Proc. 5th NZ Geothermal Workshop 1983

(Presented at Pacific Geothermal Conference 1982)

TEMPERATURE CHANGES IN THE WAIRAKEI GEOTHERMAL SYSTEM AS DETERMINED BY SILICA GEOTHERMOMETRY

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ABSTRACT

During the last two-decades the temperatures of the geothermal waters supplying the wells at Wairakei have been monitored continuously by silica geothermometry. The method is ideal since the operation of the wells is not influenced during sample collection and the assessed temperatures are correct to ±3°C.

Since 1958, the temperatures of the supply waters to different wells and to different parts of the Wairakei system have decreased. Some well water temperatures have fallen as much as 80°C, although most have fallen by smaller amounts. This paper provides an overview of changes in the Wairakei borefield as seen from the perspective of silica temperatures and chloride values in the deep, hot water. Results are interpreted and discussed in relationship to the physically measured temperatures, the discharge enthalpies of the wells, the measured aquifer pressure and the local hydrology.

INTRODUCTION

Silica geothermometry, for monitoring deep water temperatures, has been employed at Wairakei on a routine basis since 1964. At that time, Mahon (1964) demonstrated that the silica concentrations in the deep Wairakei waters were in equilibrium with quartz in the confining rocks at the measured physical temperatures. The solubility of quartz, in near neutral solutions, had been accurately measured by Morey, et al. (1962) enabling a correlation between measured silica concentrations and their relationship with quartz solubility values at equivalent temperatures to be assessed.

Silica concentrations, measured in surface discharge waters from wells, were corrected to their original values in the deep water. Comparing the deep concentrations with the solubility of quartz enabled the temperatures of the waters supplying the various wells to be estimated. Comparison of the estimated temperatures with the actual measured temperatures suggested the silica method was accurate to 2-3°C. The value and importance of the method, as compared with temperatures measured physically, were discussed by Mahon (1966).

During the early investigations at Wairakei, silica levels in the discharge waters were carefully monitored, particularly for those wells which had shown a change in temperature. It was found that the silica concentrations followed very closely the temperature changes in the wells. This suggested that the kinetics of silica deposition or solution were fast enough for the silica geothermometer to be confidently used to follow relatively rapid changes in the supply water temperatures.

In recalculating silica concentrations from surface discharge conditions to deep conditions, three important physical parameters have to be considered. These are the temperature and pressure of sample collection and the enthalpy of the discharge. By 1964, all the wells at Wairakei had been fitted with vertical twin tower silencers. These were, in fact, atmospheric separators and the waters discharged from them were at the local boiling point of 98.4°C. Except in those cases where only small quantities of water were discharged, the amount of evaporation between atmospheric separation and sample collection was minimal. Calculations required both the well-head separation pressure and the atmospheric separation pressure and temperature as well as the enthalpy.

Until the mid 1970's, this method of collection was available at all wells and, thus, the conditions for sampling throughout the system were identical. During the 1970's. multi-staged separating units called flash plants were introduced at Wairakei. The twin-tower silencers were by-passed and separated water from two or more wells was run to a flash plant. Water samples from wells connected to flash plants were taken, under pressure, from the well-head separator water line. In this case, only the pressure of the water line and the enthalpy were required when calculating the silica values back to the concentrations in the deep water.

Wells at Wairakei do not all draw from a single hot water phase. In some cases the discharge enthalpy of a well is higher than that expected from the maximum downhole temperature, indicating the presence of excess steam in the discharge. This condition was prevalent during the sixties in a number of wells.

Since the evaporation of water is dependent on the total heat content of the discharge, correction of silica concentrations, at atmospheric or higher pressures to deep concentrations, must take account of the discharge enthalpies.

In the sixties and early seventies, silica was determined by a modified ammonium molybdate colorimetric method. Later, atomic absorption spectroscopy was adopted, which proved somewhat quicker than the molybdate method. Relatively good agreement was obtained between the two methods.

Silica Temperatures; 1964 to 1980

(a) General Comments

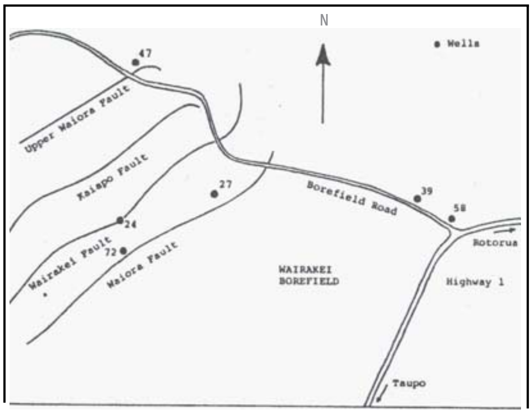
From 1964 to 1980, the temperature of the water supplying each production well at Wairakei was monitored using silica geothermometry. During this time the water supplying the great majority of wells fell in temperature by 15 to 80°C. Maximum temperatures, in a number of western production wells in the late 1950's, were around 260°C so that the average decrease in temperature would probably range from 25 to 35°C.

