TECTONIC SETTINGS OF LOW ENTHALPY GEOTHERMAL SYSTEMS IN NEW ZEALAND: A REVIEW

A. G. REYES & R. JONGENS

Institute of Geological and Nuclear Sciences, 30 Gracefield Road, Lower Hutt, New Zealand

SUMMARY – Low-enthalpy geothermal resources are widely distributed in New Zealand and include (1) hot spring systems with <90°C discharge temperatures in the North and South Islands and offshore islands in the north, (2) periphery of high-enthalpy geothermal systems within the Taupo Volcanic Zone, (3) 120-160°C waters at >3.5 km depth in abandoned oil wells and (4) natural heat flow 15-20 m below the surface. Hot spring systems in New Zealand are found in four major tectonic settings characterised by: (1) subduction-related volcanism and rifting in the Taupo Volcanic Zone, (2) intraplate volcanism and associated hot mantle upwelling, (3) rapid rise of hot waters introduced along fractures in the East Cape accretionary prism of North Island, (4) rapid uplift and thrusting in the Alpine Fault and parts of the East Cape. Most hot spring waters, outside the main high-enthalpy geothermal areas, Taupo Volcanic Zone and Ngawha, are derived from deeply circulating groundwaters that may bear some imprints of mantle-derived volatiles, saline formation water or metamorphic water. Within the accretionary prism in the East Cape of North Island, reservoir waters originate from seawater and dehydration of marine clays. Although New Zealand has an installed capacity of 308 MWt, its vast geothermal resources remain largely untapped for direct utilisation of heat.

Keywords – New Zealand, low enthalpy waters, geothermal, tectonics, hot springs

1. INTRODUCTION

In some countries all heat energy stored below 15-20 m from the surface, where geothermal heat flux dominates, is regarded as a geothermal resource (Rybach and Sanner, 2000). With this new definition, almost all of New Zealand can be regarded as a geothermal resource as the temperature range of a geothermal resource is expanded from <20 to >300°C.

The 1991 Resource Management Act of New Zealand arbitrarily refers to >30°C waters as geothermal and <30°C as groundwater. As pointed out by Hunt (1996), there is no scientific basis to this division. Hunt (1996) defines geothermal waters with temperatures <100°C as low-temperature and those with >100°C as high-temperature. The division between low- and high-enthalpy geothermal fluids can be set at 180°C. Power can be generated from high-enthalpy fluids at >180°C, using flash steam turbines. Low–enthalpy fluids at <180°C are harnessed for power using binary cycle plants (70-180°C) and for direct use of heat (Ellis and Mahon, 1977).

Grindley and Williams (1965) and Wood (1978) divided hydrothermal activity in New Zealand into four types: (1) direct volcanic exhalations on the flanks of Tongariro; (2) high intensity fields in active volcanic areas in the TVZ; (3) low intensity fields in decadent volcanic areas such as Ngawha, Coromandel, Waikato and Banks Peninsula; and (4) non-volcanic hot springs found along fault systems in South Island and areas in eastern North Island such as Morere and Te Puia. We revise this division in terms of the spatial distribution of geothermal systems with respect to tectonic setting and sources of fluids and anomalous heat.

2. DIRECT USE OF GEOTHERMAL HEAT

New Zealand has an installed power generating capacity of 437 MWe provided by five geothermal systems in the Taupo Volcanic Zone (TVZ) and one at Ngawha in Northland, where a binary plant produces 9 MWe (Lund and Freeston, 2001).

In 1994 New Zealand was ranked 7th in the world for direct usage of geothermal energy, having an installed capacity of 264 MWt (Fridleifsson, 1996). At the end of 1999, the installed capacity for direct usage in New Zealand was 308 MWt (Lund and Freeston, 2001), mostly produced from waste waters and waste steam in the power-generating Kawerau, Ohaaki, and Wairakei geothermal systems. The largest user of direct

