GEOCHEMISTRY AND GEOTHERMAL PROSPECTIVITY OF THE HYDROCARBON-PRODUCING TARANAKI SEDIMENTARY BASIN

A. G. Reyes

GNS-Science, I Fairway Drive, Avalon, Lower Hutt 5011, New Zealand

a.reyes@gns.cri.nz

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ABSTRACT

In a previous nation-wide study of low-enthalpy geothermal systems in New Zealand, the Taranaki peninsula was deemed sixth of the six regions in New Zealand with the highest geothermal prospectivity, albeit the only one where the minimum estimated recoverable heat (0.54 PJ/a) and estimated temperature range (<100-200ºC) are based on data from abandoned subaerial oil and gas wells. This submission examines fluid geothermometry in more detail as part of a study on the geochemical compositions of oil and gas well discharges and their effects on future geothermal exploitation. Bottomhole temperatures (BHT) of wells in Taranaki vary from <50ºC to about 175ºC. The highest subsurface temperatures (>150ºC) based on solute chemistry occur at New Plymouth, Kapuni and Stratford, with moderate temperatures (100-150ºC) at Onaero, Kaimiro, Ngatoro, McKee and Waihapa, and the lowest in the west at Te Kiri (<100ºC). High temperatures at New Plymouth may be related to the shallowing of the upper mantle but high temperatures at Kapuni and Stratford may be due to rapid ascent of hot fluids via deep faults. Subsurface temperatures at Taranaki show that geothermal energy can be harnessed for power generation and direct heat use. Because of the likelihood of liquid condensation, the presence of gases >C6 would require a different distribution system for geothermal fluids for power or direct heat use if fluids from petroleum wells are directly harnessed for geothermal energy. However, the use of deep borehole heat exchangers at Taranaki may obviate the problem of hydrocarbon gas condensation and hydrocarbon solidification during geothermal production.

1. INTRODUCTION

1.1 Study area

The Taranaki Peninsula is within a 100,000km^2 sedimentary basin (King and Trasher, 1996) that extends mostly offshore (Palmer and Andrews, 1993; King and Thrasher, 1996), with a basin fill of up to 9000m of Cretaceous to Quaternary rocks (Crown Minerals, 2004; Townsend et al, 2008). The peninsula covers about 3500km^2 west of the Taranaki Fault (Fig. 1a), comprising only 3.5% of the Taranaki Basin. Andesitic volcanoes at Taranaki are the most westerly expression of subduction related andesitic volcanism in New Zealand (Locke et al, 1994) where the subduction interface is estimated to be at -250km (Williams et al, 2013). The volcanoes become younger from Sugar Loaf Islands/Motumahanga and Paritutu in the north at 1.8Ma to the south at Egmont (<130ka) and Fantham's peak (<3.2ka; Townsend et al, 2008).

Taranaki is the only oil, gas and condensate producing region in the country (www.mbie.govt.nz) where the onshore region has about 250 plugged and abandoned wells (Fig. 1b), >150 actively used for oil and gas production and injection, and another 200 plugged, shut-in, being developed or of unknown state (NZP&M data). Oil seeps at gas vents at New Plymouth spurred drilling for oil in the area as early as 1866 (Clarke, 1912). But with the discovery of gas at Kapuni in 1959, most hydrocarbon exploration has been focused on Eocene and later Miocene to Pliocene sediments away from New Plymouth (Smale et al, 1999; Crown Minerals, 2004).

The conversion of unused petroleum wells for geothermal energy exploitation in onshore New Zealand, often focused on onshore Taranaki, has been studied since 2007 (Reyes 2007; Angalwa, 2014; Reyes, 2015, 2018, 2019 and 2020). Recent encouragement to further study the geothermal prospectivity of the onshore Taranaki basin has been spurred on by (1) the government's initiative, under the Paris Agreement, to reduce greenhouse gas emissions by 30% below 2005 levels by 2030 and to attain carbon neutrality by 2050 (www.mfe.govt.nz) and (2) the depletion of reserves in the region (Reyes, 2019). Other countries such as China (Wang et al, 2016) and Croatia (https://www.powerelectronicsnews.com) have succeeded in converting petroleum wells for district-wide direct heat use and geothermal power production. However, the long-term success of this source of geothermal energy is still unknown and the conversion of a petroleum system to a geothermal-producing region has to overcome various still-unstudied factors in New Zealand including well ownership and socio-economic, environmental, scientific and technical hurdles (e.g., Reyes, 2019).

