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Tectonic Settings of Low Enthalpy Geothermal Systems in New Zealand: An Overview

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ABSTRACT

Low enthalpy geothermal resources are widely distributed in New Zealand and include (1) hot spring systems with <90^{o}C discharge waters in the North and South Islands and offshore islands to the north of North Island, (2) peripheries of high-enthalpy geothermal systems within the Taupo Volcanic Zone, (3) 120-160^{o}C waters at >3.5 km depth in abandoned hydrocarbon wells, (4) natural heat flow below 15-20 m from the surface. Hot spring systems in New Zealand are found in four major tectonic settings characterized by (1) subduction-related volcanism and rifting in the Taupo Volcanic Zone, (2) intraplate volcanism and associated hot mantle upwelling or deep-seated mantle upwelling in a continental rift zone, (3) rapid rise of heated waters along faults in the North Island forearc, and (4) rapid uplift and thrusting along the Alpine Fault Zone in South Island and parts of the North Island forearc. Most hot spring waters, outside the main high-enthalpy geothermal areas of the Taupo Volcanic Zone and Ngawha, are derived from deeply circulating meteoric waters that may sometimes bear imprints of mantle-derived volatiles, saline formation water or metamorphic water. Within the North Island forearc, saline reservoir waters originate from seawater and the dehydration of marine clays. New Zealand has an installed thermal power of 308 MWt. A conservative estimate, of the total annual extractable energy from all the low-enthalpy sources in the country, amounts to 55.7 PJ. Of these only 10% is being exploited at present, for direct utilization of heat.

1. INTRODUCTION

A geothermal resource is a volume of rock where heat can be economically harnessed for conversion to power or direct utilization. Heat is mined from fluids circulating in the rock or, in the case of geothermal ground source heat pumps, directly from the ground or circulating groundwater. With technological advances in heat pumps and their increasing use in Europe, the USA (Fridleifsson, 2003; Rybach and Sanner, 2000) and Japan (Yasukawa and Takasugi, 2003), the absolute temperature of a rock or fluid that can be considered geothermally significant could be as low as 4^{o}C (Lund and Freeston, 2001). In Central and Northern Europe all heat energy stored below about 15 m from the surface, where the temperature field is governed by terrestrial conductive heat flow, the thermal conductivity of rocks and groundwater flow, is considered geothermal energy (Rybach and Sanner, 2000). On the opposite end of the spectrum, deeper wells are being drilled in high-temperature power- producing geothermal systems (>3500 m) and temperatures >350^{o}C intersected (e.g., Sasaki et al., 2003). Thus, with the technological advances in the last 20 years the definition of an economically viable geothermal resource has broadened to a resource that extracts heat from the rock or circulating aquifer waters at temperatures ranging from as low as 4^{o}C to as high as sub-magmatic (400^{o}C) and from 20 m to >3,500 m depths.

In this paper the division between high- and low-enthalpy geothermal systems is set at 180^{o}C. Power can be generated from high-enthalpy fluids at >180^{o}C using flash steam turbines. Low-enthalpy fluids <180^{o}C are harnessed for power using binary cycle plants (107-180^{o}C) and for direct use of heat (<120^{o}C).

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 Taupo Volcanic Zone (TVZ), (3) low intensity fields in decadent volcanic areas such as Ngawha, Coromandel, Waikato and Banks Peninsula (Fig. 1) and (4) non-volcanic hot springs found along fault systems in South Island and areas in North Island such as Morere and Te Puia. In this paper New Zealand geothermal systems are grouped in terms of their spatial distribution with respect to tectonic setting and sources of fluids and anomalous heat.

