

MANGATETE: EVOLUTION OF A PALEO-HYDROTHERMAL SYSTEM, TAUPO VOLCANIC ZONE (TVZ).

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ABSTRACT

Hydrothermal activity in the TVZ occurs along two NE-SW trending alignments, located on either side of the Taupo Fault Belt (TFB). Lack of present-day hydrothermal activity within the TFB can be explained if the belt behaves as a major recharge zone to the large-scale convection system. However, siliceous hot-spring deposits (sinters) within the fault belt attest to a rich history of past hydrothermal activity: i.e. the current disposition of the convection system is not necessarily ‘steady-state’.

The Mangatete paleo-hydrothermal system is located on the Whirinaki fault, where inferred cross-faults presumably provide enhanced permeability. Displacement on the Whirinaki Fault has exposed deposits of hydrothermal eruption breccias, zeolitised lake sediments and sinter. In situ sinter is patchy, distributed over a 1.5 km² area, and surrounded by extensive debris flow deposits (maximum ~2 ka BP) containing ex situ sinter clasts. Sinter fabrics preserve paleoenvironmental signatures and assist in reconstructing the geographical extent of the paleo-hydrothermal field. ¹⁴C dating establishes geothermal activity from possibly as long ago as 32 kyr (ex situ sinter), and definitely over a period of 18.5 ka to 8.5 ka (in situ sinter) in the immediate Mangatete N & S quarry area, with sinters in surrounding areas dated from ~17.9 ka to <3 ka. This extinct geothermal system is co-linear with other paleo-hydrothermal manifestations extending NE for ~5 km, and is parallel to another fossil geothermal area, ~5 km to the northwest, extending from Parsons Rd to Waikaukau Rd.

Present day geothermal fields are delimited by regions of low electrical resistivity (<10 Ωm) and are generally considered stable for tens to hundreds of thousands of years. Mangatete suggests that such plumes in the TVZ are capable of migration, or of extinction, after <35 kyr duration of thermal activity. Episodic magmatic intrusions into the lower crust are considered necessary to provide the heat to energize convective circulation. Mangatete could be the result of a magmatic intrusion that was not maintained, but which created a mid-crustal hot plate.

1. INTRODUCTION

The Mangatete paleo-hydrothermal area is located in the Ngakuru Graben, within the TFB (Fig. 1), where seismic movement on the Whirinaki Fault has produced a 25 m high

footwall exposing geothermally altered sediments that two adjacent quarries have exploited for commercial use, thereby enhancing access to the local associated stratigraphy (section 3). The observed deposits create a cognitive conundrum: based on the accepted understanding of geothermal activity within the TVZ, Mangatete should not be there (section 4).

