GEOTHERMAL PROSPECTIVITY OF LOW-TEMPERATURE REGIONS IN NEW ZEALAND

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ABSTRACT

Based on fluid geothermometry of discharges from cold and hot springs, wells and underground mines; and hydrocarbon well measurements and projections, the estimated temperatures at depth in low-temperature regions, outside the Taupo Volcanic Zone and Ngawha, vary from about 55 to 250°C. The minimum estimated recoverable heat energy (calculated at 10% of accessible heat) from aqueous solutions, in these low-temperature geothermal resources, is 3.1 PJ/a, which is but a tiny fraction of heat energy that can be harnessed conductively from the rock. e.g. GSHP at shallow depths of <300m. Based on 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: Coromandel, Auckland, Hauraki Rift Zone, Western Waikato, Bay of Plenty and Taranaki, These six regions hold about 75% (at >20°C) of the recoverable heat energy estimated from aqueous solutions in low-temperature regions.

1. INTRODUCTION

By definition, heat energy only becomes a geothermal resource when it is technologically and economically recoverable. 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°C (Gagne-Boisvert and Bernier, 2017) to >350°C. The objective of this study, however, is to compare the geothermal prospectivity of low-temperature geothermal resources in New Zealand based on accessible aqueous solutions, and excludes any geological assessment of GSHP installations. To assess the relative geothermal prospectivity of low-temperature regions, outside the Taupo Volcanic Zone (TVZ) and Ngawha, more than 100 thermal and cold springs (Reyes et al, 2010), about 500 abandoned hydrocarbon wells and >500 underground mines (Reyes, 2015) were examined. Subsurface temperatures were estimated using solute chemistry of discharges from hot and cold springs, mines and wells; and/or bottomhole temperatures of hydrocarbon wells and underground mines based on measured data (www.nzpam,govt.nz) and the regional heat flow map of Allis et al (1998).

2. TYPES AND SOURCES OF HEAT

Conventional heat resources in New Zealand (Figure 1) are associated with thermal spring systems (Figure 2) where geological and hydrological conditions converge to focus heat and enhance heat- and fluid-transfer to the surface. Discharge temperatures of thermal springs are as high as 100°C in high-temperature geothermal systems and varies from 17°C (4°C above the average annual air temperature) to 87°C with a median of 50°C in low-temperatures regions.

Unconventional heat resources are located outside thermal spring systems where heat output, thermal gradients, relative permeability and volume of circulating fluids are lower than in conventional sources; and where the mode of heat transfer is dominated by conduction rather than convection. Also considered unconventional are anthropogenic heat sources in cities where elevated groundwater temperatures, due to human activity, create urban heat islands (e.g., Zhu et al, 2010) and in industrial areas where manufacturing processes e.g., cement-making, steel production and others can produce waste heat (Forni et al, 2014). Heat from unconventional geothermal resources can be accessed by ground source heat pumps, by drilling new wells and using hundreds of available abandoned deep hydrocarbon 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 aqueous solutions or act as a focus for advecting hot thermal aqueous solutions from depth (Reyes, 2015). The term "high-grade" (Figure 1) refers to the economic extractability of heat and not to temperature.