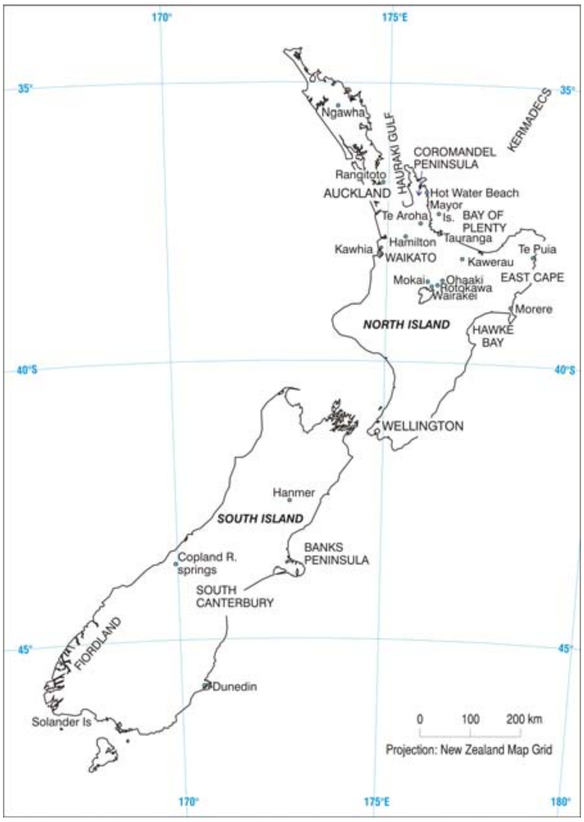

Figure 1: Location of place names mentioned in text.

2. DIRECT USE OF GEOTHERMAL HEAT

New Zealand has an installed power generating capacity of 437 MWe provided by six high - enthalpy geothermal

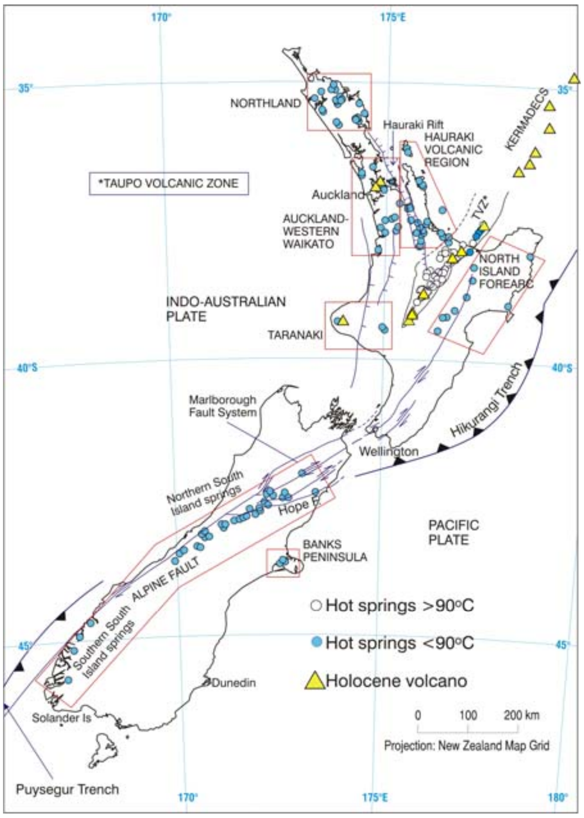

Figure 2: Major tectonic features of New Zealand and location of hot springs and Recent volcanoes (Mongillo and Clelland, 1984; Aitchison, 1985; Hochstein, et al., 1986; Petty et al., 1987; Anderson et al., 1993; Allis and Shi, 1995; Allis et al., 1998; de Ronde et al., 2001; DSIR and GNS unpublished reports).

systems in the 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 increased to 308 MWt (Lund and Freeston, 2001), mostly produced from waste waters and waste steam in the power-generating Kawerau, Ohaaki and Wairakei geothermal systems (Fig. 1). The largest user of direct 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 for maintaining a greenhouse. Other cascade uses of geothermal fluids from the two other power-generating geothermal systems include prawn-framing 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 and the virtual absence of any ground source heat pump application in the country, geothermal resources are under utilized 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. 2). 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 and forearc. An actively growing accretionary prism, partly exposed on land in the east coast of North Island (North Island Forearc in Fig. 2), 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 (Stern, 1987; Gamble et al., 1993; Bibby et al., 1995). The effect of subduction is further manifested in the Quaternary Taranaki volcano (Fig. 2), located 140 km southwest of the TVZ (Downey et al., 1994).

Northland 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-Western Waikato regions (Smith, 1989; Smith et al., 1993) although some in Kawhia, Western Waikato, have a convergent margin signature (Briggs et al., 1989).

