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Geochemical Monitoring Before and During Six Years of Power Generation at Ngawha, New Zealand

Richard B Glover[1] and Tricia M Scott[2]

[1]Glover Geothermal Geochemistry, Auckland, New Zealand

ggg@pl.net

[2]NZ Environmental Ltd, Kerikeri, New Zealand

tricia@nzenvironmental.co.nz

ABSTRACT

We report the results of an eight-year monitoring programme at Ngawha and examine the data to assess the nature of the reservoir fluids and whether any changes have occurred. The main production reservoir contains liquid at 230ºC, 1250 mg/kg chloride, and 1.4 wt% carbon dioxide. Three typical areas of spring discharge are found viz: Spa, Waiariki and Tiger. The highest chloride water (1180 mg/kg) is observed at Jubilee Bath in the Spa area, evidence of the least dilution of the deep water. Waiariki baths (e.g. Universal contains 260 mg/kg) are more dilute and are classified as bicarbonate water. Tiger bath (400 mg/kg Cl and 930 mg/kg SO_4) is typical of acid sulphate springs where the deep water is diluted with water containing sulphate formed from oxidation of hydrogen sulphide.

From July 1998 to March 2004, 20 Mt of fluid have been produced by the wells (and reinjected). Linear regression of chemical concentrations are used to determine trends with time. Although some of the data show a large scatter, observed changes are consistent with less deep water and/or more steam and gas reaching the surface features. The production wells, NG9 and NG12 are now discharging some reinjected fluid.

1. INTRODUCTION

Ngawha geothermal field is located approximately 250 km north-north-west of Auckland and about 5 km east of Kaikohe. Ngawha is the only high temperature geothermal system in the north of New Zealand. Surface manifestations are sparse (Mongillo, 1985). The geothermal reservoir is regarded by Maori as 'Taniwha'. Local people think of Lake Omapere as the heart, and Ngawha Springs as the head and the eye. The system is seen as a living being commanding respect and awe.

The Ngawha springs are in an old lake basin. What is unusual about this area is a deposit of cinnabar or mercuric sulphide. For many years claims were made about the curative properties of the mercuric Ngawha mud, principally for the treatment of syphilis. Written accounts of bathing in Ngawha's hot waters and muds go back to the missionary William Wade (1842), who noted, "The springs at this place are much resorted to by diseased natives from the Bay of Islands, who bring baskets of provisions with them, and remain on the spot to use the sulphur warm-bath till a cure is effected."

Herbert (1921) referred to "a remarkable group of hot springs at Ohaeawai... in the midst of old workings of a mercury mine, itself desolate in a setting of old gum fields." He wrote of the hot mud containing globules of cinnabar,

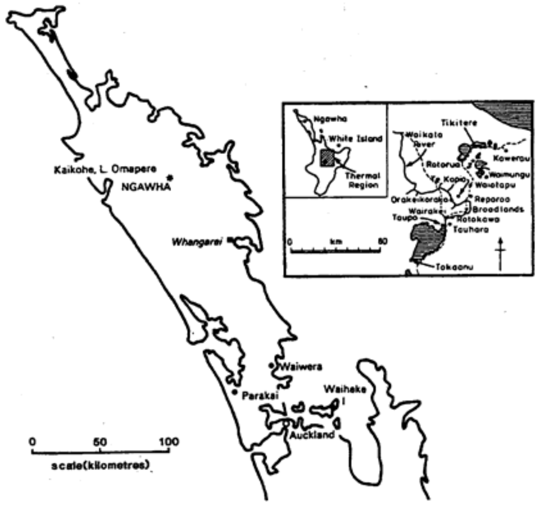

Figure 1: Ngawha and the Taupo Volcanic Zone Locations (Mongillo, 1985)