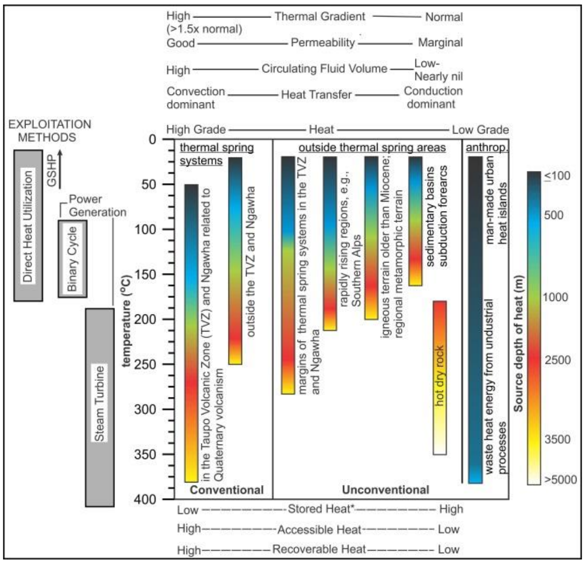

Figure 1: Temperature ranges, source depths, geological settings and general physical characteristics of conventional and unconventional geothermal resources, including anthropogenic sources (anthrop.), in New Zealand. General exploitation methods for a given temperature range are shown on the left. *Stored heat is higher for unconventional heat sources due to larger volume (adapted from Reyes, 2016).

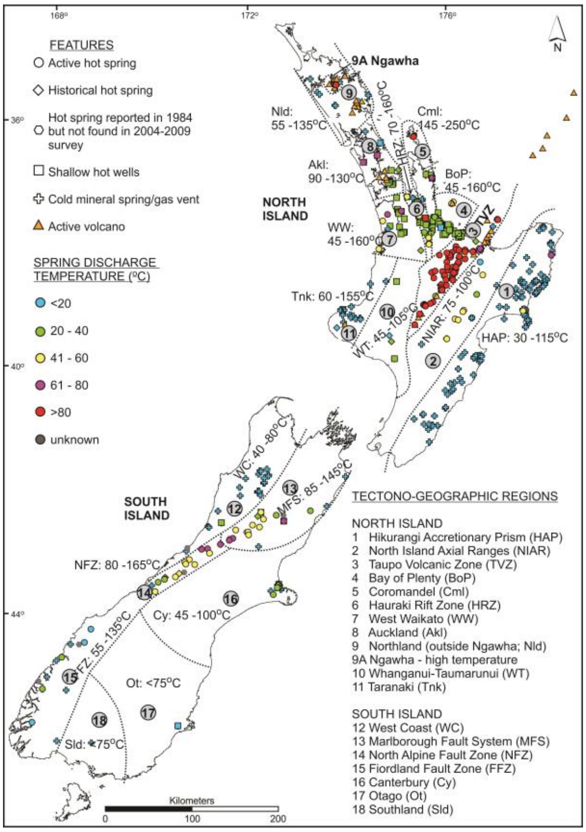

Figure 2: Map showing the distribution of springs and their discharge temperatures in the 18 major tectono-geographic regions of New Zealand and estimated median subsurface temperatures for each region, except the TVZ (3) and Ngawha (9A) which are a high-temperature geothermal regions (from Reyes, 2015 and 2016).

Radioactive decay is essentially the main source of all heat generated in the crust (Jaupert and Mareschal, 2003), although specific tectonic settings, geographic locations, geological processes and hydrological factors in New Zealand enhance heat and mass transfer to depths where heat extraction is economical (Reyes, 2016), e.g., regions of (1) Miocene to Recent volcanism and magmatic intrusions including mantle diapirism, widespread in the North Island, (2) rapid crustal uplift in the Southern Alps and advection of hot metamorphic fluids along faults in the South Island and (3) rapid fluid upflow along faults in the forearc in the North Island. Self-limiting geological processes such as sustained shear heating, exothermic chemical reactions during metamorphism may increase temperatures of the rock or circulating fluids. Deep influx of cold meteoric water in the Southern Alps (Reyes, 2010) or Taranaki (Allis et al 1997) lowers temperatures of rising hot fluids. Near some beaches in New Zealand, solar-warmed lenses of seawater beneath less dense cold stream waters generate localized and ephemeral heat leading to reports of hot springs in several areas.