It has been estimated that recoverable geothermal heat from Taranaki abandoned wells is at least 0.54PJ (Reyes, 2015). The geothermal prospectivity of Taranaki is 6th highest of the regions outside the Taupo Volcanic Zone and Ngawha for both direct and power use. Bottomhole temperatures (BHT) of wells in Taranaki vary from <50ºC to about 175ºC (e.g., Reyes, 2015).

The aim of this paper is to present previous fluid geochemical data (e.g., Short and van Rijen, 1963; Goulden, 1965; Robertson Research, 1976; Carter, 1983; Core Laboratories and Peter Vause Ltd., 1983; Carter et al, 1984; Giggenbach et al, 1993; Lyon et al, 1996, Giggenbach, 1997) from a geothermal perspective including deep temperatures, fluid sources and fluid compositions.

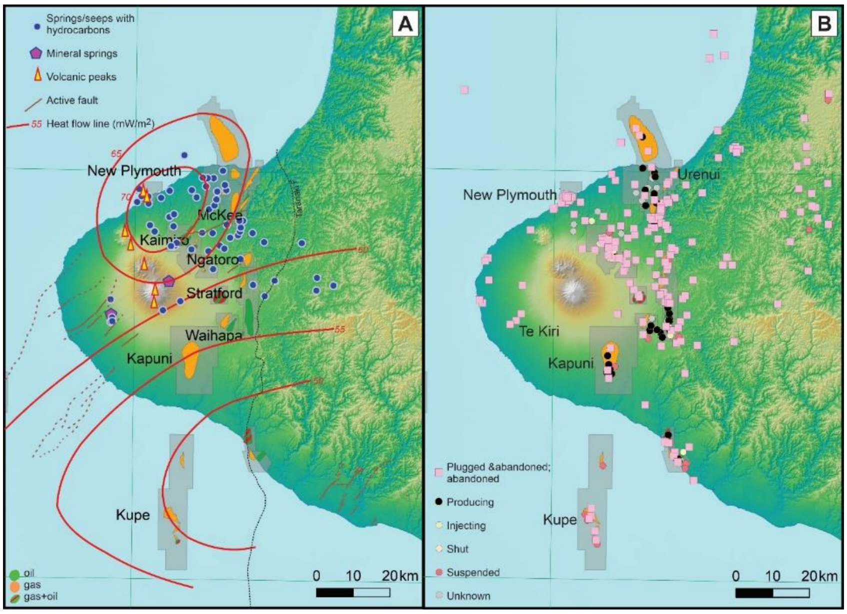

Figure 1: [A] Map location of seeps, active faults and the Taranaki fault, heat flow contours and hydrocarbon fluid types and [B] location of abandoned and other hydrocarbon wells (King and Trasher, 1997; Funnell et al, 1996; Townsend et al, 2008; MBIE, 2020; GNS-Science database from NZP&M).

2. AQUEOUS FLUIDS

2.1 Sources

The location map of fluid samples and location names are shown in Fig. 2. The "McKee" region in this paper consists of McKee, Tuhua, Pouri, Toetoe, Mystone and Mangahewa (Mghw in Fig. 2) wells (Fig. 3).