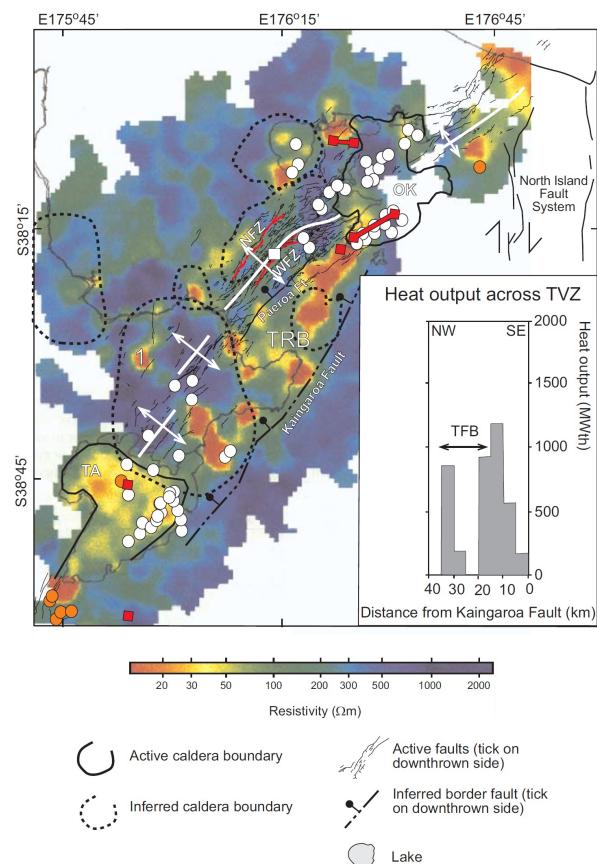


Fig. 1. Electrical resistivity of Central TVZ (nominal array spacing = 500 m) (after Stagpoole and Bibby, 1998) in relation to <61 ka volcanic vents (white circles, silicic; orange circles, andesitic; red squares, basaltic), rift segments and inferred caldera boundaries (after Nairn et al., 1994; Gravley et al., 2007). Geothermal fields indicated by low resistivity (coloured red). Mangatete = white square. Ngakuru Graben is between NFZ (Ngakuru Fault Zone) and WFZ (Whirinaki Fault Zone) (solid red lines). The rift axes of the Taupo Fault Zone (TFB) are defined by the change in polarity of fault

facing directions and are shown by white line and annotated with the extension direction as defined by the pattern of active fault traces (after Rowland and Sibson, 2001). Inset shows variation of the heat output from the geothermal systems, summed for 5-km-wide strips parallel to the eastern margin of the TVZ (from Bibby et al., 1995). (Modified from Rowland and Sibson, 2010).

2. GEOTHERMAL ACTIVITY IN THE TVZ

2.1 Regional geology

The TVZ is a region of crustal extension with associated volcanism and geothermal activity (Wilson et al., 1995) with near-surface thermal reservoirs due to shallow magmatic intrusions into the stretched lower crust (Bibby et al., 1995). Geothermal activity is concentrated in the central 125-km-long rhyolitic zone with some 20 high-temperature geothermal fields with aquifer temperatures $>250^{\circ}\text{C}$, following a NE-SW strike from, approximately, Tokaanu to Kawerau, with a smaller, co-linear geothermal field ~ 25 km NW, extending approximately from Mokai to Rotorua. (Fig.1: Bibby et al., 1995; Rowland & Sibson, 2004).

These two zones of geothermal activity are separated by the Taupo Fault Belt (TFB), a region of parallel, NE-SW striking normal faults. Within the TFB, the Ngakuru Graben (Grindley, 1959) is a ~ 4.5 km wide subsiding basin of pumice terraces and stratified lake sediments between the Whirinaki Fault to the east, and the Ngakuru Fault to the west (Fig. 1). Detailed mapping by Villamor & Berryman (2001) recorded a complex fault system with between 10 and 15 NE-SW trending structural features, dipping both NW and SE, and in places, with fault strands only 400 m apart. Fault trace lengths vary from a few hundred metres to tens of kilometres, with fault splays making it difficult to distinguish separate faults. No NNW-striking faults were mapped by Villamor & Berryman (2001), but we recorded NW-SE lineaments within the mapping area (Figs 2, 3), in keeping with the NNW structures of Rowland et al. (2010), and Downs et al., (in review). Further, Grindley (1959) mapped a ~ 1.5 km gap in the "Ohakuri Formation" horst at the location of the Mangatete Quarry, which indicates that a major NW-SE trending structure may be present at depth. Faulting within the TFB and Ngakuru Graben likely enhanced permeability allowing downward movement of cold meteoric water to recharge the hydrothermal convection system (Bibby et al., 1995; Rowland & Sibson, 2004; Dempsey et al., 2011).

Extensive Quaternary lakes within the TVZ, formed by volcanic calderas becoming catchments for volcanic sands and silts (Manville, 2001), also are recognized in the Ngakuru Graben by lacustrine volcanic sandstones, siltstones and diatomite beds, which are finely stratified, horizontal to sub-horizontal, and poorly to moderately compacted (Villamor & Berryman, 2001; Brathwaite, 2003). Zeolitised lake sediments of Upper Pleistocene age are paraconformable with the overlying Mangatete surface paleo-hydrothermal system of sinters, breccias and debris deposits.

