CALDERAS AND GEOTHERMAL SYSTEMS IN THE TAUPO VOLCANIC ZONE, NEW ZEALAND

C Peter Wood

Institute of Geological & Nuclear Sciences Ltd, Wairakei Research Centre
Taupo, New Zealand

Key Words: Calderas, Geothermal Systems, Taupo Volcanic Zone. New Zcaland

ABSTRACT

Silicic calderas and geothermal systems in the Taupo Volcanic Zone (TVZ) of New Zealand are spatially related. Eight calderas, active since 1.6 Ma, occupy 45% of the TVZ. Boundaries of calderas arc often speculative, but of 20 geothermal systems considercd, 15 occur on or next to a caldera margin where there is enhanced deep permeability: the best examples are at Haroharo where systems occur at the intersection of volcanic lineations and caldera embayments, and at Rotorua. Drillhole evidence supports a realignment of Whakamaru caldera margin through the Wairakei-Tauhara geothermal field. Four geothermal systems have no known caldera associations. Most calderas were shaped by eruptions around 0.35-0.15 Ma, and possibly many of the currently active geothermal systems originated in this period. However, there is no strong geological evidence for a genetic link between sub-caldera magma chambers and geothermal systems in the TVZ.

1. INTRODUCTION

Geothermal systems often occur in or adjacent to large, young, silicic caldera volcanoes. The association is predictable since a caldera marks where a large volume of magma has risen, possibly from a zone of crustal fusion, and lodged at shallow depths prior to catastrophic eruption. A caldera with a history of periodic cruption and collapse over tens to hundreds of thousands of years implies the existence of a stable heat source, high heat flow and perhaps continuously magma-charged chambers surrounded by large volumes of hot rock. Add to this the permeability created by collapse in deep-rooted fractures and surficial zones of slumped and brecciated rocks, and many factors conducive to the formation of a long-lived, large geothermal system are present.

Calderas and geothermal systems abound in the Taupo Volcanic Zone of New Zealand (TVZ), described as a type example of the association by Wohletz and Heiken (1992). However, there is no consensus that the association is more than random coincidence (Bibby et al., 1995). In particular, is there a genetic relationship or do calderas merely provide access to unrelated heat sources? Much new research on TVZ volcanism and geothermal activity has been presented in special volumes of Geothermics (Allis and Lumb, 1992; Hunt and Glover, 1994) and Journal of Volcanology and Geothermal Research (Simmons and Weaver, 1995). and a major radiometric dating study (Houghton ct al., 1994) has provided the first reliable chronological framework for the TVZ. Hence this is an opportune time to review the association of calderas and geothermal systems as a basis for further discussion about thc origin and development of geothermal activity in the TVZ.

2. TAUPO VOLCANIC ZONE

The Taupo Volcanic Zone (TVZ; Fig. 1) is the consequence of Pacific plate subduction beneath the North Island of New Zcaland. The thin continental crust (–15 km, Stem and Davey, 1987) spreads at rates up to 18 mm/year (Darby and Williams, 1991) rcsulting in active rifting and subsidence. Since c. 1.6 Ma, the central TVZ has been the most frequently active and productive region of rhyolitic volcanism on earth (Houghton et al., 1994). producing an estimated 10 000 - 15 000 km^3 of rhyolite, and subordinate dacite, andesite and basalt. Debate continues whether TVZ is a migrating andesitic arc and zone of asymmetric crustal spreading (eg. Stem, 1987), or an andesite-dacite arc with bimodal rhyolite-basalt back arc (eg. Cole, 1990). Whichever is the case, it is a matter of observation that most geothermal fields are contained within the area of rhyolite volcanism. There is general agreement that geothermal heat output is about 4 000 MW (Bibby et al., 1995), while Hochstein et al. (1993) estimate that 70% of the total heat transfer in the TVZ is by geothermal fluids.

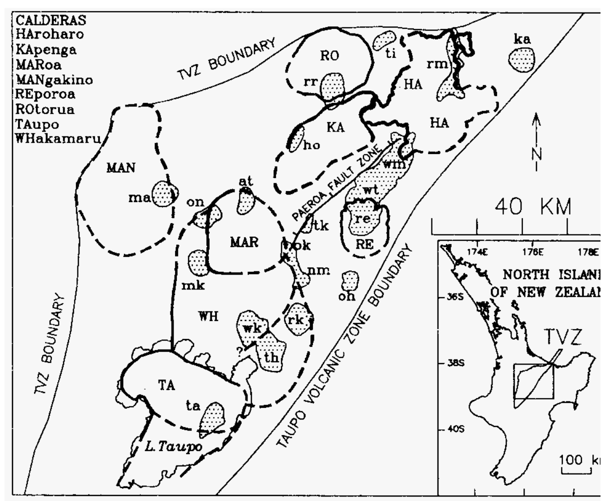

Figure 1. Map of the central Taupo Volcanic Zone showing caldera boundaries as heavy solid or dashed lines (where less certain). Geothermal fields are stippled areas labelled: at=Atiamuri, ho=Horohoro, ka=Kawerau, ma=Mangakino, mk=Mokai, nm=Ngatamariki, oh=Ohaaki, ok=Orakeikorako, on=Ongaroto, re=Reporoa, rk=Rotokawa, rm=Rotoma, rr=Rotorua, ta=Taupo, th=Tauhara, ti=Tikitere, tk=Te Kopia, wk=Wairakei, wm= Waimangu, wt=Waiotapu.