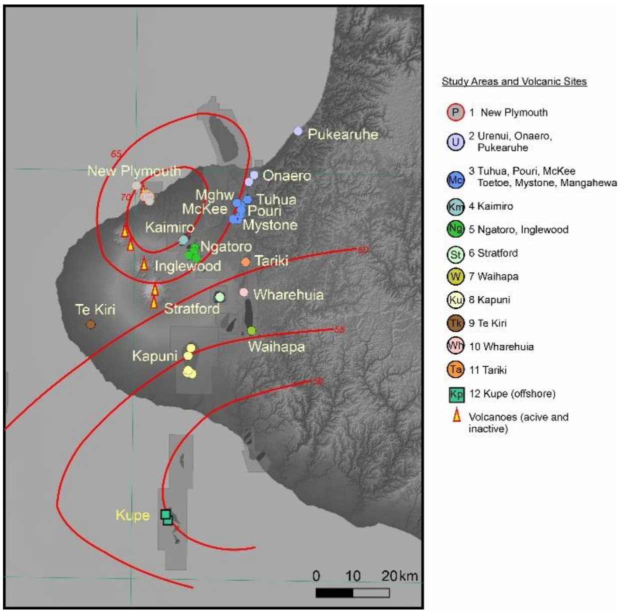

Figure 2: Sample location map except for western offshore Maui. Heat flow contours from Funnell et al, 1996.

Based on relative Cl, B and Li compositions, aqueous discharges from Ngatoro and Kaimiro wells (Figs. 2 and 3) appear to be a mixture of seawater and sedimentary formation waters being diluted with meteoric water, (#4 in Fig. 3) whilst Mckee, Wharehuia and Waihapa have less seawater but more sedimentary formation water mixing with meteoric water (#5 in Fig. 3). There are two Kapuni points. One appears to be a product of mixing of formation and meteoric waters (Kapuni-11) whilst the other consists of hot greywacke water mixing with formation water and then diluted by meteoric water (Kapuni-15).

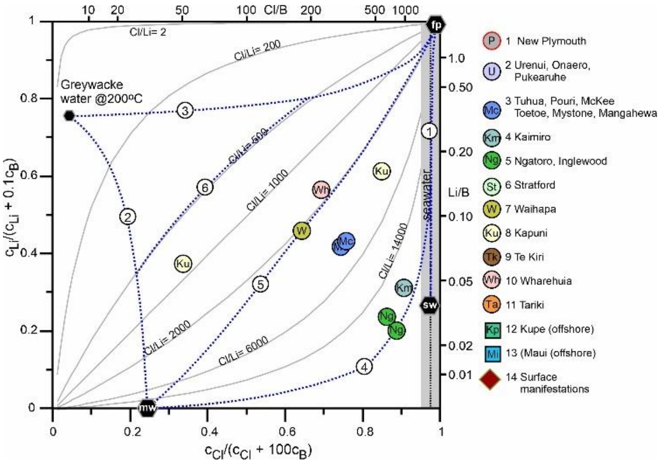

Figure 3: Cross plot of $C_{Cl}/(C_{Cl} + 100C_B)$ vs $(C_{Li}/(C_{Li} + 0.1C_B)$ showing end member compositions: fp= formation water; sw= seawater; mw= meteoric water; greywacke= greywacke dissolved in water at 200ºC from Ellis and Mahon (1967) and mixing lines: (1) seawater and formation water, (2) greywacke and meteoric water, (3) formation water and greywacke water, (4) formation-seawater and meteoric water, (5) formation water and meteoric water and (6) formation water-greywacke water and meteoric water-greywacke water.

Fluid inclusion (Reyes, 1998; Taylor, 2002; Killops et al, 2009; Reyes, unpublished work) and studies on fluid chemistry (e.g., Lyon et al, 1996) suggest that the aqueous fluid compositions within the Eocene and Miocene sedimentary formations vary in salinity and oil, gas and condensate contents. Aqueous fluids discharged by wells in this study are assumed to be a combination of fluids from different sedimentary formations. A cross plot of Cl with $\delta^{18}O$ shows discharges from Kapuni, Urenui, "McKee" wells, and Wharehuia along Line 1 in Fig. 4A linking a hypothetical formation water of unknown Cl content and a near-zero Cl water with positive $\delta^{18}O$ akin to partial water of clay dehydration.