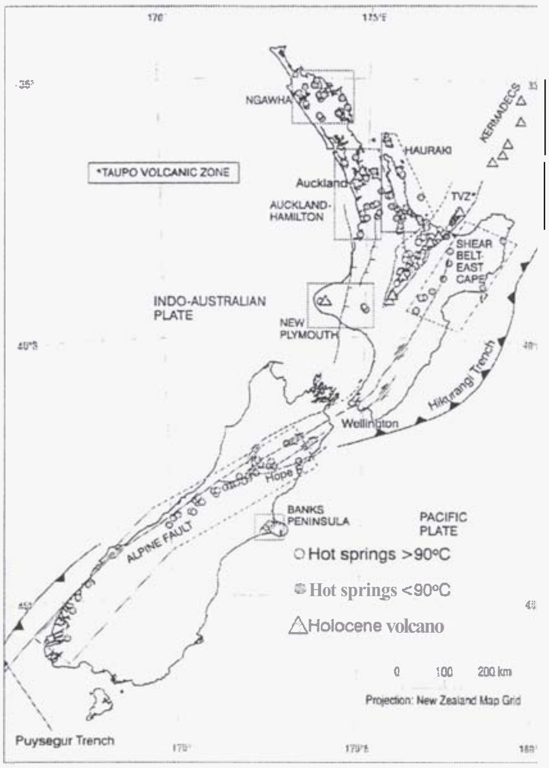

Figure 1 - Major tectonic structures of New Zealand, location of Recent volcanoes and hot-springs (Mongillo and Clelland, 1984; Aitchison, 1985; Petty et al, 1987; Allis and Shi, 1995; Allis et al., 1998; de Ronde et al., 2001; DSIR and GNS unpublished reports).

heat is the Tasman Pulp and Paper Mill in Kawerau, where a 210 MWt plant generates clean process steam for timber- and paper-drying, electricity generation and maintaining a greenhouse. Other cascade uses of geothermal fluids fkom the two other power-generating systems include prawn farming and drying of agricultural products. About 49 MWt is used for space-heating, bathing and swimming (Thain and Freeston, 1995, Thain and Dunstall, 2000; Lund and Freeston, 2001). Given the vast geothermal resources available in New Zealand, direct usage of heat is under utilised and hence, could be greatly expanded.

3. TECTONIC SETTING

The New Zealand micro-continent straddles the boundary zone between the Pacific and Indo-Australian plates. The oblique convergence of these two plates has established conversely dipping subduction zones along the eastern margin of the North Island (Hikurangi trench) and southwest of Fiordland (Puysegur trench) (Fig. 1). Linking the two subduction zones are the Alpine Fault and Marlborough Fault System, together representing a trench-trench transform.

Along the eastern margin of the North Island, westward subduction of the Pacific plate beneath the continental crust forms the Hikurangi trench. An actively growing accretionary prism, partly exposed on land in the east coast of North Island, has formed along the converging edges of the two plates (Davey et al., 1986) and is backed by a zone of strike-slip shear along the North Island axial ranges. Further west, subduction is manifested by active andesitic volcanism, crustal thinning, rifting, subsidence, high heat output and massive rhyolitic volcanism of the TVZ (Stem 1987; Gamble et al., 1993; Bibby et al., 1995). The effect of subduction is further observed in the Quaternary Taranaki volcano, located 140 km SW of the TVZ (Downey et. al., 1994).

The Alpine Fault is a zone of transpression where the Indo-Australian plate is being forced beneath the South Island resulting in uplift of the Southern Alps. North of the Alpine Fault, the transform breaks into a system of major strike-slip faulting and deformation (Marlborough Fault System) and accommodates the transition to Hikurangi trench subduction. At the southern end of the Alpine Fault, offshore Fiordland, the transition to subduction along the Puysegur trench is more abrupt. The transition is controlled by inherited structures that may have resulted in tearing of the down-going Indo-Australian plate (Lebrun et al., 2000). Immediately adjacent to the plate boundary is the Fiordland basement block which began rising in the Late Miocene and continues today (Turnbull et al., 1993). On Solander Island, immediately south of Fiordland, subduction-related andesites outcrop (Reay, 1986).

Northland, Auckland, and the Coromandel Peninsula record a succession of Miocene to Early Pleistocene arc-related volcanism that relates to the Australian-Pacific convergent margin migrating southeastwards to its present position. Late Miocene to Recent basaltic intraplate volcanism occurs in the Northland and Auckland-Hamilton regions (Smith, 1989; Smith et al., 1993) although some in the Kawhia (Hamilton) area have a convergent margin signature (Briggs et al., 1989). In the South Island, intraplate volcanism was widespread in the Cenozoic. Early to middle Tertiary volcanism was probably related to a mildly extensional or tectonically stable regime following the opening of the Tasman Sea (Weaver et al., 1989). During the Miocene, large intraplate shield volcanoes erupted at Banks Peninsula and Dunedin. Intraplate basalts of Pliocene age (2.5 Ma) occur in South Canterbury (Smith, 1989).

4. MAJOR HOT SPRING AREAS

In New Zealand there are several sources of low-enthalpy heat: (1) hot spring systems with discharge temperatures <90°C in the North and South Islands and outlying islands, (2) edges or boundaries of high-enthalpy geothermal systems in the TVZ, (3) 120-160°C waters at >3.5 km depth in abandoned oil wells and (4) natural heat flow 15-20 m below the surface.