3. CALDERAS

Mangakino. Mangakino is oldest of the eight calderas active in the past 1.6 Ma (Fig. 1). Situated on the western edge of the TVZ, it is a 20 km-wide basin with a large negative gravity expression (Wilson et al., 1984). Dates on Mangakino-sourced ignimbrites bracket two periods of eruption and inferred collapse at c.1.6 - 1.45 Ma and 1.25 - 0.91 Ma (Houghton et al., 1994). No intracaldera lavas are known, but may be buried.

Kapenga and Rotorua. Kapenga volcanic centre was recognised as a caldera complex by Wilson et al. (1984) from its broad negative gravity anomaly, and is now considered by Houghton et al. (1994) to be the locus of at least three caldera-forming ignimbrite eruptions dating back to 1.04 Ma. The youngest is the Pokai Ignimbrite (Karhunen, 1993) erupted in the 0.31 - 0.22 Ma period, though Wood (1992) considered Pokai Ignimbrite might have a Rotorua source. The most recent eruptions from Kapenga occurred near its east margin next to Haroharo caldera, producing the 0.065 Ma Earthquake Flat Pyroclastics ignimbrite after a period of rhyolite dome effusion, but without caldera collapse. A few isolated rhyolite domes extruded between 0.22 Ma and 0.065 Ma occur in the northern part of the complex.

Rotorua caldera formed during the eruption of the Mamaku Ignimbrite (0.22 Ma, Houghton et al., 1994). Despite being a topographic basin with drillhole evidence of downfaulting and overthickening of Mamaku Ignimbrite across the southern boundary (Wood, 1992), the caldera lacks a distinct gravity anomaly (Hunt, 1992) and appears more as the northern continuation of the Kapenga gravity low, though separated from it by a narrow gravity high (Rogan, 1982). A large intracaldera rhyolite dome complex was built in the south prior to 0.065 Ma, with smaller, more central effusions at ≤20 ka (Wood, 1992). Large displacements of Mamaku Ignimbrite across the NW rim of the adjacent Kapenga caldera (~300m; C P Wood, unpub. data) raise the possibility of synchronous collapse of Rotorua and Kapenga following magma withdrawal from chambers lying beneath both calderas and erupted in the south of Rotorua caldera. The NW rim of Kapenga caldera coincides with, and is probably controlled by, SW-NE regional faulting which may account for some displacement of Mamaku Ignimbrite, but contemporaneous collapse of the two calderas would be consistent with the gravity observations.

Reporoa. Reporoa caldera has a marked gravity anomaly, and formed in a single episode when 100 km' of rhyolite magma erupted as the 0.24 Ma Kaingaroa Ignimbrites (Nairn et al., 1994). No subsequent large pyroclastic eruptions are known, and rhyolite and dacite lavas that poured into the caldera from the SW margin are now largely buried by lacustrine sediments (Wood, 1994). The north rim of the caldera is strongly scalloped.

Haroharo. Haroharo caldera is a central region of collapse surrounded by peripheral rhyolite domes together comprising the Okataina Volcanic Centre (Nairn, 1989). The caldera is irregularly shaped, with scalloped rims and prominent embayments (Fig. 2), and is more or less coincident with a large negative gravity anomaly (Rogan, 1982). Two collapse episodes are attributed to the 0.28 Ma Matahina Ignimbrite (Bailey and Carr, 1994) and 0.065 Ma Rotoiti Pyroclastics eruptions, since when Haroharo caldera has been progressively filled by rhyolite domes and associated pyroclastics from Haroharo and Tarawera volcanoes. Post-caldera vents strike obliquely in two SW-NE parallel bands, the Haroharo and Tarawera Linear Vent Zones (Naim, 1989). Wilson et al. (1984) used gravity and magnetic modelling to infer the presence of magma at 3km below sea level beneath the caldera centre. Haroharo is separated from Kapenga to the east (Fig. 1) by a narrow zone of higher gravity interpreted to be a basement ridge (Rogan, 1982). Many rhyolite domes were extruded between Haroharo and Kapenga with no clear separation in time or space.