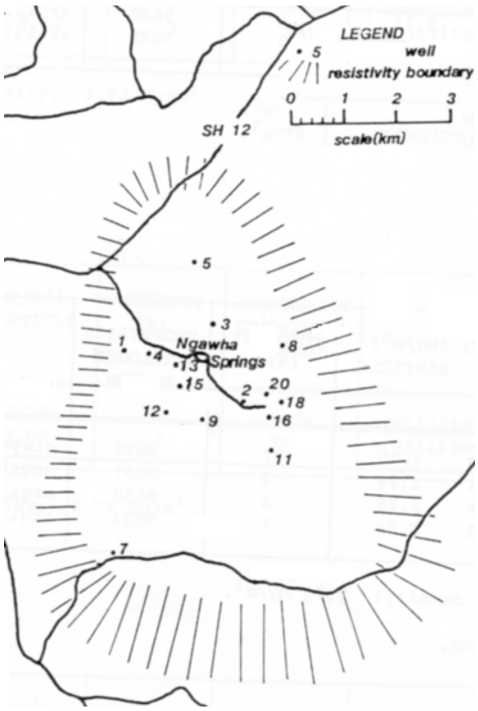

Figure 2: Ngawha Springs and well locations

being used as a parasiticide by Maori people of the area. NB. In the past Ngawha was known as Ohaeawai. Davey and van Moort (1986) reported 900 mg/kg mercury in stream sediments in the Tiger bath area.

The baths are also valued for treatment of arthritis, skin diseases such as eczema and ringworm, and some people drink small quantities of the water as a 'pick-me-up' and even as a cure for cancer. Serious geothermal investigations were started by the DSIR in the early sixties and the scientific work carried out during the next twenty years were published in the DSIR Geothermal Report #7, (Browne et al. 1981).

2. RESERVOIR CHARACTERISTICS

2.1 Subsurface geology

The subsurface geology is deduced from the drill cuttings and cores from 15 drillholes, all but NG1were drilled in the 1980's.

The Waipapa Group basement of mainly argillite with lesser amounts of fine greywacke sandstone is the geothermal reservoir (aquifer) for the field.

This is overlain by up to 600m of allochthonous Cretaceous and Tertiary marine sediments, (Petty, 1985). The upper sedimentary unit comprises mainly a grey non-calcareous siltstone called the Ngatuturi Claystone. It was encountered down to a maximum depth of 243 m below the surface.

A middle 'melange' unit follows. This is a distinctive unit of sheared, mixed and brecciated multi-coloured shales of various ages. This has been found up to 220 m thick (NG16).

A lower unit is a very mixed group lithologically but rather than being a brecciated melange, variable size 'blocks' made up of different lithologies occur in sheared relationships to each other. In some holes only one rock type was drilled in this interval e.g. argillaceous limestone. Other rock types encountered are calcareous brecciated shales, glauconitic sandstone, calcareous sandstone and interbedded fine sandstone and siltstone.

2.2 Permeability

The permeable reservoir in the Waipapa Group basement is overlain by low permeable units. The permeable reservoir extends to a depth of 1.5 km below sea level. It contains liquid water at 210 to 230˚C, 1250 mg/kg chloride and about 1 to 2 wt% gas. Below the permeable zone temperatures rise to over 300˚C but permeability is proven to be poor. The gases discharged with the well waters and via the baths have equilibrated at higher temperatures (up to 400˚C).

2.3 Surface flow

Mass flow of deep chloride water to the surface can be deduced from the chloride flux in the run-off waters. The flows from the main thermal baths and Spa areas flow into the Mangamutu stream. This flows, together with flow from Lake Tuwhakino and spring discharges, into the Ngawha stream. In the "baseline" monitoring period, i.e,. 1996 to June 1998, the Mangamutu stream (Figure 3) discharged a chloride flux of 0.82 and 2.8 g/s (mean and maximum respectively). For a deep water chloride concentration of 1250 mg/kg the chloride fluxes equate to 0.66 and 2.2 kg/s of water at 230˚C. The total flow from all the thermal discharges is measured at the Ngawha Weir. The total mean chloride flux (excluding flood values) is 2.3 g/s equivalent to 1.8 kg/s water. This compares with 250 g/s chloride and 150 kg/s of water at 265˚C in Geyser Valley, Wairakei, prior to development. In Rotorua the chloride flow, including subsurface flow in Lake Rotorua, is 540 g/s and 390 kg/s of water at 250˚C, (Glover 1992). The heat flow associated with the chloride flux at Ngawha is < 2 MWt. This is very small compared with 174 and 423 MWt calculated for Geyser Valley (Wairakei), and Rotorua respectively.