3. STORED, ACCESSIBLE AND RECOVERABLE HEAT

3.1 Stored heat in rock

Estimates of stored heat reserves in the rock are based on a simplified equation (e.g., Garg and Combs, 2011) with the following assumptions: (1) rock porosity is 0.01 indicating that heat is mostly stored in the rock, (2) the general composition of the rock remains the same from surface to 3500 m and thus the specific heat capacity and density are constant at 0.86 kJ/kg and 2760 kg/m^3, respectively, values midway between greywacke and andesite, (3) the base temperature in the North Island is 15^{o}C and 12^{o}C in the South Island, (5) thermal gradients derived from the heat flow map of Allis et al (1998) are divided into low (30^{o}C/km), moderate (35^{o}C/km) and high (80^{o}C/km) and (6) the total areas included in the calculations exclude national parks, reserves, protected public and private land and lakes.

The estimated volumetric stored heat from near-surface to 3.5 km in low-temperature regions of New Zealand is 6.5x higher than for the high-temperature regions in the Taupo Volcanic Zone (TVZ) and Ngawha, at 3.6 x 10^{15} PJ/a, by virtue of the larger area covered by low-temperature regions at 119600 km^2 compared to 8700 km^2 for the TVZ and Ngawha. However most of this heat is locked in the rock.

3.2 Accessible heat in hydrocarbon wells and underground mines

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. Based on a few data available, 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^{o}C compared to bottomhole temperatures of up to 180^{o}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

Low-temperature Region	No.	Wells		Mines		Thermal springs
		Accessible	Recoverable	Accessible	Recoverable	At Depth
North Island						
Hikurangi Acc. Prism	1	1.2	0.12	nd	nd	0.17
N. Island Axial Ranges	2	0.07	0.007	0.02	0.002	0.03
Bay of Plenty	4	0.02	0.002	0.22	0.022	0.11
Coromandel	5	0.02	0.002	0.16	0.016	0.21
Hauraki Rift Zone	6	0.01	0.001	0.32	0.032	0.2
W. Waikato	7	0.34	0.034	nd	nd	0.72
Auckland	8	0.03	0.003	0.12	0.012	0.43
Northland	9	0.17	0.017	nd	nd	0.003
Whanganui	10	0.53	0.053	nd	nd	0.008
Taranaki	11	5.4	0.54	nd	nd	nd
South Island						
West Coast	12	1.04	0.104	0.52	0.052	nd
Marlborough Fault Sys.	13	nd	nd	0.13	0.013	0.09
N. Alpine Fault Sys.	14	nd	nd	nd	nd	0.025
Fiordland Alpine Fault Sys.	15	0.13	0.013	nd	nd	0.01
Canterbury	16	0.11	0.011	nd	nd	0.002
Otago	17	0.04	0.004	0.51	0.051	nd
Southland	18	0.16	0.016	nd	nd	nd
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 2 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).

conservative assumptions (Reyes, 2015). Compared to the heat energy that can be potentially harnessed from the rock, this is but a small fraction.

4. GEOTHERMAL PROSPECTIVITY

Figure 3A 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 hydrocarbon wells and underground mines. Conventional geothermal resources occur in 12 of the 17 low-temperature regions (Table 1; shaded in Figure 3A). 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 (Figure 2). 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 3A). 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 Otago and Southland the lowest. The maximum BHT (bottomhole temperature) in hydrocarbon wells, drilled down to 35 to 5490m in the North Island, varies from 15°-170°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.

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 3B), 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 29,390 in Western Waikato.