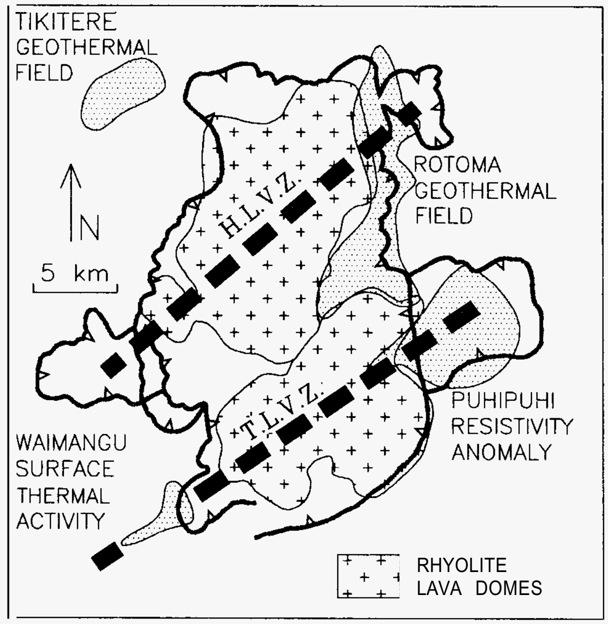

Figure 2. Haroharo caldera margin (after Nairn, 1989) is shown as a heavy toothed line. The Haroharo (H.L.V.Z.) and Tarawera (T.L.V.Z.) Linear Vent Zones cross the lava dome complexes of Haroharo and Tarawera volcanoes. Geothermal fields are shown as stippled areas: Rotoma and Puhipuhi areas are after Bromley et al. (1988). Waimangu covers the main area of surface activity along the rift of the 1886 Tarawera eruption. Tikitere geothermal field is extracaldera.

Maroa. Maroa caldera (Wilson et al., 1986) has a modest negative gravity anomaly coincident with the northern end of Whakamaru caldera. It has erupted basalt, rhyolitic ignimbrite and voluminous rhyolite lava from 0.3 Ma to 15 ka. Lava and ignimbrite volumes may each exceed 100 km'. Ohakuri Ignimbrite (0.27 Ma by Grindley et al., 1994, and 0.23 Ma by Houghton et al., 1994) is the oldest and largest inferred Maroa ignimbrite, possibly from an embayed basin in the north near Atiamuri where a geothermal well penetrated 580 m of ignimbrite (C P Wood, unpub. log) compared with less than 150 m at outcrop outside the basin. Because no single large (≥ 100 km^3) ignimbrite has an unequivocal Maroa source, Wilson et al. (1986) considered the caldera was produced by continued small-scale collapse over a long period.

Whakamaru The term "Whakamaru-group ignimbrites" was introduced by Wilson et al. (1986) for the products of caldera-forming eruptions from vents in the southern central TVZ that represent the most intense period of voluminous rhyolitic magma discharge in the region ever. They occur in most drilled geothermal fields and include the Wairakei, Rangitaiki, Whakamaru, Paeroa and Te Kopia ignimbrites. A series of $^{40}Ar/^{39}Ar$ ages bracket the 0.31 - 0.36 Ma period (Houghton et al., 1994) while zircon fission-track ages on Paeroa and Te Kopia ignimbrites span 0.34 - 0.38 Ma (Grindley et al. 1994). Detailed stratigraphic relationships and possible correlations between group members are as yet unresolved, so magma volumes cannot be estimated accurately but a total of >1000 km^3 seems likely.

The location of the eruptive vents is controversial. Grindley (1960) and Briggs (1976) sourced the Whakamaru Ignimbrite at Lake Taupo, and Lamarche and Froggatt (1993) suggested there were four vents in a 40 km-long belt from southem Lake Taupo to Maroa. Keall (1988) and Grindley et al. (1994) considered Paeroa ignimbrites came from **NE** of Maroa caldera near the Paeroa Fault scarp. Wilson et al. (1986, 1994) believe the most likely provenance for all Whakamaru-group ignimbrites is a single large Whakamaru caldera north of Lake Tdupo, which is the structure I discuss here in relation to geothermal activity.