Table 1: Surface flows:

Site	Measured Cl	Calculated Deep Cl water		Calculated	
		flow	temp	CO_2	Heat flow
	g/s	kg/s	ºC	g/s	MWt
Mangamutu	0.82	0.66	230	7.9 to 110	0.65
Ngawha Weir	2.3	1.8	230		1.8
Geyser Valley	250	150	265	75	174
Rotorua	540	390	250		423

The minimum CO_2 fluxes can be calculated from the chloride flux and the CO_2/Cl in the deep fluid. For the Spa and Waiariki baths area this is 7.9 g/s.

There is evidence from NG1 that the gas/water ratio increases near the surface. For this shallow well (590 m deep) the gas in total mixture in the well is 16 wt%. If we use this figure then the CO2 flux is 110 g/s. For Wairakei, the CO_2 flux before production was 75 g/s.

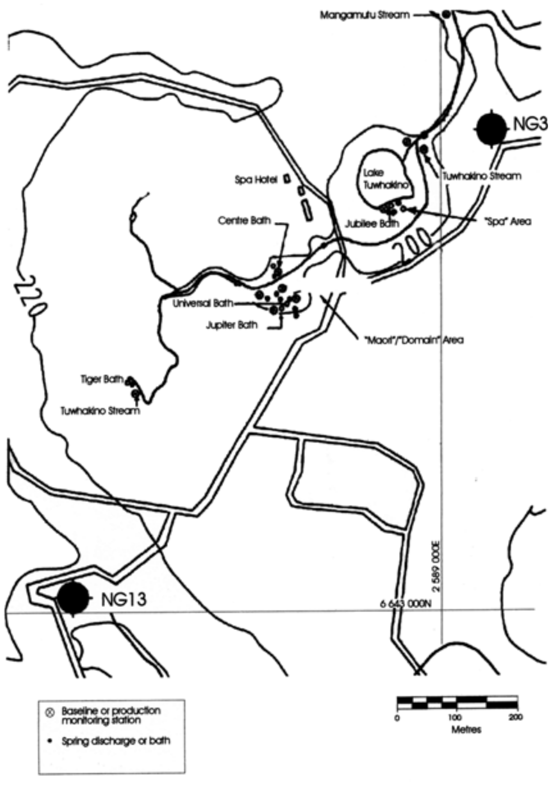

Figure 3: Map of the central Ngawha thermal area.

2.4 Deep and shallow fluid

The deep component is characterised by high chloride (1250 mg/kg) and boron (900 mg/kg) (Scott and Glover, 2000). The water will be saturated with silica (390 mg/kg) at depth. Due to the low vertical permeability, as evidenced by the low flows at the surface, the water rises very slowly and this allows the silica to equilibrate to the lower near-surface temperatures and thus the bath waters are not over saturated with silica. Most of the well waters, as expected, plot in the mature or chloride water position (Cl >70% and low SO_4).