New Zealand has more than 150 reported hot springs (Mongillo and Clelland, 1984; Petty et al., 1987) with >80% occurring in North Island, islands in the Hauraki Gulf and Bay of Plenty and seabed and <20% in the South Island. In this paper, hot springs in New Zealand are divided into 9 geographical regions: Ngawha (Northland), Auckland-Hamilton, Hauraki, TVZ, Shear Belt-East Cape and Taranaki in North Island; Banks Peninsula and Alpine Fault in South Island (Fig. 1). All boiling hot springs and springs with >90°C discharge temperatures occur in the TVZ. The temperature range of hot and warm springs outside the TVZ is c. 22°C to 87°C (Table 1). Cold springs and oil seeps are widespread along the North Island east coast, New Plymouth area and northern South Island, with relatively fewer localities in Ngawha and southern South Island (Townend, 1999).

4.1 Taupo Volcanic Zone

Tectonically, the TVZ is characterised by a broad band of crustal rifting, dominated by large-scale rhyolitic volcanism, in the west, and a line of Quaternary arc-type andesitic volcanoes on its eastern margin. The TVZ is the most active Quaternary rhyolitic system in the world in terms of fi-equency and productivity of eruptions (Wilson et al., 1995). It has a total extrusive magma flux of c. $0.3 m^3/s$, super-imposed by a geothermal heat flux of 4200 + 400 MW, equivalent to another $1.2 m^3/s$ of magma intruded into the crust (Hochstein, 1995). Among active centres of large-scale rhyolitic volcanism world-wide, the TVZ exhibits the highest intensity of crustal heat transfer (c. 2600 MW/100 km), with most of the heat transferred by hydrothermal fluid convection (Hochstein, 1995). Reasons for the anomalously high heat flux and massive rhyolitic eruptions in the TVZ (e.g., Hochstein, 1995 and references therein) are not fully resolved.

About 20 geothermal systems, separated from each other by c. 15 km, occur in the TVZ (Weir, 1998). Thermal spring discharge temperatures in the TVZ vary from near ambient to 99°C. On average, reservoir temperatures in the TVZ geothermal systems range from 260-280°C, with temperatures of 325-330°C measured in Mokai and Rotokawa wells (1994).

Giggenbach (1995) recognised two distinct source fluids in the TVZ geothermal systems, in keeping with its dual tectonic make-up. Along the E margin, geothermal well discharges have CO_2/Cl, B/Cl and Li/Cs ratios and CO_2 contents higher than those located in the W. In the E, the $CO_2/^3He$ and N_2/Ar ratios suggest contribution from subducted marine sediments whereas volatiles in the western geothermal systems, within the zone of rifting, have a mantle-derived signature. Fluids in the E contain about 14% arc-type magmatic component, compared with only 6% in the W (Giggenbach, 1995).

4.2 Ngawha, Northland

The latest episode of volcanism in Northland is dominated by Late Miocene to Recent basalts. Geochemical variations in basalt compositions led Smith et al. (1993) to invoke a layered sublithospheric mantle, beneath Northland, where the upper layer has an arc-type geochemical signature inherited from an earlier period of plate convergence. The Ngawha geothermal system is located in an area of Quaternary basalts in Kaikohe, within an ENE fault block, where the age of basalts ranges from 0.06 to 1.4 Ma (Skinner, 1986; Smith et al, 1993). The thermal anomaly in the geothermal system is believed to be related to felsic magma at depth deduced fi-om the presence of a rhyolitic lava dome near Kaikohe (Smith et al., 1993).

In 1998, a 9 MWe capacity power plant was commissioned in Ngawha, with another 15 MWe planned for the future (Huttrer, 2001).

About 20 springs, with discharge temperatures of 20° to 87°C, occur in the area. A large quantity of gas, dominated by CO_2, is being discharged from the thermal manifestations. Native Hg at Ngawha Springs was mined until 1934 (Petty et al., 1987). Of the springs, 50% are HCO_3-rich, 25% Cl-rich and 25% acid-SO_4. The majority of the HCO_3 springs are formed by absorption of CO_2 into groundwater. The Ngawha deep reservoir is characterised by high gas concentrations and neutral pH Cl waters high in B contents (Sheppard and Giggenbach, 1985). Waters at depth have equilibrated at a temperature of 230-235°C (Giggenbach, 1991), consistent with measured temperatures in most of the wells. In one well however, >320°C was intersected at 2255 m (Mongillo, 1985).

Deep fluids in Ngawha are affected by absorption of a mantle-type gas, caused by hydrothermal scavenging of ^3He from a solidifying basaltic magma at depth (Giggenbach et al., 1993a). Stable isotope values of ^{18}O and D (Sheppard and Giggenbach, 1985) fi-om deep well discharges imply a high arc-type magmatic component that seems to corroborate the model of a layered sublithospheric mantle (Smith et al., 1993).

