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# Assessing the Flow of Thermal Waters in Low-Temperature Mineral Spring Systems in the South Island, New Zealand

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## ABSTRACT

The majority of thermal waters in the South Island discharge along the Alpine Fault. The rest occur in coastal Canterbury, Taieri Basin, West Coast and Southland. Surface discharge (maximum of 66°C measured in this survey) and inferred subsurface temperatures (200 ± 10°C) are higher in the Alpine Fault than in the rest of South Island. About 99% of the annual thermal water flow and surface heat output are released from the Alpine Fault springs at ~7 x $10^8$ L/a and ~113 TJ, respectively. Along the Alpine Fault Zone thermal mineral waters are derived from heated meteoric waters gaining solutes from interaction with fault comminuted rock, contributions from the subducted slabs in the northeast and southwest of the South Island and probable metamorphic fluids at depth. These are diluted by cold meteoric waters. Serpentinisation reactions in Fiordland result to unusually high pH and very low total dissolved solid contents in mineral waters. Anomalous heat along the Alpine Fault Zone is caused by rapid uplift. Formation waters occur in the West Coast and cold seawater mixes with heated meteoric waters in coastal Canterbury. In the South Island the relative permeability of faults or fractures, topographic gradient, elevation and uplift rates affect fluid flow, heat transfer and solute transport. Relatively higher permeability in the Marlborough Fault System compared to other parts of the Alpine Fault allows inflow of cold meteoric water from the surface but also rapid ascent of hot solutions from depth. In contrast the recirculation of solutions in the No. Alpine Fault may be more circuitous, the fault zone relatively less permeable or the fluid source deeper. Fault-comminuted rock along the Alpine Fault enhances and hastens kinetic rates of reaction with aqueous solutions resulting to high $HCO_3$/Cl ratios with low Mg/Ca and K/Na ratios. Where fluid flow is restricted, rates of reaction between fault-comminuted rock and solutions may be protracted, giving rise to oversaturated silica solutions at depth. Where high permeability faults allow large throughput of cold meteoric waters, silica concentrations in surface discharges decrease.

## 1. INTRODUCTION

In this paper thermal springs have discharge temperatures 4°C above the mean annual ambient temperature (Reyes et al, in prep.) which varies from 10°C in the South Island to 16°C in the North Island (Mullan et al, 2007). Geothermal is used to refer to active hydrothermal systems that are being explored or exploited for direct heat use and/or power generation.

There are about 350 mineral spring systems in New Zealand. Of these, 135 to 140 are thermal and mostly distributed onshore. At least another 12 hydrothermal systems vent at the seafloor, from the Bay of Plenty (Sarano et al, 1989) to the Kermadec volcanic arc (de Ronde et al, 2001). About 80% of onshore spring systems are located in the North Island and adjacent islands, with the rest found in South Island (Figure 1). Apart from natural discharges, at least another 12 locations of hydrothermal mineral water upflow were discovered only after drilling wells for domestic or industrial use and during exploration for coal, oil and gas in the North and South Islands (Reyes et al, in prep.). Hydrothermal spring systems in New Zealand occur in regions where the surface conductive heat flow is >50 mW/$m^2$ (Figure 1).All geothermal power generation and about 90% of the energy for direct heat use are being produced from the two high temperature geothermal regions: the Taupo Volcanic Zone and Ngawha in Northland (Thain et al, 2006). In these active volcanic regions maximum discharge temperatures from springs are >90°C up to local boiling temperatures (98-100°C). Reservoir temperatures are up to >300°C (e.g., Thain, 1985). More than 85% of the low-temperature thermal mineral springs in North Island are being used, mainly for bathing, household use, baleonology, mineral water production, cultivation of greenhouse plants, fish farming (Thain et al, 2006) and for ground source heat pumps. In the South Island, however, only two of the spring systems, Maruia (Ma) and Hanmer (Hn), have been commercially developed, using the 50-55°C hot waters for swimming pools and heat exchangers. Except for Maruia (Ma), Hanmer (Hn), Kotuku in the West Coast, Fox in Fox Glacier, Sylvia Flats in the Lewis River and coastal Canterbury, most of the hot springs are located in areas at least 2 km walk from the road and hence are seldom used except by trampers or hunters (Reyes and Christenson, 2008).

Fluid flow is the main factor for solute transport and heat transfer in most geothermal systems. Where permeability is low, solute diffusion and heat conduction may be significant. This study is focused on the South Island where thermal springs and well waters emanate from (1) the Alpine Fault, a major active crustal deformation front, and (2) within the relatively quiescent Pacific plate east of the Alpine Fault. This paper assesses variations in fluid flow rates and surface heat output with tectonic activity, and discusses some of the factors affecting fluid flow and solute concentrations.