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 downgoing 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 and Uruski, 1993). In the South Island, intraplate volcanism was widespread in the Cenozoic. Early to middle Tertiary volcanism was probably related to a mildly extensional 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 (Fig. 1). Intraplate basalts of Pliocene age (2.5 Ma) occur in South Canterbury (Smith, 1989). On Solander Island, immediately south of Fiordland, subduction-related Quaternary andesites outcrop (Reay, 1986).

4. MAJOR SOURCES OF LOW-ENTHALPY HEAT

There are several sources of low-enthalpy heat in New Zealand: (1) hot spring systems with discharge temperatures <90^{o}C in the North and South Islands, (2) edges or boundaries of high-enthalpy geothermal systems in the TVZ and Northland, (3) 120-160^{o}C waters at >3.5 km depth in abandoned hydrocarbon wells in Taranaki and offshore Taranaki, Northland, northeastern North Island and offshore South Island and (4) natural heat flow from about 15 m below the surface to deeper levels.

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

Table 1: General characteristics of hot spring localities using data compiled from [1]Mongillo and Clelland (1984), [2]Petty et al. (1987), [3]Sheppard and Johnston (1985), [4]Allis and Shi (1995), [5]Stern (1987), [6]Simpson (1987), [7]Whiteford (1990), [8]Funnell et al. (1996), [9]Shi et al. (1996), [10]Townend (1997), [11]Townend (1999), [12]Field et al. (1997), [13]Allis et al. (1998), [14]Giggenbach et al. (1993a). *T_{NK}- Na-K geothermometer (Giggenbach, 1991), $^{+}$based on T_{SiO_2} (opal). R/R_A = isotopic composition of He in terms of measured values with respect to air, corrected for air contamination.

Areas	Discharge $T(^oC)_{maximum}$ [1-4]	Heat flux[5-13] mW/m^2	Maximum R/R_A ratio[14]	Major gas [14]	Water composition	Reservoir T_{NK}^{*} (^oC)
North Island						
Northland	87	80-100	>4	CO_2	Neutral Na-Cl, Na-HCO_3	235-300
Auckland-Western Waikato	71	60-80?	2	N_2	Neutral Na-Cl, Na-HCO_3	100-150
Hauraki Volcanic Region	85	80-100	1	N_2, CO_2	Neutral Na-Cl, Na-HCO_3	225- 265
TVZ	99	Ave.= 800	>4	CO_2	Mainly neutral Na-Cl	240-330
North Island Forearc	62	~40; isolated values of 90, 170	3.4	CH_4	Neutral Na-Cl	80-110 (gas= 140)
Taranaki	26	55-60	<0.25	N_2	Neutral Na-(Ca)-Cl	100
South Island						
Alpine Fault, (north and south)	82	<60 but w/ isolated values of 90, 190	2-4	Mainly N_2	Neutral Na-Cl, Na-HCO_3	180-200
Banks Peninsula	49	40-60	<1	No data	Neutral Na-Cl, (Na-HCO_3-SO_4)	(<120^{+})

Gulf and Bay of Plenty and seabed, extending to the Kermadecs. Less than 20 percent of the springs are found in South Island. In this paper hot springs in New Zealand are divided into nine geographical regions consisting of Northland, Auckland-Western Waikato, Hauraki Volcanic Region, TVZ, North Island Forearc and Taranaki in North Island; Banks Peninsula and the northern and southern Alpine Fault springs in South Island (Fig. 2). All boiling hot springs and springs with >90^{o}C discharge temperatures occur in the TVZ. The temperature range of warm and hot springs outside the TVZ is just above ambient to 87^{o}C (Table 1). Cold springs, oil seeps and mud volcanoes are widespread in the North Island east coast. Cold springs and oil seeps are also found in the Taranaki region, Northland and South Island (Townend, 1999).