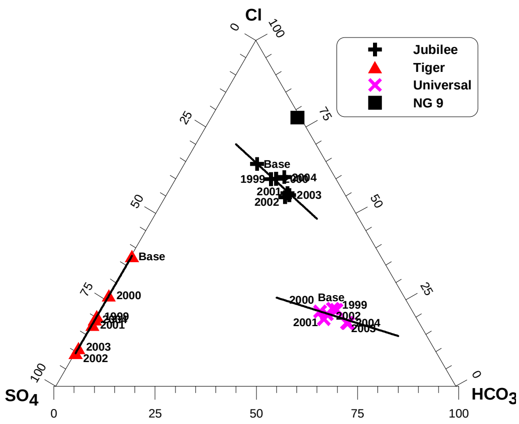

Figure 4: Cl - SO_4 - HCO_3 Ternary plot

One set of data from NG9 is plotted in Figure 4 as an example of the well waters. Jubilee Bath, which has the highest chloride, 1250 mg/kg, has a silica content of 156 mg/kg. The Cl/SiO_2 wt ratio = 8.0, compared to the ratio in the deep water of 3.0. The normal silica terraces found in most thermal areas are thus absent at Ngawha. Jubilee bath is distinct from all the other features in that it has the highest contribution of deep water component. Although the composition has varied, the baseline value is closest to the downhole samples from NG4 and NG13. This water can also be classified as chloride-water (Glover 2001). The chemical concentrations in the waters and proportions of individual gases in the gas collected from the bath are similar to those in the wells. Thus this bath has the most direct contact with the deep reservoir. The flow of the deep water to Jubilee appears to be sufficient to prevent the access of the water from the shallower reservoir.

Steam and gases separate from the rising water and heat the near surface waters. Condensation of steam also allows cool gas to discharge. The shallow reservoir is characterised by low (<70 mg/kg) chloride and high calcium-magnesium and bicarbonate concentrations. This water is formed by absorption of steam and carbon dioxide released from the higher temperature waters below, forming aggressive solutions preferentially leaching calcium and magnesium from the country rock. When mixed with the deep water, the latter is diluted and its originally low magnesium is increased so that the Mg/Cl ratio increases. Universal Bath is typical of this category and can be defined as a bicarbonate-chloride-water.

Oxidation of hydrogen sulphide to sulphuric acid, either close to the surface, or in near stagnant baths, produces the low pH waters found in Tiger Bath which has a particularly high gas flow.

These three baths, Jubilee, Universal and Tiger demonstrate the change from a deep chloride water to a bicarbonate water at slightly higher surface elevation, to an acid sulphate water at the highest surface elevation, and have been extensively monitored. The locations of these features are shown in Figure 3. The relative chloride, bicarbonate and sulphate compositions of these features and the deep water, represented by well NG9, are shown in Figure 4. The ternary plot shows average composition of the waters from Jubilee, Universal, and Tiger baths for the baseline data and yearly periods (April to March) during production. Linear regression fits have been calculated for the water from each bath. These show a gradual decrease in the percentage of chloride with time in each of the three waters. This trend is discussed in Section 2.7.

2.5 Gas Species discharged

Constituents in the gases discharged at the surface are in different proportions to those at depth. Hydrogen sulphide, which is very chemically reactive is removed in the shallow waters so that the CO_2/H_2S ratio in the production wells (100 to 110) increases to 160 to 240 in the gas discharging in the baths. Sheppard and Johnson (1984) correctly inferred that the waters in contact with the gas stream are saturated with respect to the gases and therefore the thermal system has reached a stable state

The highest CO_2/H_2S ratios were found in the most ebullient baths (Tiger, Centre, Jupiter, and Jubilee) all of which are whitish-grey in colour. This indicates that some of the hydrogen sulphide had been oxidised to sulphur. The lowest ratio was seen in Universal which has a very low gas discharge and is greenish-black in colour.

Ammonia is also removed from the gas as it bubbles through the bath water. This is demonstrated by the change in the CO_2/NH_3 ratio which rises from between 150 and 250 in the production wells to between 17,000 and 80,000 in the gases discharged in the baths.

2.6 Production of Power

The station began production in July 1998 and uses 10,000 tonnes per day. The fluid is withdrawn from NG9 and NG12. After heat is extracted the fluid (less the gases in the vapour state) is reinjected into wells NG11 and NG18. Thus the net mass withdrawal is small. The chemistry of the water and steam discharged by NG9 and NG12 is monitored together with the fluid reinjected into NG11 and NG18. In addition downhole samples are collected from deep monitor wells NG4 (at 800 m) and NG13 (at 1000 m).