## 2. GEOLOGICAL SETTING

South Island is dominated by the oblique collision of the Pacific and Australian plates, marked by the Southern Alps and the Alpine Fault where dextral displacement of 480 km has been accommodated since the Miocene (Wellman, 1953; Sutherland and Norris, 1995; Barnes et al, 2005). The Alpine Fault acts as a hinge between two subduction zones of opposite polarity, the west-dipping Hikurangi subduction zone in the NE and the east-dipping Fiordland subduction zone in the SW (Waschbusch et al, 1998).

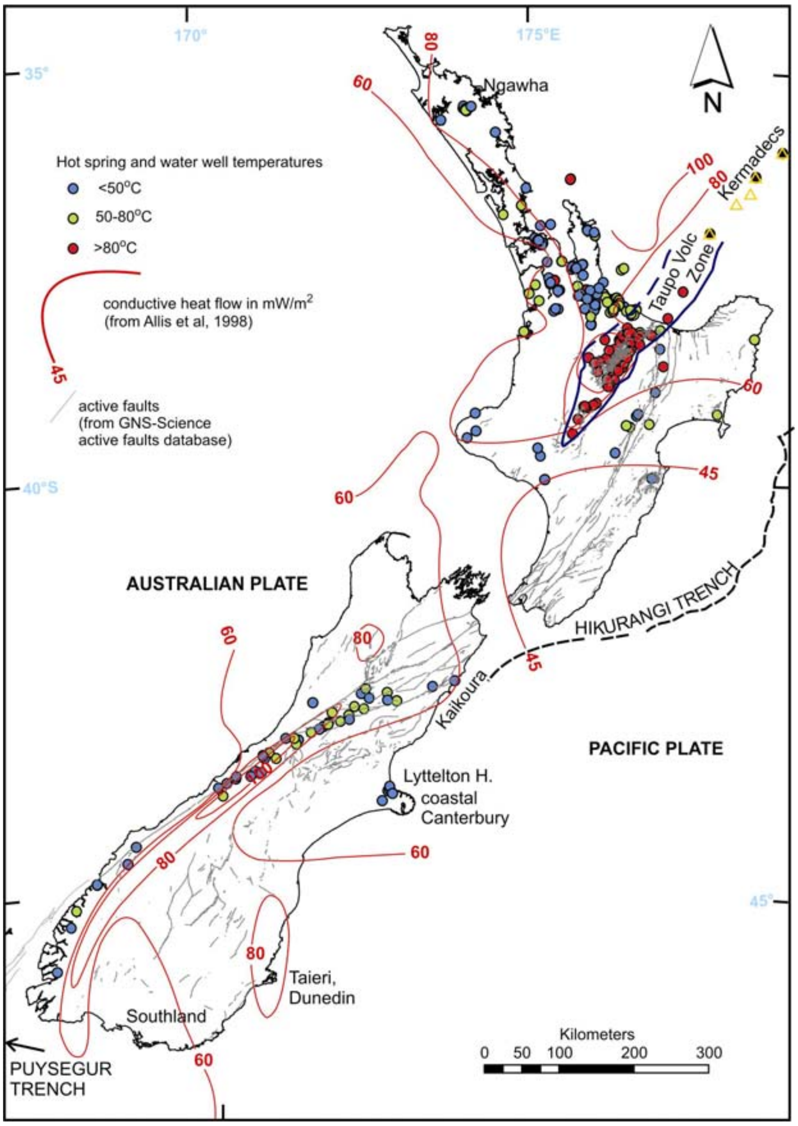


**Figure 1: Location map of thermal mineral springs and wells in New Zealand, active faults, surface conductive heat flow contours and place names used in text.**

Along the Alpine Fault the frequency of seismic events is high in the northeast and southwest ends of South Island. The Pacific plate in the northeast is subducted under the Australian plate and the Australian plate in the southwest is subducted beneath the Pacific plate. Where continent to continent collision is paramount along the Alpine Fault, seismicity is relatively low but the exhumation rate, conductive heat flow (Figure 1) and displacement rates are the highest along the deformation front (Wellman, 1979; Berryman et al, 1992; Allis and Shi, 1995; Kohler and Eberhart-Phillips, 2003).