2.2 Hydrothermal circulation cells

Seismic studies suggest that within the TVZ, the upper mantle (Stratford & Stern, 2004, 2006), or a zone of prolific

mafic intrusions (Harrison & White, 2004, 2006), rises to ~ 15 km depth and is overlain by Jurassic volcaniclastic marine sandstones that form the regional basement (Mortimer, 1994). That basement is brittle from < 8 km deep (Bryan et al., 1999), and contains the fluids that constitute the hydrothermal system. Modelling the convection pattern of a fluid in a porous medium heated from below indicates that the hydrothermal fluids circulate in convection cells to depths of 5-8 km (Bibby et al., 1995), in agreement with surface observations that the mean spacing between geothermal fields is ~ 10 -15 km. Bibby et al. (1995) pointed out that the rock between the hot mafic region at 15 km depth, and the base of the convection zone at ~ 8 km, is not sufficiently conductive to maintain surface heat flow. Thus periodic magmatic intrusions are needed to replenish the thermal capacity of the system.

Electrical resistivity measurements (Mussett & Khan, 2000) utilize the fact that mineral-laden hydrothermal waters are good electrical conductors, and indicate the presence of hydrothermal fluids within the immediate subterranean levels. Stagpoole & Bibby (1998) mapped electrical resistivity (to 500 m depth) in the TVZ (Fig 1). The conductive subterranean areas (red) are situated predominantly east of the Paeroa Fault, below the sediments in the Reporoa Basin, or otherwise west of the axial fault belt, in close agreement with the distribution of thermal manifestations and hot ground as defined through geothermal exploration.

The few available age estimates for the major geothermal fields range from 240 kyr to 500 kyr duration (Rowland & Sibson, 2004 and references therein) suggesting that the circulation cells are relatively stable. Kissling (1998, 1999) and Dempsey et al. (2011) modeled TVZ geothermal circulation, and identified a degree of transience, with components of hydrothermal plumes diverging, or merging, at rates of up to 1-2 km per 100 kyr. However, their models maintain a central zone, approximating the TFB, which remains free of hydrothermal plumes.

2.3 Surface expression of hydrothermal fluids

Approx. 2.5 km of the upper layers of the TVZ consist of low-density pyroclastic infill (Bibby et al., 1995). Hydrothermal fluids venting at the surface may have experienced considerable lateral migration within this infill, and surface vents do not necessarily mark the immediate location of permeable paths through underlying impermeable rock (Hedenquist, 1990).

In contrast, lacustrine sediments and rhyolitic domes form aquitards across which faults may provide conduits, particularly where across-strike faults intersect rift-parallel faults (Wan & Hedenquist, 1981; Cochrane & Wan, 1983; Rowland & Sibson, 2004). The surface expression of fluids at Mangatete is likely a consequence of structures coincident with the NW-SE lineaments intersecting the rift-parallel (NE-SW) Whirinaki Fault at this location (Figs 2, 3).

Therefore, hydrothermal surface expression depends upon tectonic extension to bring magma close to the surface; periodic magmatic intrusion into the lower crust to provide heat flow in excess of the natural conductivity; meteoric water descending through faulted recharge zones supplying rising hydrothermal plumes at characteristic lateral spacing; intersections between cross-strike and rift-parallel faults to

provide permeable paths to the surface; and low-density infill through which epithermal fluids find pathways (potentially convoluted) to the surface.



Fig. 2. Major lineaments (red lines) and displaced river channel implying a cross-fault, NW-SE structural element at Mangatete. Scale bar = 500 m.

2.4 Sinter

Geothermal systems manifest at the surface as hot springs in topographically low lying areas where hydrothermal water level rises and intersects the ground surface (Simmons, 1995; Walter, 1996). Siliceous sinter predominantly precipitates from nearly neutral pH, alkali-chloride waters from deep reservoirs where temperatures exceed 175°C (Fournier & Rowe, 1965).

Where the hydrothermal water level is much lower, steam condensate from deep sub-surface boiling is reduced on contact with the atmosphere to produce acid-sulphate waters that leach and erode country rock, and produce distinctive acid-alteration on exposed surfaces (White et al., 1956; Rodgers et al., 2002; Rodgers et al., 2004; Schintie, 2005, 2007).

3. MANGATETE

3.1 Two quarries

The Mangatete paleo-hydrothermal system is located approximately 20 km south of Rotorua (Fig 1) within the Ngakuru Graben. There the Whirinaki Fault has exposed a 25 m high footwall, dipping ~78° to the west, and exposing commercially valuable deposits that have been utilized from two quarries, giving good exposure of the underlying sediments with evidence of paleo-geothermal activity. The North Quarry has provided conglomerate for local road fill, and the site is also littered with cobbles and boulders preserving sinters, silicified tree fragments and thermally altered deposits.