2.7 Results of the monitoring programme

Although up to 15 different chemical constituents have been analysed regularly in the water samples collected; this paper concentrates on chloride, bicarbonate and sulphate in the three bath waters, and chloride and carbon dioxide in NG9 and NG12. Frequent sampling of Universal and Jupiter baths in 1997 showed that the baths were effected by recent rainfall (Scott & Glover, 2000). Thus data collected when >18mm rain had fallen within 3 days of sampling has been discarded and not plotted in the following graphs. The chemical parameters are plotted against time. Zero time is the beginning of production in July 1998 so that the baseline monitoring data from 1996 plot at negative time. Linear regression fits to each set of data are shown in Figures 5, 6, 7 and 8 below. The concentration of each chemical parameter is shown on the left, with the equation in the middle, and the calculated percentage change from the beginning of production to 5.75 years of production (March 31 2004) on the right of each graph.

2.7.1 Jubilee Bath

Jubilee bath (Figure 5) shows a negligible change in chloride concentration over the period of station operation (to 5.75 years operation). There is an apparent decrease of

150 mg/kg between the baseline and the production data. However, the decline of chloride is small at 1.6% since production began, being about 0.3% per annum. The sulphate has declined by 19.7% during production a change of 3.4% per annum. The regression analysis for bicarbonate shows that the relationship with time is not significant. All the graphs show large fluctuations within the historical data.

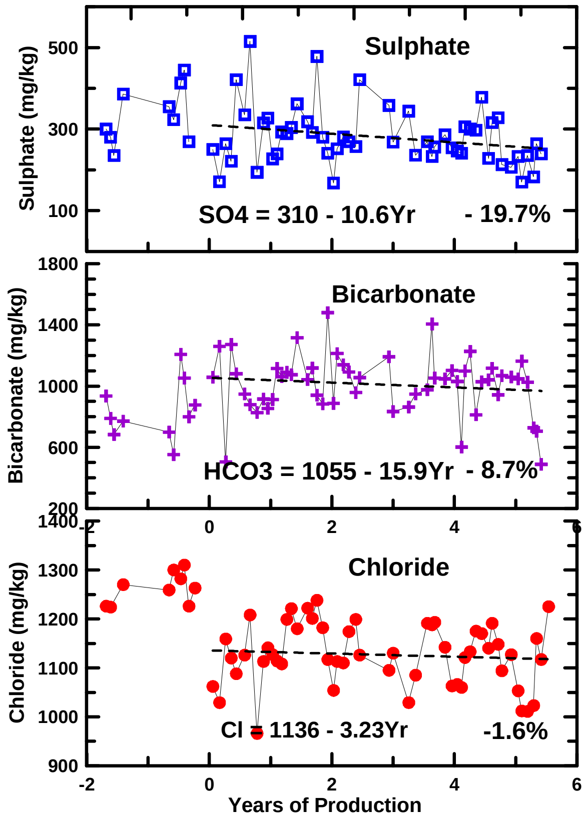

Figure 5: Sulphate, bicarbonate and chloride concentrations in Jubilee bath versus years of production.

2.7.2 Universal Bath

Universal bath (Figure 6) shows a chloride decrease of 17% with a highly significant correlation with time (P = <0.001). This is equivalent to a decrease of 3% per annum. However, as the chloride levels in Universal measured during the baseline were significantly lower than those recorded in the 1980's, the trend may well be a historical trend and not due to production. The decrease in temperature recorded in Universal was greater than in Tiger, the decrease of chloride in Universal was similar to that in Tiger. This indicates that, in Universal bath, the loss of heat carried by rising chloride water is not compensated by an increase in steam and gas, as is the case with Tiger. Thus Universal is mainly heated by the rising chloride water, in contrast to Tiger bath, which is mainly heated by steam and gas. The dilution in Universal bath is by Mg-HCO_3 water. This is shown by the increases since production started of 7% in the HCO_3 concentration and 50% in the Mg/Cl ratio.

