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Geochemistry of the Lihir Geothermal Field, Papua New Guinea

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ABSTRACT

The Lihir mine is located on Lihir Island, Papua New Guinea and is currently one of the largest epithermal gold mines in the world. The mine is situated inside an active geothermal system. A number of wells have been drilled and discharged to reduce underground pressures to enable open pit mining to proceed. Recently, a 6 MW generator has been installed, and a further larger, power plant is planned for early 2005.

Deep deviated wells (>1000 m depth) have been used to lower pressures in the deep reservoir, while more shallow (500–600 m), vertical wells have been utilised to reduce pressures in the upper formations. Temperatures of the fluid range from 230–270°C. The fluids that are discharged have very high total dissolved solids content (>100,000 ppm) and are unusual because of the very high sulfate concentrations (>30,000 ppm). The sulfate concentrations indicate equilibrium with anhydrite, which is pervasive in the rocks. Calcite scaling occurs in many wells, and antiscalant dosing is reasonably successful. Although the geothermal field is situated adjacent to the sea, isotope analyses indicate that the geothermal fluid has a magmatic and meteoric water component. The meteoric water component is not reflected in the argon concentrations in the gas analyses.

1. INTRODUCTION

The Lihir Gold Project is located on Lihir Island, Papua New Guinea. The mine site incorporates an active geothermal system, which introduces unique conditions for the operation of the mine site. Commencing in 1999, a number of wells have been drilled to intercept fluids from the deep geothermal reservoir, and to de-pressurise the geothermal aquifers to allow mining to take place. These wells have been discharged where possible, and chemical samples collected. Where the wells have not discharged, downhole chemical sampling has usually been carried out.

The geothermal wells at Lihir have been conveniently classed into two categories based primarily on the depth of the fluid reservoir that they intercept. The **intermediate** wells are drilled vertically, and intercept fluids at depths of 300-800m. **Deep** wells are usually deviated and intercept fluids at > 800m.

1.1 Location and Geology

Lihir island is one of a chain of four islands lying to the east, and parallel to New Ireland in the east of Papua New Guinea. (Figure 1). The island is approximately 20 km x 13 km and the Ladolam gold deposit is located in the SE end of the island. The island consists of three Pliocene-Pleistocene sub-arial volcanoes, all of which have experienced sector collapses into the sea. The gold mine and geothermal system is located within the 4x6 km collapsed crater of the Luise volcano, which is the youngest of the three volcanoes at about 1Ma. Luise volcano is comprised of alkali basalt and trachybasalt vesicular flows and abundant blocky to sandy pyroclastic breccias and tuffs.

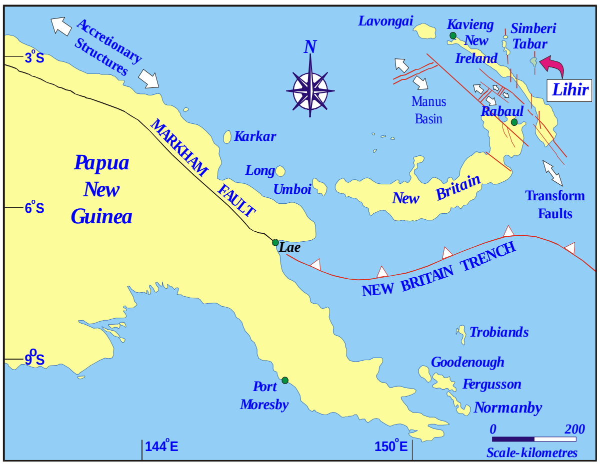

Figure 1: Location of Lihir island

2. WATER CHEMICAL DATA

There are currently 125 water analyses of samples from the geothermal wells and a total of 38 steam analyses available. The positions of the deep and intermediate well are shown in Figure 2 and 3, respectively. The deep well wellheads are positioned outside the active mining area and are deviated under the active mining areas. The intermediate depth wells are located adjacent to the mining areas and have been mined out in some cases, and shortened in others.

2.1 Deep Wells

The deep wells are all deviated and are designed to depressurise the deep geothermal aquifer. The drilled depths range from 1385 to 1760 m. All of the deep wells except GW04 have been discharged, and chemical samples obtained during discharge. The deep wells are subject to calcite scaling in the production casing and extended discharge has usually only been while antiscalant chemicals have been added.

