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Estimating the potential of low-temperature geothermal resources outside active volcanic regions in New Zealand

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ABSTRACT

The heat reserves down to 3.5 km in about 120,000km^2 of onshore New Zealand, outside the main active volcanic regions where thermal gradients are only 30-35^{o}C/km, are estimated to be about 36.5 x 10^{14} PJ/a. A miniscule amount of this tremendous stored heat can be accessed and recovered at shallow depths via ground source heat pumps. However, the main foci of this paper are low-temperature sources in New Zealand where heat is transferred by fluids including >550 low-temperature thermal and non-thermal spring systems outside active volcanic zones, hundreds of abandoned underground coal and mineral mines, >500 abandoned petroleum wells, and thousands of shallow domestic, industrial and mine exploration drill holes. Drillholes and mines can hold conductively-heated aqueous solutions or act as a focus for advecting hot thermal fluids from depth.

Low-temperature springs in New Zealand with surface discharges of ambient to 87^{o}C are widely spread in regions of magmatism (Pleistocene arc-volcanism, Recent intraplate volcanism and post-Miocene mantle diapirism), rapid crustal uplift, rapid upflow of hot metamorphic or subduction fluids from great depths along permeable faults and normal heat gradients in metamorphic terrain and uplifted sedimentary basins. Subsurface temperatures vary from 55-250^{o}C, based on fluid geothermometry, with minimum estimated accessible heat (>20^{o}C) of 20PJ/a and recoverable heat of 2PJ/a. Because of the dearth of uncontaminated fluid samples from abandoned underground mines and wells, bottomhole temperatures (BHT), based on measured data or estimated from the heat flow map of New Zealand, are often used instead of fluid geothermometry to determine subsurface fluid temperatures in some regions. Thus, at a minimum, underground mine and well temperatures vary from ambient to 175^{o}C (BHT). Accessible heat, estimated from minimum flowrates, are 8.6PJ/a (for 400 wells) and 0.8 PJ/a (for 58 mines) or recoverable heat of 0.86PJ/a and 0.08 PJ/a, respectively.

Although there is still a widespread perception in New Zealand to associate geothermal energy with thermal springs and volcanic regions, the onshore landmass can be viewed as one big geothermal system where ground source heat pumps and heat exchangers can be universally employed to extract heat from shallow ground or water reservoirs for low-temperature direct heat applications; and deeper heat sources accessed via thermal spring discharges, wells and underground mines.

1. INTRODUCTION

Heat from the earth is an inexhaustible and ubiquitous resource generated mainly by pervasive radioactivity and enhanced where tectonic, structural and hydrological conditions converge to focus heat- and fluid-transfer (Reyes et al, 2015). Localised heat, although often ephemeral, may also be generated by exothermic chemical processes such as olivine hydrolysis (Allen and Seyfried, 2004) or oxidation of various sulphide minerals (Baker and Banfield, 2003), shearing along large faults (Graham and England, 1976), or solar-warmed seawater encroaching below the surface of less dense cold streams or lakes near the sea (Reyes et al, 2010). Low-temperature heat can also be anthropogenic including elevated groundwater temperatures in cities that create urban heat islands from human activity (e.g., Zhu et al, 2010) and waste heat that can be harnessed from manufacturing processes in industrial areas e.g., cement-making and steel production (Forni et al, 2014; Papapetrou et al, 2018) or the operation of recreational facilities such as ice rinks (https://tekaposprings.co.nz). Whether natural or anthropogenic, heat becomes a geothermal resource only when it is economically accessible and technologically recoverable. The enthalpy of fluids, the main commodity in a geothermal resource, becomes a critical factor only when development goes beyond ground source heat pumps (Reyes, 2015). By employing ground source heat pumps (GSHP), any heat energy stored below 6m, or at the depth where ground temperatures remain constant through the seasons, is considered geothermal energy (Rybach and Sanner, 2000). Thus, temperatures of geothermal resources can vary from <0^{o}C (Gagne-Boisvert and Bernier, 2017) to >350^{o}C.

The objective of this study, however, is to assess the geothermal prospectivity of low-temperature geothermal resources in New Zealand based on geology, accessible aqueous solutions and requisite temperatures for heat energy application, whether for direct application or power generation. To assess the relative geothermal prospectivity of natural low-temperature regions (outside the high-temperature systems of the Taupo Volcanic Zone and Ngawha) more than 100 thermal and cold springs (Reyes et al, 2010), >500 abandoned petroleum wells and >500 underground mines (Reyes, 2015 and 2018) were examined. Subsurface temperatures were estimated using solute chemistry of discharges from hot and cold springs, mines and wells; and/or bottomhole temperatures (BHT) of petroleum wells and underground mines based on measured data (www.nzpam,govt.nz), general and local regional heat flow maps (Studt and Thompson, 1969; Funnell et al, 1996; Allis et al, 1998; Townend, 1999), and general methods developed by Funnell et al (1996) for estimating BHTs in various petroleum systems in New Zealand.

2. GENERAL TYPES OF HEAT RESOURCES

Reyes (2015) divided heat resources in New Zealand into conventional and unconventional (Figure 1) for ease of discussion. Conventional heat resources are related to thermal spring systems where heat energy can be used directly and/or harnessed using conventional extraction and energy conversion techniques. Discharge temperatures of thermal springs are as high as 100^{o}C in high-temperature geothermal systems and varies from 17°C to 87°C with a median of 50°C in low-temperature regions throughout the country. A spring is defined as thermal when discharge temperatures are at least 4°C above the average annual air temperature, a temperature difference that is palpable in the Southern Alps of New Zealand. Mass flow rates from springs and wells can be >200 kg/s in high-temperature regions but are <30 kg/s in low-temperature systems (Reyes et al, 2010). Thermal springs in low-temperature regions are used mainly for bathing (e.g., Reyes, 2015).

Unconventional heat resources are located outside thermal spring systems and can be natural or anthropogenic. Reservoir characteristics of natural unconventional resources, such as thermal gradient, relative permeability and volume of circulating fluids are lower compared to conventional sources in a given region, with the mode of heat transfer dominated by conduction rather than convection. Heat energy from either type can be exploited for direct heat use or power generation with the use of binary cycle or steam turbines dependent on the temperature range of the geothermal fluids (Figure 1), although the extraction methods for unconventional heat energy resources may require EGS technology including various forms of borehole heat exchangers.