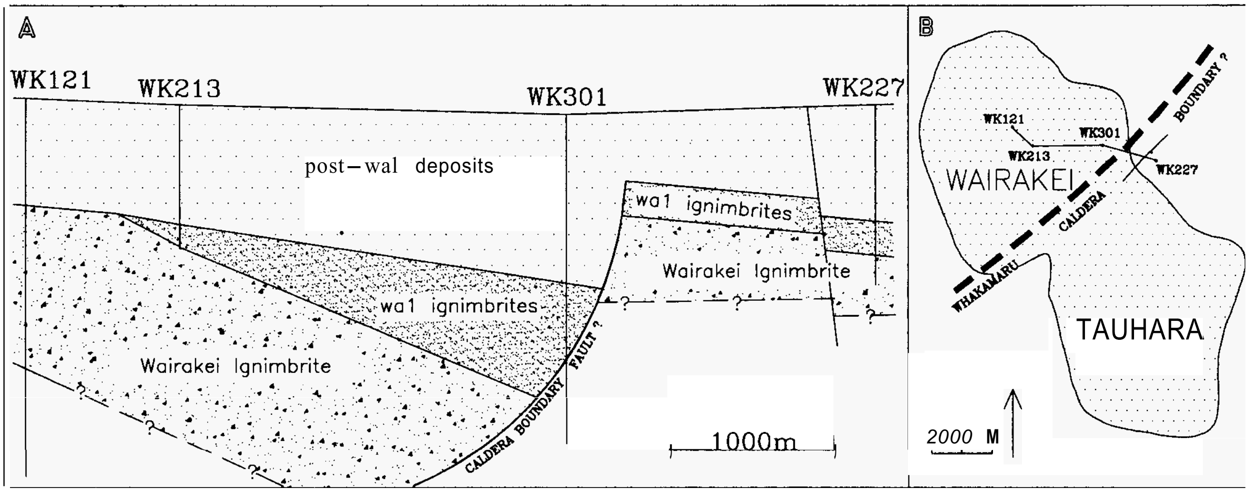

Figure 3. Schematic geological cross-section through 4 Wairakei drillholes, showing the postulated SE boundary of the Whakamaru caldera. Horizontal and vertical scales are equal.

The margins of Whakamaru caldera are poorly defined on all but the western side where rhyolite domes were extruded along N-S aligned boundary faults. West of these faults, Whakamaru Ignimbrite is <200 m thick, whereas geothermal wells inside the caldera at Mokai penetrated >600 m of overthickened ignimbrite downthrown by up to 800 m (C P Wood, unpub. logs). The north and south caldera margins are obscured by the younger Maroa and Taupo calderas, and the eastern boundary is largely speculative. To the SE, Wilson et al. (1986) suggested the boundary curved around the Rotokawa and Wairakei-Tauhara geothermal fields where drillhole data indicate that Wairakei Ignimbrite may be overthickened by intracaldera accumulation.

Here I present evidence that the caldera boundary may in fact pass through the Wairakei - Tauhara field (Fig. 3). The surface of Wairakei Ignimbrite dips at –30" from about 200 m below sea level (bsl) in well WK121 (where it is 960 m thick) to *460* m bsl in well WK213 (thickness unknown), interpreted by Healy (1984) as tilting of the ignimbrite down to the SE. In well WK227, 4.2km further east, the ignimbrite surface occurs at 500 m bsl. Between WK213 and WK227, well WK301 reached 1600 m bsl but Wairakei Ignimbrite was missing (ECNZ, 1992; C P Wood, unpub. log). Instead there were 450 m of Waiora Formation ignimbrites (wa, of Grindley 1965), greatly overthickened correlatives of units that directly overlie Wairakei Ignimbrite elsewhere in the geothermal field. The wa_1 ignimbrites may have come from vents within Whakamaru caldera northwest of Wairakei, and ponded in a depression between the tilted Wairakei Ignimbrite block and a listric boundary fault of the Whakamaru caldera along which the block collapsed and rotated. WK301 may have penetrated the fault as shown in Fig. 3. Regional subsidence and sedimentation in the Taupo-Reporoa depression have obscured and buried the caldera margin.

Taupo. Taupo volcano **is** the most frequently active rhyolitic centre in the TVZ, with major caldera-forming events documented at 22.6 ^{14}Cka and 1.85 ka (Wilson, 1993). Most collapse occurred during the 22.6 ka Oruanui eruption which produced an oval cauldron cut into the south side of Whakamaru caldera, now occupied by northern Lake Taupo. The southward extension of the caldera is less certain.

4. GEOTHERMAL SYSTEMS

The locations of geothermal systems (Fig. 1) are based essentially on electrical resistivity interpretations from various sources, supported by field observations and drilling data.

Mangakino. An area of low resistivity overlaps the postulated east caldera margin where small hot springs flowed prior to flooding by a hydro-lake on the Waikato River. The relationship between geological structure and thermal activity is unknown. An investigation well (MA1) confirmed 180°C fluid at *500* m depth, but hydrothermal alteration in cores indicated past temperatures ≥220°C (C P Wood, unpub. log), suggesting a waning system.

Rotorua and Kapenga. Rotorua geothermal system is located mainly in the south of Rotorua caldera, but extends south into Kapenga caldera (Bibby et al., 1992). Most surface activity occurs within *5* km of Rotorua caldera rim, where many shallow drillholes have tapped fluid up to 216°C (boiling for depth) contained in Mamaku Ignimbrite and lava dome aquifers, structurally controlled by arcuate caldera boundary faults and transverse regional faults (Wood, 1992). A small thermal area at Rotokawa within the east side of Rotorua caldera may be a separate system from that in the south (Bibby et al., 1992). Minor thermal manifestations occur close to the trace of the northern Kapenga boundary fault within 1 km of major hot springs inside Rotorua caldera boundary. Elsewhere in Kapenga caldera, modem thermal activity is limited to a small area at Horohoro near the west caldera boundary faults. Widespread old sinters and hydrothermal eruption breccias at Horohoro show that considerable surface discharge has occurred since 0.065 Ma, declining to the present mild activity.