The deep geothermal fluid at Lihir is very saline. An analysis (ppm) of a typical deep reservoir fluid is:

Na	23050	K	4500	Ca	~40
Li	17.4	SO_4	28350	Cl	18980
SiO_2	460	B	119	HCO_3	8600

pH_{250} 6.86

The fluid chemistry is unusual, in that it contains very high sulfate concentrations (~30,000 ppm).

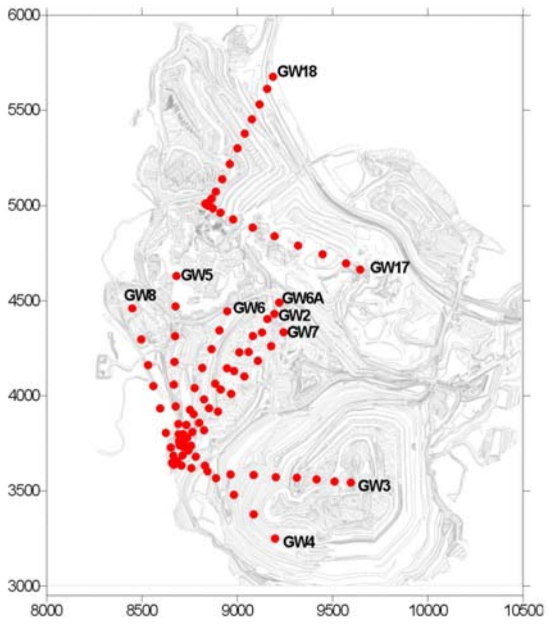

Figure 2: Well tracks of the deep geothermal wells. The label is at the deepest end of the wells.

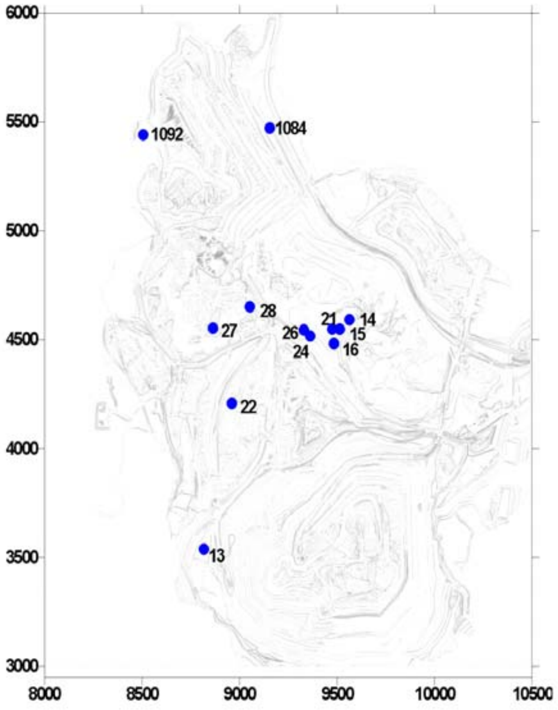

Figure 3: Positions of the intermediate depth geothermal wells, and DDH1084 and DDH1092. All wells are vertical

Where reliable Ca analyses are available, geochemical modeling shows that the geothermal water is probably in equilibrium with anhydrite ($CaSO_4$) in the reservoir. None of the usual cation geothermometers reliably predict the temperatures measured at the bottom of the wells (240-300°C), although the empirical Na/K geothermometer of Truesdell (1976) comes closest. Silica geothermometers are typically affected by the deposition of silica prior to analysis, as the very high TDS increases the rate of deposition even when the samples are diluted as quickly as possible after sampling.

Cl/B analyses indicate that there is a common parent fluid for all of the deep wells except GW18 (Figure 4). This well has a markedly different Cl/B ratio. It also has a somewhat higher reservoir chloride concentration, indicating that if it is derived from the same fluid then it has boiled somewhat before reaching the well. GW18 is drilled in a northerly direction and terminates vertically below the shores of Luise harbour. This well also has the highest temperatures recorded at Lihir. If the GW18 fluid is compared to the average of all other wells, then the Na, K, Li, SO_4 concentrations are lower and the Cl, B, and F are higher. This would suggest that the GW18 water has been diluted by water that is enriched in Cl, B and F. One possible mechanism that would be consistent with this data, would be that the diluting fluid was a condensate from a high temperature phase separation. At higher temperatures (>300°C), significant concentrations of Cl, B and F are distributed into the vapour phase, and dilution of the deep geothermal fluid with such a condensate could give the observed concentrations.