The northwestern section of the Alpine Fault splays into four major fault zones of the Marlborough Fault System including Wairau, Awatere, Clarence and Hope (Browne, 1992). Transcurrent motion along the four major fault zones accommodates nearly all plate motion (Eberhart-Phillips and Reyners, 1997; Wilson et al, 2004). The rates of displacement in the four faults generally increases from northwest to southwest (Eberhart-Phillips and Reyners, 1997) at 3-5 mm/a on the Wairau (Berryman et al, 1992), 6-8 mm/a on the Awatere, 4-8 mm/a on the Clarence and 18-35 mm/a along the Hope (Bourne et al, 1998; Eusden et al, 1999). Thirteen of the 19 thermal springs along the Marlborough Fault System discharge along the Hope Fault. In the last 150 years, large historical earthquakes have been recorded on the Awatere and Hope faults (Bourne et al, 1998). Most of the rocks exposed on the Marlborough Fault System are Torlesse greywacke and inferences from seismic tomography indicate that this rock extends down to mid-crust (Eberhart-Philips and Reyners, 1992; Wilson et al, 2004).

The Torlesse greywackes and argillites on the east of the Southern Alps grade into the Haast schist, of increasing metamorphic grade, towards the west. The increase in metamorphic grade from chlorite to biotite, to garnet, to oligoclase and finally K-feldspar, is mainly related to uplift and exhumation along the Alpine Fault and, in part, to localized shear heating (Grapes, 1995). Thermal springs along the No. Alpine Fault discharge from schist.

Thermal springs in Fiordland are located in a region where the Median Batholith, Western Fiordland Orthogneiss (Mortimer et al, 1999), schist and dunite (Landis and Coombs, 1967) are exposed on the surface.

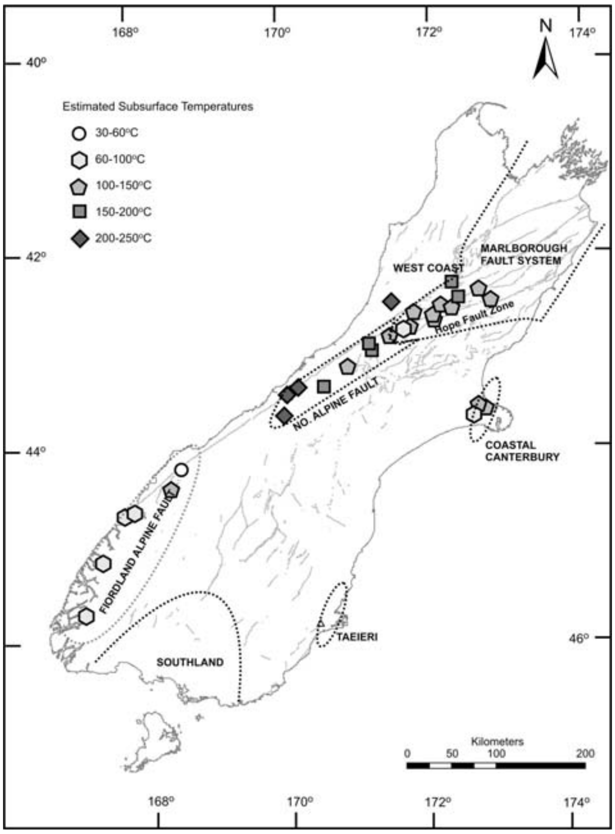


**Figure 2: Maximum inferred subsurface temperatures in the 7 regions of the South Island.**

On the continental crust of the Pacific plate in eastern South Island, widespread eruptive products from intraplate volcanism in the Tertiary have been dated 5.8 Ma in Banks Peninsula and 10 Ma in Dunedin (Sewell and Weaver, 1989). The youngest volcanics in the South Island are subduction related adakites in Solander Island erupted 400 to 150 ka (Mortimer et al, 2008). No thermal springs have been reported in this area. Coastal Canterbury springs discharge from volcanic rocks and mineral waters in Taieri, Dunedin emanate from alluvial schist.

## 3. DISTRIBUTION OF SPRINGS

There are at least 60 mineral spring systems in South Island, nearly 70% of which are thermal. Thermal mineral waters occur in 6 tectono-geographic regions in South Island including (1) coastal Canterbury Plains, (2) northern Taieri Basin near Dunedin, (3) Marlborough Fault System (Marlborough Fault), (4) Northern Alpine Fault Zone (No. Alpine Fault), (5) Fiordland Alpine Fault Zone (Fiordland Alpine Fault), (6) West Coast located in the northwestern half of the South Island west of the Alpine Fault, and (7) Southland (Figure 2). A few hydrocarbon wells in Southland have thermal gradients >30°C/km (Reyes, 2007) but no mineral waters were collected during this survey. Methane-rich gases were, however, sampled from gas seeps derived from buried coal (Lyon and Giggenbach, 1990).