A conservative estimate of the total annual extractable energy from all the low enthalpy sources in New Zealand is 55.7 PJ including hot spring systems (3.4 PJ assuming an average temperature of 45^{o}C at a total mass flow of 800 kg/s and a capacity factor of 0.70), natural heat flux for ground source heat pump use (45.4 PJ assuming an average conductive heat flux of 40 mW/m^2 distributed over 90% of the country using a capacity factor of 0.15), abandoned hydrocarbon wells (0.12 PJ assuming 100 wells at a temperature of 120^{o}C and a capacity factor of 0.15) and presently installed systems (6.8 PJ using a capacity factor of 0.7 after Lund and Freeston, 2001). The annual extractable energy, from these low-enthalpy sources, amounts to a saving of 3.9 million tonnes of fuel oil per year (TOE). The calculation excludes other possible cascade uses of low-enthalpy waste waters from the high-enthalpy geothermal systems being exploited at present. Essentially only 10% of the low-enthalpy geothermal resources of New Zealand have been exploited, so far.

4.1 Taupo Volcanic Zone

Tectonically the TVZ is characterized by a broad band of crustal rifting, dominated by large-scale rhyolitic volcanism, in the west, and a line of Quaternary andesitic volcanoes on its eastern margin. The TVZ is the most active Quaternary rhyolitic system in the world in terms of frequency and productivity of eruptions (Wilson et al., 1995). It has a total extrusive magma flux of c. 0.3 m^3/s, superimposed by a geothermal heat flux of 4600 MW, equivalent to another 1.2 m^3/s of magma intruded into the crust (Hochstein, 1995). Among active centers of large-scale rhyolitic volcanism worldwide, the TVZ exhibits the

Table 2: Tectonic settings, sources of fluids and origins of high temperatures in hot spring systems in New Zealand.

Areas	Tectonic setting	Sources of fluid discharges	Origins of high temperatures
North Island			
TVZ	Subduction-related arc-type and back-arc rifting volcanism	Arc-type magma, subducted materials, mantle volatiles, meteoric waters	Magma, upwelling hot mantle
Northland	Intraplate basaltic magmatism w/ felsic affinities in an extensional regime	Mantle volatiles, ?some arc-type magma, meteoric waters	Upwelling hot mantle
Auckland-Western Waikato	Intraplate basaltic magmatism in an extensional regime	Heated deep circulating meteoric waters	Hot mantle, partly manifested in the latest intraplate basaltic volcanoes
Hauraki Volcanic Region	Rifting	Heated deep circulating meteoric waters; some formation waters	Upwelling hot mantle; TVZ volcanism may affect Tauranga
Taranaki	Quaternary arc-type volcanism	Heated deep circulating meteoric waters; some formation waters	Arc-type magma at depth
North Island Forearc	Accretionary prism	Seawater, water from marine clays; rapid rise of warm saline waters expelled at depth	Rapid uplift; thrusting
South Island			
Alpine Fault (north and south)	Trench-trench transform fault system	Heated deep circulating meteoric waters; mantle volatiles introduced through seismic pumping; metamorphic water	Rapid uplift of Alps brings hot rock to shallower depths
Banks Peninsula	??	Heated deep circulating meteoric waters	

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 vary from near ambient to 99^oC. On average, reservoir temperatures in the TVZ geothermal systems range from 260-280^oC, with temperatures of 325-330^oC measured in Mokai and Rotokawa wells (Thain, 1994).

Giggenbach (1995) recognized two distinct source fluids in the TVZ geothermal systems, in keeping with its dual tectonic make-up. Along the eastern margin, geothermal well discharges have CO_2/Cl, B/Cl and Li/Cs ratios and CO_2 contents higher than those located in the west. In the east, 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 east contain about 14% arc-type magmatic component, compared with only 6% in the west (Giggenbach, 1995).

4.2 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 systems in Northland is located within an area of Quaternary (0.06-1.4 Ma) basalts (Skinner, 1986; Smith et al., 1993). The thermal anomaly in the geothermal systems is believed to be related to felsic magma at depth, deduced from the presence of nearby a rhyolitic lava dome (Smith et al., 1993).

About 20 springs, with discharge temperatures of 20^oC to 87^oC, 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 characterized 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^oC (Giggenbach, 1991), consistent with measured temperatures in most of the wells. In one well however, >320^oC 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) from deep well discharges imply a high arc-type magmatic component that seems to corroborate the Smith et al. (1993) model of an arc-type signature in a layered sublithospheric mantle.

