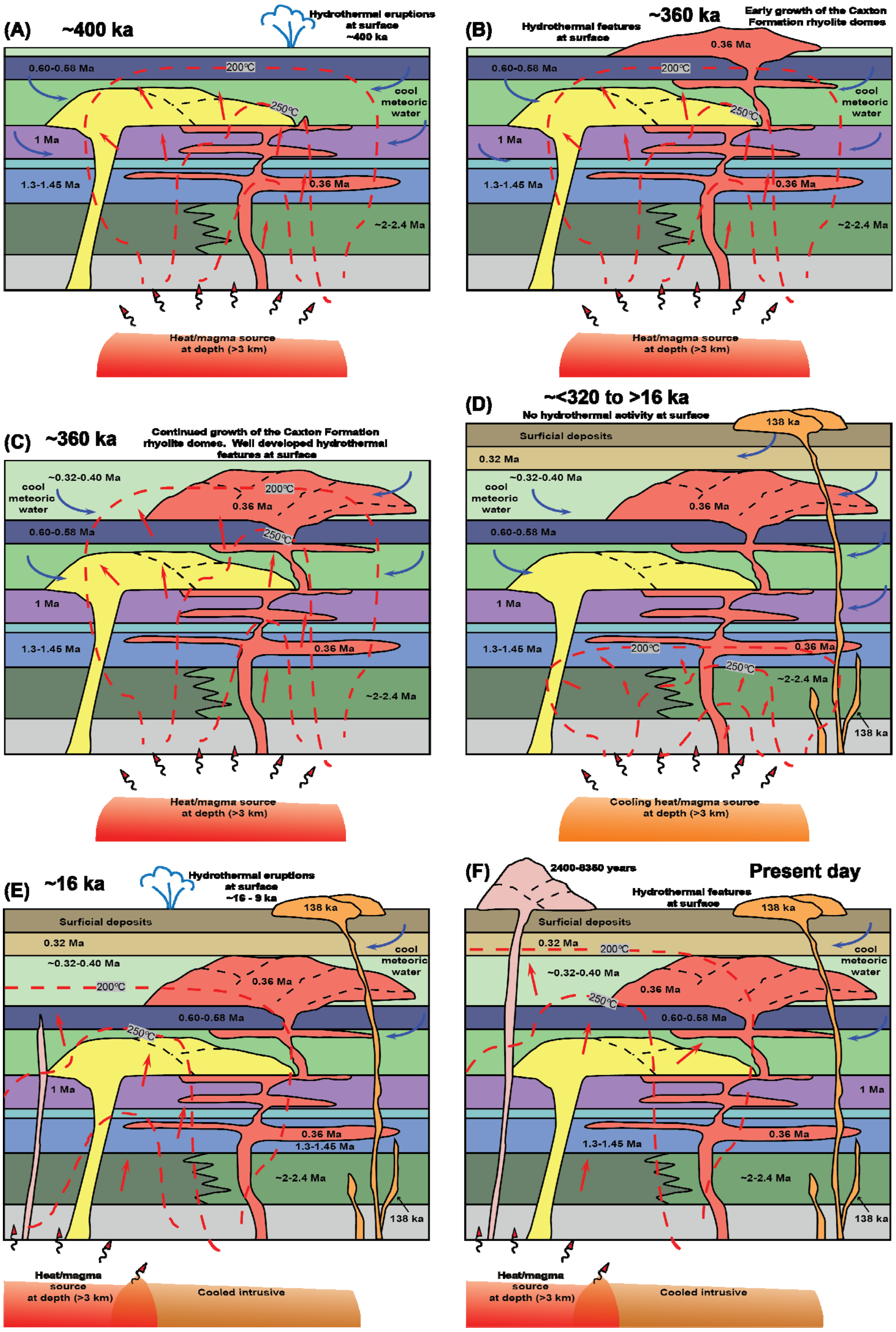
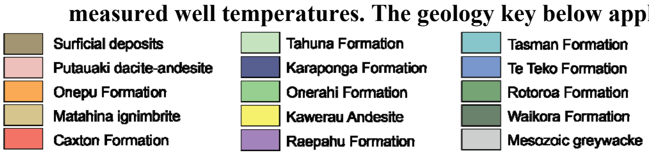


Figure 4: This depicts, in schematic cartoons, the development of thermal flux beneath the Kawerau Geothermal Field. The isotherms in each cartoon are approximate and implied only, and are not determined by data or measured well temperatures. The geology key below applies to all the cartoons.