In this paper the No. Alpine Fault corresponds to the 3rd section of Berryman et al (1992) between Inchbonnie and Haast and the Fiordland Alpine Fault includes the 4th section of Berryman et al (1992) and extends to the southwest end of South Island (Figure 2). The Fiordland Alpine Fault Zone is located near the leading edge of a young subduction zone (Eberhart-Phillips and Reyners, 2001) where the continental crust is thick (Kohler and Eberhart-Phillips, 2003), the heat flow low (Allis et al, 1998) and the mantle is 80 km deep (Eberhart-Phillips and Reyners, 2001) with, apparently, no heat from the mantle being conducted to the surface.

Thermal discharges in coastal Canterbury and Taieri Basin are about 100 km east of the Alpine Fault, and nearly 400 km apart. The 20°C mineral waters in Taieri discharge from a well located on the northeastern end of the Taieri tectonic depression.

Mineral springs often emerge along the edges of, or in rivers but a few trickle through swamp as in Motukarara in Christchurch, discharge under the sea or seep along the intertidal region of beaches in Lyttelton Harbor or Kaikoura (Figure 1).

## 4. TEMPERATURES AND HEAT SOURCES

Surface discharges from springs range from 16.7°C in the Cascade Terraces along the Fiordland Alpine Fault, to 66°C in Julia Hut spring along the Taipo River near the junction of the Marlborough Fault System and the No. Alpine Fault. Discharge temperatures as high as 80°C were reported in Anchorage Cove in Fiordland, below about 9 m of seawater; and 71°C in Julia springs (Mongillo and Clelland, 1984). However, Anchorage Cove could not be accessed during this survey and the temperature measured in Julia springs was only 66°C in 2005. Seasonal changes in the height of rivers along the Alpine Fault, which have measured temperatures of 5 to 8°C (this study) may cause fluctuations in surface discharge temperatures of thermal springs located in river banks. Inferred subsurface temperatures range from 100-185°C in the Marlborough Fault System; 35-135°C in the coastal Canterbury and Fiordland Alpine Fault springs; and up to 200 ± 10°C No. Alpine Fault (Figure 2).

The main source of heat along the Alpine Fault is due to rapid uplift (Allis et al, 1979) caused by the collision of two continental plates (e.g., Kohler and Eberhart-Phillips, 2003). Koons (1987) postulated that an uplift rate of 6 to 7 mm/a could bring the 350°C isotherm to depths of 6 to 8 km beneath the Southern Alps. According to Allis et al (1979) 140-350°C may be intersected as shallow as 2 km in the region of highest uplift. However, these temperature estimates do not consider the temperature-swamping effect of deep-penetrating cold meteoric water channeled along permeable faults. Other sources of heat along the Alpine Fault may be caused by sustained shear heating (Gerbault et al, 2003); although studies on pseudotachylites along the Alpine Fault (e.g., Sibson et al, 1979) indicate that shear heating is usually localized and short-lived. Slightly elevated temperatures in some Fiordland mineral springs may be due to serpentinisation processes (Neal and Shand, 2002).

The latest active volcanism exposed on the surface in the Dunedin region, was about 10 Ma ago (Sewell and Weaver, 1989). However, an island of high heat flow, 80 $mW^2$ (Allis et al, 1998) and an above normal thermal gradient in the Taieri Basin, near Dunedin, exists. To explain these, Godfrey et al (2001) suggested that heat from hot mantle emplaced 10 My ago is just reaching the surface at present. The existence of an actively degassing hot mantle source is surmised from (1) seismic studies showing a low velocity crust coinciding with a highly reflective region (Godfrey et al, 2001) and (2) an isotopic He signature $R/R_A$ of 6.64 indicating entrainment of about 83% of mantle volatiles (Giggenbach et al, 1993) from gas discharges in Taieri well, assuming that the source of $CO_2$ and He is not decoupled. To the west of the Alpine Fault in the West Coast, the Kotuku well which discharges 22°C waters (this study), is located in an island of high surface conductive heat flow ranging from 84 to 99 $mW/m^2$ (Townend, 1999) and in a region where deep earthquakes are absent (Kohler and Eberhart-Phillips, 2003). The absence of earthquakes may indicate a hotter more plastic crust in parts of the West Coast.

In summary inferred subsurface temperatures in the South Island thermal mineral spring systems is as high as 200 $\pm$ 10°C along the Alpine Fault and up to 135°C in coastal Canterbury (Figure 2). The main sources of heat include rapid uplift along the Alpine Fault and deep mantle sources.