Because of reservoir characteristics and the use of conventional methods for harnessing, the heat output of conventional heat resources is deemed economically high-grade as opposed to low-grade for unconventional systems. Heat from unconventional resources can be accessed by drilling new wells, preferably deep; and using hundreds of available abandoned deep petroleum wells, thousands of shallow domestic, industrial and mine exploration drill holes, and hundreds of abandoned underground mineral and coal mines. These infrastructures can hold conductively-heated fluids, act as a focus for advecting hot thermal aqueous solutions from depth (Reyes, 2015) or, in the absence of fluid flow, be used as ready-made deep pipes for EGS (Enhanced Geothermal Systems) and deep BHE (Borehole Heat Exchanger) for geothermal energy extraction (e.g., Caulk and Tomac, 2017).

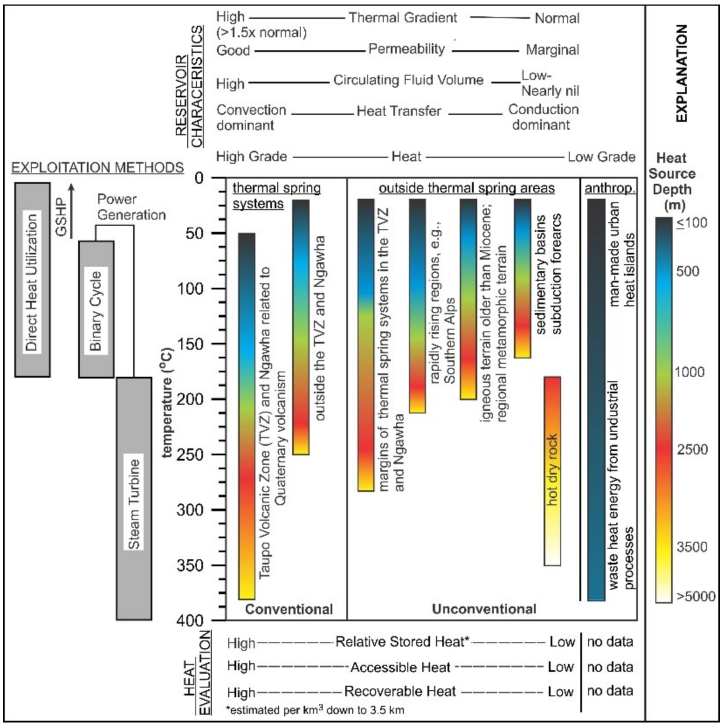

Figure 1: Temperature ranges, source depths, general geological settings, reservoir characteristics, exploitation methods, and heat evaluation of conventional and unconventional geothermal systems in New Zealand including anthropogenic (anthrop.) sources (adapted from Reyes, 2017).

As mentioned above, the term "high-grade" refers to the economic extractability of heat and not to temperature. High grade conventional geothermal resources discharge large volumes of chemically-benign hot aqueous solutions or steam from surface discharges or from subsurface permeable zones via wells drilled down to about 3500m. Despite high temperatures and good permeability, a geothermal resource can be rendered low-grade by widespread corrosive fluids, the rate of exploitation-related hydrological degradation, and socio-political and environmental considerations.

3. GEOSCIENTIFIC EVALUATION OF LOW-TEMPERATURE GEOTHERMAL SYSTEMS IN NEW ZEALAND

Onshore New Zealand is divided into 18 regions based on geological and tectonic features related to surface fluid discharges (Reyes et al, 2010). There are at least 100 thermal and another 400 to 450 cold high-Cl spring systems (composed of one or more springs within a given area) with about 80% of spring systems located in the North Island (Figure 2).

The initial nation-wide evaluation of low-temperature geothermal systems in New Zealand (Reyes, 2015) included (1) an estimate of stored heat at depth, (2) temperature measurements of warm to hot discharges from thermal springs, shallow wells and seepages in underground mines, (3) chemical evaluation of subsurface temperatures from thermal discharges in (2), cold high-chloride springs and fluids from deep wells, (4) calculation of BHTs in deep petroleum wells, (5) assessing relative depths of hot aqueous fluids in wells or mines and (6) an evaluation of heat sources as related to geology.

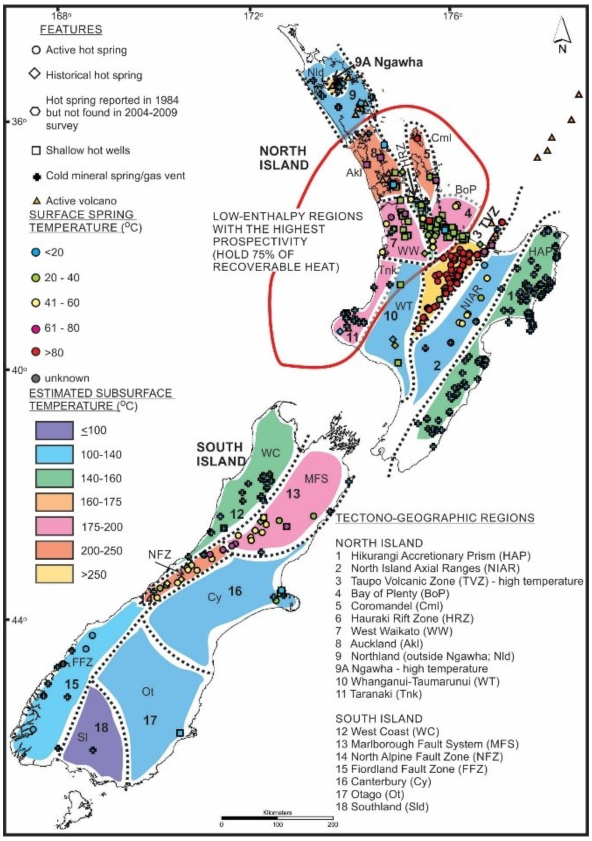

Figure 2: Map showing 18 different tectono-geographic regions in New Zealand, hydrothermal and volcanic surface features, surface temperatures of springs and shallow wells, estimated maximum subsurface temperatures (Table 1) and the regions with the highest geothermal prospectivity (modified from Reyes, 2016).