It is not possible to study each individual well’s temperature change during the period. To illustrate the general temperature changes that have occurred in the Wairakei system, six wells have been selected for this study. Two of these wells, 39 and 58, are located in the eastern production field, the remaining four, 24, 27, 47 and 72 are in the western production field, (Figure 1). Of the latter, weils 27 and 72 are located on the Waiora Fault, well 24 is located on the Wairakei Fault, while well 41 is located on the Upper Waiora Fault.

Table 1 shows the drilled depths of the wells, the reduced levels below sea level, and depths of the solid casings. Also tabulated are the maximum physically measured temperatures after the wells were initially drilled and the maximum values in 1964 and 1980. In some cases, wells were not operating over the entire period or the records were not available. In these cases, the dates of the measurements are shown below the table. The 1980 bottom hole pressures are listed, together with the equivalent saturation temperatures. The calculated silica temperatures for 1964 and 1980 are listed for comparison.

As Mahon (1966) commented, it is sometimes difficult to compare silica temperatures with physically measured temperatures, particularly in a well which has been discharging for some time. If water supplying a well loses steam into the country before reaching the well, the measured temperature may be less than the silica temperature. Although the kinetics of silica deposition are rapid, it is doubtful that silica equilibration to the low temperature, resulting from steam loss, would occur in the time available if steam loss occurred near the well. It is probably true that the silica temperature is closer to the supply water temperature to a well than the temperature measured in a well itself. Similarly, the silica temperature is an integrated temperature rather than the temperature measured at any particular depth in a well. If a well is supplied from two or more sources, whose temperatures differ, the silica temperature represents the integrated temperature of the sources.

FIGURE 1: Location of selected wells, Wairakei Borefield, New Zealand



Further evidence for the validity of the silica temperature comes by comparing it with the temperature measured in a well immediately after shutdown and the temperature measured in a well while it is discharging. In both cases the agreement is much greater than with temperatures measured in a well after it has been closed and left standing.

(b) Discussion of Results

Figure 2 shows the silica temperatures in wells over the period 1964 to 1980. For comparison a line showing the saturation temperatures for the measured pressures at -200 m (reduced level) for the same period is shown. The saturation line is drawn to illustrate the likely temperature trend rather than the absolute temperatures in any particular well or part of the system. Whether pressure measured in a particular well represents the real aquifer pressure in the local environs may only be realised by the recovery of pressure in a well after it has been closed and left standing for a reasonably long time. Wells 24, 27, 39, 47 and 72 are drilled to depths equal to or greater than -260 m while well 58 is drilled to a somewhat shallower depth of -122 m.

TABLE 1: Depths, temperatures and pressures for selected wells, Wairakei Borefield, New Zealand.

Well No.	Depth of Wells, m			Measured T in Wells, °C			P well bottom bars, A	$T_{saturation}$ for P, °C 1980	T_{SiO_2}, °C	
	Actual	Reduced level below sea level	Solid Casing	Max. (year)	1964	1980			1964	1980
24	832	-400	345	258 (1954)	246	226	46	259	247	(233.5)*
27	613	-200	424	257 (1956)	250	234	32	237.5	247.5	236
39	614	-220	301	251 (1955)	250	224	31	236	237	224
47	733	-285	630	258 (1958)	250	224	38	247	251	231
58	493	-122	304	244 (1959)	222	-	23	219	239.5	(234.5)**
62	620	-205	473	252 (1961)	250	233	32	237.5	251	236

* for 1979

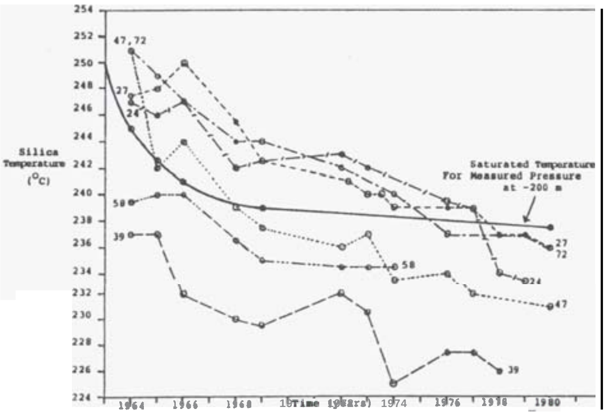
** for 1974

Excellent agreement between measured temperatures and silica temperatures in wells 24, 27, 47 and 72 was apparent in 1964. The agreement in the eastern wells 39 and 5%was relatively poor. A mass heat balance of the steam and water discharged from the wells in the eastern production field at this time, however, suggested a supply water temperature to the zone of around 238°C. This temperature was reflected in the silica temperatures to both wells 39 and 58.