The South Quarry lies ~10-15 m stratigraphically below the North Quarry, and ~100 m to the SSW, and is positioned upon a 25 m exposure of lacustrine sediment that has been thermally altered to zeolite, and commercially exploited. Above the paraconformable top of the lacustrine sediments are exposures of conglomerate, paleosol, and sinter. The quarries are surrounded to the west, east and south by extensive exposures of silicified lacustrine sediments, and a younger debris flow deposit.

3.2 Local area survey

The Whirinaki Fault dominates the mapped area, with three major branches forming three major terraces, and several parallel and sub-parallel lineaments of limited length presumed to reflect splays (Fig. 3). An extensive hydrothermal eruption breccia is exposed at the North Quarry (section 3.3), with a smaller exposure ~1 km to the south (Fig. 3, dark blue). The major terraces, designated High, Intermediate and Low according to their elevation, each have one or two in situ exposures of sinter that were separately sampled for ¹⁴C dating, as also was an ex situ sinter block from atop the North Quarry. Surrounding the terraces is a debris flow deposit (Fig 3, green region), poorly sorted, with boulders and cobbles and including conglomerates, lithics and volcanics. Associated with the debris flow are sinter clasts, the original locations of which are unidentified. The existence of the geographically extensive sinter-bearing debris flow deposit, and charred tree branches and logs at its base, establishes that considerable hydrothermal activity took place in the greater Mangatete area.

NW-SE trending lineaments cause minor breaks in the terraces and accommodate two streams. In addition, several significant NW-SE lineaments (Figs 2, 3) suggest sub-surface faulting with this cross-strike orientation, orthogonal to the rift trend itself.

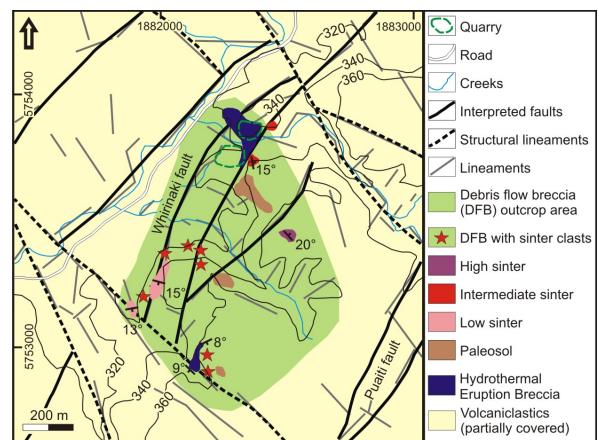


Fig. 3. Mangatete Geology

3.3 North Quarry Breccia

The North Quarry constitutes a breccia that is a matrix-supported mixture of poorly sorted, mainly sub-rounded to sub-angular cobbles and pebbles of mixed lithologies (clay, volcanics, lithics and reworked conglomerates) in a matrix of clay and sand. There are minor angular lithic clasts (<12 mm). Horizontal to sub-horizontal bedding planes separate beds of alternating coarse and fine deposits, some of which pinch out laterally. The beds are not graded, and there is no overall stratigraphic pattern evident in the quarry face.

We consider this deposit, by comparison with Browne and Lawless (2001), and lacking obvious fluvial elements in the bedding, to be a hydrothermal eruption breccia (HEB), although it differs significantly from established HEBs in the area (e.g. Parson's Rd; Frying Pan Lake, Waimungu) which contain much larger clasts (boulders) in an ~80% clay matrix. Our identification is supported by Leonard et al. (2010). A 1.8 m long boulder near the North Quarry that

preserves a now broken, hydrothermally altered conduit is of uncertain provenance, and its relationship to the hydrothermal eruption is uncertain.

3.4 Sinters

Sinter facies can be differentiated by mineralogy and paleoenvironmentally significant macro- and micro-fabrics, including microbial components (e.g. Campbell et al. 2001). Geothermal alkali-chloride systems develop characteristic biofacies (Walter, 1976; Cady & Farmer, 1996) as microbiota thrive in particular temperatures and alkalinity, and generate lithofacies that systematically change as the fluids cool further from the vent.