2.7.3 Tiger Bath

Tiger bath (Figure 7) now has chloride concentrations significantly below the baseline value (513 mg/kg) and have been below 350 mg/kg since June 2000. However, the last three analyses suggest a return to higher chlorides and

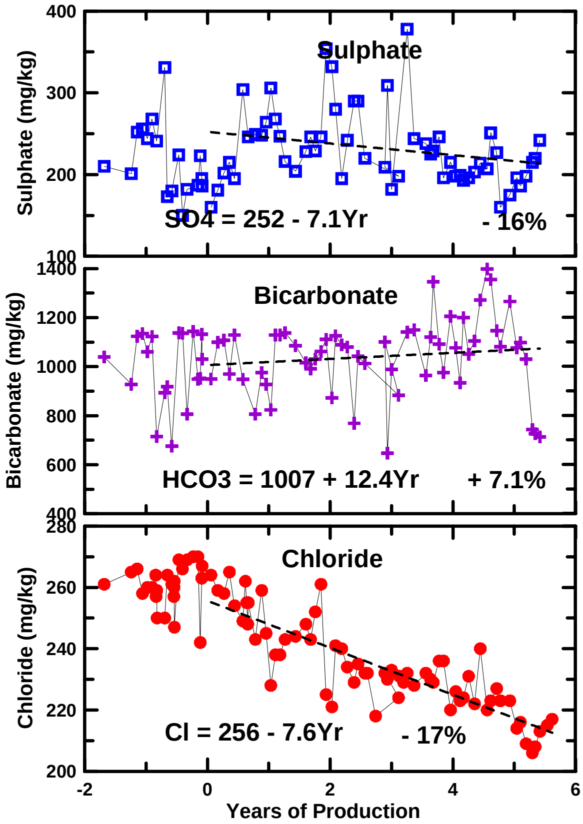

Figure 6: Sulphate, bicarbonate and chloride concentrations in Universal bath versus years of production.

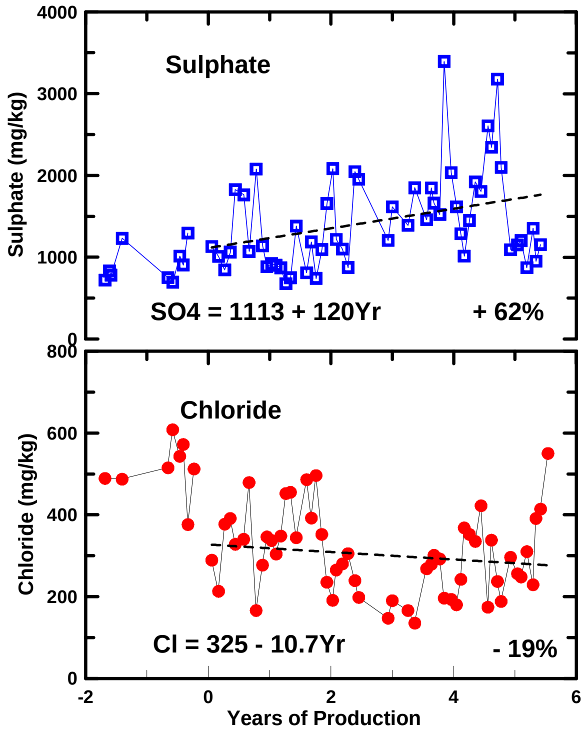

Figure 7: Sulphate and chloride concentrations in Tiger bath versus years of production.

less dilution is apparent during the 2003-2004 year than in previous yearly Production periods when dilution increased with time. Dilution has been by Mg-SO_4-acid water. The average value of Mg/Cl for the year to March 31 2004 is 250% of the baseline value and the Cl/SO_4 is 47% of the baseline value. The regression analysis shown in Figure 7 shows a calculated decrease in chloride of 19% and an increase in sulphate of 62%. The correlation between sulphate and time is significant, ($p = 0.01$), and there is a definite inverse relationship between chloride and sulphate, i.e. the diluting fluid in this area has low chloride and high sulphate. The fact that there has only been a small decrease in temperature, accompanied by a large decrease in chloride concentration, suggests that the heat flow in this area is maintained by the combined effects of steam and gas. This is supported by the increase in sulphate, which is associated with hydrogen sulphide carried by steam, flowing into the shallow water.

2.7.4 Production Well Chemistry

The water from wells NG9 and NG12 is characterised by a high CO_2 concentration in the total fluid of 1.3 to 1.4 wt.%. The chloride calculated at atmospheric pressure ranged from 1660 to 1680 mg/kg. The reinjected fluid has 1250 mg/kg of chloride, close to the chloride in the total fluid taken from the producing wells.

