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WATER-ROCK INTERACTION IN A LOW-ENTHALPY BACK-RIFT GEOTHERMAL SYSTEM, NEW ZEALAND

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ABSTRACT

Conductively heated waters in the active back-arc Hauraki Rift Zone emerge from 15 spring and 5 blind thermal systems along three NW-SE trending major faults, parallel to the strike of the rift. The total flow rate of surface thermal waters is ~7 x 10^8 L/a, with a total thermal energy of ~410 TJ. Silica and cation geothermometers indicate <200°C waters within drillable depths consistent with the unusually high HCO_3/Cl ratios in the solutions. The waters are mainly heated groundwaters with minor seawater influx in the north and 17% mantle input in the southernmost spring nearest the Taupo Volcanic Zone. Waters discharging along the inactive Hauraki fault in the east are more saline than waters emerging along the other two fault systems but still have high HCO_3/Cl ratios. Hence the source of these saline solutions may be due to more extensive dissolution of greywacke at depth or mixing of deep Cl waters with HCO_3-rich waters stored at shallower depths within the greywacke basement and Plio-Pleistocene graben fills. The above normal heat flow in the region, from whence thermal springs with temperatures of 23 to 57°C discharge, is probably caused by heat just reaching the surface from updoming of hot asthenosphere at depth, 7 to 10 Ma ago.

1. INTRODUCTION

Approximately 2% of thermal water flow and 2% of surface heat energy in onshore New Zealand (Figure 1, inset) is derived from low-enthalpy spring systems outside the Taupo Volcanic Zone. Of these low-enthalpy spring systems 86% of the thermal waters and 96% of thermal energy come from North Island and the rest from South Island. A spring system may contain one or more springs. A spring is thermal when the discharge temperature is 4°C above the mean annual air temperature. In New Zealand the mean air temperature which varies from 10°C in South Island to as high as 16°C in some regions of North Island. Hence a thermal spring in the South Island Alps may not be thermal in the North Island (this study). Discharge temperatures of low-enthalpy thermal springs in New Zealand range from 16.5°C in the Cascade Terraces of Fiordland in the South Island to 87°C in Great Barrier Island of the North Island. More than 85% of the low-enthalpy spring systems in the North Island are being used mainly for swimming complexes, domestic use, balneology, mineral water production, space heating, plant cultivation, and, more recently, ground source heat pumps (Thain et al., 2006). Only two of the ~55 thermal spring and blind thermal systems in South Island have been commercially developed mainly because of the rugged and remote locations of most of these systems. Low-enthalpy thermal systems are widely spread in the country but the high-enthalpy geothermal regions, in the Taupo Volcanic Zone and Ngawha in the North Island, occupy only 3% of onshore land. At present the installed capacity for power production in these two regions is 431 MWe, to be increased to >600 MWe in the next few years (*www.nzgeothermal.org.nz*).

The objectives of this study are to discuss the source of heat and solutes in the Hauraki Rift Zone and the water-rock interaction processes that cause variations in the chemical composition of solutions.

2. GENERAL SETTING OF THE HAURAKI RIFT ZONE AND ADJACENT REGIONS

The Hauraki Rift Zone (HRZ) is one of 17 low-enthalpy tectono-geographic regions in the country, located at least 50 km away from recent andesitic and rhyolitic volcanism in the Taupo Volcanic Zone in the south-southwest and at least 60 km from recent intraplate basaltic volcanism in Auckland in the north-northwest. It is an active back arc continental rift developed behind and parallel to the NW-SE trending Miocene to mid-Pliocene Coromandel Volcanic Zone in the east (Figure 1) but at an angle to the active Taupo Volcanic Zone in the southeast. The HRZ was initiated by arching of the crust about 7-10 Ma ago, induced by upward-moving asthenospheric rocks which heated the crust beneath the rift. These rocks are still at elevated temperatures today (Hochstein and Ballance, 1993) causing above normal surface heat flow at 80 to 90 mW/m^2 (Allis et al., 1998). The rift basin is filled with Pliocene to Pleistocene alluvial volcanic-derived sediments, peat and ignimbrite (Brathwaite and Christie, 1996), estimated by Edbrooke (2001) to be <2 km in thickness. The rift is underlain by a basement of Mesozoic greywacke.