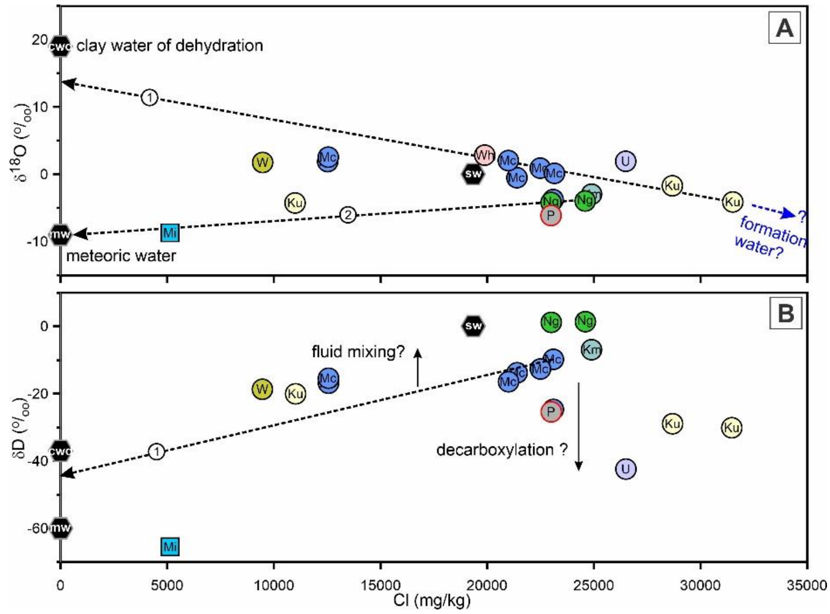

Figure 4: Cross plot of Cl (mg/kg) vs [A] $\delta^{18}O$ and [B] δD. cwd: clay water of dehydration, mw= meteoric water, sw= seawater, cwd= water of clay dehydration. Line (1) mixing of formation water and diluted water of clay dehydration and (2) mixing of formation water and meteoric water.

Water of clay dehydration is expelled when smectite transforms to illitic clays during diagenesis at >100ºC (e.g., Volker and Stipp, 2015). The hypothetical formation water has a Cl composition nearest that of the deepest well drilled at Kapuni at Kapuni KD-1. Line 2 in Fig. 4A indicates influx of meteoric water at Ngatoro, Kaimiro and a Kapuni well (Kapuni-11) and Maui, partly supported by results in Fig. 3. The "McKee" well discharges, in a plot of Cl vs δD (Fig. 4B) fall along Line 1 linked to mixing with partial clay water of dehydration. Discharges with δD values above Line 1 (Fig. 4B) may be due to input of seawater at Ngatoro and mixing of different formation waters at McKee (McKee-2 and 5A), Kapuni (Kapuni-11) and Waihapa wells. In contrast, well discharges from New Plymouth (P), Urenui and two Kapuni wells (Kapuni-KD1 and 8) have lower δD values than Line 1 and may be a result of decarboxylation of acetic or formic acid generated from vitrinites to produce CO_2, a process suggested by Killops et al (1996) for Taranaki. Thus, unlike geothermal systems in active volcanic terrain in New Zealand, the stable isotope compositions of aqueous fluids at Taranaki are decoupled.

2.2 Temperatures

In most geothermal systems, whether high- or low-enthalpy, the Na-K and K-Mg geothermometers (Giggenbach, 1988) appear to be most reliable in predicting subsurface temperatures at depth, where fluids interact with rock formations containing calc-alkaline components such as feldspars and micas. The well discharges falling along the full equilibrium line in Fig. 5A have apparently equilibrated with feldspars at about 120°C at Kupe, 140°C at Waihapa, and 180°C at Kapuni (Kapuni-11), and >200°C in other Kapuni wells with the highest Cl contents (Kapuni-KD 1 and 8) and Toetoe well in the "Mckee" region.