## 5. FLOWRATES, THERMAL ENERGY AND TEMPERATURE DISTRIBUTION

The flow rates of thermal springs in the South Island range from <1 to 185 L/min with the highest measured in Maruia springs located along the Awatere Fault of the Marlborough Fault System.

In terms of yearly output, coastal Canterbury has the lowest flow rate at 0.089 x $10^8$ L/a and the Marlborough fault System springs have the highest at 4.5x$10^8$ L/a (Figure 3A). Thermal water released along the Marlborough Fault System is ~4x that of the No. Alpine Fault (1.1x$10^8$ L/a) and 3.8x of the Fiordland Alpine Fault springs (1.2x$10^8$ L/a).

The higher flow rates and the higher number of thermal springs along the Marlborough Fault System may indicate greater permeability relative to the No. and Fiordland Alpine Faults. The higher permeability may be due to the Marlborough Fault System being the site where 80 to 100% of plate motion between the Australian and Pacific plates is being accommodated (Eberhart-Phillips and Reyners, 1997).

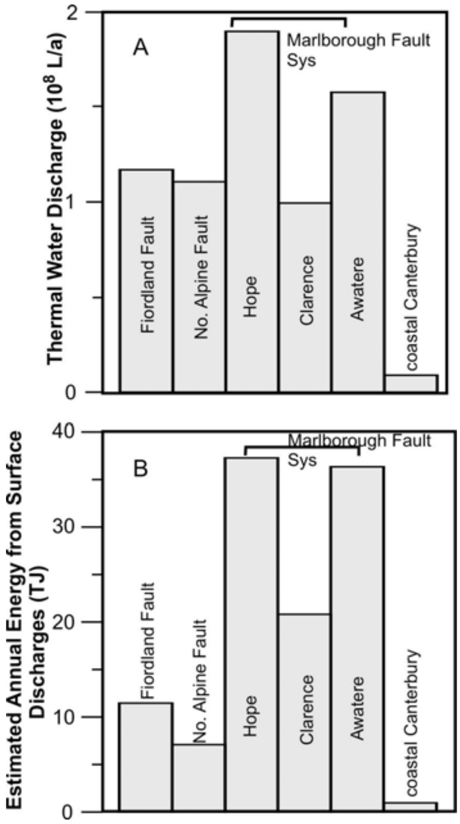


**Figure 3: Minimum annual thermal water flow rate (L/a) and thermal energy (TJ) estimates in 4 regions of South Island.**

The major fault splays of the Marlborough Fault System are characterized by high rates of displacement (e.g., Berryman et al, 1992) and marked by large earthquakes recorded in the last 150 years (Bourne et al, 1998). Such active tectonism would instigate and maintain open pathways for fluid flow that may affect fluid circulation and temperatures as discussed below.

The heat transferred by or held in the fluids is inferred from the potential minimum annual surface thermal energy of the spring systems. As shown in Figure 3B the thermal energy output in South Island ranges from 1 TJ in coastal Canterbury to a high of 94 TJ in the Marlborough Fault System. In contrast the surface thermal energy in springs along the No. Alpine Fault is ~7.1 TJ and 11.5 TJ Fiordland Alpine Fault. Along the Alpine Fault heat is more efficiently transported to the surface where fluid flow is high, apparently aided by active tectonic movement in the form of frequent earthquakes in the Marlborough and Fiordland Alpine Faults (e.g., Kohler and Eberhart-Phillips, 2003).

### 5.1 Temperatures and Fluid Flow

Subsurface temperatures are higher in the No. Alpine Fault (~200$^o$C) than in the Marlborough Fault System springs (~185$^o$C); although surface discharge temperatures are generally higher in the latter. This apparent ambiguity may be caused by differences in permeability among the faults which, in turn, may affect the inflow of cold groundwater, the upflow from depth of heated equilibrated fluids and the speed of circulation of solutions. The Marlborough Fault System is probably more permeable than the No. Alpine Fault, being in a region where most of the plate motion is being accommodated (Eberhart-Phillips and Reyners, 1997). It is possible that, due to higher permeability, the Marlborough Fault System accepts massive inflow of cold meteoric water from the surface. However, at the same time, high permeability also allows rapid ascent of hot solutions from depth resulting to less heat being conducted away from the rising hot solutions to the confining rock. In contrast, the recirculation of solutions in the No. Alpine Fault may be more circuitous, the fault zone less permeable or the fluid source deeper resulting to conduction of heat away from the fluids to the rock and lower surface discharge temperatures.