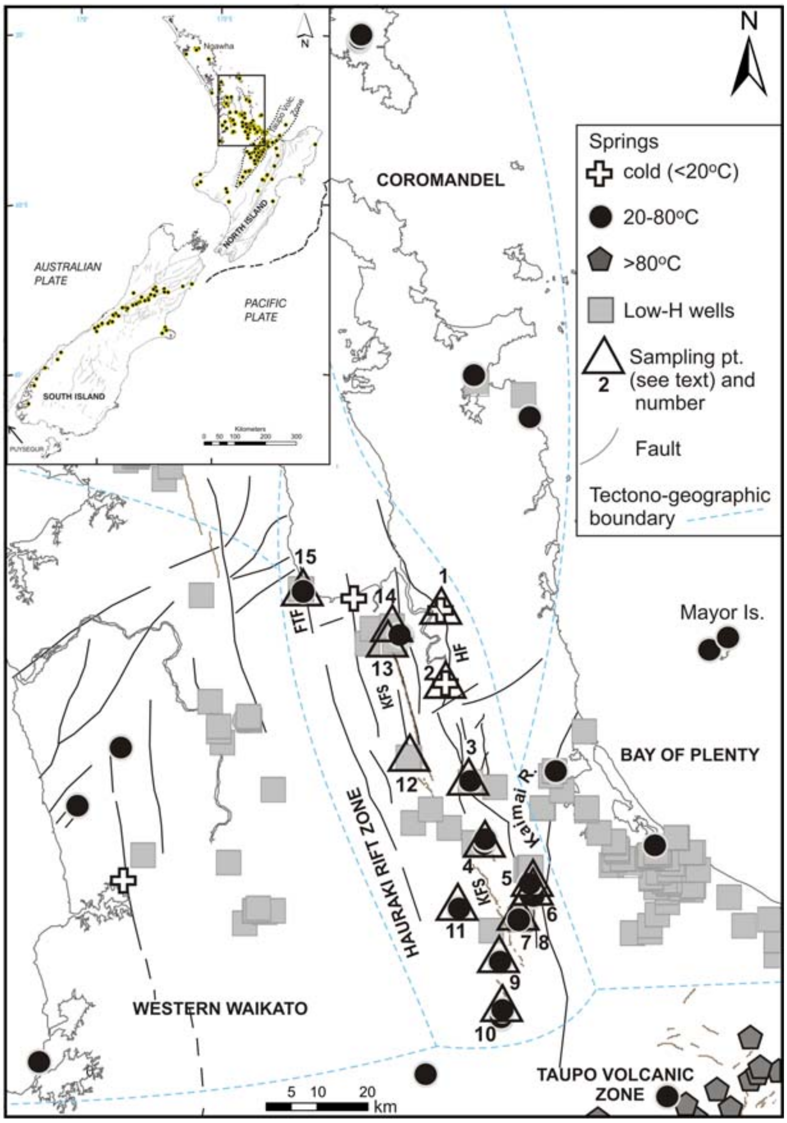

FIGURE 1: Location map of all mineral springs and wells discharging low-enthalpy waters (low-H), faults (FTF, KFS, HF, see text for explanation) and the boundaries of tectono-geographic regions (this study); inset shows thermal spring distribution in New Zealand

Fifteen spring and five blind thermal systems are distributed along a NW-SE direction on the geologically inactive Hauraki fault (HF) in the east, the active Kerepehi fault system (KFS) in the middle and the inactive Firth of Thames Fault (FTF) in the west (Figure 1), where a geologically active fault has moved in the last 125,000 years (e.g., Edbrooke, 2001). There are five mineral springs along the Hauraki fault including the cold springs Puriri (1) and