Mineralogically, sinter deposits as noncrystalline opal-A, and then transforms systematically to paracrystalline opal-CT, then to opal-C, and finally to microcrystalline quartz (Jones & Segnit, 1971; Herdianita et al., 2000; Rodgers, 2001; Rodgers et al., 2002, 2004). Two or more sinter phases commonly co-exist within microscopic proximity (Campbell et al., 2001), and diagenesis proceeds at different rates (Lynne et al., 2004, 2005, 2006, 2007; Campbell & Lynne, 2006) making the mineralogical transformation itself unsuitable as a proxy for relative dating of sinter.

Macroscopically, many primary characteristics are preserved in sinters despite diagenetic overprinting that destroys much of the fine-scale microstructure (Cady & Farmer, 1996). Modern sinters in the TVZ and in Yellowstone are used as effective analogues for fossil deposits: the modern facies progression from vent to distal locations is equally apparent in Jurassic sinter deposits in Argentina (Guido & Campbell, 2009, 2010, 2011; Guido et al., 2010), and elsewhere. Guido & Campbell (2011) developed a comprehensive scheme of facies associations uniting structural, lithological, textural and biotic features in a sequence that appears to be consistent geographically and chronologically, and may be applied to Mangatete.

The Mangatete sinters were examined with optical microscopy, environmental scanning electron microscopy (ESEM), and X-ray powder diffraction (XRD). Owing to text limitations for this article, detailed description of the sinter is in preparation for publication elsewhere. Suitable plant-rich samples were dated by AMS ^{14}C dating at Rafter Laboratories, Lower Hutt.

3.4 Geothermal activity at Mangatete

In situ sinters at Mangatete date from \sim 18 ka to \sim 8.5 ka with no chronological succession apparent, with respect to elevation, between the different terraces. Sinter within the debris flow is dated at \sim 3 ka, and fossil carbonized wood at the base of the debris deposit was dated at 1972 ± 15 yrs BP. An isolated, ex situ sinter cobble from atop the North Quarry was dated at \sim 32.5 ka.

The studied sinter is almost exclusively opal-A, with only minor traces of hydrothermally altered minerals (Browne, 1978). In contrast, sinters at Sinter Island in Lake Ohakuri (Campbell & Lynne, 2006), \sim 20 km to the SSW, are dated to 456 yrs BP, and yet preserve the full sequence of silica diagenesis. This lack of diagenetic progression at Mangatete appears to indicate little to no burial or alteration of the sinter itself over, at least, an \sim 18 kyr interval.

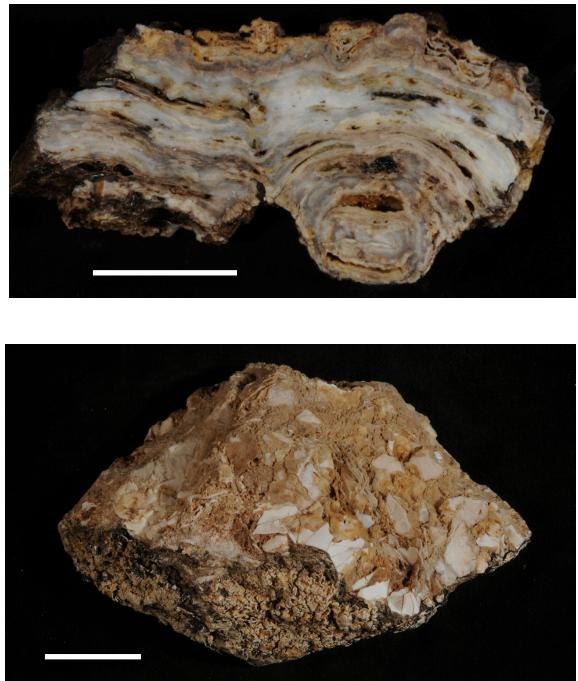


Fig 4. Sinter fabrics. Above: Highly silicified, wavy to domal stromatolite from a deep, quiescent mid-temperature pool. Scale bar = 5 cm. Below: Packed fragmental sinter. Sinter sheets from the bed of a hot water stream, eroded and broken by turbulent flow, and redeposited downstream at a point bar. Scale bar = 2 cm.