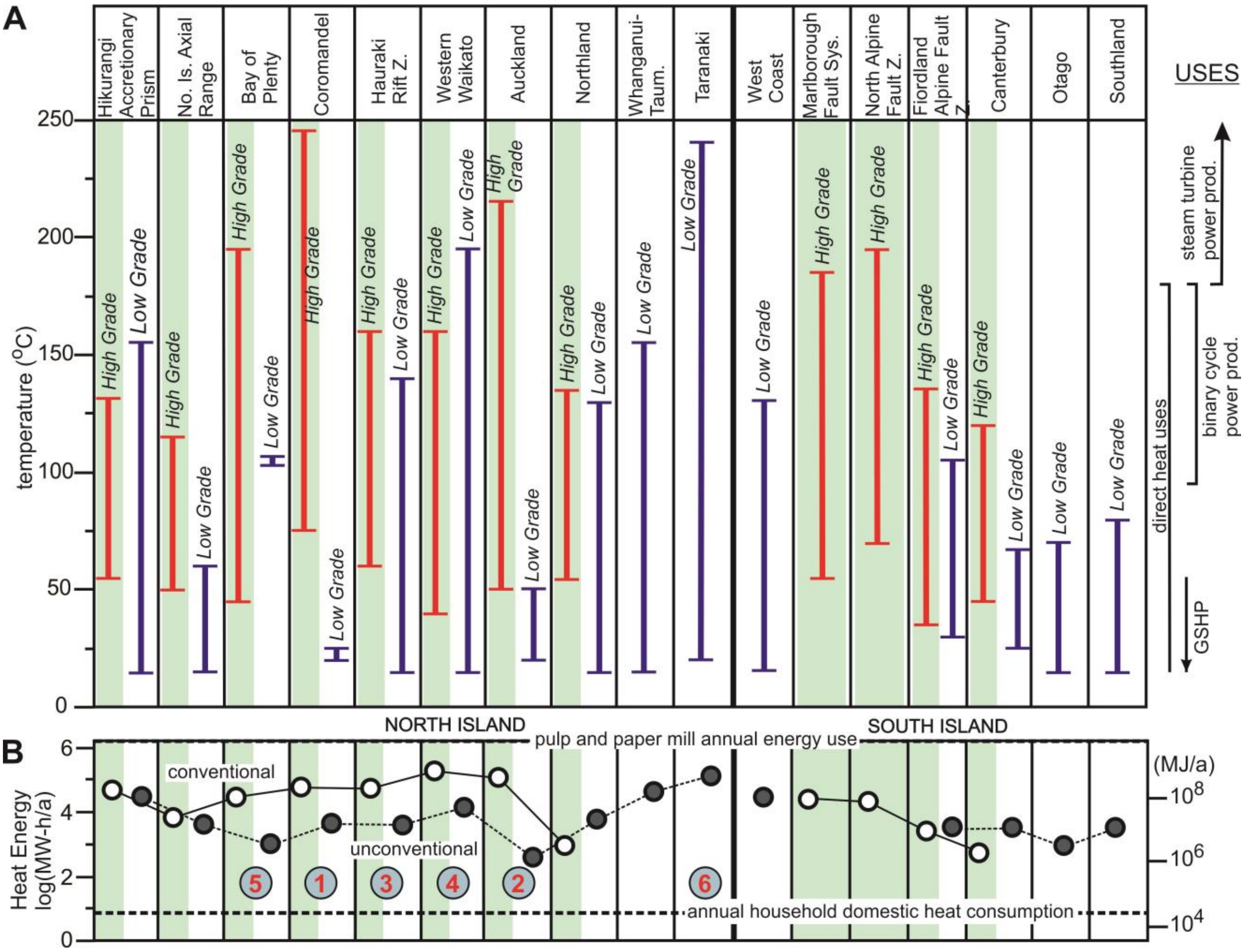

Figure 3: (A) Estimated temperature ranges from high- (red line, shaded) and low-grade (blue line) geothermal sources in the 17 low-temperature regions. On the right are possible uses for the geothermal resources. (B) Minimum estimated heat energy for conventional and unconventional geothermal resources 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 with the highest, 1, located in Coromandel (adapted from Reyes, 2015).

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): Coromandel, Auckland, Hauraki Rift Zone, Western Waikato, Bay of Plenty and Taranaki. These six regions hold 75% of the recoverable heat energy in low temperature regions at temperatures >20^{o}C.

5. CONCLUSION

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^{o}- 250^{o}C, the range of median temperatures in unconventional geothermal resources, at about 40^{o}-170^{o}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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