Paeroa (2) and thermal springs Te Aroha (3), Sheenan (5) and Gravesons (6); eight along the Kerepehi fault system (Okoroire (10), Taihoa (9), Crystal (7), Ramaroa (8), Manawaru (4), Scherers (11), Waitoa (12), Ngatea (14) and Kerepehi (13)), with the last two discharging from wells now. Only Miranda springs (15) lie on the Firth of Thames fault. All thermal discharge systems, except for Te Aroha which emerges from Miocene volcanics, discharge from recent alluvial sediments or Pleistocene siltstone, sandstone and gravel terraces. Discharge temperatures range from 23 to 57°C except for the ~83°C waters geysering from a 70 m deep well in Te Aroha. The total flow rate of thermal waters discharging from the HRZ springs is ~7 x 10^8 L/a with the KFS springs providing about 65% of the thermal water flow. The HRZ springs have a total thermal energy of ~410 TJ.

3. GEOCHEMICAL TRENDS AND TEMPERATURES

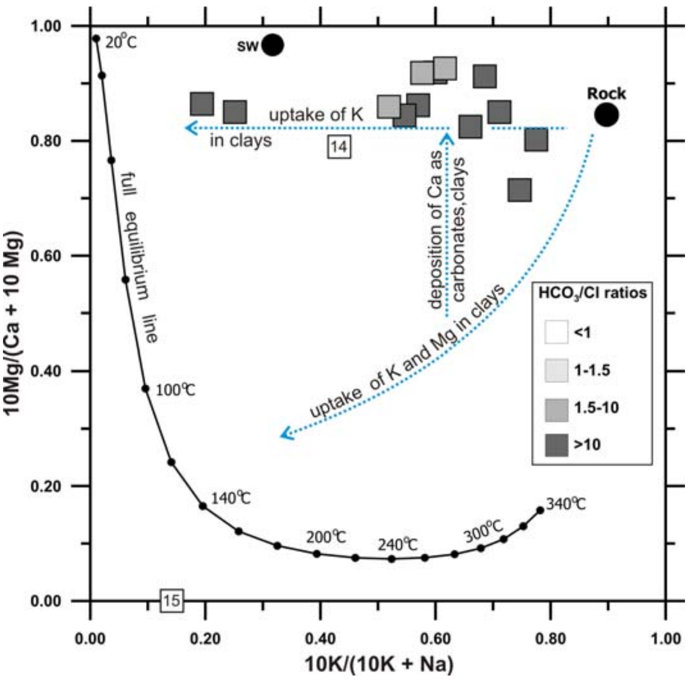

FIGURE 2: Plot of the HRZ waters on a 10K/Na – 10Mg/Ca diagram (adapted from Giggenbach and Glover, 1992) as HCO_3/Cl ratios vary; SW= seawater

In low-enthalpy discharges of New Zealand, HCO_3 and Cl are the main anions with relatively high SO_4 only found where there is recent copious seawater influx or where microbial action causes the oxidation of dissolved H_2S. Most mineral waters in the HRZ are Na-HCO_3 with HCO_3 concentrations ranging from 50 mg/kg in Miranda springs in the NW to 5300-6680 mg/kg in two springs emanating along the Hauraki fault e.g., Te Aroha (3) and Puriri (1), where Cl concentrations are also the highest at 572 and 155 mg/kg, respectively. With the exception of Ngatea (14) and Miranda (15), which have similar HCO_3/Cl ratios of 0.4, the Hauraki Rift Zone waters have some of the highest HCO_3/Cl ratios among the low-enthalpy discharges in New Zealand, ranging from 3 to 44 with a median value of 24.