3.1 Stored Heat

Stored heat was roughly estimated using equation 1 (e.g., Garg and Combs, 2011):

$$W = 8.766\{[V(1-\Phi)C_{rock}\rho_{rock}(t_f - t_i)] + [V\Phi C_{water}\rho_{water}(t_f - t_i)]\} \quad (1)$$

where W is heat energy in MW-h/a(°C), V= volume in m^3, Φ= porosity assumed to be 0.01 in the calculation to indicate that heat is mostly stored in the rock, C_{rock}= 0.86 kJ/kg (specific heat capacity), ρ_{rock}= 2760 kg/m^3 (density), C_{water}= 4.18 kJ/kg, ρ_{water}= 1000 kg/m^3, t_i= base or cut-off temperature (°C) at 15°C in the North Island and 12°C in the South Island, and t_f= source temperature (°C).

The calculation assumes a constant rock composition down to 3500m and a total area of 128,300 km^2 (Reyes, 2015). This area is divided into three different regions with the following thermal gradients: low (30°C/km), moderate (35°C/km) and high (80°C/km for the Taupo Volcanic Zone and Ngawha) based on the general surface heat flow map of New Zealand (Allis et al, 1998) converted to thermal gradients (Funnell et al, 1996). Thus, from 250 to 3500m, the total stored heat estimate for all thermal gradient regions is: 11.9×10^{20} MW-h/a (42.3×10^{14} PJ/a). Due to an area 14x larger than the high-temperature region, stored heat in the low-temperature regions is 6.5x greater, although stored heat/km^3 in high-temperature regions is at least 2x higher. However most of this heat is locked in the rock and need to be made accessible then recovered (Figure 1) as discussed in Section 4.

3.2 Surface and Estimated Subsurface Temperatures of Aqueous Fluids

The highest measured temperature from thermal discharges from springs, shallow wells and seepages in underground mines in low-temperature regions is 87°C in the Coromandel Peninsula in the North Island and lowest at 17°C in Fiordland in the South Island (Figure 3A). The median temperature in North Island thermal springs is 50°C compared to 44°C in the South Island (Reyes et al, 2010). In addition to thermal springs there are about 400 subduction-related cold springs occurring along the Hikurangi Accretionary Prism in the east coast of the North Island (Figure 2), with maximum Cl of nearly 27,000 mg/kg (Reyes et al, in prep.). Another 50-100 cold springs discharge sedimentary formation aqueous fluids with maximum Cl concentrations of 47,000 mg/kg. The latter are distributed in the North Island Axial Ranges, Taranaki, Western Waikato and Northland in the North Island and mostly in the West Coast and Marlborough Fault System in the South Island. The high chloride concentrations of cold springs indicate that the aqueous fluids originate from depth. Thus, aside from thermal discharges, cold high-chloride spring fluids and petroleum well discharges are also included in assessing subsurface temperatures using solute geothermometry, provided there is no active seawater incursion and, in the case of petroleum wells, all components from drilling fluids have deteriorated with time.

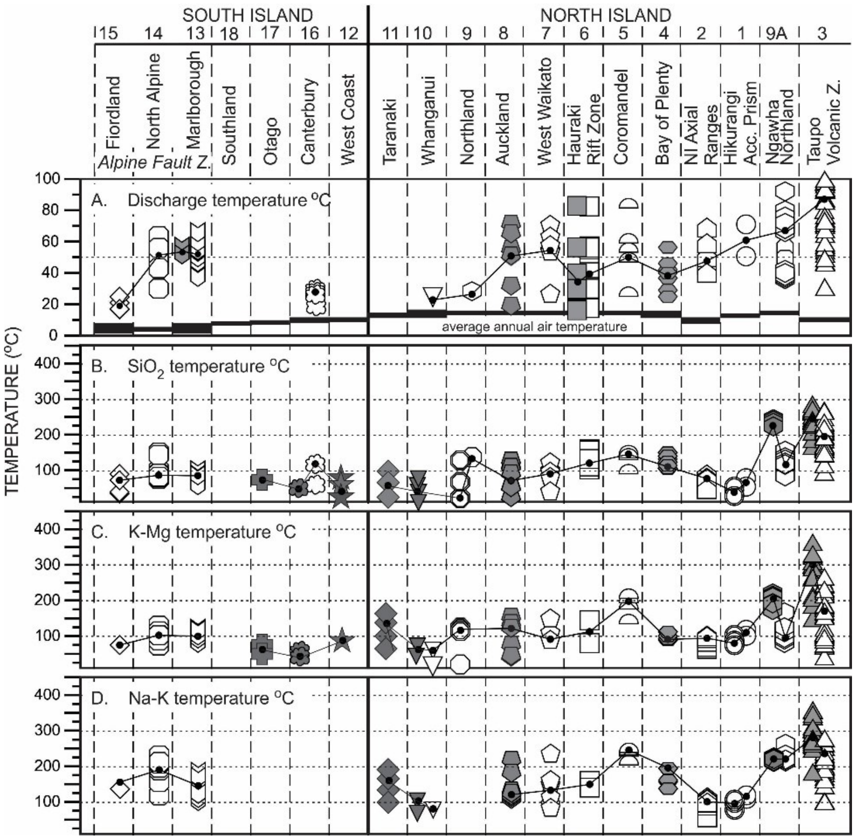

Figure 3: Temperatures in the different low-temperature tectono-geographic regions of New Zealand as compared to the Taupo Volcanic Zone and Ngawha: (A) measured surface spring discharge temperatures compared to ambient air temperatures, and estimated subsurface temperatures based on the (B) SiO_2, (C) K-Mg, and (D) Na-K geothermometers (modified from Reyes et al, 2010). Grey= wells, white= springs, black dots are median values