The lowest temperatures recorded in the deep wells are in GW3 and GW4, and the chloride concentrations in these wells indicate dilution with meteoric water.

The deep wells have a varying amount of excess enthalpy, from liquid enthalpy wells through to wells with significant steam inflow.

2.2 Intermediate Wells

The intermediate wells were drilled to relieve steam pressure and drain the fluids in the depths that were typically to be mined. These wells often therefore have excess enthalpy, and the enthalpy is increasing with time. In a rather unusual feature of a combined geothermal field and mine, some of the wells have been mined out with time, and others have had the wellhead lowered. It is steam mainly from these intermediate wells that currently supply the 6 MW power station.

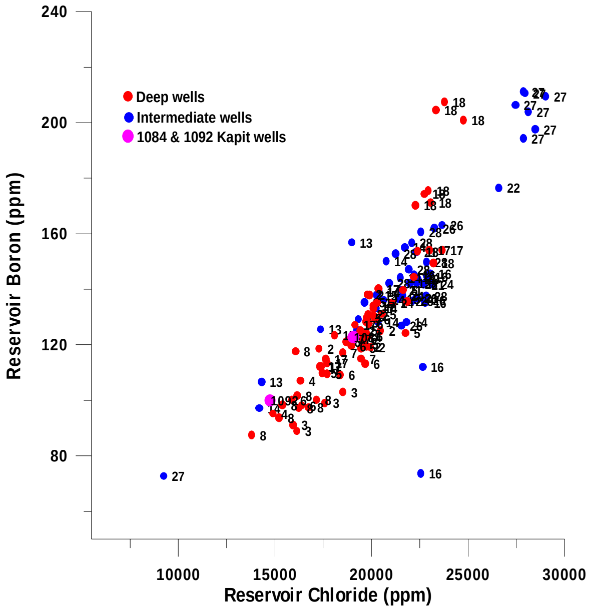

Figure 4: Cl/B concentrations for all well data at Lihir.

In general, the chemistry of the intermediate wells reflects the boiled nature of the fluids. The concentrations in the waters entering the wells are greater than the deep wells, but for most wells, the ratios of the chemical species are the same as those of the deep wells. The exception is GW27, which, judging by the concentrations of the chemical species, is the most boiled of the intermediate wells. The ratios of the chemical species in this well are more similar to those of GW18, than to the other deep wells (see for example the Cl/B ratios in Figure 4).

Interestingly, water samples have also been collected from the diamond drill holes DDH1084 and DDH1092. DDH 1084 is a shallow well almost vertically above the deep termination of GW18. The concentrations in the water from DDH1084 are about 70% those of GW18, and the element ratios are similar to GW18, except for the Cl/B ratio which is similar to the other deep wells. The chemistry of these two shallow wells does not seem to show a seawater influence, however, stable isotopic data is equivocal (see later).

2.3 General Water Chemistry of Lihir Geothermal Wells

The water samples collected from the GW wells are collected at a variety of sampling conditions ranging from atmospheric pressure weirbox samples to downhole samples. They are also collected from wells which have discharge enthalpies close to their expected values from downhole temperature measurements, and wells which have varying degrees of excess enthalpy. Investigating the *ratios* of the components in the geothermal water is a method that avoids many of the problems that arise due to the differences in concentrations for different sampling and well types.

Components of the geothermal water can be considered to be either mainly conservative or reactive. Conservative components are not generally precipitated as minerals, and do not react with the surrounding country rock. Reactive components react with surrounding country rock, or are precipitated as minerals, either in the country rock, or in the well casing or surface pipework. Chloride seems to be the only truly conservative component in the Lihir geothermal waters. Therefore, the behaviour of the other chemical species were investigated initially as their ratio to chloride ion.

The Cl/B ratio in figure 4 has already been discussed. The other major anion besides chloride is sulfate. The Cl/SO_4 diagram is shown in Figure 5.