To assess the effects of shallow processes attending the generation of high HCO_3/Cl ratios in the HRZ waters, such as prolonged interaction of waters with rock at shallow depths or mixing with lower temperature waters, the ratios of 10K/Na are plotted against 10Mg/Ca (Figure 2). There are three major processes represented in this diagram: rock dissolution in highly immature waters marked “rock”, equilibration with crustal rock along the full equilibrium line (Giggenbach, 1988) and seawater mixing. None of the waters in the HRZ are in equilibrium with the rock including the Cl-rich waters in Ngatea and Miranda. Ngatea waters have a high Mg/Ca ratio suggesting seawater influx. However, Miranda (15) has excess Na and Ca relative to K and Mg probably caused, in part, by deposition of smectite at depth. The high Mg/Ca ratios of waters with $HCO_3/Cl >3$ point to water-rock interaction far from equilibrium conditions involving dilute groundwaters affected by absorption of CO_2 (e.g., Giggenbach and Glover, 1992) and deposition of Ca-bearing minerals such as aragonite, calcite, Mg-bearing calcite, ankerite, monohydrocalcite, and mixed-layer clays at the point of discharge in the springs.

On a plot of F, Li and B, the Cl-rich waters of Miranda springs have a higher F/Li ratio of 4 than waters with high HCO_3/Cl ratios (Figure 3). In the latter the B concentrations relative to Li and F increase with increasing HCO_3 concentrations and total dissolved solids (TDS) with the TDS increasing to >1500 mg/kg from the KFS to the HF waters. Aside from higher B concentrations, the waters of Puriri, Paeroa and Te Aroha, discharging along the HF, also have higher Ba, K, Na, Sr and Cl concentrations and higher B/Cl, Cl/F, Ba/Rb and CO_2/CH_4 ratios compared to the KFS discharges. Thus the HF acts as a conduit for more saline and B-rich solutions containing high CO_2 possibly rising from a Cl-reservoir or a region of greater rock dissolution at deeper depths. Along the KFS, I and Sr tend to increase with decreasing elevation suggesting storage of mineral waters in stratigraphic layers containing organic material and high in Sr. Of the rock formations underlying the HRZ, only the graben fill has peat (Brathwaite and Christie, 1996) where I (Fehn and Snyder, 2003) may originate. The Li, Na, Rb and Cl contents of waters, rising along all three fault systems, increase with increasing temperatures.

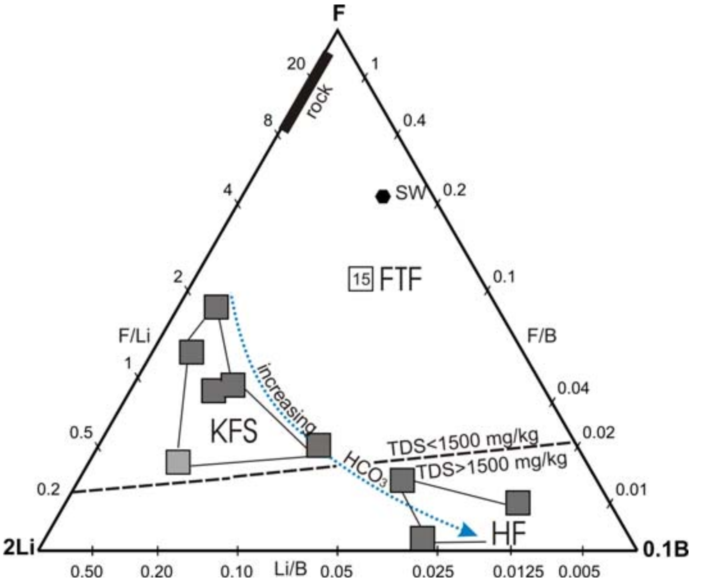

FIGURE 3: Relative contents of F, Li and B among springs discharging from the Kerepehi fault system (KFS), Hauraki fault (HF) and Firth of Thames fault (FTF). Shadings as in Figure 2