4.3 Auckland-Hamilton

About 12 thermal springs have been mapped north of Auckland and between Auckland and Hamilton. Spring discharge temperature is as high as 71°C in L. Waikare although most are 50-65°C.

Waters discharged from >50 shallow domestic wells (<436m) in Auckland have temperatures ranging from above ambient, at 14°C, to 63°C (KRTA Ltd, 1986). The B/Li ratio of the domestic borehole waters is >1 and is probably due to equilibration of shallow heated groundwater with sedimentary formations. Neutral pH Na-CI waters have a calculated reservoir temperature of 100-150°C.

Although Auckland has the youngest Quaternary intraplate basalt volcano in the country (750 yr B.P.; Smith, 1989), Rangitoto, no springs occur in its immediate vicinity. However, warm springs are reported in East Tamaki and Whitford (Edbrooke, 2001) located c.18 kms SE of Rangitoto; and c. 8 kms SE of the 9000-9300 yr B.P. basaltic Mt. Wellington eruptive products (Heming and Barnet, 1977). There may be a causal relationship between Quaternary basaltic magmatism and the warm springs in Auckland. However, stable isotope analysis indicates heated meteoric waters (Hochstein, 1978). The predominance of N_2 in the gas discharges further supports the absence of any magmatic contribution to the chemical composition of the springs (Giggenbach et al., 1993a). Despite the absence of mantle and magmatic signatures in the spring discharges, Giggenbach et al. (1993a) argue that the presence of intraplate basaltic volcanic fields in the area still suggests that upwelling hot mantle most likely contributes to the high convective heat flow (Table 1).

4.4 Hauraki

The Hauraki Volcanic Region is characterised by episodic Miocene to Pleistocene volcanism of andesitic-dacitic and rhyolitic composition. It includes the Coromandel Range, Paeroa, Tauranga and islands in the Hauraki Gulf (Skinner, 1986) and occurs within the Hauraki continental rift (Hochstein et al., 1986). The Hauraki springs discharge neutral pH Na-CI and Na- HCO_3 heated groundwaters, with temperatures as high as 85°C in Te Aroha and 71°C in Hot Water Beach (Hochstein, 1978). Although all discharging thermal waters in Hauraki are heated groundwater, water flowing from one shallow well may contain saline pore waters (Hochstein and Nixon, 1979). Within Hauraki, heated groundwaters have equilibrated to 225°C at depth. However the calculated reservoir temperature of 265°C, from shallow well discharges in Tauranga, is higher (Simpson and Stewart, 1987). Thermal activity in Hauraki cannot be directly attributed to Quaternary volcanism but instead may be caused by a hot upper mantle swell (Hochstein and Nixon, 1979). The higher temperature of equilibration of waters in Tauranga may result from its proximity to high temperature geothermal systems in the TVZ.

4.5 New Plymouth

Despite the presence of the Quaternary andesitic Taranaki volcano in New Plymouth, discharge temperatures of springs are <30°C (Brown et al., 1986) and the calculated reservoir temperature is only 100°C. The eastern hot springs are N_2-rich whereas the western springs are high in CH_4. Both sets of springs are located in a region of low R/R_A signifying the absence of mantle and volcanic contributions to the spring discharge gases. (Giggenbach et al., 1993a). However the relatively high conductive heat flow in New Plymouth is deemed to be due to deep seated magmatic intrusions in the crust (Shi et al., 1996).

4.6 North Island Shear Belt-East Cape

The numerous saline cold springs (Field et al., 1997), warm springs (15-22°C) and nine hot springs (47-62°C) in the growing accretionary prism in the eastern region of the North Island of New Zealand have a R/R_A value of 3.35 signifying the presence of about 40% mantle He (Giggenbach et al., 1993a, b). The mantle volatiles probably migrate along a fracture zone separating the downgoing Pacific plate slab from the overriding plate. The spring waters are mixtures of seawater and water of dehydration of marine clays. The waters have equilibrated at depth to about 110°C and the gases, at 140°C. Localised high heat flow in the North Island Shear Belt- East Cape area, manifested by hot springs at Te Puia, for example, may be caused by the rapid rise of warm fluids expelled at great depths (Giggenbach et al., 1993a, b) and rapid uplift of parts of the East Cape (Field et al., 1997).

4.7 Alpine Fault

About 25 hot springs have been located along the central and northern portion of the Southern Alps, parallel to the Alpine Fault and Marlborough fault Zone (including the Hope Fault). Spring discharge temperatures range up to 82°C but are typically 50 ± 20°C (Allis and Shi, 1995). The hot springs discharge dilute Na-Cl and -HCO_3 heated groundwaters (Barnes et al., 1978) which have equilibrated, at depth, to 180-200°C. At these temperatures, Allis and Shi (1995) believe that meteoric waters have circulated to depths <3 km. The high temperatures in the Alpine Fault springs are attributed to rapid uplift of 10mm/yr in the Southern Alps, bringing higher temperature rock to shallow levels (Allis and Shi, 1995).