## 6. CHEMICAL COMPOSITIONS OF SOLUTIONS

As shown in Figure 4, the springs in South Island discharge Cl, Cl-$HCO_3$ and $HCO_3$ waters, with 80% of the springs having $HCO_3$/Cl ratios of >1. There is a strong smell of $H_2S$ in several Alpine Fault springs where dissolved $H_2S$ varies from 1.5 to 30 mg/kg, $SO_4$ concentrations are low and tendrils of amorphous sulfur bearing bacteria occur below the water surface. Once exposed to the atmosphere during sampling and subsequently, if left unfiltered, dissolved $H_2S$ in the mineral waters is oxidized (Dillon et al, 2007) resulting to an increase in $SO_4$ concentrations. The high $SO_4$ concentrations in the Haupiri spring, sampled by Barnes et al (1978) is higher than in a recent sample and may be due to $H_2S$ oxidation after sampling. The Barrier River (B) spring waters were also not filtered immediately after sampling.

The $HCO_3$/Cl ratios in the South Island range from 0.002 to 69, with the highest value in found in the Taieri basin near Dunedin. Along the Marlborough Fault System the $HCO_3$/Cl ratio in mineral waters range from 0.2 to 58 with the lowest values measured in the three northeastern most springs nearest the Hikurangi Trench (Figure 1). The $HCO_3$/Cl ratios in the No. Alpine Fault mineral waters vary from 0.02 to 7; and from 0.01 to 22 in Fiordland. The well in Kotuku, in the West Coast discharges saline waters with Cl contents of 46,720 mg/kg, 2.4x that of seawater, and has similar chemical compositions as formation waters (e.g., Hanor, 1994).

### 6.1 Fluid Circulation and K, Na, Mg, and $SiO_2$ contents

In thermal mineral waters emanating from volcanic and sedimentary rocks in the North Island, cooling and mixing with groundwater result to higher $HCO_3$/Cl ratios (Giggenbach and Glover, 1992). In the 10K/(10K+Na)-10Mg/(10Mg+Ca) diagram (Figure 5), compositions of these mineral waters usually plot away from the full equilibrium line towards higher Mg/Ca ratios as $HCO_3$/Cl ratios increase. In contrast, thermal mineral waters discharging from greywacke and schist in the Marlborough Fault System, No. Alpine Fault and Fiordland Alpine Fault, $HCO_3$-rich mineral waters generally plot closer to the full equilibrium line (Figure 5) at about 150$^o$ to 200$^o$C.