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

4.3 Auckland-Western Waikato

Twelve spring systems have been mapped immediately north of Auckland, in Auckland, between Auckland and Hamilton and along the western coast of the Waikato region (Mongillo and Clelland, 1984; Edbrooke, 2001). Spring discharge temperature is as high as 71^oC although most cluster at 50-65^oC. Waters discharged from >50 shallow domestic wells (<436 m depth) in Auckland have temperatures ranging from 14^oC to 63^oC (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-Cl waters have a calculated reservoir temperature of 100-150^oC.

Although Auckland has the youngest Quaternary intraplate basalt volcano in the country, Rangitoto (750 a B.P.; Smith, 1989), no springs occur in its immediate vicinity. However warm springs are reported in East Tamaki and Whitford (Edbrooke, 2001) located c. 18 kms southeast of Rangitoto and c. 8 kms southeast of the 9000-9300 a B.P. basaltic Mt. Wellington (Heming and Barnet, 1986). There may be a causal relationship between Cenozoic back-arc basaltic magmatism (Cole, 1986) and the warm springs in Auckland and Western Waikato. 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 back-arc basaltic volcanic fields suggests that upwelling hot mantle at depth most likely contributes to the high conductive heat flow (Table 1).

The 54^oC springs in a 30 m^2 area at the intertidal zone in Kawhia are located about 50 km south of the nearest Holocene basalts. Volcanic activity nearest the springs, associated with back-arc intraplate and subduction-related magmas, ceased 200 000 or more years ago (Waterhouse and White, 1994). Hence there are no obvious sources of heat for the hot springs in Kawhia.

Within the city of Hamilton, a water well with slightly a elevated temperature of 27^oC at 135 m has been used for space heating and cooling of a commercial building using an open loop geothermal heat pump (Mongillo and Clelland, 1984). This is the only reported use of a geothermal heat pump in New Zealand, so far.

4.4 Hauraki Volcanic Region

The Hauraki Volcanic Region (HVR) is characterized by episodic Miocene to Pleistocene volcanism of andesitic to dacitic and rhyolitic composition. It includes the Coromandel Peninsula, areas southwest of the Coromandel Peninsula, Tauranga and islands in the Hauraki Gulf (Skinner, 1986). In this paper the offshore Hauraki Gulf islands included in the HVR are west of latitude 176^o E (Fig. 1).

The HVR springs discharge neutral pH Na-Cl and Na-HCO_3 heated groundwaters, with spring discharge temperatures as high as 85^oC in Te Aroha and 71^oC in Hot Water Beach (Hochstein, 1978). Although all discharging thermal waters in the HVR are heated groundwater, water flowing from one shallow well appears to contain saline pore waters (Hochstein and Nixon, 1979). In the Coromandel Peninsula, southwest Coromandel and Hauraki Gulf islands springs, groundwaters have equilibrated to 225^oC at depth. In Tauranga however the reservoir temperatures, calculated from shallow well discharges, is higher at 265^oC (Simpson and Stewart, 1987).

Heightened heat flux in the HVR may have several causes. For the springs located within the Hauraki Rift, such as the springs located southwest of the Coromandel Peninsula, high heat flow may be associated with a hot upper mantle swell (Hochstein and Nixon, 1979).

Volcanism in the Coromandel Peninsula and the Hauraki Gulf islands is Miocene to Early Pleistocene in age (Edbrooke, 2001) and may be too old to generate the high heat flux necessary for the hot springs to form. The nearest Holocene volcanism, to the Coromandel springs, are back-arc volcanism associated with the Auckland-Western Waikato springs at least 40 km to the west and rhyolitic volcanism in Mayor Island 30 km to the east. These sources of heat may be too far to have any influence on the heat flux. The nearest source of heat for the Coromandel and Hauraki Gulf Islands springs, that could be identified at present, is the postulated hot upper mantle swell associated with the Hauraki Rift.

The higher temperatures of equilibration for the Tauranga thermal waters may result from their proximity to the western edge of active volcanism in the TVZ (Fig. 2).

4.5 Taranaki

Despite the presence of the Holocene andesitic Taranaki volcano, discharge temperatures of springs are <30^oC (Brown et al., 1986). and the calculated reservoir temperature is only 100^oC (Table 1). The eastern hot springs are N_2-rich and the western ones 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 the Taranaki region is deemed to be due to deep-seated magmatic intrusions in the crust (Shi et al., 1996).