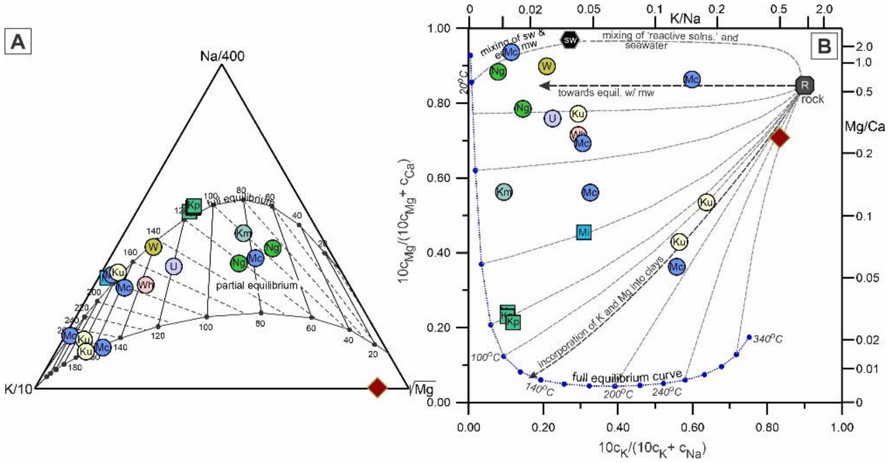

Figure 5: [A] Ternary Na-Mg-K diagram (Giggenbach, 1988) showing Na-K and K-Mg temperatures and [B] cross plot of $10c_K/(10c_K + c_{Na})$ vs $10c_{Mg}/(10c_{Mg} + c_{Ca})$ plot from Giggenbach (1991) with full equilibrium curve recalculated for low-enthalpy waters (Reyes et al, 2010).

Other well discharges plot within the partially equilibrated region at about 90°C (Ngatoro) to 180°C (Tuhua well in the "McKee" region). However, the plot $10c_K/(10c_K + c_{Na})$ vs $10c_{Mg}/(10c_{Mg} + c_{Ca})$ in Fig. 5B shows that most of the samples plotted within the full equilibrium line and partially equilibrated region (Fig. 5A) actually show a high degree of mixing with seawater, meteoric water and congruently dissolved crustal rock. Of the discharges, only the offshore well discharges at Kupe plot at or near the full equilibrium line in both diagrams. Hence, the use of the K-Na and K-Mg geothermometers in predicting subsurface temperatures in the Taranaki system may not necessarily give reliable results and need to be counterchecked using several geochemical plots and geothermometers. Inconsistencies between the two diagrams (Figs. 5A and B) at Taranaki may be due to sampling of aqueous fluids prior to well stabilization when introduced fluids from drilling are still masking formation water compositions.

In summary aqueous fluids discharged by Taranaki wells are a mixture of high-Cl formation waters from different sedimentary rock intervals, water from clay dehydration, fluids generated from the maturation and oxidation of hydrocarbons, meteoric water, congruently dissolved sedimentary rock at depth and in several wells, fluids introduced during drilling.

3. GAS COMPOSITIONS

3.1 Sources

The isotopic $\delta^{13}C$ and δD compositions of CH_4 gas in both onshore and offshore well discharges cluster within the region of oil-associated thermogenic gas, with one Maui well discharge extending to late-mature thermogenic (LMT) gas and some Kaimiro gases (K) appearing to be mixed with CH_4 from secondary microbial (SM) methanogenesis (Fig. 6).

Ternary diagrams in Figs. 7A and B show that New Plymouth (P) and offshore Maui (Mi) well discharges have the highest mantle signatures at 60% and 37%, respectively. In contrast, gases from Kapuni and offshore Kupe are largely crustal (Giggenbach, 1997). CO_2 gas is depleted at New Plymouth and offshore Maui whereas CO_2 is added during diagenesis at Kapuni, Waihapa and some wells in the "McKee" region. Interestingly, despite the proximity to the 1.8Ma andesitic volcanic remnants, the relative N_2-Ar-^{4}He concentrations of the New Plymouth discharges show a high mantle component but no andesitic gas signature (Fig. 7B).

3.2 Temperatures

A plot of relative CO_2, CH_4 and N_2 (Fig. 8) corrected for air shows that discharges from the New Plymouth (P) and Kapuni (Ku wells have the highest relative CO_2 contents with median CO_2/CH_4 ratios of 2.0 and 1.0, respectively and CH_4-CO_2 temperatures >170°C. Most of the wells in the "Mckee" region, Urenui, Te Kiri, Kaimiro and offshore Kupe are CH_4-rich with median CO_2/CH_4 ratios <0.05 and CH_4-CO_2 temperatures <125°C. Stratford, Waihapa and offshore Maui well discharges are in between with median CO_2/CH_4 ratios of 0.15-0.42 and CH_4-CO_2 temperatures 140-155°C.

