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# Evolution of a dynamic paleo-hydrothermal system at Mangatete, Taupo Volcanic Zone, New Zealand

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ABSTRACT

Recent quarrying and active faulting at Mangatete, Taupo Volcanic Zone (TVZ), New Zealand, illuminate a rare spatial and temporal window on a dynamic Late Quaternary geothermal system. Detailed geological mapping, stratigraphic logging, AMS $^{14}C$ dating, and textural and mineralogical analyses were used to construct a complex history of hydrothermal, volcanological and tectonic activity from ~36 to 2 ka. Extinct, surface hydrothermal manifestations occur over a ~2 km$^2$ area, and include *in situ* siliceous sinters distributed on normal fault terraces, an inferred hydrothermal eruption breccia (HEB) containing acid-etched sinter blocks, another probable HEB that was bathed in silicifying thermal fluids, and sinter clasts that were entrained in a debris flow associated with a volcanic ash event. Preserved sinter textures typical of near-neutral pH, alkali chloride spring discharge channels, aprons, terraces and affiliated marshes comprise plant-rich, palisade, tufted bubble mat, and domal stromatolitic fabrics. In addition, a packed fragmental sinter facies is shown herein to constitute silicified microbial mats that were broken, transported and deposited as point bar deposits in thermal spring-fed streams. Moreover, four unusual siliceous sinter fabrics—vuggy, globular spongy, scalloped, and arcuate wavy layered—are interpreted to have formed from local acid-sulfate-chloride thermal springs, possibly associated with paleofumaroles. The reconstructed history of paleo-hydrothermal activity indicates that the oldest sinters (~36 ka) at Mangatete developed in alkali chloride hot springs, but then underwent post-depositional alterion/overprinting by acid-sulfate steam condensate and were dismembered, possibly by a hydrothermal eruption. Low pH hot-spring discharges forming the unusual, inferred acid sinter fabrics were localized in the same area. A shift in paleo-hydrology is evidenced by unaltered, alkali chloride sinters dated between ~22 and 3 ka. A cluster of sinter dates between 22.7 and 20.7 ka denote thermal fluid emissions around the time of the Okareka eruption (~22.1 ka). An ~11 kyr gap in sinter ages followed, which overlaps with a time of relative quiescence in local fault movement in between the Rotorua and Rotoma eruptions, as determined from previous paleo-seismicity studies on the Whirinaki Fault in the Mangatete area. At ~9.4 ka, hot spring activity in thermally fed streams slightly postdated the Rotoma eruption (~9.5 ka). The locations and ages of the youngest (post-9.4 ka) alkali chloride sinters and silicified paleosols in relation to Whirinaki Fault movements indicate an overall westward migration of siliceous spring discharge. Dated charcoal (~1.8 kyr) in ash at the base of a locally extensive, volcaniclastic debris flow, containing sinter blocks of a range of ages and mineralogical maturity, suggests its affiliation with the Taupo eruption. Mangatete sinters occur along SW–NE striking faults parallel to the regional trend of the TVZ, which dissect the topography into stepped terraces. Inferred basement cross-faults in the study area, i.e. structural lineaments orthogonal to this trend, may have served as fluid pathways at depth, initiating and maintaining hydrothermal activity at Mangatete for more than 30 kyr. Within the larger Ngakuru Graben (~150 km$^2$), the ages and distributions of sinters and hydrothermal eruption breccias, including those at Mangatete, show that significant hydrothermal activity occurred for more than 60 kyr, in an area lacking such activity today. Thus, Mangatete retains a rare stratigraphic record within the TVZ sinter archive of changing geothermal fluids, resulting from shifts in paleo-phreatic water levels. Moreover, although limited, the presented age data imply a relationship among seismic activity, volcanic ash fall events, and the occurrence of permeable pathways for upward migration of thermal fluids. Finally, whereas currently active TVZ geothermal fields appear to be stable over

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tens of thousands of years or more, the fossil hydrothermal systems in the wider Mangatete area demonstrate the possibility of much greater temporal variability in the lateral expression of local surface manifestations of thermal fluid discharge through time.