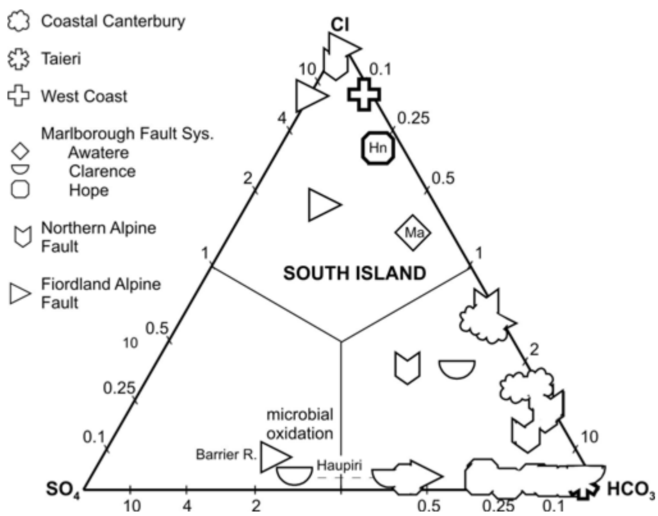


**Figure 4: Relative Cl, $HCO_3$ and $SO_4$ concentrations of South Island thermal mineral waters.**

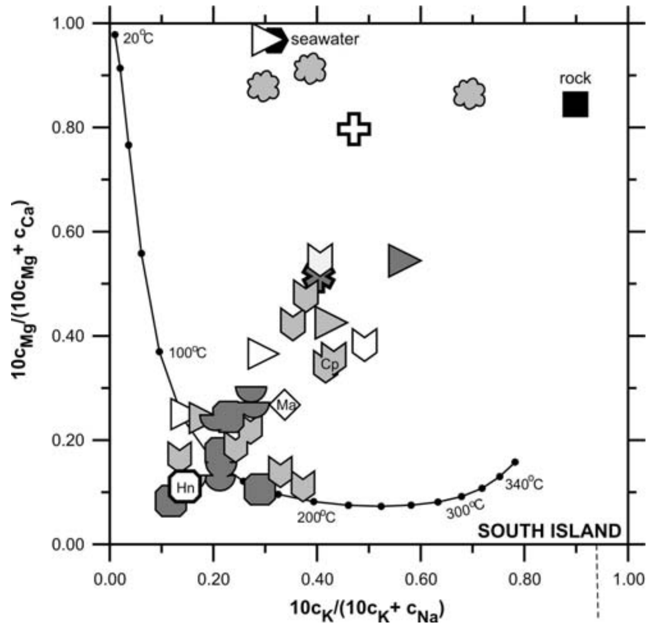


**Figure 5: The relative K-Na and Mg-Ca concentrations of South Island springs. Symbols are the same as in Figure 4.**

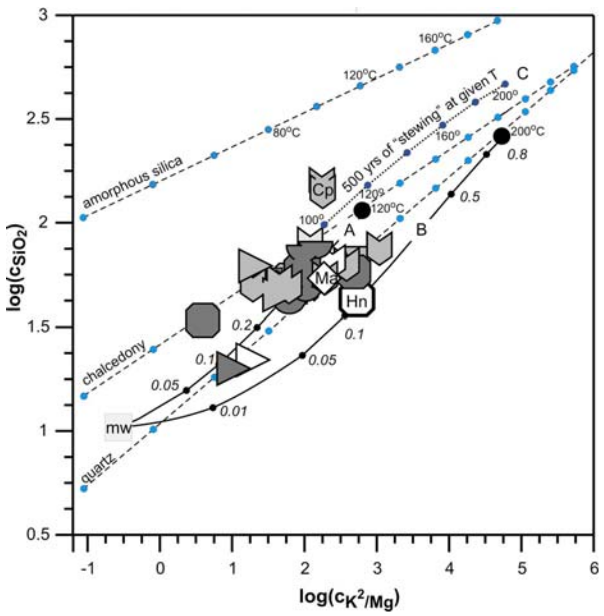


**Figure 6: Cross plot of log($c_{K^2/Mg}$) and log ($c_{SiO_2}$). MW= median meteoric water composition of New Zealand waters. Symbols are the same as in Figure 4.**

The approach to near equilibrium of these $HCO_3$-rich mineral waters is probably enhanced by kinetic reactions associated with the large surface area-to-volume ratios presented by fault comminuted rock along the Alpine Fault. The higher surface area hastens reactivity between water and rock (e.g., Pedersen et al, 1997). The shift away from the full equilibrium line may be caused by a shorter interaction time between rock and fluid, lower rock: water ratios and/or recent influx of cold meteoric water.

To further dissect the processes involved in solute transport in the South Island, mineral waters are plotted in a $\log(K^2/Mg) - \log(SiO_2)$ diagram and the solubility lines for amorphous silica, chalcedony and quartz drawn for comparison. For low temperature mineral waters where silica temperatures are <200$^{o}$C, it is assumed that the waters are in equilibrium with chalcedony or α-cristobalite (Henley et al, 1984). Apart from the Copland springs (Cp), thermal mineral waters along the Alpine Fault plot along a narrow range of silica concentrations from 40-75 mg/kg between the chalcedony and quartz solubility lines but at a wide range of K/Mg ratios. This trend may be caused by mixing of ascending hot mineral waters with cold low-$SiO_2$ meteoric water (lines A and B) resulting in lower silica concentrations and an apparent shift from the chalcedony to the quartz solubility line. The high silica concentrations in the Copland mineral waters (Cp) may be due to cooling, or mixing with silica-enriched solutions at depth prior to ascent to the surface. As shown in line C of Figure 6, prolonged and cumulative kinetic interaction of hot mineral solutions with quartz would increase silica concentrations in solution. Each point along line C was calculated, using the Geochemist's Workbench (Bethke, 2005), assuming kinetic interaction of quartz with hot solutions at a given temperature.

### 6.2 Elevation, Topographic Gradients, Rates of Uplift and Fluid Flow

The lower the topographic gradient in the Alpine Fault springs the higher the proportion of hot Cl waters, from depth. Furthermore, as the flow rate of individual springs increase along the No. Alpine Fault, the concentrations of Cl, K, Na and Li also increase.

On a scale of at least 100,000 $km^2$, the discharge temperatures of mineral waters are higher along the Marlborough and No. Alpine Faults where the highest uplift rates have been measured at 2-17 mm/a (Wellman, 1979), compared to Fiordland, Taieri or coastal Canterbury where the uplift rate is <2 mm/a. However within individual regions of the Alpine Fault, on a scale of <1000 $km^2$, discharge and inferred subsurface temperatures show little correlation with uplift rate. Instead temperatures are affected strongly by topographic gradient and elevation. Temperatures decrease with an increase in the topographic gradient due to the influx of cold meteoric waters. Similarly temperatures decrease with elevation as thermal mineral waters traverse more rock to the surface and cool conductively.