Assuming that both thermal and high-chloride cold aqueous fluids have attained near-equilibrium at depth, with respect to silica and based on plots on the Na-K-Mg triangular diagram (Giggenbach, 1988), then the estimated subsurface temperatures in the low-temperature regions vary from 25°-215°C based on the K-Mg geothermometer and 20°-160°C using the silica geothermometer (Giggenbach, 1993), with the highest temperatures in the Coromandel Peninsula in the North Island and the North Alpine Fault Zone in the South Island at 150°C (Figures 3B and C). The highest Na-K temperatures are up to 250°C in the Coromandel Peninsula (Figure 3D), 215°C in Auckland in the North Island and nearly 230°C in the North Alpine Fault Zone in the South Island. The lowest inferred temperatures are at Whanganui in the North Island and Otago in the South Island (Figure 2). The only aqueous fluid discharges available from Taranaki are petroleum well discharges. One well with apparently no more drilling fluid contamination indicate subsurface temperatures as high as 190°C using the Na-K geothermometer (Figure 3D). In general, the higher the discharge temperatures of thermal springs in the North Island, the higher the estimated subsurface temperatures. In contrast, subsurface temperatures have no direct correlation with surface discharge temperatures. Instead, subsurface temperatures are highly affected by elevation, flowrates, topographic gradient and rate of uplift (Reyes et al, 2010).

3.3 Bottomhole Temperature Estimates

There are >500 abandoned petroleum wells in all regions except in the North Alpine Fault Zone (region 14 in Figure 2). In this region two sites were drilled by the Deep Fault Drilling Project (DFDP) under the auspices of the International Continental Scientific Drilling Program, with one research well attaining a depth of about 815m (Townend et al, 2017) with a thermal gradient of 125°C (Sutherland et al, 2017)

About 40% of all abandoned petroleum wells are located in Taranaki. These are located within or near populated areas where access to geothermal energy (or cogeneration of geothermal and gas), for power and direct heat use, would benefit the large energy-intensive dairy, food-processing and horticultural industries in the region. Other regions with a significant number of abandoned wells are the Hikurangi Accretionary Prism in the East Coast of the North Island (region 1 in Figure 2) where nearly 25% of the wells occur, Whanganui-Taumarunui (region 10), and the West Coast of the South Island (regions 12, 14 and 15).

Vertical depths of abandoned petroleum wells range from 17 to 5065m (Figure 4) with the majority drilled below 3000m. Twelve of the 13 wells drilled to >4000m are located in Taranaki with one found in the Hikurangi Accretionary Prism (region 1). Stabilized downhole temperatures are rarely measured in petroleum wells although temperatures during or just a few hours after drilling are available. In the absence of stable downhole temperatures, BHTs are roughly estimated using surface conductive heat flow data (Funnell et al, 1996; King and Trasher, 1996; Funnell and Allis, 1997; Field et al, 1997; Allis et al, 1998; Cook et al, 1999) and roughly converted to thermal gradient using a factor of 2.1 (Funnell et al, 1996) and an average surface temperature of 12°C for the South Island and 15°C for the North Island. A comparison of BHT with measured downhole temperatures, aqueous solution chemical geothermometry and homogenization temperatures of the latest aqueous fluid inclusions (Reyes, 2015) suggest that values are probably within +20°C of stable well conditions.

The estimated BHTs of abandoned wells vary from near ambient to 175°C, with the latter occurring at 4450m in New Plymouth-2 in Taranaki. Most of the wells plot between thermal gradients of 25°- 45°C/km with Rotokautuku-1 in the East Coast at 90°C/km and the deep DFDP well in region 14 in the South Island at about 120°C/km. About 22% of the wells have BHT>95°C suitable for power generation using a binary cycle or hybrid system and the rest can be used for direct heat applications. Nearly 80% of wells with BHT>95°C are located in Taranaki. The rest occur in the Hikurangi Accretionary Prism (region 1), Northland (region 9), Whanganui-Taumarunui (region 10), West Coast (region 12) and the Fiordland Fault Zone (region 15).

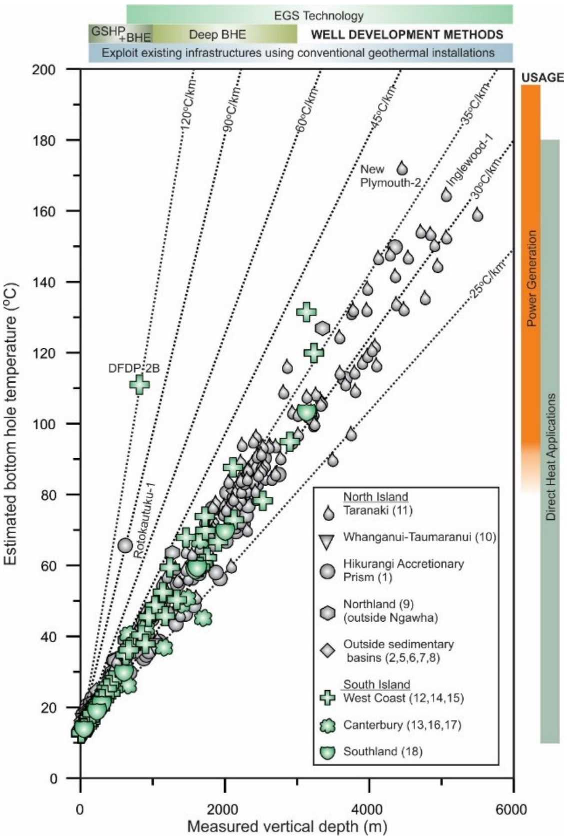

Figure 4: Measured depth vs estimated bottomhole temperature of abandoned wells in onshore sedimentary basins. Numbers in parenthesis correspond to regions in Figure 4. Bars on right show general heat use for a given temperature range. On top are general well development methods based on depth and temperatures. GSHP= Ground Source Heat Pump, BHE= Borehole Heat Exchanger, EGS= Enhanced/Engineered Geothermal System.

The map shown in Figure 2 shows the maximum estimated subsurface temperatures in each region estimated from geothermometry of aqueous fluid discharges and BHT estimates, except in Southland which is solely based on well BHTs. Based on subsurface temperatures, the most viable regions in New Zealand are Coromandel Peninsula, Auckland and the North Alpine Fault Zone with estimated subsurface temperatures of 200-250°C; Bay of Plenty, Western Waikato, Taranaki and the Marlborough Fault System with temperatures of about 175-200°C at depth (Figure 2).