## 1. Introduction

Active high-temperature geothermal systems in continental settings result from large-scale, coupled transfer of heat and mass within the shallow crust, and can manifest subaerially as diverse hot springs and vapor discharges. Such systems indicate potential energy resources at depth (Lynne, 2012), and can have a close spatial relationship with epithermal mineralization (e.g., Fournier and Rowe, 1965; Krupp and Seward, 1987; Sillitoe, 1993; Guido and Campbell, 2011). Moreover, their surface manifestations serve as analog “extreme environments” for settings where life may have taken hold on early Earth and possibly other planets (e.g., Farmer and Des Marais, 1999; Farmer, 2000; Konhauser et al., 2003; Ruff et al., 2011). Fossil geothermal systems also provide evidence for the locations of past magmatism and thermal fluid flow in zones of crustal weakness. In this paper, we ascertain the changing paleo-hydrology of a well-exposed fossil geothermal system, the Mangatete sinter and associated deposits, Taupo Volcanic Zone (TVZ), New Zealand, which is preserved in an area that is today regarded as hydrothermally extinct. Our results provide new insights on the time-scales and variable fluid histories of the local surface manifestations of hydrothermal convection systems.

More than 20 major, active, high-temperature (>250 °C) geothermal systems occur within the TVZ (Fig. 1), an 18,000 $km^2$ region of active crustal extension (~10 mm/yr; e.g., Villamor and Berryman, 2001), typified by largely rhyolitic volcanism, and present-day high crustal heat flow (2600 MW/100 km) along the length of the rift axis (Bibby et al., 1995; Hochstein, 1995). High-temperature geothermal systems are recharged by meteoric water descending to depths of 7–8 km, where they are heated and rise to sustain large-scale hydrothermal convection plumes (Giggenbach, 1984; Hedenquist, 1986; Rowland and Sibson, 2004). The shallow boundaries of the geothermal systems are approximated by domains of low resistivity marking rising thermal fluids (Bibby et al., 1995). These fluids migrate through pre-volcanic basement in the TVZ to reach laterally extensive, near flat-lying, permeable, Quaternary volcaniclastic deposits (<1.6 Ma; Wilson et al., 1995), with local thicknesses of up to 3 km (e.g., Ngatamariki geothermal field; Boseley et al., 2010). The surface expression of a geothermal system can be offset laterally from its upflow by several kilometers (Hedenquist, 1986; Bertrand et al., 2012).

Most geothermal fluids may be categorized by three end-member, major anion-based compositions (Jones and Renaut, 2003; Renaut and Jones, 2011). First, bicarbonate springs generally produce travertine ($CaCO_3$) deposits, which result from dissolution of ascending $CO_2$ into shallow groundwater that later degasses, although travertine deposition also may be influenced by cyanobacteria (Farmer, 2000; Pentecost, 2003). Second, alkali chloride springs of nearly neutral pH originate from magmatically heated, deep reservoir-derived chloride waters saturated with amorphous silica, and typically form siliceous sinter (opal-A: $SiO_2.nH_2O$) deposits (White et al., 1956, 1964). Third, acid-sulfate waters develop where ascending $H_2S$ oxidizes above the piezometric surface to cause dissolution of country rock, with some local precipitation of vapor phase (e.g., sulfur) and hydrothermal alteration minerals (e.g., kaolin, alunite and silica residue; Rodgers et al., 2004; Jones and Renaut, 2012). Where acid-sulfate waters mix with deep reservoir-derived chloride fluids (Ellis and Wilson, 1961; Krupp and Seward, 1987; Hedenquist and Browne, 1989), acid sinters may form (Jones et al., 1999a,b; 2000; Mountain et al., 2003; Schinteie et al., 2007). Such deposits are termed acid sinters because the silica originates from the deep, hot (>250 °C), chloride fluid reservoir, rather than leaching from surface country rock to form silica residue (Rodgers et al., 2002, 2004). Alkali chloride sinters and acid sinters are distinguished from one another based on differences in deposit thicknesses and textures, the latter of which are at least partly controlled by particular biotic compositions. In particular, near-neutral pH, alkali chloride springs deposit sinter of up to tens of meters in thickness, and sustain distinctive organism communities distributed over a