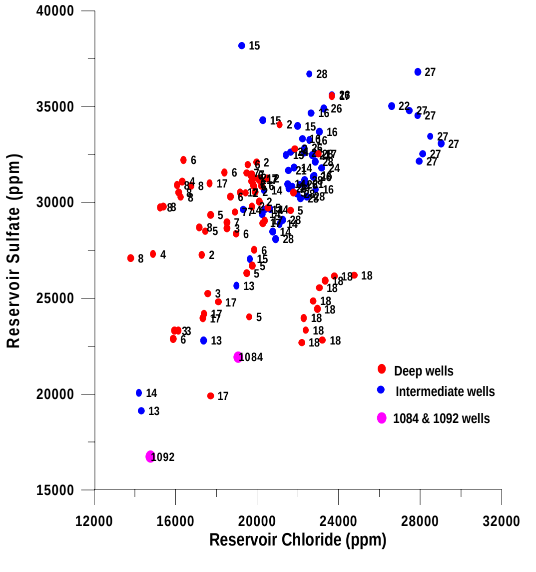

Figure 5: Reservoir Cl/SO_4 concentrations for all well data

The wells that have the higher temperatures have lower SO_4/Cl ratios, which is consistent with the retrograde solubility of anhydrite. Anhydrite is pervasive in the reservoir, and is thought to have been precipitated when seawater invaded the geothermal field after the sector collapse. Once again, wells 18 and 27 are quite different in their chemistry to the rest of the wells and reflect a higher temperature source water.

The reservoir Cl/Li relationship is shown in Figure 6. Lithium is usually considered to be almost conservative in geothermal fluids. However, it is obvious from Figure 6 that there is considerable variation in the Cl/Li ratio. This variation is also present in the Na/Li ratio. There is perhaps a possible temperature effect in these data in that many of the cooler wells have higher Li/Cl ratios, however, the variation does not seem to be totally systematic. The temperature trend is opposite to that expected. (Fouillac and Michard, 1981).

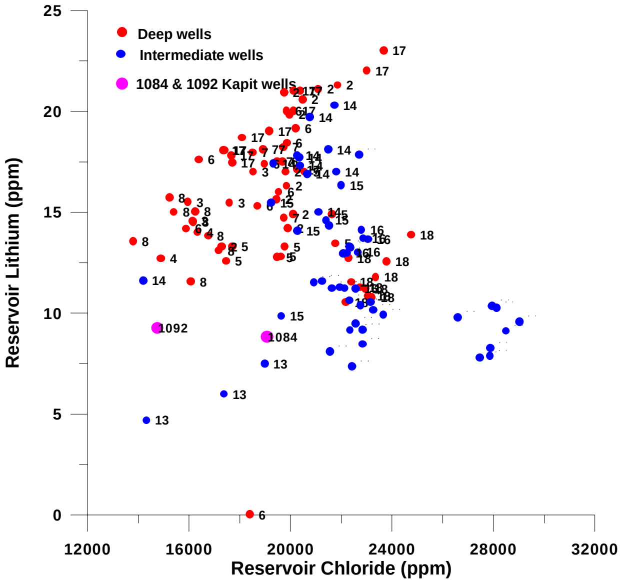

Figure 6: Reservoir Cl/Li concentrations for all well data

Cl/Na and Cl/K ratios show no unexpected features. The Na/K ratios are shown in figure 7.

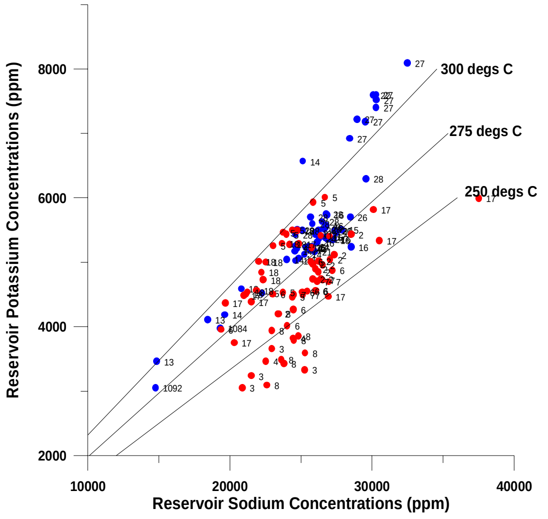

Figure 7: Reservoir Na/K concentrations for all well data

Figure 7 shows that the Na/K ratio varies significantly. The Na/K geothermometers as they are traditionally expressed have been shown previously to be inappropriate at Lihir, due probably to the very high total dissolved solids in the Lihir waters, and perhaps the absence of feldspars in some of the country rocks. The only cation geothermometer that had any (slight) credibility in the Lihir conditions was the Truesdell (1976) empirical Na/K geothermometer. Temperature isotherms for this geothermometer are shown in Figure 7.