The deep circulation of meteoric waters (Allis et al, 1979), the mainly crustal origin of volatiles and the absence of any mantle-derived volatiles is true for most of the N_2-enriched Alpine Fault springs (Giggenbach et al, 1993a). However, there

Table 2- Tectonic settings and source of fluids in hot spring localities.

Areas	Tectonic setting	Source of fluids
North Island		
TVZ	Arc-type andesitic and rift-type rhyolitic/basaltic magmatism	Arc-type magma, subducted materials, mantle volatiles
Ngawha	Extensional regime, upwelling of hot mantle, intraplate basaltic magmatism w/ felsic affinities	Mantle volatiles, ?some arc-type magma
Auckland-Hamilton	Extensional; hot mantle, partly manifested in the latest intraplate basaltic volcano	Heated deep circulating meteoric waters
Hauraki	Rifting	Heated deep circulating meteoric waters; Tauranga may be affected by fluid run-off from the TVZ; some formation waters
New Plymouth	Quaternary arc-type volcanism	Heated deep circulating meteoric waters; some formation waters
Shear Belt-East Cape	Accretionary prism; rapid uplift; thrusting	Seawater, water from marine clays; rapid rise of warm saline waters expelled at depth
South Island		
Alpine Fault	Alpine Fault, Southern Alps; rapid uplift of Southern Alps brings hot rock to shallower depths	Heated deep circulating meteoric waters; mantle volatiles introduced through seismic pumping; metamorphic water
Banks Peninsula	??	Heated deep circulating meteoric waters

is evidence of mantle-derived volatiles at Hanmer (Hope Fault) and metamorphic gases from a vigorously discharging spring in the Copland River (Alpine Fault). In the SW end of South Island, R/R_A ratios suggest high concentrations of mantle He. It is believed that the rapid escape of mantle gases in this area may be induced by ongoing fracturing of rock, in a highly compressive regime caused by subduction. Fracturing allows mantle He to escape into circulating crustal fluids (Giggenbach et al., 1993a).

4.8 Banks Peninsula

The neutral Na-Cl and $Na\text{-}HCO_3\text{-}SO_4$ hot springs of Banks Peninsula in South Island occur in a region where the R/R_A ratio is <1 (Giggenbach et al., 1993a) and the conductive heat flux approximately 40-60 mW/m^2 (Pandey, 1981). The equilibration temperature of waters at depth is <120°C. The Banks Peninsula is not obviously affected by the rapid rise of the Southern Alps and therefore the thermal anomaly may be caused by other factors, as yet unknown.

5. SUMMARY AND CONCLUSIONS

The tectonic settings (Fig. **2)** of New Zealand hot spring areas and the origins of their fluids are summarised in Table 2.

Hot spring systems in New Zealand are found in four tectonic settings characterised by: (1) Quaternary subduction-related, rifting and intraplate volcanism including deep-seated magma bodies, (2) upwelling of hot mantle (3) rapid rise of hot waters introduced along fractures in the accretionary prism in the East Cape of North Island and **(4)** rapid uplift and thrusting in the Southern Alps and parts of the East Cape.

Within the TVZ, discharge fluids are derived from two sources: arc-type magmatic waters derived from subducted materials in the eastern margin, and mantle-rich volatiles in the zone of rifting and intense rhyolitic volcanism in the west. Ngawha has a large mantle component in its fluid discharges associated with intraplate basaltic volcanism.

Outside the TVZ and Ngawha, most hot spring waters originate from deeply circulating groundwaters. In some cases, circulation to depths near a solidifying basaltic magma may leave mantle imprints in the circulating waters. Or mantle-derived volatiles may be actively introduced into the groundwater system by active fracturing in deep faults. In some springs, small percentages of connate or metamorphic water are present. Waters discharged in hot springs from the accretionary prism in the east coast of North island, originate from seawater and water from dehydration of marine clays.

The complex and diverse tectonic make-up of New Zealand yields a wide range of environments and sources of fluids for hot spring systems. A large number of hot spring areas with reservoir temperatures >150°C are distributed all over the country and are generally untapped for direct heat utilisation. Other geothennal resources such as heat from abandoned oil wells and natural heat flow below the ground have not been used at all. Despite having an installed capacity of 309 MWt for direct heat usage, New Zealand has vast geothermal reserves that remain unexploited.