Figure 8 shows that the CO_2 content has decreased in time by 30% of its original value in NG9 and 16% of the original value in NG12. The correlation with time for NG9 is highly significant ($p = <0.001$).

The chloride content at atmospheric pressure in both wells has shown little change with time.

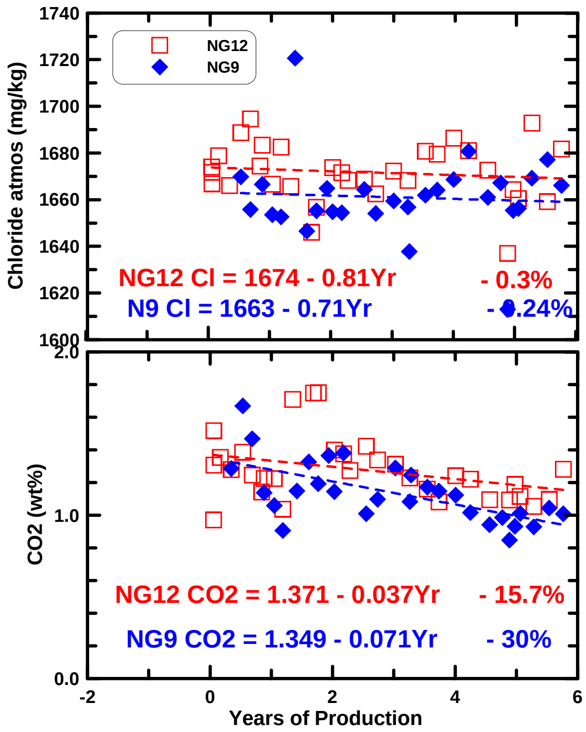

Figure 8: Chloride concentration at atmospheric pressure (mg/kg) and CO_2 in total discharge (wt%) for NG9 and NG12 versus years of production

The gas and chloride trends may be explained by return of some reinjected fluid to the production wells. The reinjected fluid has CO_2 removed from the original fluid and thus lowers the CO_2 content in the production wells. Up to 30% of the current discharge from NG9 may be from reinjected fluid. The difference in the amount of reinjectate reaching the two production wells is due to their proximity to NG11 and NG18. NG9 is 1.44 and 1.59 km from NG11 and NG18 respectively whilst NG12 is 2.09 and 2.25 km from the same wells.

The negligible change in chloride content indicates that the reinjectate has been heated conductively to the temperature of the aquifer supplying the production wells. If it had not been heated then the chloride content at atmospheric pressure would have decreased in the production well as would the discharge enthalpy. This deduction is supported by the stable silica content in the production wells. Thus a chemical signature of the reinjectate is observed in the NG9 and NG12. As the reinjectate mines the heat in the reservoir between the reinjection and production wells it will, eventually, not attain the temperature/enthalpy of the original production well fluid. Thus a decrease in enthalpy will occur in the fluid discharged by the production wells. This will result in a lower steam fraction and thus lower chloride content at atmospheric pressure should be observed.

3. CONCLUSIONS

- The permeable reservoir at Ngawha contains liquid at about 230ºC, 1250 mg/kg chloride and 1.4 wt% gas.
- Mass flow rates of chloride from the Ngawha Springs and baths locality is ca. 0.82 g/s. This represents 0.66 kg/s of deep reservoir fluid.
- Three types of fluid are discerned at the surface viz: Chloride water (e.g. Jubilee bath); bicarbonate-chloride water (e.g. Universal bath); acid-sulphate water (e.g. Tiger bath).
- All three baths decreased proportionally in chloride during Station operation when compared with the baseline data. This indicates less of the deep reservoir fluid reaching these baths.
- During production Universal bath has been diluted with water containing higher magnesium and bicarbonate.
- During production Tiger bath has been diluted with a higher sulphate and lower chloride water.
- Constant chloride concentration and decreasing CO_2 content in wells NG9 and NG12 may be explained by reinjected fluid reaching the wells.

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