Temperatures using the CO_2-Ar geothermometer of Giggenbach (1991) indicate deep temperatures $\leq$100°C at Ngatoro and offshore Kupe, 110-170°C in the "McKee" region, Kaimiro, Waihapa and offshore Maui. The highest CO_2-Ar ratios, with well discharges that are most oxidizing, are located at Kapuni and New Plymouth where temperatures are 200-240°C (Fig. 9), similar in range to the Na-K temperatures from aqueous solutions. Although New Plymouth and Kapuni discharges have the highest gas temperatures, the source of heat is different. The high mantle signature implies a shallowing of the hot upper mantle at New Plymouth. In contrast, the

Kapuni gases are crustal in origin suggesting that advection of high temperature aqueous and gaseous fluids may be rapidly circulated along deep crustal structures.

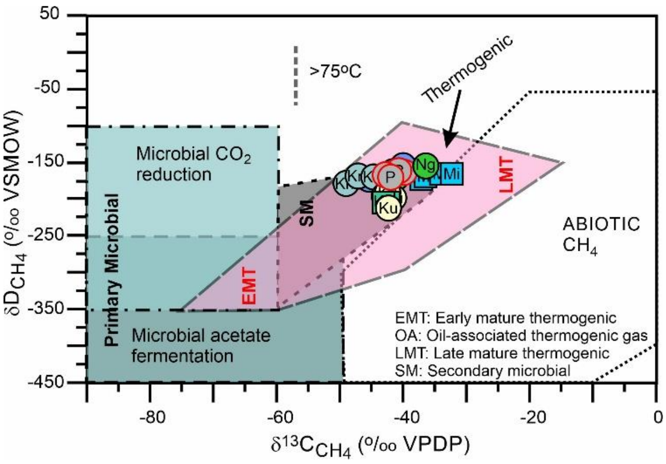

Figure 6: Cross plot of $\delta^{13}C_{CH4}$ vs δD_{CH4} based on Milkov and Etiope (2018) with temperature cut-off from Clayton (1991).

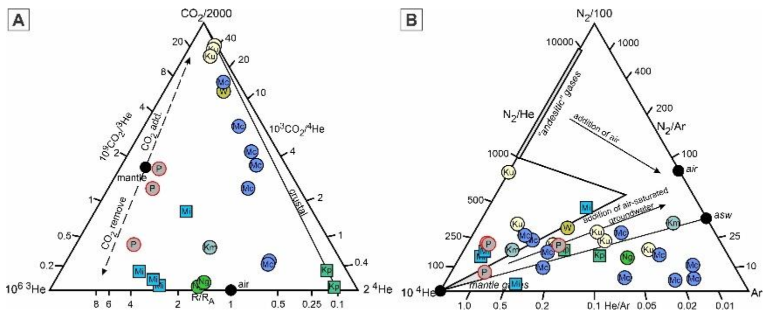

Figure 7: Relative compositions of [A] CO_2-^4He and ^3He and N_2-Ar-^4He after Giggenbach et al (1993).

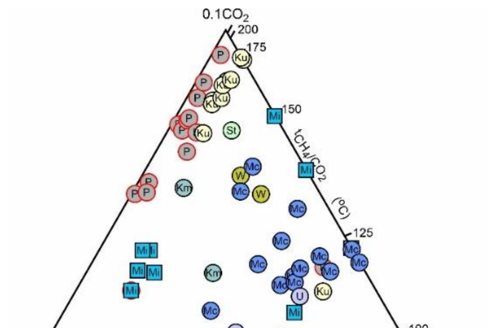

Figure 8: Relative compositions of CO_2. CH_4 and $N_{2,c}$ corrected for air. CH_4-CO_2 temperatures after Giggenbach (1991); asw= air-saturated water

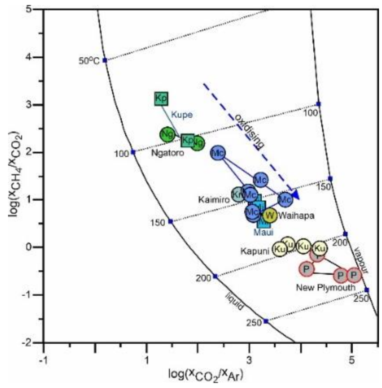

Figure 9: Cross plot of $\log(x_{CO2}/(x_{CO2} + x_{Ar}))$ vs $\log(x_{CH4}/(x_{CH4} + x_{CO2}))$ after Giggenbach (1991).