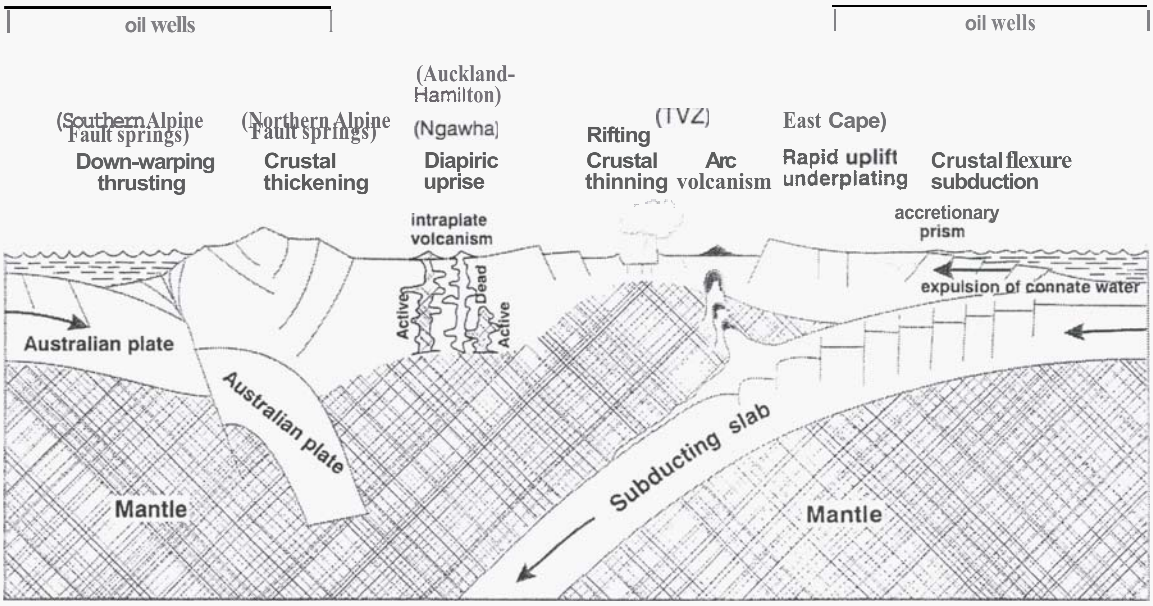

Figure 2- Idealised cross-section of New Zealand showing the different tectonic settings of geothermal systems (adapted from Giggenbach et al., 1993a, Lebrun et al., 2000).

REFERENCES

Aitchison, J.C. **(1985)** Hot springs along the Alpine Fault, Cascade River Valley, South Westland, New Zealand. NZ J Geol Geophysics, **28,755-756.**

Allis, R.G., Funnell, R. and Zhan, **X. (1998)** From basins **to** mountains and back again: N.Z. basin evolution since **10** Ma. In: Arehart, G.B., Hulston, J.R. (eds) Proc. 9th Intl Symp Water-Rock Intercation, Taupo, New Zealand, **3-7.**

Allis, R.G., Henley, R.W., Carman, A.F. **(1979)** The thermal regime beneath the Southern Alps. In: Walcott, R.I. and Cresswell, M.M. (eds) The origin **of** the Southern Alps. The Royal Soc of NZ, Bull. **18, 79-85.**

Allis, R.G., Shi, **Y. (1995)** New insights to temperature and pressure beneath the central Southern Alps, New Zealand. NZ J Geol Geophysics,**38,585-592.**

Barnes, I., Downes, C.J., Hulston, J.R. **(1978)** Warm springs, South Island, New Zealand, and their potentials to yield laumontite. Amer J Sci, **278, 1412-1427.**

Bibby, H.M., Caldwell, T.G., Davey, F.J., Webb, T.H. **(1995)** Geophysical evidence on the structure of the Taupo Volcanic Zone and its hydrothermal circulation. J Volcanol Geoth Res, **68, 29-58.**

Briggs, R.M., Itaya, T., Lowe, D.J., Keane, A.J. **(1989)** Ages of the Pliocene-Pleistocene Alexandra and Ngatutura volcanics, western North Island, New Zealand, and some geological implications. NZ J Geol Geophys, **32, 417-427**

Brown, L.J., Homer, D.L., Petty, D.R. **(1986)** Thermal and mineral water springs in the middle reaches of the Wanganui River. NZ Geol. Survey Record. **18, 13-19.**

Davey, F.J., Hampton, M., Lewis, K., Pettinga, J.R. **(1986)** Structure of **a** growing accretionary prism, Hikurangi margin, New Zealand. Geology, **14,663-666.**

de Ronde, C.E.J., Baker, E.T., Massoth, G.J., Lupton, **J.E.**, Wright, I.C., Feely, R.A., Greene, R.R.(2001) Intra-oceanic subduction-related hydrothermal venting, Kermadec volcanic arc, New Zealand. Earth Planet. Sci. Lett., **193, 359-369.**

Downey, W.S., Kellett, R.J., Smith, I.E.M., Price, R.C., Stewart, R.B. **(1994)** New palaeomagnetic evidence for the recent eruptive activity of Mt Taranaki, New Zealand. J Volcanol Geoth Res, **60, 15-27.**

Duncan, A.R., Pantin, H.M. **(1969)** Evidence for submarine geothermal activity in the Bay of Plenty. NZ J Marine Freshw Res., **3,602-606.**

Edbrooke, S.W. (2001) Geology of the Auckland area. IGNS 1:250,000 map 3, New Zealand.