(A) Early magmatic intrusion related to the Caxton magmatic system created thermal instability and hydrothermal eruptions at surface ~400 ka. (B) Initial growth of the Caxton Formation rhyolite domes and development of a convection plume at ~360 ka. Hydrothermal features would have been present at surface. (C) Further growth of the Caxton Formation rhyolite domes and emplacement of the Tahuna Formation tuffs and sediments. A well-developed hydrothermal system would have been present. (D) Cooling of the magmatic intrusion at depth would have resulted in collapse of the hydrothermal convention plume and hydrothermal activity at surface would have ceased. (E) Early intrusion related to the Putauaki magmatic system created thermal instability and hydrothermal eruptions at surface ~16 to 9 ka. (F) Growth of the Putauaki dacite-andesite dome complex and the development of a hydrothermal convection plume since ~9 ka. Hydrothermal features would have been present at surface since that time. This reflects the present day situation in the Kawerau Geothermal Field.

A change from subsidence to uplift of ~3 mm/yr average at ~370 ka is inferred from sections on the western shoulder of the modern Whakatane Graben at Matata from $^{40}Ar/^{39}Ar$ ages of interbedded tephras (G.S. Leonard et al., unpublished data; Leonard et al., 2008). This change also reflected the onset of uplift of the eastern shoulder of the present-day Whakatane Graben (Mouslopolou et al., 2007, 2008) and development of the present-day highly active rifting regime in this area.

Cumulative rates of fault movement determined from offsets in the top of units through time show the NE-SW faults have accumulated more fault movement over time and that the modern rates can only have been active for <50,000 years (based on elevation differences of the top surface of Matahina ignimbrite).

4. EVOLUTION OF HEAT SOURCES

Hydrothermal eruption breccias in eastern parts of the field (of ~16 ka and ~9 ka age; Nairn and Wiradiradja, 1980; Lowe et al., 2013) demonstrate that hydrothermal activity was occurring at shallow levels at least at those times (Fig. 4E). These hydrothermal eruption breccias are linked to intrusion of magma associated with the onset of Putauaki activity. The initiation of magmatism beneath the area ~16 ka is also reflected in a generation of hydrothermal calcite and quartz with a O^{18} enriched isotope signature, reflecting a pulse of magmatic CO_2 into the system. As meteoric fluid overwhelmed the early input of magmatic fluid (Fig. 4F), both fluid inclusion microthermometry and stable isotope data show a change to the present-day fluid chemistry (low salinity, meteoric-dominated waters).

An earlier period of hydrothermal activity is indicated by a hydrothermal eruption breccia in the Tahuna Formation, stratigraphically beneath the Caxton Formation extrusive domes (Browne, 1979). The heat supply driving the contemporaneous hydrothermal system is inferred to be related to the magmatic system that gave rise to the Caxton Formation rhyolite and the temporally associated Tahuna Formation tuffs (Fig. 4A). This system would have been initiated around 400 ka, then decayed away after ~360 ka when eruptions ceased (Fig. 4B-C). The isotopic signature attributed to the Caxton magmatic system is meteoric in origin, indicating that the magma was acting only as a heat source to drive the hydrothermal system, and was not actively contributing fluids and CO_2.

This work suggests there have been two geothermal systems in the Kawerau area over the last ~400 kyr. The thermal state of the system during the time period between the earlier Caxton and current Putauaki magmatic-driven systems is not known (Fig. 4D). It is likely though that activity waned or became extinct between these events as the volume of magma represented in the Caxton system (~10 km^3 maximum) would be able to feed an active geothermal system only for periods of the order of 10^2 to 10^4 years (e.g. Cathles, 1977).

5. CONCLUSIONS

This paper shows the importance of consistency in description in overcoming problems in cross-correlation. In geothermal development, where it is inevitable several geologists may be required describe and log drillcuttings and core, that periodic re-evaluation and review of the correlations is essential. A robust dating programme feeding into stratigraphy and structural studies being used to infer system development can be invaluable, and will provide confidence in the stratigraphic interpretations, help clarify controls on permeability and reduce risk for subsequent well targeting and drilling operations.

ACKNOWLEDGEMENTS

We acknowledge funding support for this project from Mighty River Power Ltd and its permission, along with that of Ngati Tuwharetoa Geothermal Assets Ltd, to publish these data. Thanks also go to A8D Trust, Putauaki Trust, Te Tahuna Putakuaki Trust and other local Maori trusts for access to well core and cuttings. Additional funding came from a Victoria University PhD scholarship to SDM and for CJNW from the FRST Programme "Deep Geothermal Resources" through subcontracts from The University of Auckland, by courtesy of Mike O'Sullivan. Thanks also to Patrick Browne and Michael Rosenberg for valuable comments and discussion on the geology at Kawerau.

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