4.6 North Island Forearc

Saline cold springs (Field et al., 1997), warm springs (15-22^oC) and hot springs (47-62^oC) in the North Island forearc are located within the axial ranges shear belt (Cole, 1990)

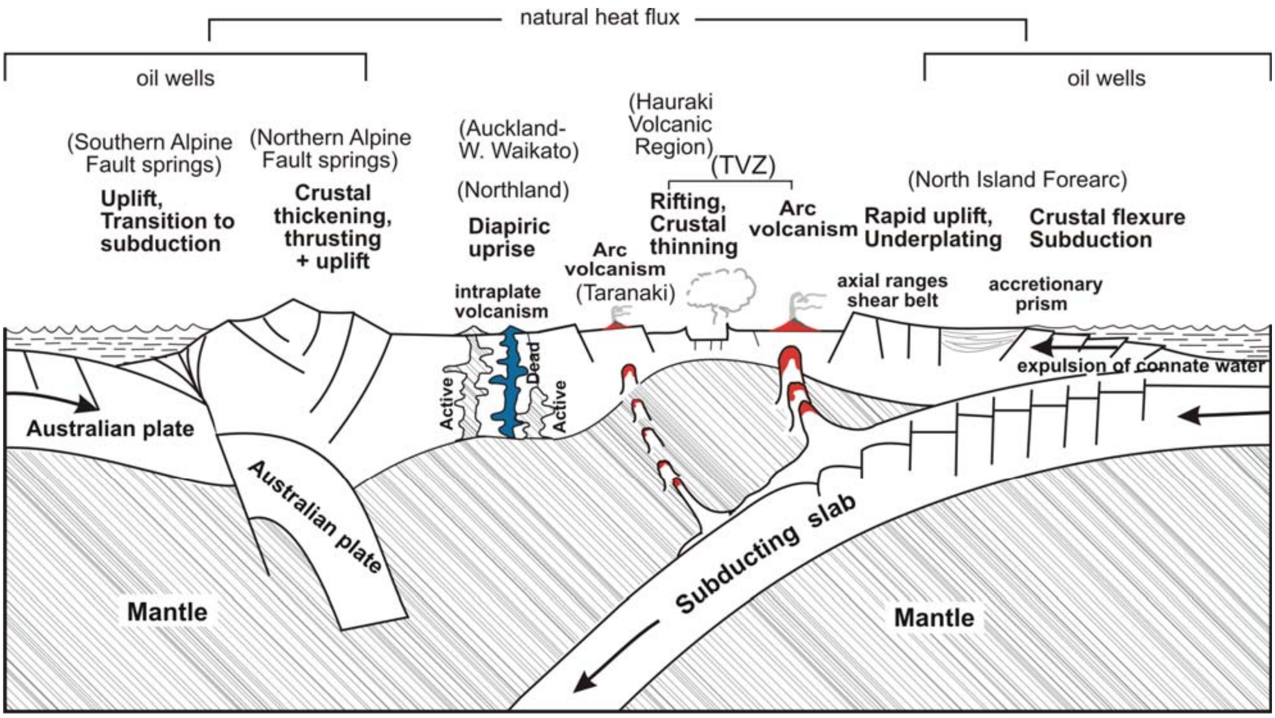

Figure 3: Idealized cross-section of New Zealand showing the different tectonic settings of geothermal systems and sources of geothermal heat (adapted from Giggenbach et al. 1993a; Koons et al., 1998 and Lebrun, et al., 2000).

and the accretionary prism between Hawke Bay and East Cape (Fig. 1). Salinities in these springs range from 5000 to 26000 mg/kg Cl and Cl/Br ratios are close to that of seawater (Giggenbach et al., 1993b). Stable isotope and chemical compositions suggest that the spring waters are mixtures of seawater and water of marine clay dehydration. Waters at depth have equilibrated at 110^{o}C and the gases at 140^{o}C. The R/R_A values in the springs range from 0.1 to as high as 3.35, with the highest value signifying the presence of about 40% mantle He (Giggenbach et al., 1993a and b). mantle volatiles probably migrate along a fracture zone separating the downgoing Pacific plate slab from the overriding plate. Localized high conductive heat flow at the Te Puia and Morere hot springs, for example, may be caused by the rapid rise of warm fluids expelled at great depths (Giggenbach et al., 1993a and b) and rapid uplift of parts of the forearc (Field et al., 1997).