3.4 Source of Hot Aqueous Fluids with Respect to Well Depths

One of the questions that may arise when converting abandoned petroleum wells for geothermal use is whether the source depth of thermal fluids is within drilled depths or if wells need to be deepened. Because the estimated BHTs in wells or mines in the low-temperature regions are based on a regional thermal gradient, the 1:1 correspondence band at +10°C defines a conductive heating trend. Any aqueous fluid samples from wells or mines that plot on this band have heated conductively at or near the point of discharge (Figure 5A) or equilibrated with respect to the K-Mg temperature within the well (Figure 5B). In contrast, samples with measured discharge temperatures that plot to the right of the conductive band are affected by the influx of cold meteoric water (1 in Figure 5A). Aqueous fluids from Taranaki and the West Coast plotting to the right of the conductive band (1 in Figure 5C) had equilibrated with the silica geothermometer at depths shallower than total well depths and/or have been affected by cold meteoric water influx. The farther to the right of the band, the greater the amount of cooling in the well.

Samples that plot to the left of the conductive band (2 in Figures 5B to D) indicate upflow of hot aqueous fluids from below drilled depths in the following regions: Hikurangi Accretionary Prism, Western Waikato, Taranaki and Wanganui in the North Island and Otago and Canterbury in the South Island. In general, the farther to the left from the conductive band, the deeper the source of the equilibrated fluids relative to the drilled depth of wells which, in the samples studied, varies from 925-995m in the Hikurangi Accretionary Prism, 45-310m in Western Waikato, 915-3660 in Taranaki, 2315m in Wanganui, and 15-35m in Canterbury and Otago.

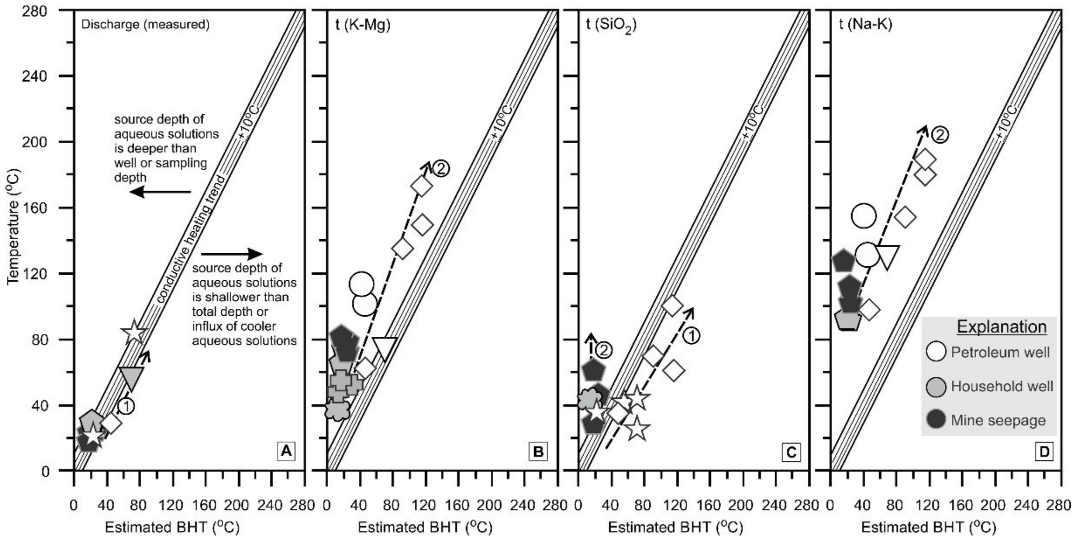

Figure 5: Plots of estimated bottomhole temperature at total well depths or sampling point of underground mine aqueous fluid samples with respect to (A) measured discharge, (B) SiO_2, (C) K-Mg and (D) Na-K temperatures (modified from Reyes, 2015). Symbols are the same as in Figure 2.

3.5 Geology and Heat Sources

One the main difficulties in the exploration of low-temperature geothermal systems outside the TVZ and Ngawha is predicting permeability at depth and the possibility of cold water influx. Understanding the tectonic settings of fluid discharges, whether thermal or cold, may provide insight to possible hydrological conditions and permeability at depth.

Approximately 90% of the low-temperature spring systems in New Zealand are distributed along the present-day convergence of the Pacific and Australian plates, which varies from subduction in the North Island to oblique plate collision in the South Island. Subduction fluids are expelled along the Hikurangi Accretionary Prism and are chemically traceable in the North Island Axial Ranges in the North Island and the northern Marlborough Fault System in the South Island albeit modified by temperature, mixing with surface and heated meteoric waters and greater interaction with the rock. Most thermal aqueous fluids in the South Island are discharged along the Alpine Fault Zone where plate collision results to rapid uplift of the Southern Alps, elevated geothermal gradients and fault-shearing of rocks.

Outside the active convergent zone thermal fluids- whether from springs, wells or mines- are discharged from an ancient accretionary prism (Northland), sedimentary basins (Taranaki, Whanganui-Taumarunui, Western Waikato, West Coast in the South Island), regions of Holocene volcanism in Auckland and Taranaki; regions of Miocene to Pleistocene volcanism (Coromandel, Northland, Western Waikato); and a region of continental back-arc rifting in the Hauraki Rift Zone (Hochstein, 1978). The sources of heat and solutes in low-temperature aqueous fluids, outside the TVZ and Ngawha, are decoupled except for rapidly ascending hot subduction waters in the Hikurangi Accretionary Prism springs, low-temperature Ca-Cl waters in Fiordland in the South Island derived from serpentinisation (Reyes et al, 2010) and ascending hot metamorphic fluids at Copland springs in the Southern Alps.

Essentially, the wide range of tectonic settings of low-temperature geothermal resources in New Zealand can be related to variations in thermal gradients and heat transfer, permeability and circuitry of fluid pathways, sources of solutes and the extent of fluid-rock interactions.

A pseudo-section across New Zealand in Figure 6 shows temperature variations with depth under different tectonic, structural and geographical conditions. Radioactive decay is essentially the main source of all heat generated in the crust (Jaupert and Mareschal, 2003), although specific tectonic settings and geographic locations in New Zealand are conducive to heat production shallow enough to be economically harnessed.