On closer inspection of Figure 7, it appears that there may be a systematic relationship between sodium and potassium concentrations in the Lihir wells. Of the deeper deviated wells, those that would normally be considered to have lower temperature feeds, such as GW02, GW03, GW08, generally lie closer to the sodium axis, whereas the higher temperature wells such as GW05, GW06 and GW17 lie closer to the potassium axis. This is the same trend that would be expected for the Na/K geothermometer. For the shallower intermediate depth wells, for which the Na/K geothermometer predicts hotter feeds, there may be a kinetic effect present, where the temperature at which the Na/K ratio came to equilibrium is “frozen” in the solution as it cools. The disparity between measured and calculated temperatures is particularly marked for GW13.

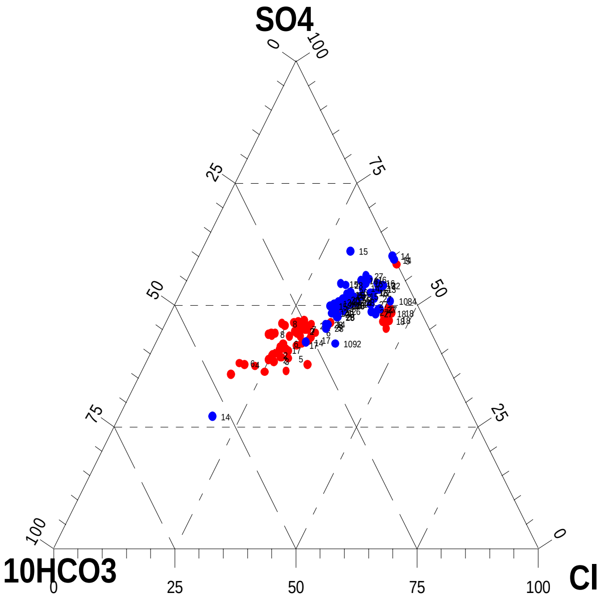

Figure 8: $SO_4/HCO_3/Cl$ ternary diagram for all Lihir data

The $SO_4/Cl/HCO_3$ diagram is usually utilised to distinguish varying types of geothermal fluid, such as deep chloride, acid sulfate etc. At Lihir, the very high sulfate concentrations in the deep fluid do not allow this discrimination. However, the diagram (Figure 8) is still useful.

The most notable feature of this diagram is the very distinct boundary between the deep wells (in red) and the intermediate wells (in blue). The Cl/SO_4 ratio is similar for all samples, however, the relative amount of bicarbonate is greater in the deep well samples. This indicates that the intermediate wells produce fluid of lower bicarbonate, and hence have already boiled and lost the accompanying steam (and CO_2) by the time that they reach the well. Unlike all of the other deep wells, the samples from GW18 have proportionately lower bicarbonate, and therefore are shown to have lost steam before entering the well. This implies that the GW18 fluid is probably on an outflow zone.

3. GAS CHEMICAL DATA

A total of 38 steam analyses from GW wells are available. The gas content in the *total discharge* ranges from 0.083 wt% to 2.80 wt% with an average of 1.09 wt%. The gas content in the *steam* samples analysed ranges from 0.97 wt% to 9.17 wt% with an average of 3.34 wt%. The very high gas contents in the steam were collected at very high separation pressures, and could therefore be expected to be increased.

The gases can give information about the source of the geothermal fluids (Giggenbach, 1991). The ratios of argon (Ar), helium (He) and nitrogen (N_2), can delineate three major sources of the gases. Low helium, and N_2/Ar ratios of ~ 38, are typical of gases entrained in **meteoric** water. There is a **magmatic** component, which is distinguished by N_2/Ar ratios of ~800, and a **crustal** component consisting mainly of radiogenic helium. The gas analyses (figure 9) from the geothermal wells are all very similar in their He, Ar and N_2 ratios, and lie on a mixing line between crustal and magmatic components. This position is normally occupied by gases from vapour dominated systems and is also similar to that of gases from the Ngawha geothermal field in New Zealand. It suggests that there is only a small meteoric water component in the deep geothermal fluid, however this conclusion is contrary to the stable isotope data discussed later.