As shown previously all the waters discharging in the HRZ are immature (Figure 2) with excess Mg relative to K and Na except for Puriri (1) and Te Aroha (3). Hence temperatures of the unperturbed deep waters, based on the K/Na geothermometer of the two samples, are 140 to 160°C. The SiO_2 and K^2/Mg geothermometers give an estimate of subsurface temperatures just before discharge, and are subject to cooling through dilution and conduction (e.g., Giggenbach and Glover, 1992). In the HRZ, the silica and K^2/Mg temperatures range from 55 to 160°C. The temperature of equilibration of waters based on the convergence of saturation indices of aluminosilicate minerals, calculated from waters with Al^{3+} concentrations of 0.007 to 0.63 mg/kg, using REACT (Bethke, 1996; T_{REACT} in Table 1) ranges from 40 to 95°C. REACT results are similar to the K^2/Mg temperatures (Te Aroha, Puriri, Paeroa, Okoroire, Waitoa and Kerepehi) except for Ramaroa (8) where the last equilibration occurred at the point of discharge at 40°C. The geochemical modelling shows that essentially, waters in the HRZ are conductively-heated meteoric waters that had reacted with rocks containing albite, K-feldspar, pyroxenes, chlorite, phlogopite, saponite, beidellite, clinoptilolite and amesite

TABLE 1: Range of discharge (°C) and estimated subsurface temperatures using the silica, K^2/Mg, K/Na geothermometers (Giggenbach, 1991) and calculated using REACT (Bethke, 1996)

Fault	$T_{discharge}$	T_{SiO_2}	$T_{K^2/Mg}$	$T_{K/Na}$	T_{REACT}
Hauraki fault	17-50 (well: 83)	120 - 140	60 - 140	140 - 160	60-80
Kerepehi fault system	23-57	100 - 160	55 - 95	excess Mg	40-95
Firth of Thames fault	56	85	80	excess Mg	no convergence

4. ISOTOPIC VARIATIONS

Gases discharged along the Hauraki fault are high in CO_2, with excess CO_2 relative to CH_4 suggesting an extraneous source for CO_2. In contrast, CH_4 and/or N_2 are predominant (Giggenbach et al., 1993) in discharges along the Kerepehi fault system and the Firth of Thames fault. The values of $\delta^{13}C$ (CO_2)

for gases discharging in all springs range from -17.7 to -9.1‰ (Lyon and Giggenbach, 1991) showing that the source of CO_2 is crustal.

The $^{3}He/^{4}He$ values in the HRZ spring gases range from 0.3 to $1.35R_A$ Giggenbach et al. (1993). The lowest value, 0.3 R/R_A was measured in one of the northern springs, Kerepehi (12) along the KFS but the highest, indicative of 17% mantle volatiles, occurs in Okoroire (10) the spring nearest the Taupo Volcanic Zone (Figure 1). Thus the southern sector of the HRZ may be affected by a backwash of mantle volatiles from the Taupo Volcanic Zone.

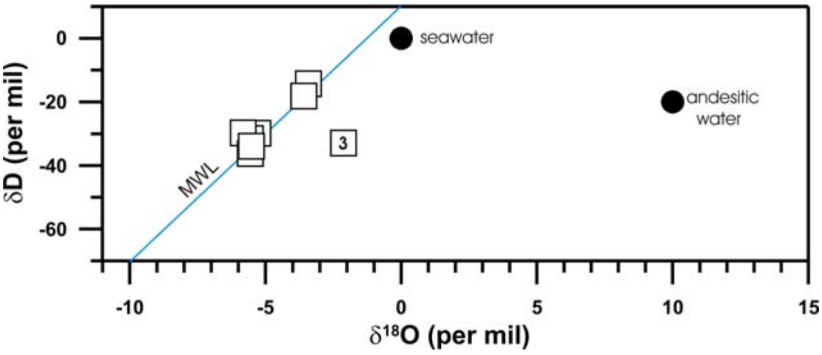

FIGURE 4: Cross plot of $\delta^{18}O$ against δD of the HRZ waters showing MWL (meteoric water line), seawater and andesitic water (data from this study; andesitic water value from Giggenbach, 1992)