4. DISCUSSION

4.1 Trends

The positive correlation between R/R_A values with estimated heat flow values suggest that the depth of the hot upper mantle is shallowest at New Plymouth and deepest in offshore Kupe (Fig. 10A). The highest median mantle influx onshore, assuming a value of $8R/R_A$ for the mantle (Simmons et al, 1987), is at New Plymouth at about 50% and at Kaimiro and Ngatoro at about 25% with the lowest in the "McKee" region, Waihapa and Kapuni (Fig. 10B).

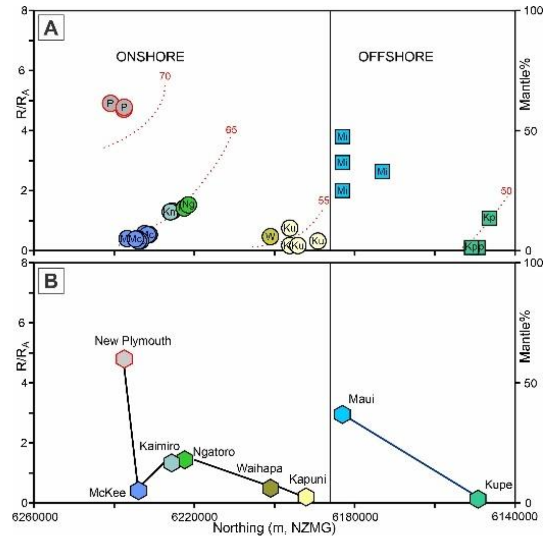

Figure 10: North-south trend of [A] individual R/R_A values and mantle% and [B] median R/R_A values in the different regions. R/R_A: ratio of mantle (^3He) to crustal helium (^4He) in the sample relative to R_A, the ratio in air (1.4×10^{-6}, Ozima and Podosek, 2002)

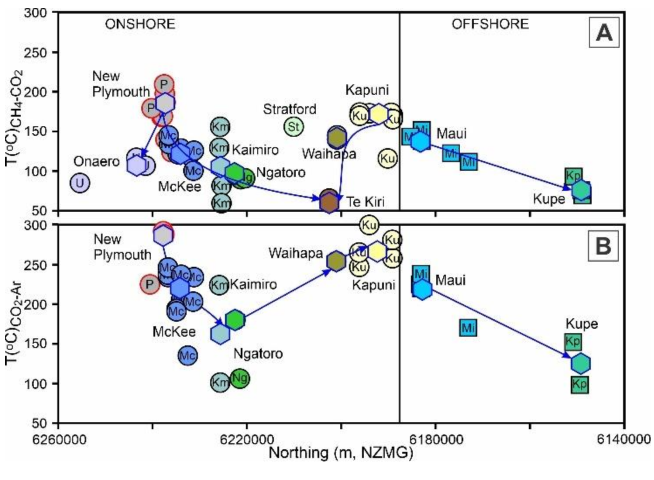

Figure 11: North-south trend of [A] CH_4-CO_2 and [B] CO_2-Ar temperatures with median values connected by lines.

However, as shown in Figs. 11A and B, high mantle input does not necessarily correlate with high subsurface temperatures. Although New Plymouth discharges with the highest mantle signature have the highest CH_4-CO_2 gas temperatures (>200°C), discharges from Kapuni and Mckee with crustal or near-crustal signatures (near 0% mantle input) have temperatures (125-175°C) higher than Kaimiro and Ngatoro (<125°C) with higher mantle input at about 25%. It is possible that advection of high temperature fluids in regions of low heat flow and low mantle input may be caused by deep permeable structures that act as channels for the rapid ascent of hot fluids, similar to the North Island East Coast hot springs (Reyes et al, 2010).

Figure 12 is a map showing general deep temperatures in the different regions. Thus, the highest temperatures at >150°C occur at New Plymouth, Kapuni and possibly Stratford, with 100-150°C at Onaero, the "McKee" region, Ngatoro, Kaimiro and Waihapa and <100°C at Te Kiri and offshore Kupe.