Haroharo. There are a few, small hot-spring areas dispersed within Haroharo caldera, and two recognised geothermal fields (Waimangu-Rotomahana and Rotoma) at its margins (Fig. 2). Waimangu-Rotomahana geothermal system is located where the Tarawera Linear Vent Zone transects an embayment in the SW caldera boundary. Prior to the June 1886 eruption of Tarawera volcano, voluminous discharge of hot water was confined within the embayment near Rotomahana, but when basalt magma erupted through a 17 km-long rift across Mt Tarawera, the volcanic fissures opened new conduits that allowed the surface expression of the geothermal system to extend beyond the embayment and become the present Waimangu thermal area. The thermal effects of basalt dyke intrusion may have had less impact on the system than the pressure perturbations caused by drastic shallow hydrological changes (Simmons et al., 1993). Rotoma geothermal system is located at the intersection of Haroharo Linear Vent Zone and the Rotoma caldera embayment, structurally analogous to Rotomahana-Waimangu. Bromley et al. (1988) located a narrow belt of low resistivity associated with warm springs and fumaroles near Rotoma, extending south for 10 km along the scalloped caldera rim. South of Rotoma, the NW end of the Tarawera Linear Vent Zone passes through the Puhipuhi embayment, where Bromley et al. (1988) reported an area of low resistivity and altered ground that they attributed to a waning geothermal system.

Waiotapu and Reporoa. Waiotapu and Reporoa geothermal fields occur in the south of a 25 km-long belt of continuously low resistivity that includes Waimangu. Debate continues about the location of hydrothermal plumes and possible directions of lateral flows within this region (see Hunt and Glover. 1994). Waiotapu thermal area is located on the tilted, but relatively stable Paeroa Block lying between the eastern boundary of the TVZ and the Paeroa Fault Zone. A wide variety of thermal features occur in an 18 km^2 area extending north from the rim of Reporoa caldera. Waiotapu was drilled but never exploited, though three wells located between 0.3 km and 1.5 km from Reporoa caldera margin, encountered fluid at boiling-point-for-depth, with a maximum of 295°C measured at 1 000 m depth.

There are two areas of boiling springs and hot ground in the centre of Reporoa caldera where RPI drillhole recorded 240°C at 950 m depth. However, there are two thermal inversions in the temperature profile of RP1, and a continuous decline over the lower 300 m, suggesting that hot water does not rise as a plume in the middle of the caldera (Wood, 1994). Hedenquist and Browne (1989) modelled Waiotapu system as an upflow zone 1.5 km north of Reporoa with lateral flow southwards towards the caldera. Wood (1994) proposed that the area of upwelling extends from southern Waiotapu beneath the northern boundary of Reporoa caldera, whereas Bibby et al. (1994) interpreted resistivity data as an upflow centred to the NW of Waiotapu thermal area. Giggenbach et al. (1994) concluded from gas chemistry that the roots of two extinct volcanoes midway between Waiotapu and Waimangu were the main heat sources, with possibly another at depth below Reporoa caldera.

Maroa and Whakamaru. Maroa caldera is surrounded on all but the south side by active or extinct geothermal systems, but lacks significant thermal activity within the central part of the dome complex, On the SW side, Maroa domes form the east boundary of Mokai geothermal field which lies entirely within the surrounding Whakamaru caldera. Mokai has few surface features, but drill holes have proved a large, high-temperature (>300°C measured) system hosted in TVZ volcanics and sediments penetrated to 2100 m bsl. Ongaroto recistivity anomaly, 10 km north of Mokai in the Waikato River valley, coincides with the postulated intersection of the Whakamaru and Maroa calderas. Much of the anomaly may be lateral outflow from Mokai (Bibby et al., 1995) though a more direct feed cannot be discounted.

Atiamuri thermal area is situated on the north margin of Maroa caldera in the basin inferred to be the source of the Ohakuri Ignimbrite. A temperature of 165°C at 600 m depth was measured in the only drillhole, though hydrothermal alteration in cores indicated ≥200°C in the past (C P Wood, unpub. log). Another indication of declining geothermal activity along the north side of Maroa is the exposed, fossil hydrothermal system at Ohakuri, due east of Atiamuri (Henneberger, 1988). On the SE margin of Maroa caldera, voluminous hot springs discharge from Orakeikorako geothermal system at the projected conjunction with the eastern boundary of Whakamaru caldera, and the Paeroa Fault Zone. Displacements of ignimbrite sheets and variations in tuffaceous sediment thicknesses in Orakeikorako drillholes indicate faulting and deposition possibly related to collapse and infilling of Maroa caldera (Browne and Lloyd, 1987).

A continuous zone of low resistivity connects Orakeikorako with Ngatamariki to the south, though Bibby et al. (1995) regard them as separate geothermdl systems. Wilson et al. (1986) considered that the eastern boundary of Whakamaru caldera controlled the N-S alignment of rhyolite domes on the west side of Ngatamariki. One deep (2700 m) drillhole at Ngatamariki penetrated a diorite pluton surrounded by a phyllic alteration aureole unrelated to the modem hydrothermal system. The age of the diorite is unknown, but the intrusion predated the eruption of Whakamaru-group ignimbrites (Browne et al., 1992), and can be linked to neither caldera collapse nor the present geothermal system.