The $\delta^{18}O$ vs δD (Figure 4) diagram shows most of the waters plotting along the meteoric line except for the geysering well in Te Aroha with isotopic values of δD = -32.4 ‰ and ^{18}O = -2.1‰ apparently affected by magmatic input of about 20%. However there is no geological evidence of active magmatism on the surface, the $^{3}He/^{4}He$ values of the gases are close to air (Giggenbach et al., 1993) and the $\delta^{13}C$ (CO_2) values (Lyon and Giggenbach, 1992) indicate crustal origins. Without any compelling magmatic evidences nearby, the only source for the $\delta^{18}O$ enrichment in Te Aroha is possibly dissolution of calcite in the greywacke basement, underlying the Miocene andesites, where Woldemichael (1998) estimated $\delta^{18}O$ values of 4 to 18‰ for the metamorphic waters depositing the calcite.

5. SUMMARY AND CONCLUSIONS

On a gross level, the general decrease in the HCO_3/Cl ratio from southeast to the northwest is due to seawater influx. However, it is possible that the wide range of HCO_3/Cl ratios (0.4 – 44) with widely varying Cl concentrations (13 – 572 mg/kg) and the lack of deep sources of extraneous CO_2 may be caused by non-equilibrated dissolution of carbonates (Kaufmann and Dreybrodt, 2007) in the basement greywacke following silicate hydrolysis (Hutcheon and Abercombie, 1990) accompanying the alteration of feldspars and pyroxenes to clays such as chlorite, saponite, beidellite and amesite or zeolites like clinoptilolite.

The above normal heat flow of 80 to 90 mW/m^2 (Allis et al., 1998) in the region, from whence thermal springs with temperatures of 23 to 57°C discharge, is probably caused by heat just reaching the surface from updoming of hot asthenosphere at depth, 7 - 10 Ma ago. As shown in Figure 5, the waters discharged in the HRZ consist mainly of heated groundwater with minor seawater in the north and minor contributions of magmatic volatiles in the south nearest the Taupo Volcanic Zone. However the B/Cl ratios of solutions and the CO_2/CH_4 ratios of gases increase towards the Hauraki fault where solutions are more saline, have higher total dissolved solids and higher Cl/F and B/F ratios than fluids from the Kerepehi fault system. Thus the Hauraki fault is a conduit for saline waters. The Kerepehi fault system is geologically active and more permeable than the Hauraki fault, as evinced by the greater amount of thermal water being discharged annually from this fault. Hence most of these ascending saline waters are most likely diluted by greater volumes of inflowing ground waters in the springs along the Kerepehi fault system.