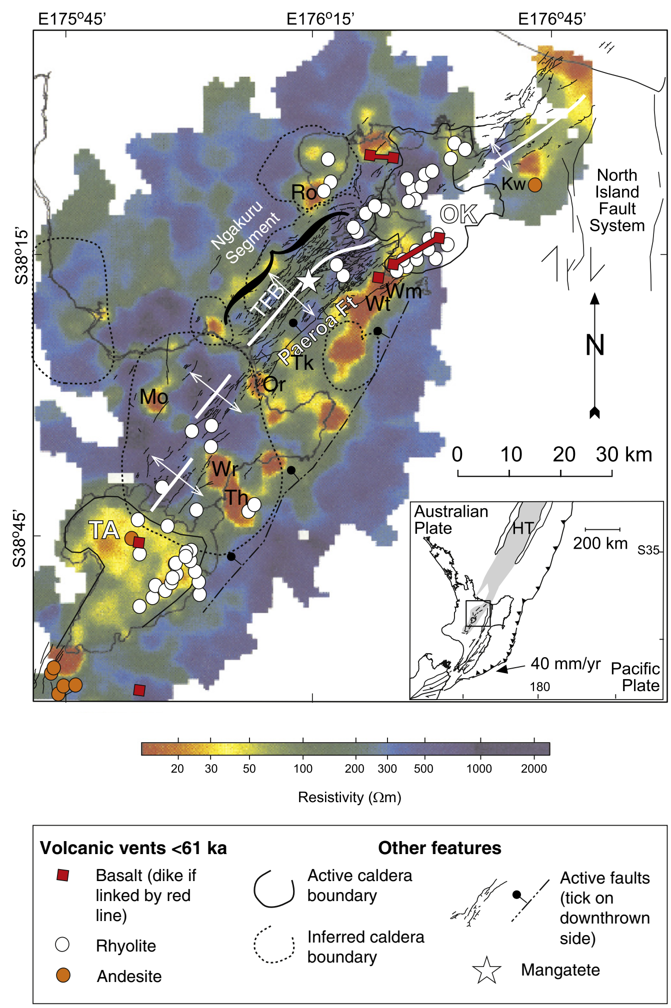


**Fig. 1.** Electrical resistivity map of the Taupo Volcanic Zone (TVZ), with nominal array spacing at 500 m (after Stagpoole and Bibby, 1998) in relation to rift segments, accommodation zones, interpreted basement structures (after Wan and Hedenquist, 1981; Rowland and Sibson, 2004), and inferred and active caldera boundaries (TA, Taupo; OK, Okataina; after Nairn, 2002). TFB = Taupo Fault Belt. Geothermal fields, indicated by low resistivity (color-coded red), are labeled as: Kw, Kawerau; Mo, Mokai; Or, Orakeikorako; Ro, Rotorua; Th, Tauhara; Tk, Te Kopia; Wm, Waimangu; Wr, Wairakei. Igneous composition of young (<61 kyr old) volcanic vents includes basalt (red squares), rhyolite (white circles), and andesite (orange circles). Rift axes are defined by changes in polarity of fault-facing directions, shown by white lines and annotated with extension direction as delineated by the pattern of active fault traces (Rowland and Sibson, 2001). The Mangatete study area (star) is situated in the Ngakuru tectonic segment. Inset shows submarine extension of the TVZ into the Havre Trough (HT), and position of the back arc rift system of the TVZ in relation to the active subduction margin of eastern North Island, New Zealand.