The location of the SE boundary of the Whakamaru caldera in relation to the Wairakei-Tauhara and Rotokawa geothermal fields is speculative. Wilson et al. (1986) drew their boundary around the fields but if it is much further to the NW, as shown in Fig.3, then most or all of Rotokawa and Tauhara fields lie close to, but outside the caldera, whereas most of Wairakei is within. The deep upflow zone at Wairakei has not been precisely located but must be inside the Whakamaru caldera.

Taupo. In the east side of Taupo caldera, low resistivity and high heat flow in Lake Taupo surround a submerged lava plug in the vent of the 1.85 ka Taupo eruption, which may have created deep-reaching permeability that has facilitated the rise of a geothermal plume (Bibby and Caldwell, 1992). Hydrothermally altered lithic clasts found in the deposits ofthe ^{14}C 22.6 ka eruption that created most of the caldera (Wilson, 1993) imply that a geothermal system existed at Taupo prior to caldera collapse.

Extracaldera Geothermal Systems. Kawerau, Ohaaki, Tikitere (including Taheke) and Te Kopia geothermal areas are neither at the margin of, nor in any known caldera. Kawerau and Ohaaki are close to the eastern edge of the TVZ, where deep drillholes have penetrated 1-2 km of Quaternary volcanics overlying Mesozoic basement that is progressively faulted down from SW to NE. Tikitere lies in a graben trending NE from Rotorua caldera, close to the NW side of Haroharo caldera, but despite this proximity there is no strong evidence to link the geothermal system with either caldera. Te Kopia thermal area is located on the Paeroa Fault scarp 10 km NE of Orakeikorako, and the two systems may be connected at depth (Bignall and Browne, 1994).

5. DISCUSSION

Calderas and geothermal fields occupy 45% and 8% of the area of the TVZ respectively so some spatial overlap by chance can be expected. For a correlation to be meaningful, geothermal activity should occur in a systematic volcanic or structural association with calderas. Mere co-location is insufficient evidence for a genetic connection. Significant associations include a) intracaldera lava dome complexes which may overlie magma and have a permeable volcanic substructure, b) extensional fault zones crossing resurgent structural domes (not known in the TVZ), c) caldera ring faults that penetrate deep into the zone of magma accumulation and may be the loci for intrusions, d) caldera margins where listric collapse faults, megabreccias and pumiceous tuffs provide good permeability, and e) the intersections of tectonic or volcanic lineations with caldera structures.

The summary of caldera-geothermal system associations (Table 1) lists only Taupo, hidden beneath a lake, as solely intracaldera. Taupo geothermal system may be located on permeable ring faults or in a brecciated vent facies of the 1.85 ka eruption. If Wilson et al. (1986) are correct, Wairakei and Tauhara may also lie completely within a caldera, but if so, their geology and structure provide no information to decide whether the association is genetic or fortuitous. Most of the TVZ systems lie across or next to a caldera margin, though the precise position and nature of the boundary has been obscured by regional subsidence and faulting in many cases. Rotoma and Waimangu are good examples of systems developed where profound volcanic structures meet a scalloped caldera rim, and at Rotorua, hot spring locations and drilling data clearly place the system in the arcuate collapse zone at the caldera margin.

Table 1. Caldera associations of central TVZ geothermal systems. Estimates of the total heat output in megawatts (MW) are from the summary in Bibby et al. (1995).

System	Extra	Margin	Intra	MW
Kawerau	x			100
Te Kopia	x			150
Tikitere	x			120
Ohaaki	x			~140
Atiamuri		x		10
Mangakino		x		4
Ngatamariki		x		38
Ongaroto		x		?
Orakeikorako		x		–340
Rotoma		x		220±60
Rotorua		x		470±50
Waimangu		x		325±80
Taupo			x	120
Rotokawa	x	x		300
Waiotapu	x	x		540
Horohoro		x	x	4
Mokai (+ Ongaroto)		x	x	400± 160
Reporoa		x	x	15
Wairakei		x	x	420
Tauhara	x	x	x	110

The structure of other marginal systems is less obvious, and their near-surface (to c. 2km depth) dimensions may have been strongly influenced by regional faulting and local stratigraphy even though underlying caldera ring faults may have provided necessary deep permeability in the basement. A caldera margin is important not just for its intrinsic permeability, but also because it could be the locus for post-caldera intrusions (and related extrusions) large enough to generate a hydrothermal convection cell. This may be the case at Rotorua where the main complex of intracaldera rhyolite domes occurs close to the southern boundary, possibly over concealed ring faults. At Maroa, domes largely fill the caldera and overlap its boundaries, suggesting magma bodies located beneath the caldera margin provided energy for the peripheral geothermal systems.