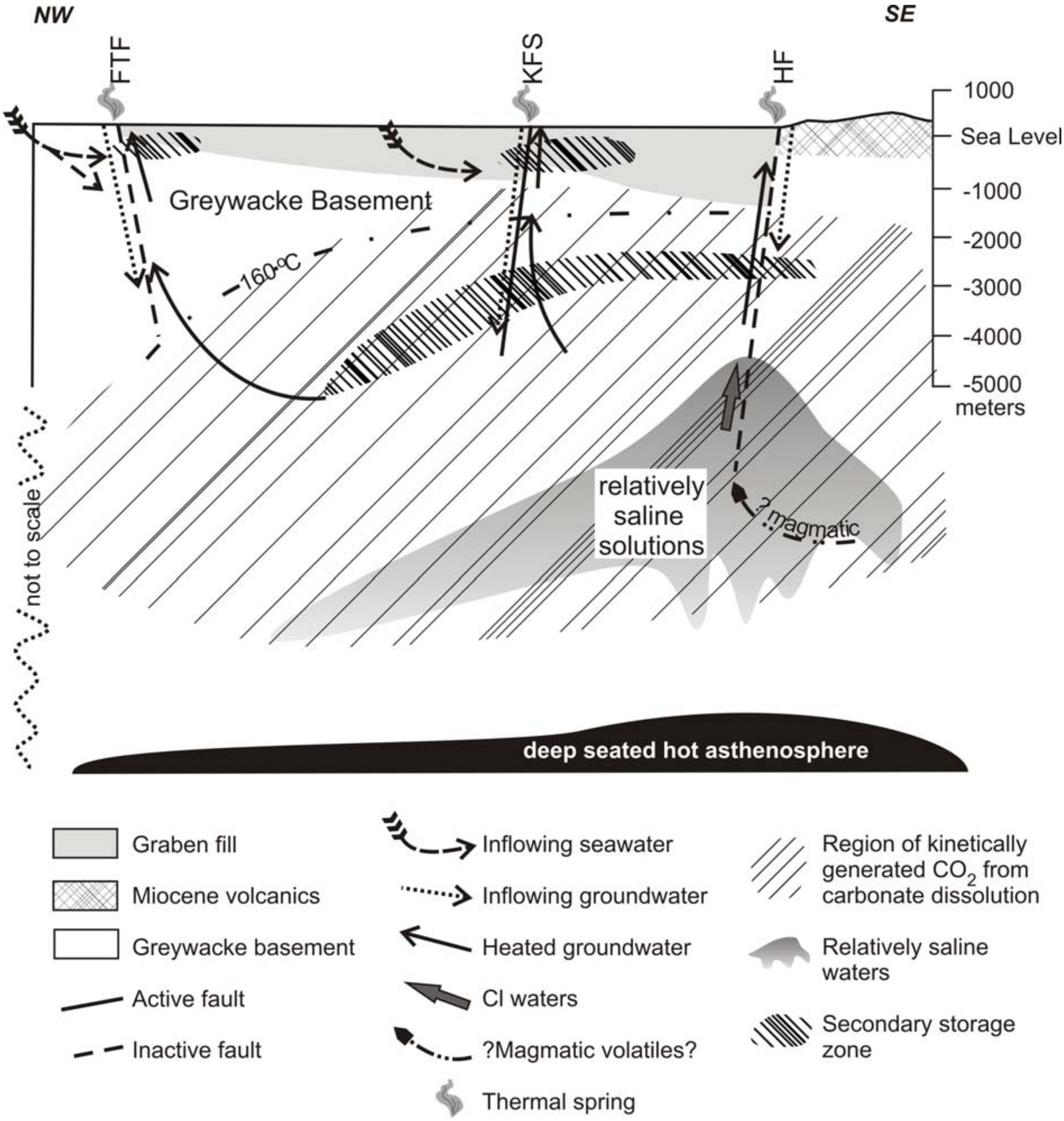

FIGURE 5: Model of the low-enthalpy Hauraki Rift Zone geothermal system showing major rock formations, fault systems, sources of solutions and heat, intermediate thermal water storage zones and estimated temperature within drillable depths

As shown in Figure 5 the HRZ is underlain by greywacke where CO_2 is generated from carbonate dissolution caused by alteration processes such as the formation of smectite from feldspars, pyroxenes and other detrital aluminosilicate minerals in the greywacke, or the conversion of kaolinite to illite with increasing water-rock interaction during diagenesis. Saline waters rising along the Hauraki fault from deep levels are either derived from depths (1) where there is greater greywacke dissolution, hence the increase in HCO_3 as the Cl, Sr, Li, K, Ba and B concentrations increase or (2) from a separate Cl reservoir at depth where ascending saline waters mix with HCO_3-rich waters originating from dissolved greywacke stored in shallower secondary storage reservoirs within the greywacke basement or the graben fill. Reservoir temperatures within drillable depths are <200°C based on the silica and cation geothermometers consistent with the unusually HCO_3/Cl ratios of the water discharges.

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