Ellis, A.J., Mahon, W.A.J. (1977) Chemistry and geothermal systems. Academic Press, New York, 392 pp.

Field, B.D., Uruski, C.I., others (1997) Cretaceous-Cenozoic geology and petroleum systems of the East Coast region, New Zealand. IGNS Mon. 19, New Zealand.

Fridleifsson, I. (1996) The role of geothermal energy in the world. GHC Bull Aug. 1996, 1-5.

Funnell, R.H., Chapman, D., Allis, R.G.; Armstrong, P. (1996) Thermal state of the Taranaki Basin, New Zealand. J. Geophysical Res. 101(B11), 25197-25215.

Gamble, J.W., Smith, I.E.M., Graham, I.J., Kokelaar, B.P., Cole, J.W., Houghton, B.F., Wilson, C.J.N. (1993) The petrology, phase relations, and tectonic setting of basalts fi-om the Taupo Volcanic Zone and Kermadec island arc. J Volcanol Geoth Res, 54,265-290.

Giggenbach, W.F. (1991) Chemical techniques in geothermal exploration. In: D'Amore, F. (ed) Applications of Geochemistry in Geothermal Reservoir Development, 119-144, UNITAR/ UNDP, Rome, Italy.

Giggenbach, W.F. (1995) Variations in the chemical and isotopic composition of fluids discharged fiom the Taupo Volcanic Zone, New Zealand. J Volcanol Geoth Res, 68, 89-116.

Giggenbach, W.F., Sano, Y., Wakita, H. (1993a) Isotopic composition of helium, and CO_2 and CH_4 contents in gases produced along the New Zealand part of a convergent plate boundary. Geochim Cosmochim Acta, 57,3427-3455.

Giggenbach, W.F., Stewart, M.K., Sano. Y., Goguel, R.L., Lyon, G.L. (1993b) Isotopic and chemical composition of waters and gases from the East Coast accretionary prism, New Zealand. IAEA TECDOC-788,209-299.

Grindley, G.W., Williams, G.J. (1965) Geothermal waters, Ch. 15. In: Williams, G.J. (ed) Economic geology of New Zealand, 8th Commonwealth Min Metall Cong Aust NZ.

Heming, R.F., Barnet, P.R. (1977) The petrography and petrochemistry of the Auckland volcanic field. In: Smith, I.E.M. (ed) Late Cenozoic volcanism in New Zealand. Royal Soc of NZ Bull 23, 64-75.

Hochstein, M.P. (1978) Geothermal systems in the Hauraki rift zone (New Zealand)- an example for geothermal systems over an inferred upper mantle swell. Proc. Alternative Energy Sources, 2599-2610.

Hochstein, M.P. (1995) Crustal heat transfer in the Taupo Volcanic Zone (New Zealand): comparison with other volcanic arcs and explanatory heat source models. J Volcanol Geoth Res, 68, 117-152.

Hochstein, M.P., Nixon, I.M. (1979) Geophysical study of the Hauraki Depression, North Island, New Zealand. NZ J Geol Geophys, 22, 1-19.

Hochstein, M.P., Tearney, K., Rawson, S., Davey, F.J., Davidge, S., Henrys, S., Backhall, D. (1986) Structure of the Hauraki rift (New Zealand). Royal Soc of NZ Bull 24, Wellington, 333-348.

Hunt, T. (1996) Geothermal resources in New Zealand, an overview. GHC Bull 19.

Huttrer, G.W. (2001) The status of world geothermal power generation 1995-2000. Geothermics, 30, 1-27.

KRTA Limited (1986) Investigation of factors controlling boron concentrations in groundwaters of the Auckland region. Auckland Regional Water Board Tech. Pub. 34.

Lebrun, J.-F., Lamarche, G., Collot, J.-Y., Delteil, J. (2000) Abrupt strike-slip fault to subduction transition: the Alpine Fault-Puysegur Trench connection, New Zealand. Tectonics, 19,688-706

Lund, J.W., Freeston, D.H (2001) World-wide direct uses of geothermal energy 2000. Geothermics, 30, 29-68.

Mongillo, M.A. (1985) The Ngawha geothermal field: an introduction and summary. In: Mongillo, M.A. (ed.) The Ngawha geothermal field: new and updated scientific investigations, DSIR Geoth ReportNo. 8, 3-15.