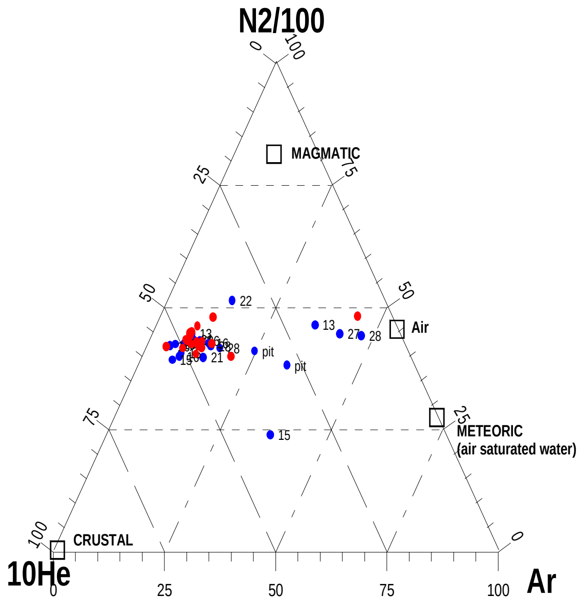

Figure 9: He, Ar, N_2 trilinear plot of all gas analyses

The Lihir geothermal gases do seem to be depleted in argon, compared with data from other geothermal systems. The only gas sample from GW22 displays slightly more of a magmatic component, but without further analyses from this well, it is equivocal. One of the GW15 samples is an outlier and probably represents an analytical error. Several of the samples display varying contamination by air during the sampling process as evidenced by their mixing line towards the atmospheric air. The samples from the Leinitz pit are, as expected, on a mixing line between the deep geothermal water and gas saturated meteoric water.

There exist a number of geothermometers based on the gas concentrations in the steam. However, for these to be valid, they should ideally represent gas samples from a single feed. With production, most of the wells now produce with excess enthalpy, and where there is a steam feed that is separate from the water feed, it may not be valid to utilise gas geothermometers.

Furthermore, gas reactions are often kinetically hindered, and thus the temperature of equilibration may not represent the most recent temperature that the gases encountered. Of the gas constituents, hydrogen is probably the most reactive and argon, on the other hand, is inert. Both gases are also very insoluble in water, which suggests that the distribution into the steam phase will be approximately equal for both gases. Giggenbach (1991) therefore proposed a gas geothermometer based on the ratio of hydrogen to argon (HA). When it is applied to the available Lihir geothermal well data, the temperatures in Figure 10 are obtained.

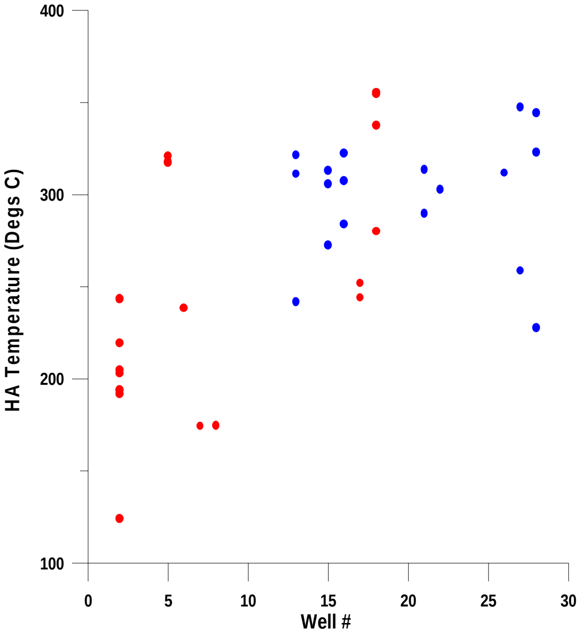

Figure 10: HA gas geothermometer temperatures. Red denotes deep wells and blue denotes intermediate wells.

The temperatures derived from the HA gas geothermometer display a wide range of values both between different wells and within data from the same well. For the deep wells, lower temperatures are predicted by wells 2, 6, 7, 8, and 17, whereas wells 5 and 18 predict higher temperatures. The trend, if not the actual temperatures, corresponds with observed temperature data. In general, the intermediate wells predict higher reservoir temperatures than the deep wells, however, nearly all of these wells display excess enthalpy. Other gas geothermometers display similar variation.