The measured surface discharge and estimated subsurface temperatures of low-temperature thermal fluids are generally higher in the North Island than in the South Island. This is primarily because of the widespread distribution of Pliocene to Recent arc-type and intra-plate volcanism related to relatively shallow magmatic and mantle heat sources located west of the North Island Axial Ranges. The highest grade geothermal systems occur in the volcanically very active TVZ, an amalgamation of hydrothermal convection cells within a region of unusually high heat flow, in fractured crust with enormous heat and mass flows (e.g. Hochstein, 1995).

Quaternary back-arc basaltic volcanic fields in Western Waikato, Auckland and parts of Northland (Huang et al, 2000) suggest that hot mantle or ponded basaltic melts at depth may contribute to the high conductive heat flow and the existence of thermal springs in these regions. High surface conductive heat flow in Taranaki is coincident with the active volcano (Funnell et al, 1996) indicating the presence of deep-seated magmatic intrusions although the massive deep influx of cold meteoric water through sand layers lowers temperatures (Allis et al, 1997). Surface thermal springs with temperatures of 87°C and inferred subsurface temperatures of 250°C in the Coromandel may be from heat conducted from deep-seated and still-hot magmatic Pleistocene intrusions (Reyes et al, 2010).

There are restricted pockets of high heat flow in the Hikurangi Accretionary Prism. The presence of two thermal springs in the north of this region is uncommon in a subduction forearc. But a recent analysis (Reyes et al, in prep.) based on measured field flow rates show that hot aqueous fluids ascend from depth at a faster velocity than cold aqueous fluids. Thus, hot springs exist in the Hikurangi Accretionary Prism partly because less heat is being conducted away from rapidly-ascending hot fluids, into the rock.

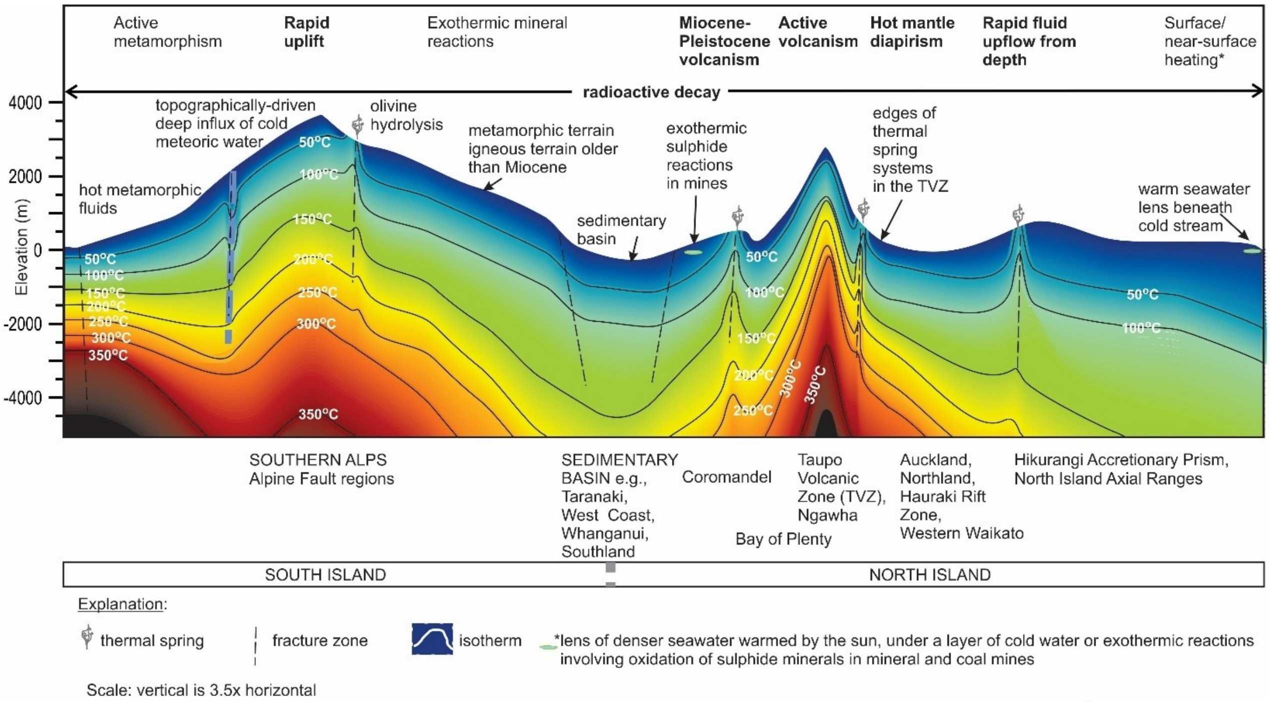

Figure 6: Pseudo cross section across New Zealand showing isotherms, general geology, faults and sources of heat (modified from Reyes, 2015).

In the South Island the main source of heat along the Alpine Fault Zone is derived from rapid uplift along the Southern Alps caused by the collision of two continental plates (e.g., Allis et al, 1979). Locally however, the effects of uplift rates to the surface discharge and estimated subsurface temperatures are overwhelmed by the effects caused by elevation, hydrological and topographic gradients and volume of throughput. Exothermic reactions during hydration of minerals, e.g., serpentinization, may account for warm aqueous solutions in some of the springs in the South Island (Reyes et al, 2010). Advection of hot metamorphic fluids along specific faults of the Alpine Fault Zone or shallower occurrences of granite bodies may also contribute to the high thermal gradient in the DFDP well drilled along the Alpine Fault Zone (Toy et al, 2017; Townend et al, 2017) and existence of thermal springs in this region. In the latter the contribution of hot metamorphic fluids rising from depth is evinced by the chemical and isotopic compositions of the thermal aqueous solutions (Reyes et al, 2010). However, sustained shear heating may only be a transient and localized event in the Alpine Fault Zone (e.g., Sibson et al, 1979).

Hot mantle diapirism may contribute to the high heat flow in the Hauraki Rift Zone in the North Island and possibly parts of Otago in the South Island. Exothermic reactions related to deposition of sulfide minerals, oxidation reactions in hydrocarbon systems and mineral hydration reactions may contribute to heat output in localized regions of New Zealand. However, the contribution of exothermic reactions to crustal heat generation is deemed minimal by several authors e.g., Peacock (1987) and short-lived (e.g., Martin and Fyfe, 1970).