The time-span of the TVZ geothermal systems is largely unknown. Browne and Lloyd (1987) reported estimates of >0.2Ma for Kawerau, and ~0.3Ma for Ohaaki and Wairakei. Wood (1994) suggested that Waiotapu and Reporoa systems postdate the 0.24Ma formation of Reporoa caldera. Catastrophic eruption of many large ignimbrites occurred in the 0.35-0.15Ma period (Houghton et al. 1994), and only extinct Mangakino and youthful Taupo are not known to have been shaped by these caldera-forming events. Possibly many of the currently active geothermal systems were generated, or at least enhanced, by the large magma chambers that must have accumulated in the upper crust during this period.

The total heat output of central TVZ geothermal systems can be grouped according to their caldera associations only within broad limits because the position of some of the largest systems is equivocal. Extracaldera systems account for 13-31%, intracaldera systems from 25-36%, and marginal systems from 35-66% heat output.

In summary, this review of the caldera-geothermal system relationship in the TVZ suggests that caldera margins provide permeability that gives groundwater access to deep heat sources. Surprisingly, hydrothermal convection cells are not common at the surface in areas where voluminous intracaldera rhyolite domes have accumulated, presumably directly above the sub-caldera magma chambers (though this may be true in some specific instances). Hence a genetic link between caldera-forming magmatism and geothermal systems cannot be directly proven.

ACKNOWLEDGEMENTS

I am grateful to my many colleagues involved in volcanological and geothermal research in the TVZ for sharing their thoughts and giving access to unpublished data. Funded by the Foundation for Research, Science and Technology. Institute of Geological and Nuclear Sciences contribution 439.

REFERENCES

Allis, R.G. and Lumb. T. (1992): Editors of Special Issue. Rotorua Geothermal Field, New Zealand. Geothermics. 317p.

Bibby, H.M.; Caldwell, T.G.; Davey, F.J. and Webb, T.H. (1995): Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. Journal of Volcanology and Geothermal Research: TVZ Special Volume (in prep.).

Bibby, H.M.; Dawson, G.B.; Rayner, H.H.; Bennie, S.L. and Bromley, C.J. (1992): Electrical resistivity and magnetic investigations of the geothermal systems in the Rotorua area, New Zealand. Geothermics, 21: 43-64.

Bignall, G. and Browne, P.R.L. (1994): Evolution of the Te Kopia thermal area, Orakeikorako - Te Kopia geothermal system, Taupo Volcanic Zone, New Zealand. Geothermics (in press).

Briggs, N.D. (1976): Welding and crystallisation zonation in Whakamaru ignimbrite, central North Island, New Zealand. NZ J. Geol. Geophy., 19: 189-212.

Bromley, C.J.; Bottomley, J.J. and Pearson, C.F. (1988): Geophysical exploration for prospective geothermal resources in the Tarawera Forest. Proceedings 10th NZ Geoth. Workshop: 123-128.

Browne, P.R.L.; Graham, I.J.; Parker, R.J. and Wood, C.P. (1992): Subsurface andesite lavas and plutonic rocks in the Rotokawa and Ngatamariki geothermal systems, Taupo Volcanic Zone, New Zealand. J. Volc. Geoth. Res. 51: 199-2 15.

Browne, P.R.L. and Lloyd, E.F. (1987): Water-dominated geothermal systems and associated mineralisation. NZ Geological Survey Record 22: 85-152.

Caldwell, T.G. and Bibby, H.M. (1992): Geothermal implications of resistivity mapping in Lake Taupo. Proc. 14th NZ Geoth. Workshop: 207-212.

Cole, J.W. (1990): Structural control and origin of volcanism in the Taupo Volcanic Zone, New Zealand. Bull. Volcanol.52: 445-449.

Darby, D.J. and Williams, R.O, (1991): A new geodetic estimate of deformation in the Central Volcanic Region of the North Island, New Zealand. NZ J. Geol.Geophys.34 127-136.

ECNZ (1992): Resource consent application for reinjection: Wairakei Geothermal Field. Electricorp Production, Taupo, 208p.

Giggenbach, W.F.; Sheppard, D.S.; Robinson, B.W.; Stewart, M.K. and Lyon, G.L. (1994): Geochemical structure and position of the Waiotapu Geothermal Field, New Zealand. Geothermics (in press).

Grindley, G.W. (1960): Geological Map of New Zealand 1 : 250 000 Sheet 8 Taupo. New Zealand Geological Survey, DSIR, Wellington, New Zealand.

Grindley, G.W. (1965): The geology, structure and exploitation of the Wairakei Geothermal Field, Taupo, New Zealand. New Zealand Geological Survey Bulletin 75.

Grindley, G.W.: Mumme, T.C. and Kohn, B. (1994): Stratigraphy, paleomagnetism and geochronology of silicic volcanic rocks in relation to hydrothermal events, Waiotapu/Paeroa Range area, New Zealand. Geothermics (in press).

Healy, J. (1984): Wairakei geothermal field in review. Unpublished New Zealand Geological Survey Geothermal Circular JH/10.

Hedenquist, J.W. and Browne, P.R.L. (1989): The evolution of Waiotapu geothermal system, New Zealand, based on the chemical and isotopic composition of its fluids, minerals and rocks. Geochim. Cosmochim. Acta 53: 2235-2257.