Mongillo, M.A., Clelland, L. (1984) Concise listing of information on the thermal areas and thermal springs of New Zealand. DSIR Geoth Report 9, New Zealand.

Pandey, O.P. (1981) Terrestrial heat flow in New Zealand. Victoria University of Wellington, unpublished PhD thesis.

Petty, D.R., Brown, L.J., Homer, D.L. (1987) Mineral and thermal waters and springs of North Auckland. NZ Geol. Survey, 53 p.

Reay, A. (1986) Andesites from Solander Island. In: Smith, I.E.M. (ed.) Late Cenozoic volcanism in New Zealand. Royal Soc of NZ Bull 23, Wellington, 337-343.

Rybach, L., Sanner, B. (2000) Ground source heat pump systems, the European experience. GHC Bull., March 2000, 16-26.

Sheppard, D.S., Giggenbach, W.F. (1985) Ngawha well fluid compositions. In: Mongillo, M.A. (ed) The Ngawha geothermal field: new and updated scientific investigations, DSIR Geoth Report **8,103-119.**

Sheppard, D.S., Johnston, J.R. **(1985)** Monitoring of the natural thermal features of Ngawha springs. In: Mongillo, **M.A.** (ed) The Ngawha geothermal field: new and updated scientific investigations, **DSIR** Geoth Report **8, 121-144.**

Shi, **Y.**, Allis, R., Davey, F. **(1996)** Thermal modelling of the Southern Alps, New Zealand. PAGEOPH, **146,469-501.**

Simpson, B. **(1987)** Heat flow measurements in the Bay of Plenty coast, New Zealand. J Volcanol Geoth Res, **34, 25-33.**

Simpson. B., Stewart, M.K. **(1987)** Geochemical and isotope identification of warm groundwaters in coastal basins near Tauranga, New Zealand. Chem Geol, **64, 67-77.**

Skinner, D.N.B **(1986)** Neogene volcanism of the Hauraki Volcanic Region. In: Smith, I.E.M. (ed) Late Cenozoic volcanism in New Zealand. Royal Soc **of NZ** Bull **23, 21-47.**

Smith, I.E., Okada, T., Itaya, T., Black, P.M. **(1993)** Age relationships and tectonic implications of late Cenozoic basaltic volcanism in Northland, New Zealand. NZ J. Geol. Geophys., **36,385-393.**

Smith, I.E.M. **(1989)** New Zealand intraplate volcanism, North Island. In: Johnson, R.W. (ed) Intraplate volcanism in Eastern Australia and New Zealand. Cambridge University Press, New York, **157-162.**

Thain, **I.A. (1994)** Deep drilling in Ohaaki. IGA Newsletter, **17, 7.**

Thain, I.A., Dunstall, M. (2000) **1995-2000** update report on the existing and planned utilisation of geothermal energy for electricity generation and direct use in New Zealand. Proc World Geoth Congress **2000,** Japan.

Thain, I.A., Freeston, D.H. **(1995) 1990-1995** update report **on** the existing and planned utilisation of geothermal energy for electricity generation and direct use in New Zealand. Proc World Geoth Congress, Florence, **283-288.**

Townend, J. **(1997)** Estimates of conductive heat flow through bottom-simulating reflectors on the Hikurangi and southwest Fiordland continental margins, New Zealand. Marine Geol., **141, 209-220.**

Townend, J. **(1999)** Heat flow through the West Coast, South Island, New Zealand. NZ J. Geol. Geophys., **42, 21-31.**

Turnbull, I.M. Uruski, C.I. **(1993)** Cretaceous and Cenozoic sedimentary basins of western Southland, South Island, New Zealand. IGNS Mon. **1, 86 p.**

Weaver, S.D., Sewell, R.J., Smith, I.E.M. **(1989)** New Zealand intraplate volcanism, petrological overview and tectonic relationships. In: **Johnson,** R.W. (ed) Intraplate volcanism in Eastern Australia and New Zealand. Cambridge University Press, New York, **187.**

Weir, G.W. **(1998)** Energy transport processes in a brittle-ductile intrusive model of the Taupo Volcanic Zone, New Zealand. J Volcanol Geoth Res, **84, 61-72.**

Whiteford, P.C. **(1990)** Heat flow measurements in the Bay of Plenty, New Zealand. Geophysics Div. Res. Report **221,** DSIR, New Zealand.

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M. **(1995)** Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. J Volcanol Geoth Res, **68, 1-28.**

Wood, C.P. **(1978)** Recent volcanism and hydrothermal activity. In: Suggate, R.P., Stevens, G.R., Te Punga, T. (eds) The geology of New Zealand, **v.** 1, E.C. Keating, New Zealand.