In New Zealand the highest temperatures and largest geothermal systems occur in regions of Recent arc-type volcanism and rifting. Lower temperatures and heat flow occur in regions of Pleistocene arc magmatism, Recent intraplate volcanism and post-Miocene mantle diapirism. Rapid uplift may move hot crust to shallower depths. Deep permeable structures may rapidly channel hot metamorphic or deep subduction fluids to the surface or cause the influx of cold meteoric water, depending on the hydrological regime and topographic gradient (Figure 6).

4. ACCESSBLE AND RECOVERABLE HEAT

Access to stored heat (accessible heat) is provided by natural channels for fluid flow such as faults and/or lithological contacts in natural thermal spring systems or man-made structures such as wells or underground mines, where heated aqueous solutions can potentially be transported to surface installations or circulated between wells and heat exchangers, for heat extraction. From available data, the average flow rate used to estimate accessible heat energy in hydrocarbon wells is 3 L/s, and 1 L/s for a hypothetical well drilled every 1 km^2 of the surface boundaries of underground mines (Reyes, 2015). The minimum estimate of accessible heat from onshore hydrocarbon wells at 8.6 PJ/a, is 4.6x higher than estimates for underground mines (Table 1), due to deeper wells intersecting higher temperatures. The maximum temperature in underground mines is 38°C compared to bottomhole temperatures of up to 180°C in abandoned hydrocarbon wells (Reyes, 2015).

Heat recoverability in low-temperature geothermal systems is not only dependent on the efficiency of technological infrastructures to convert heat energy to a usable form, either for direct applications or for power generation, but also to factors such as the mostly unknown present state of the wells or mine sites, ownership of and access to land, well and/or mine, expenses associated with the rehabilitation and conversion of abandoned wells and mines for geothermal use, environmental considerations when developing these geothermal resources especially where urbanization had encroached on abandoned mine sites, and the need for more studies to be able to exploit and sustain these low-grade heat sources. Because of these uncertainties a recoverability factor of 10% is used (Reyes, 2015), rather than the industry standard of 20% (e.g., AGRCC, 2010). Hence, 10% of accessible heat is equal to recoverable heat (Table 1).

The minimum estimate of recoverable heat energy from aqueous solutions in low-temperature geothermal resources in New Zealand, from hot spring systems, abandoned hydrocarbon wells and underground mines, is 3.1 PJ/a. However, this is a low estimate due to the highly conservative assumptions (Reyes, 2015). Compared to the heat energy that can be potentially harnessed from the rock, this is but a small fraction.

Low-Temperature Region	No.	Wells		Mines		Thermal springs	Maximum Subsurface Temperature (°C)
		Accessible	Recoverable	Accessible	Recoverable	At Depth	
North Island							
Hikurangi Acc. Prism	1	1.2	0.12	nd	nd	0.17	150
N. Island Axial Ranges	2	0.07	0.007	0.02	0.002	0.03	115
Bay of Plenty	4	0.02	0.002	0.22	0.022	0.11	195
Coromandel	5	0.02	0.002	0.16	0.016	0.21	250
Hauraki Rift Zone	6	0.01	0.001	0.32	0.032	0.2	160
W. Waikato	7	0.34	0.034	nd	nd	0.72	190
Auckland	8	0.03	0.003	0.12	0.012	0.43	215
Northland	9	0.17	0.017	nd	nd	0.003	130
Whanganui	10	0.53	0.053	nd	nd	0.008	130
Taranaki	11	5.4	0.54	nd	nd	nd	190
South Island							
West Coast	12	1.04	0.104	0.52	0.052	nd	130
Marlborough Fault Sys.	13	nd	nd	0.13	0.013	0.09	185
N. Alpine Fault Sys.	14	nd	nd	nd	nd	0.025	220
Fiordland Alpine Fault Sys.	15	0.13	0.013	nd	nd	0.01	105
Canterbury	16	0.11	0.011	nd	nd	0.002	120
Otago	17	0.04	0.004	0.51	0.051	nd	120
Southland	18	0.16	0.016	nd	nd	nd	<100
TOTAL (onshore, >20°C)		8.6	0.86	0.82	0.08	2	

Table 1: Estimated accessible and recoverable heat (PJ/a) for wells, mines and thermal springs in the 17 low-temperature tectono-geoographic regions. Refer to Figure 4 for numbers. The heat energy in thermal springs is calculated using the enthalpy of K-Mg or SiO_2 temperatures, assuming that measured surface flows (Reyes, et al, 2010) persist at depth. In thermal springs accessible heat=recoverable heat (adapted from Reyes, 2015). Maximum estimated subsurface temperatures are derived from solute geothermometry of thermal spring or well aqueous fluids or BHT.

5. GEOTHERMAL PROSPECTIVITY

Figure 7A shows the temperature ranges of conventional and unconventional geothermal resources for each low-temperature region, based on solute geothermometry for fluid discharges and estimated bottomhole temperatures in petroleum wells and underground mines. Conventional geothermal resources occur in 12 of the 17 low-temperature regions (Table 1; shaded in Figure 7A). The median temperatures for shallow-sourced thermal aqueous solutions in thermal spring systems vary from 55°C to 125°C with deeper-sourced fluids having median temperatures of 100°-250°C. Although overlaps may occur, median temperatures in unconventional resources are always lower by 15°-40°C than conventional ones. Median temperatures from shallow-sourced aqueous solutions in unconventional geothermal resources are 30°-85°C and 95°-100°C for deeper-sourced solutions.

Ten regions have both conventional and unconventional sources of heat (Figure 7A). Only unconventional geothermal resources occur in five of the 17 low-temperature regions including Whanganui and Taranaki in the North Island and the West Coast, Otago and Southland in the South Island. Among these five, Taranaki has the highest median solute temperatures at 135°C for shallow- and 155°C for deep-sourced aqueous solutions with a high of 190°C. Otago and Southland have the lowest. The maximum BHT (bottomhole temperature) in hydrocarbon wells, drilled down to 35 to 5490m in the North Island, varies from 15°-175°C, in contrast to 13°-130°C at 17 to 3130m in the South Island. For some regions, the maximum temperatures at depth are provided by the BHT e.g., at 105°C (3130m) in the Fiordland Alpine Fault Zone where aqueous solutions from hydrocarbon wells are not available, and at 130°C (3233m) in the West Coast where most geothermometers are inapplicable due to the very high ionic strength of well discharges.