Henneberger, R.C. (1986): Ohakuri fossil epithermal system. In Henley, R.W., Hedenquist, J.W. and Roberts, P.J. (Eds) Guide to the active epithermal (geothermal) systems and precious metal deposits of New Zealand. Monograph series on Mineral Deposits 26: 121-128. Gebruder Borntraeger, Berlin.

Hochstein, M.P.; Smith, I.E.M.; Regenauer-Lieb, K. and Ehara, S. (1993): Geochemistry and heat transfer processes in Quaternary rhyolitic systems of the Taupo Volcanic Zone, New Zealand. Tectonophys. 223: 213-235.

Houghton, B.F.; Wilson, C.J.N.; McWilliams, M.; Lanphere, M.A.; Weaver, S.D.; Briggs, R.M. and Pringle, M.S. (1994): Volcanic and structural evolution of a large silicic magmatic system: central Taupo Volcanic Zone, New Zealand. Geology (subjudice).

Hunt, T.M. (1992): Gravity anomalies, caldera structure, and subsurface geology in the Rotorua area, New Zealand. Geothermics, 21: 65-74.

Hunt, T.M. and Glover, R.B. (1994): Editors of Special Issue. The Waiotapu, Waimangu and Waikite Geothermal Systems, New Zealand. Geothermics (in press).

Karhunen, R.A. (1993): The Pokai and Chimp ignimbrites of the NW Taupo Volcanic Zone. Unpublished PhD Thesis University of Canterbury, Christchurch, New Zealand.

Keall, J.M. (1988): Volcanology and ignimbrite stratigraphy along the Paeroa Fault, Taupo Volcanic Zone. Unpublished PhD Thesis, University of Canterbury, Christchurch, New Zealand.

Lamarche, G. and Froggatt, P.C. (1993): New eruptive vents for the Whakamaru Ignimbrite (Taupo Volcanic Zone) identified from magnetic fabric study. NZ J Geol. Geophys, 36: 213-222.

Nairn, I.A. (1989): Geological Map of New Zealand 1 : 50 000 Sheet U16AC, Mount Tarawera. New Zealand Geological Survey, DSIR, Wellington, New Zealand.

Nairn, I.A.; Wood, C.P. and Bailey, R.A. (1994): The Reporoa Caldera, Taupo Volcanic Zone: source of the Kaingaroa Ignimbrites. Bull. Volcanol. (in press).

Rogan, A.M. (1982): A geophysical study of the Taupo Volcanic Zone, New Zealand. J. Geophys. Res., 87: 4073-4088.

Simmons, S.F.; Keywood, M.; Scott, B.J. and Keam, R.F. (1993): Irreversible change of the Rotomahana-Waimangu hydrothermal system (New Zealand) as a consequence of a volcanic eruption. Geology, 21: 643-646.

Simmons, S.F. and Weaver, S.D. (1995): Editors of Special Volume. Magmatism, Geothermal Activity and Heat Transfer in the Taupo Volcanic Zone of New Zealand. Journal of Volcanology and Geothermal Research (in prep.).

Stern, T.A. (1987): A symmetric back-arc spreading, heat flux and structure associated with the Central Volcanic Region of New Zealand. Earth & Plan. Sci. Let.. 85: 265-276.

Stem, T.A. and Davey, F.J. (1987): A seismic investigation of the crustal and upper mantle structure within the Central Volcanic Region of New Zealand. NZ J. Geol. Geophys., 30: 217-231.

Wilson, C.J.N. (1993): Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo volcano, New Zealand. Phil. Trans. Roy. Soc. Lond. A 343: 205-306.

Wilson, C.J.N.; Houghton, B.F.; McWilliams, M.O.; Lanphere, M.A.; Weaver, S.D. and Briggs, R.M. (1995): Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review and synthesis. Journal of Volcanology and Geothermal Research: TVZ Special Volume (in prep.).

Wilson, C.J.N.; Houghton, B.F. and Lloyd, E.F. (1986): Volcanic history and evolution of the Maroa-Taupo area, central North Island. In I.E.M. Smith (Ed.) Late Cenozoic Volcanism in New Zealand. Roy. Soc. NZ Bull., 23: 194-223.

Wilson, C.J.N.; Rogan, A.M.; Smith, I.E.M.; Northey, D.J.; Nairn, I.A. and Houghtor, B.F. (1984): Caldera volcanoes of the Taupo Volcanic Zone, New Zealand. J. Geophys. Res., 89: 8463-8484.

Wohletz, K. and Heiken, G. (1992): Volcanology and Geothermal Energy. Univ. California Press, Berkeley, 432p.

Wood, C.P. (1992): Geology of the Rotorua geothermal system. Geothermics, 21: 25-41.

Wood, C.P. (1994): Aspects of the geology of Waimangu, Waiotapu, Waikite and Reporoa geothermal areas, Taupo Volcanic Zone, New Zealand. Geothermics (in press).