Microbiota and macroscopic sinter facies ranged from medial to distal from the vent, from mid-apron pools to fen environments. Only one sample, an inferred fumarolic scalloped fabric, is likely to be proximal to a vent. Several large, well-developed stromatolites indicate lengthy periods of stable, quiescent pools (Fig. 4A). Furthermore, a fragmental packed sinter deposit (Fig. 4B) was inferred, by analogy with a modern deposit at Waimangu, as accumulating in point-bar of a hot (\sim 60°C), turbulent stream, with the deposit forming possibly tens, or hundreds, of metres from the vent.

The South Quarry base comprises 25 m of zeolite from hydrothermally altered diatomaceous and lacustrine sediments, requiring a lengthy, stable period of geothermal heat supply from beneath the quarry area (Barrer, 1982; Brathwaite, 2003; Sheppard & Hay, 2001).

The sinter in the debris flow (e.g. Fig. 6A) is from an unidentified source. It may be part of the 1972 yrs BP deposit, or there may have been a number of separate geothermal events, or sinter may have been transported from a variety of sources. Further AMS ^{14}C dating is underway to evaluate these ex situ samples.

4. DISCUSSION

4.1 The Mangatete field

The Mangatete field has been active from at least 32 kyr; however, the earliest activity is represented by float blocks, and stratigraphic continuity cannot be assumed. Beginning about 18 ka, hydrothermal fluids, from an unidentified vent(s) were depositing sinter on both the highest and lowest of the present fault terraces. The hydrothermal breccia from the North Quarry has yet to be dated, and its chronological relationship to the 18 ka sinters is unknown. Rocks at the North Quarry preserve traces of kaolin, magnetite, wüstite, hematite and wairakite, indicative of hydrothermal alteration (Browne, 1978), and surface etching and dissolution suggest that at some point the paleo-water table fell, causing acid-alteration. The date of the hydrothermal eruption is also unknown; HEBs can be initiated by falling water tables (Browne & Lawless, 2001), but there is no evidence to indicate the fall in the water table to be coterminous with the eruption. The packed fragmental sinter has been dated by ^{14}C AMS at ~ 8.5 ka, and indicates that at this time an unidentified vent was producing a hot, turbulent stream discharge. The silicified paleosol is distal to a hydrothermal vent of unknown location and date. A sinter block within the debris flow has been ^{14}C dated to ~ 3 ka.

Even allowing for quiescent periods between times of geothermal activity at the surface, a significant heat flow has been maintained at Mangatete for at least 30 kyr.

4.2 A thermal plume at Mangatete

As discussed in section 2.2, currently active hydrothermal fields are maintained with convective thermal fluid plumes. Analysis of structural controls on hydrothermal flow (Rowland & Sibson, 2004) predicts geothermal systems will be preferentially located in accommodation zones; this is consistent with the TVZ-wide present distribution, where 60% occur in accommodation zones, and none currently occur within the densely faulted rift segments.

However, a thermal plume must have been beneath Mangatete when that field was active. TVZ plume migration modeled by Dempsey et al. (2011) is an order of magnitude too low to have a plume migrate into, or out of the Ngakuru Graben with the nearest major modern plume to Mangatete being that of the Waiotapu-Waikite field, centered ~ 13 km to the east. A separate plume must be postulated as once present beneath Mangatete, which subsequently has been extinguished.

Electrical resistivity at depths <500 m (Schlumberger array spacing of 500 m) within active geothermal zones is <10 Ωm , while at Mangatete it is >150 Ωm (Stagpoole & Bibby, 1998) (Fig. 1). The very low resistivity beneath active fields (<10 Ωm) is therefore a consequence of the presence of mineral-laden hot water, and not of thermal alteration to produce electrically conducting minerals that would still be below Mangatete. An earlier study by Bibby et al. (1993a, b) mapped the immediate Mangatete region with Schlumberger array spacings of 500 m and 1000 m (Fig. 5) and found higher conductivity (<100 Ωm) nearer to the surface. This is consistent with hydrothermal alteration of sub-surface rocks to clays (Browne, 1978; Caldwell et al., 1986; Velde, 1995). Clays are relatively stable minerals that will retain their electrical conductivity long after

hydrothermal activity has ceased. Electrically conductive smectites are preserved near the surface; at a greater depth the higher pressure forms less conductive illites. Bibby et al. (1993b) showed the Mangatete Quarry to be situated at the NE tip of a thermal plume ~ 4 km long and ~ 1 km wide, extending west of Mangatete stream and south of Waikite Valley Rd, and approximating the NE-SW orientation of the regional faults.