CO_2 gas is much less soluble in the geothermal fluid than H_2S. Consequently, when the fluid boils, proportionately more CO_2 than H_2S is partitioned into the vapour phase. Thus the CO_2/H_2S ratio can provide an indication of whether the fluid has boiled previous to sampling. The data is shown in Figure 11. It is clear that in general, the intermediate depth wells (blue coloured) have a lower CO_2/H_2S ratio than the deep geothermal wells (red coloured). This implies that the intermediate depth wells have experienced boiling and phase separation prior to discharge into the well. The CO_2/H_2S ratio is also dependent on the temperature of separation as H_2S is more soluble in cooler liquid. Thus the lowest CO_2/H_2S ratio for GW02 is for steam separated at 2ba, and there is a linear increase with separation pressure to the highest CO_2/H_2S ratio separated at 20.8ba. Nevertheless, the intermediate depth wells have much lower CO_2/H_2S ratios. Significantly, GW18 has the lowest CO_2/H_2S ratio indicating the most boiling.

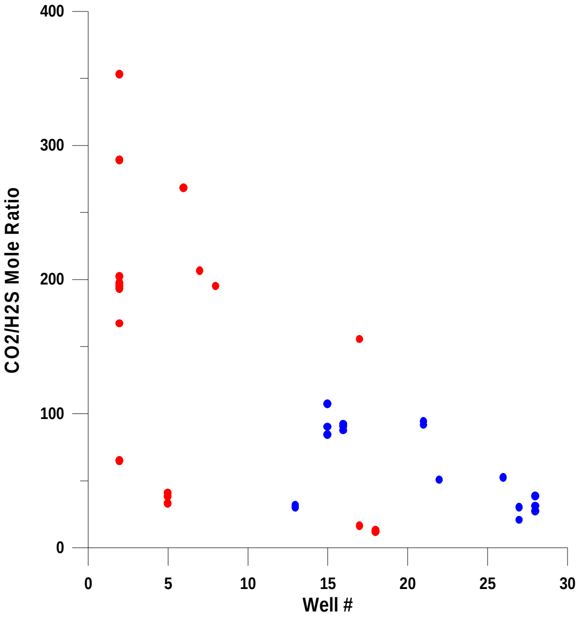

Figure 11: CO_2/H_2S ratios for all well data

4. TRACE METAL DATA

As part of a University of Auckland research project, downhole samples were collected at three Lihir geothermal wells to be analysed for trace metals. The wells chosen were GW06, GW14 and PW24. A special downhole sampler constructed of titanium was employed. This enabled the sampler to be rinsed with aqua regia to dissolve any trace metals that may have been precipitated as the sampler was de-gassed and lowered in temperature. The aqua regia wash was added to the sample, and then analysed by ICP-MS and other techniques. The PW wells are shallow (200-400m) pumped wells that are used to de-water the shallow ground waters from the mine area. The results are presented in the Table 1:

Table 1: Trace metal concentrations for GW06, GW14 and PW24 samples. Concentrations are ppb (µg/L) unless stated otherwise

Sample	GW06	GW14	PW24
Ag	6	5	<1
As (ppm)	17	18	2
Au	16	13	1
B (ppm)	132	151	45
Br (ppm)	36	39	13
Cd	<1	2	<1
Cr	12	12	<5
Cu	4450	1590	10
Hg	1	1	0
I	2470	3050	8700
K (ppm)	4200	4880	1440
Mn	620	120	4900
Mo	430	350	10
Na (ppm)	25570	24400	7300
Ni	106	122	520
Pb	23	40	<1
Sn	840	586	11
Sb	4	2	<1
Te	<1	4	<1
Tl	69	68	2
V	690	950	7
W	910	900	110
Zn	185	300	260