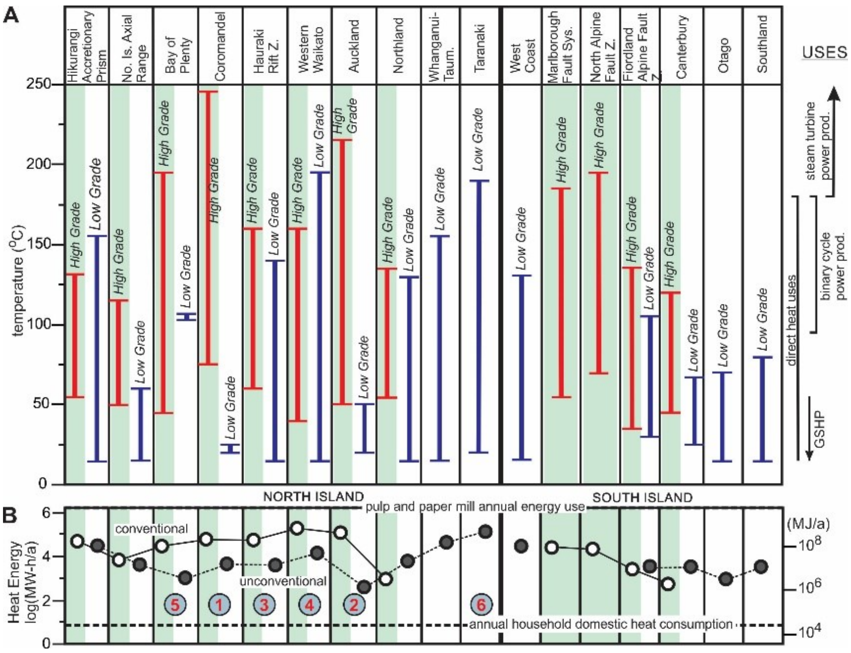

Figure 7: (A) Estimated temperature ranges from high- (red line, shaded) and low-grade (blue line) geothermal sources in the 17 low-temperature regions. On the right are possible uses for the geothermal resources. (B) Minimum estimated heat energy for conventional and unconventional geothermal resources as compared to the annual domestic heat consumption per household in New Zealand (Isaacs et al, 2010) and the total heat energy consumption of the Kawerau pulp and paper mill (Harvey and White, 2012). Circled numbers are the geothermal prospectivity of six of the regions rated 1 to 6 with 1 the highest, located in Coromandel (from Reyes, 2015).

All low-temperature regions are capable of providing heat energy for ground source heat pumps for space- and domestic water-heating and for other direct heat uses at higher temperatures. Fifteen of the regions have temperatures >95°C, potentially suitable for binary cycle power production. However, only the Coromandel region has high enough subsurface temperatures for power production using conventional steam turbines.

For most regions, the recoverable heat energy from conventional geothermal resources is higher than for lower-grade unconventional resources except in Northland, Canterbury and the Fiordland Alpine Fault Zone where thermal water temperature discharges are <30°C and flow rates (0.008-0.85 L/s) relatively low (Reyes et al, 2010).

Although the total recoverable heat energy in a given region may not be enough to operate a pulp and paper mill (Figure 7B), there is more than enough heat energy in each region from conventional and/or unconventional geothermal resources for domestic heat consumption, e.g., for 125 households in Otago and up to >29,000 in Western Waikato The geothermal prospectivity of a heat source becomes more of a local concern the lower the temperatures are, as heat use veers towards direct applications rather than nation-wide power generation. Based on a relative score that takes into account the total recoverable heat energy, maximum temperature at depth and the ratio of heat energy provided by conventional and unconventional sources of heat, the six main regions with the highest to lowest geothermal prospectivity are (Table 1, Figure 7B): 1. Coromandel, 2. Auckland, 3. Hauraki Rift Zone, 4. Western Waikato, 5. Bay of Plenty and 6. Taranaki. These six regions hold 75% of the recoverable heat energy in low temperature regions (Figure 2) at temperatures >20°C. Although temperatures as high as 220°C may be present in the North Alpine Fault Zone in the Southern Alps of the South Island, the rapid uplift, steep topography and the hydrological character of the Alpine Fault would cause massive cold water influx and drilling problems, as shown by recent drilling (e.g., Townend et al, 2017), that could render geothermal development uneconomical using available technology.

6. CONCLUSIONS

Although there is still a widespread perception in New Zealand to associate geothermal energy with thermal springs and volcanic regions, the onshore landmass can be viewed as one big geothermal system where ground source heat pumps and heat exchangers can be universally employed to extract heat from shallow ground or water reservoirs for low-temperature direct heat applications; and deeper heat sources accessed via thermal spring discharges, wells and underground mines.

Outside thermal spring systems, low-grade heat in unconventional geothermal resources can be accessed from hundreds of abandoned hydrocarbon wells, thousands of shallow domestic, industrial and mine exploration drill holes and abandoned underground mines, where these openings trap aqueous solutions for conductive heating or act as a focus for advecting hot thermal aqueous solutions from depth. Although inferred median subsurface temperatures in conventional geothermal resources may be higher at 80°- 250°C, the range of median temperatures in unconventional geothermal resources, at about 40°-190°C, can still be potentially used for a wide range of direct heat applications and possible power generation.

The very conservative estimate of recoverable heat from low-temperature conventional and unconventional geothermal resources is less than 1% of the recoverable heat energy in the TVZ. Except for a hydrocarbon well in Taranaki being used in a thermal spa, the extraction and exploitation of heat in low-temperature regions are mainly confined to thermal spring systems and ground source heat pumps, where only near surface discharges are utilised, mainly for heating swimming pools and for household purposes. At present

<20% of the estimated recoverable heat energy from low temperature conventional and unconventional geothermal resources, is being utilized.

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