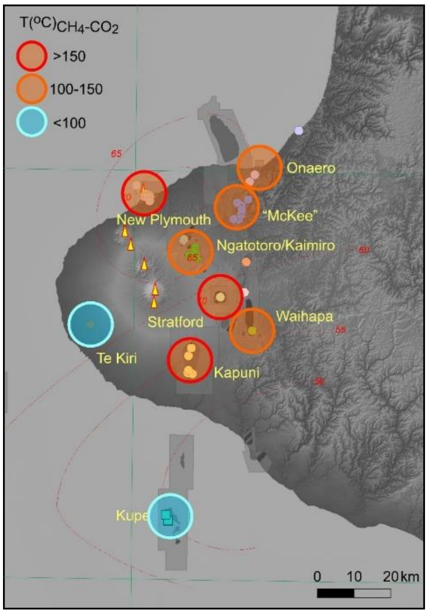

Figure 12: Temperatures at depth based on gas geothermometry in the various regions.

Unlike geothermal systems in volcanic regions of New Zealand (Taupo Volcanic Zone and Ngawha) and low-enthalpy hot spring systems outside the main geothermal power-producing areas, gases in Taranaki contain a high percentage of gases >C6 that may condense in the separator and pipelines as pressures and temperatures change (Figs. 13A and B). In Fig. 13A, the cricondenbar is the maximum pressure above which no gas can be formed regardless of the temperature and the cricodentherm the maximum temperature above which liquid cannot be formed regardless of pressure (Dustman et al, 2006). Figure 13B shows that for a given pressure, liquid hydrocarbons with varying C_n will condense at different temperatures. If hot fluids from petroleum wells will be directly harnessed for geothermal heat or power then the construction of phase diagrams from the hydrocarbon chemical composition, similar to Figs.13A and B, are essential in predicting the behaviour of hydrocarbon phases with well production (e.g., Wang and Economides, 2010), for example setting conditions to minimise condensation of hydrocarbon gases either by controlling the temperature and or the pressure (e.g., choking) in the separator and distribution lines. However, as suggested previously (Reyes, 2019) the heat from abandoned petroleum wells for direct heat and power production can simply be harnessed using deep borehole heat exchangers (e.g., Bu et al, 2012).

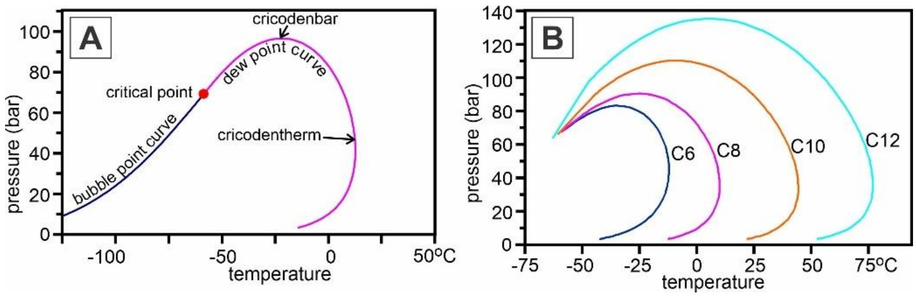

Figure 13: Simplified phase diagrams for a volatile oil hydrocarbon system showing temperature vs pressure [A] from the bubble point to the dew point curves. Only liquid exists above the bubble point curve and only vapor beyond the dew point curve. Two-phase fluids occur between the bubble and dew point curves; [B] dew point curves for C_6 to C_{12} gases (from Dustman et al, 2006).

5. CONCLUSION

Subsurface temperatures at Taranaki show that geothermal energy can be harnessed for power generation and direct heat use. The highest subsurface temperatures based on solute chemistry occur at New Plymouth, Kapuni and Stratford (>150ºC), with moderate temperatures (100-150ºC) at Onaero, Kaimiro, Ngatoro, McKee and Waihapa. The lowest temperatures occur in the west at Te Kiri (<100ºC). High temperatures at New Plymouth may be related to the shallowing of the upper mantle in this region but high temperatures at Kapuni and Stratford may be related to rapid hot fluid ascent through deep faults.

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