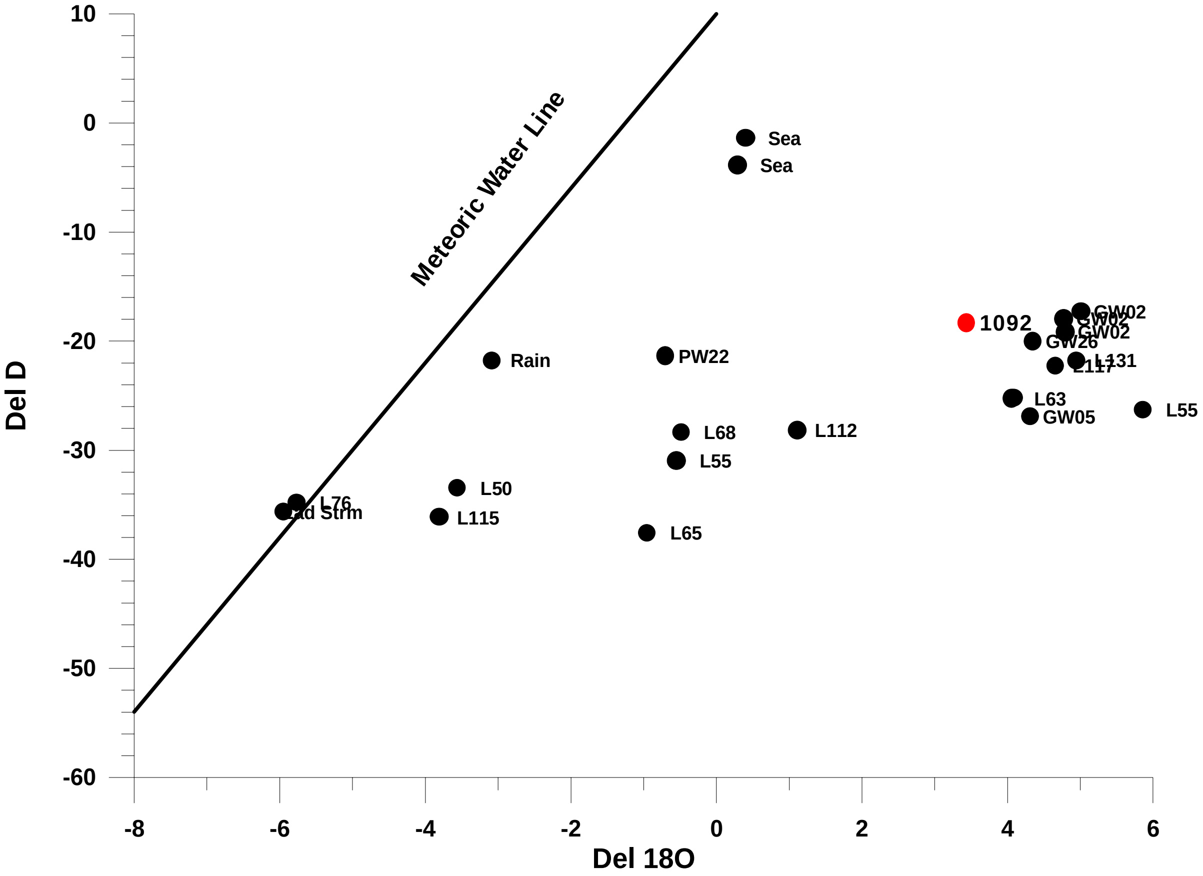

Figure 12: Stable isotope data for Lihir well data

The results indicate very high concentrations of many trace metals. Gold concentrations are high in the geothermal wells, compared to many similar analyses in NZ geothermal systems. The Au concentration is low, but still significant, in PW24. Silver concentrations are much lower compared to the gold concentrations that is found in the NZ systems. There are very high concentrations of Cu, Mo, Sn, Tl, V, W and Zn. Many of these metals are transported in the liquid phase as chloride complexes, and so it might be expected that they would have enhanced concentrations, particularly in such a mineralised area in a high chloride fluid.

5. STABLE ISOTOPE DATA

Stable isotope data has been previously collected (Geothermex, 1989). The only data to have been added recently is from well DDH1092. The total stable isotope data are shown in Figure 12.

Nearly all of this data is from exploration wells (L series) drilled before mining commenced. When the recent results, together with previous “L” series wells and other Lihir waters, are plotted on a D/^{18}O diagram, there is an obvious dilution trend between the deep GW geothermal wells, which have a typical magmatic isotope signature, and the meteoric water defined by the Ladolam Stream. Similar conclusions can be drawn from the chloride/^{18}O diagram. There could be a possible dilution by seawater for fluids produced from DDH1092 (shown in red), which is located close to the Luise Harbour shoreline.

6. CONCLUSIONS

The Lihir Geothermal Field produces geothermal waters with a high concentration of dissolved salts. The fluids are unusual for the high concentrations of sulfate. Geochemical calculations suggest that the calcium and sulfate concentrations in the deep geothermal reservoir are governed by the solubility of anhydrite. Cation geothermometers do not appear to be applicable for the Lihir fluids. Cl/B ratios indicate a common parent fluid for the Lihir wells, although GW18 has significantly different chemistry, which could possibly be explained by mixing with a high temperature condensate. Li concentrations in the geothermal reservoir show a general inverse relationship to temperature in contrast to that found elsewhere. Gas analyses yield equivocal temperatures for a number of the gas geothermometers. Stable isotope data does not indicate a seawater genesis of the geothermal water.

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