In coastal Canterbury concentrations of Cl, Ba, Br, I, K and Mg in mineral waters decrease with distance from the sea and as the topographic gradient increases, indicating greater influx and contamination by meteoric water.

### 6.3 Fluid Mixing

The D and $^{18}O$ contents of thermal mineral waters along the Alpine Fault indicate that these are mainly heated meteoric waters mixed with hot Cl-rich solutions rising from depth with temperatures of about 200$^oC$, cold meteoric water and sometimes modified by bacterial contributions. Cold seawater contributes to mineral water solute concentrations in coastal Canterbury. However the chemical and isotopic compositions of a few mineral springs indicate other sources of solutes. For example, the highly saline waters discharging from some wells and springs (Giggenbach, 1997) in the West Coast are formation waters.

Along the Alpine Fault, the northeastern most mineral waters along the Marlborough Fault nearest the Hikurangi Trench, and some springs in the Fiordland Fault nearest the Puysegur Trench in the southwest, have relatively low $HCO_3$/Cl ratios, and contain high Cl, Na, K, B, Ba, Li, and Sr relative to other mineral springs in the Alpine Fault. This may indicate the influx of deep-circulating seawater or subduction zone waters. Thermal waters discharging in Fiordland have unusually high pH (20$^oC$) at 11.1 and very low total dissolved solids (100 mg/kg) attributed to serpentinisation processes and limited diffusion of anions and cations through serpentinised dunite (e.g., Neal and Shand, 2002).

The $^{13}C$ of dissolved inorganic carbon (DIC) (Barnes et al, 1978) and He isotopic values (Giggenbach et al, 1993) in several springs in the Marlborough and No. Alpine Faults indicate the presence of metamorphic waters at depth, as suggested by studies of Upton et al (2000), for example.

## 7. SUMMARY AND CONCLUSIONS

Except for the formation waters in the West Coast the spring discharges in most regions of the South Island are of meteoric in origin. Along the Alpine Fault Zone meteoric waters gain solutes from interaction with fault comminuted rock, contributions from the subducted slabs in the NE and SW of the South Island and probably, metamorphic fluids at depth. Mineral waters along the Alpine Fault are heated at depth to as high as 200 $\pm$ 10$^oC$. Anomalous heat along the Alpine Fault Zone is generally believed to be due to rapid uplift (e.g., Allis et al, 1979).

In the South Island the relative permeability of faults or fractures, topographic gradient, elevation and to a lesser extent uplift rates, affect fluid flow, heat transfer and solute transport. The total annual thermal fluid flow and surface heat output in coastal Canterbury, is only ~1% of values calculated for thermal mineral springs discharging along the Alpine Fault. Within the Alpine Fault, the highest number of thermal springs, highest annual flow rates and highest surface heat output occur along the Marlborough Fault System. This is the region where 80 to 100% of plate motion between the Australian and Pacific plates is being accommodated (Eberhart-Phillips and Reyners, 1997), has high rates of displacement of 3 to 35 mm/a (e.g., Berryman et al, 1992) and where large earthquakes have been recorded in the last 150 years (Bourne et al, 1998).

Higher permeability in the Marlborough Fault System allows inflow of cold meteoric water from the surface but also the relatively rapid rise of hot solutions from depth such that less heat is conducted away from the rising hot solutions to the confining rock. In contrast the recirculation of solutions in the No. Alpine Fault may be more circuitous, the fault zone less permeable or the fluid source deeper. This may result to higher subsurface temperatures in the No. Alpine Fault springs than the Marlborough Fault System springs, but lower surface discharge temperatures.

Kinetic rates of reaction and thermodynamic mineral solubility affect the K/Na, Mg/Ca, K/Mg, $HCO_3$/Cl and $SiO_2$ concentrations of mineral waters discharging along the Alpine Fault. Fault-comminuted rock with high surface area enhances and hastens reactivity with aqueous solutions resulting to high $HCO_3$/Cl ratios in mineral waters of the Alpine Fault, with low Mg/Ca and K/Na ratios. Where fluid flow is restricted, kinetic reactions between fault-comminuted rock and solutions may be cumulative, giving rise to oversaturated silica solutions at depth. Where high permeability allows large throughput of cold meteoric waters, silica concentrations in surface discharges decrease.

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