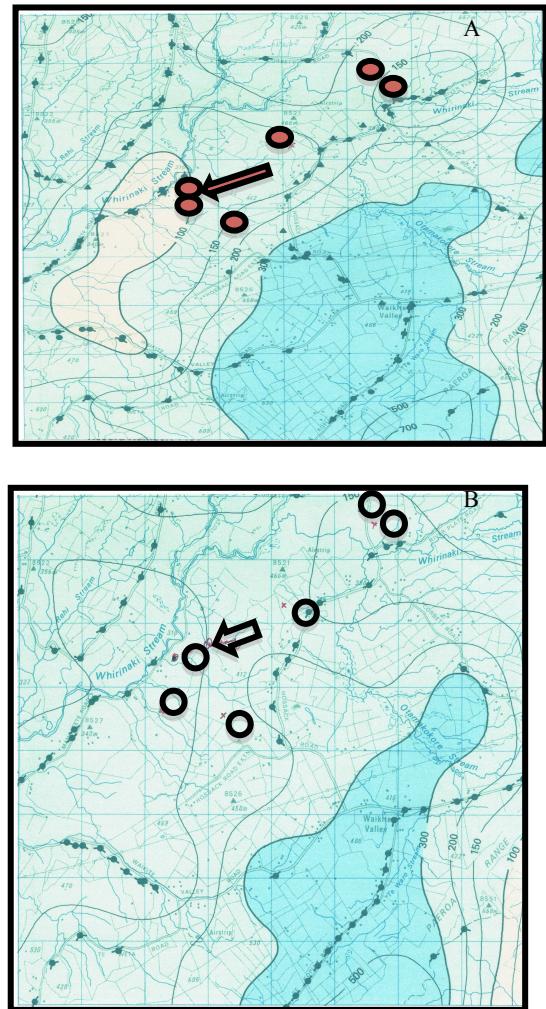


Fig 5 Electrical resistivity at Mangatete after Bibby et al., 1993. Schlumberger array spacing: A=500 m, B=1000 m. Light yellow = <100 Ωm , dark green = >300 Ωm . Arrow marks the quarries; circles mark HEB deposits. Grid squares at 1 km.

The need for a major thermal plume in the study area is enhanced when taking a wider view of the graben (Fig. 6). Additional HEBs are located 900 m to the south of North Quarry and 1200 m to the southeast. Additional HEBs are associated with large rhyolitic boulders preserving slickensides at two sites, 700 m apart, oriented parallel to the Whirinaki fault, and 700 m to the east. Two more HEBs are found NE from the North Quarry on Hossack Rd, and on Corbett Rd (at 1700 m and 3800 m distance respectively), and between them is the Whirinaki sinter (Holland, 2000, aka Otamokakore sinter) dated to ~ 60 -120 ka. These deposits follow the trend of the TFB, suggesting that they may be associated with a common structural weakness.

Approximately 5 km NW of this line of hydrothermal activity is a similar, parallel trend from the HEB at Parsons Rd to that at Waikaukau, including the Tahunaatara sinter (Campbell et al., 2004), which is overlain by the Ohakea loess (~26-17 kyr BP).



Fig. 6. Regional orientation of hydrothermal eruption breccia (yellow), rhyolitic boulders (red) and sinter (blue) in SW-NE parallel zones ~5 km apart.
—Photo: Google Earth

In summary, the Ngakuru Graben, currently a recharge zone devoid of geothermal activity, was the scene of significant geothermal activity in the past, expressed through two zones exploiting parallel structural weaknesses following the strike of the TFB, and lasting for at least 60 kyr.

4.3 Origin of the Mangatete thermal plume

Bibby et al. (1995) established that heat transfer through the base of the TVZ required magmatic intrusions into the lower crust in order to supplement the natural conductive heat flow. Some such event must have occurred beneath Mangatete, either by a rising pluton or dike. The present electrical resistivity beneath the graben shows that this heat has now dissipated. No further hydrothermal activity can occur within the Ngakuru Graben without thermal recharge from a new magmatic intrusion.

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