4.7 Alpine Fault

About 25 hot spring systems have been located along the central and northern portion of the Southern Alps, parallel to the Alpine Fault and Marlborough Fault System including the Hope Fault. Spring discharge temperatures range up to 82^{o}C but are typically 50 $\pm$ 20^{o}C (Allis and Shi, 1995). The hot springs discharge dilute Na-Cl and Na-HCO_3 heated groundwaters (Barnes et al., 1978) which have equilibrated at depth to 180-200^{o}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 10 mm/yr in the Southern Alps, bringing higher temperature rock to shallow levels (Allis et al., 1979). The deep circulation of meteoric waters (Allis et al., 1995), the mainly crustal origin of spring 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 is evidence of mantle-derived volatiles at Hanmer where springs are channeled along the Hope fault; and metamorphic gases from a vigorously discharging spring in the Copland River in the Alpine Fault proper. In volatiles from springs in the southwest end of the Alpine Fault, 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 complicated transitional zone of strike-slip shear and subduction. Fracturing allows mantle He to escape into circulating crustal fluids (Giggenbach et al., 1993a).

The model invoked by Giggenbach et al. (1993a), to explain the presence of mantle He in some of the Alpine fault springs is partly corroborated by the “U-shaped” zone of high conductivity mapped by magnetotelluric measurements beneath the Southern Alps, (Upton et al., 2000). The zone is subhorizontal at depth, in the ductile region of the crust, and is believed to be fluid-saturated. Near vertical zones of high conductivity extend to the surface along active faults. Stable isotopic analysis of calcite from the faults suggests that mid-crustal waters, generated by prograde or strain-induced metamorphism within the ductile and brittle parts of the crust, are transported upwards along faults and mix with near surface waters (Upton et al., 2000).

4.8 Banks Peninsula

The neutral Na-Cl and Na-HCO_3 warm springs (26 - 49^{o}C) of Banks Peninsula in the South Island are located more than 100 km east of the Alpine Fault. Equilibrium temperatures of waters at depth is <120^{o}C and R/R_A of volatiles is <1 (Giggenbach et al., 1993a). The most recent volcanism in the area consists of Miocene intraplate basalts dated 8-9 and 10-12 Ma (Duggan and Reay, 1986). However, any remnant heated mantle at depth is belied by the low to normal heat flow values of 35 to 60 mW/m^2 (Pandey, 1991), and the low R/R_A value.

The reason for the presence of hot springs in the Banks Peninsula is unknown.

5. SUMMARY AND CONCLUSIONS

The tectonic settings of New Zealand (Fig. 3) hot spring areas and the origins of their fluids are summarized in Table 2. Hot spring systems in New Zealand are found in four general tectonic settings characterized by: (1) subduction-related arc volcanism and back-arc rifting in the Taupo Volcanic Zone, (2) intraplate volcanism and upwelling of hot mantle in Auckland-Western Waikato and Northland and upwelling of hot mantle at depth in the Hauraki Rift, (3) rapid rise of heated waters introduced along fractures in the North Island Forearc, and (4) rapid uplift and thrusting along the Alpine Fault Zone and its subsidiaries, and parts of the North Island Forearc.

Within the TVZ, discharge fluids are derived from two primary sources: arc-type magmatic waters generated from subducted materials in the eastern margin, and mantle-rich volatiles in the zone of rifting and intense rhyolitic volcanism in the west. Ngawha in Northland has a large mantle component in its fluid discharges, associated with intraplate basaltic volcanism. Outside the TVZ and Ngawha in Northland, 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 waters. Alternatively mantle-derived volatiles may be actively introduced into the groundwater system by recent fracturing in deep faults. In some springs small concentrations of connate or metamorphic water are present. Saline waters discharged in hot springs in the accretionary prism and shear belt of the North Island Forearc 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^{o}C are distributed all over the country and <20% are being tapped for direct heat utilization. Other geothermal resources such as heat from abandoned hydrocarbon wells and natural heat flow at shallow depths have hardly been used at all. Despite having an installed capacity 308 MWt for direct heat usage, New Zealand has vast geothermal reserves that remain unexploited.

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