The waters supplying wells 27 and 72, both located on the Waiora Fault, fell by 16°C (Figure 2) during the period 1964–1980, but in 1980 the supply water temperatures on this fault were still the highest in the exploited Wairakei production field. In 1980, the silica temperatures of 236°C were close to the value of 237.5°C estimated from the measured pressure. Well 24, on the Wairakei Fault, showed a smaller decreased of around 13-14°C but its temperature in 1980 was some 2.5°C lower than 21 and 72. Well 47 showed a decrease of 20°C and generally demonstrated the relatively large temperature decreases in this part of the system.

The maximum pressure drop at Wairakei, as indicated by measurements made in wells, occurred during the period 1959 to 1965 (Stilwell, 1978; Allis, 1981). This is well illustrated by the saturation temperature curve but is not immediately recognized from the silica temperatures or the measured temperatures. Of the wells studied only wells 47 and 72 showed a trend suggesting a close relationship between water temperature and apparent system pressure. It was not until 1965–1966 that rapid changes in silica temperature in walls 24, 27, 39 and 58 occurred. It would appear that well pressures did not necessarily represent systems pressures in the vicinity of the wells or, alternatively, that water from levels deeper than the drilled depths of the wells was entering the respective discharges.

FIGURE 2: Silica Temperature vs Time for Selected Wells, Wairakei Borefield.



From 1968 onwards, pressures at Wairakei stabilised and only a minor decrease was apparent during the following twelve years. Well pressures could be assumed to be more representative of system pressure and a more direct comparison between silica temperatures and saturation temperatures was possible. In 1980 the silica temperatures and measured temperatures in wells 27, 39 and 72 were very similar and in the case of wells 27 snd 72 were close to the saturated water temperature at the measured pressure (Table 1). It would appear that the main water supply to these two wells comes from around the -200 m level. Comparison of the silica temperature in well 39 with the saturation temperature for the bottom hole pressure suggests that well 39 draws from a water source well above the bottom of the well.

Silica temperatures in wells 24 and 47 in 1980 were considerably higher than measured temperatures but considerably lower than saturation temperatures for the bottom hole pressures. It was very apparent that saturation temperatures did not occur at the bottom of the wells. It is possible that the waters supplying both wells lost considerable amounts of steam in the country before reaching the wells and that the silica temperatures were more representative of the original supply water temperatures than measured temperatures. There is similarly some evidence in the northern production field that downflow of colder water occurs when wells are closed (McCabe, et al 1981). Themeasured temperatures in closed wells may therefore not be representative of production temperaturea.

Although the history of well 58 terminated in 1974 (it was not possible to collect samples or make downhole measurements even though the well was still producing) the silica temperature in that year was the highest in the eastern production field. Other chemical evidence (Mahon 1964*) had suggested that well 58 was located above a major upflow zone to the area and the ability of the water supplying this well to remain high, even though the well is relatively shallow, tends to substantiate this earlier evidence.

(c) Silica Temperatures and Deep Chloride Concentrations

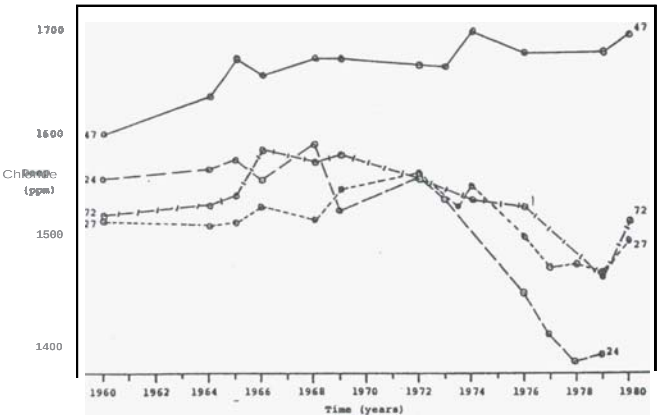
Chloride concentrations in the deeper waters at Wairakei (>300 m) are relatively constant over a wide area. For example, the concentrations in deep wells at Wairhkei and Tauhara, separated by a distance of around 8 km, are almost identical. Within the main Wairakei production field, there is little difference between the concentrations in Wairoa Fault wells and in wells in the eastern field. Concentrations tend to increase, north of the Waiora Fault area, and, for example, the initial concentration in well 47 was some 100 ppm high than that in well 27.

Within a particular zone of the Wairakei system and below a certain depth there is little change in chloride concentration with increasing depth. The apparent depth below which there is little chloride dilution or gradient around is 300 m. Above this depth the chloride concentrations slowly decrease from around 1500 ppm to 900-950 ppm at 200 m. For example, well 21, drilled to 280 m, only had a chloride concentration of around 1450 ppm. Dilution above 300 m appears to be a little variable throughout the production area but the above gradient is relatively representative Below 600 m, the common depth of the production wells, little is known about the chloride concentrations. Well 121, the deepest well at Wairakei, was drilled to 2271 m and cased to 1610 m. The major zone of permeability occurs just below the solid casing where a temperature of 252°C was measured. A maximum' temperature of 272°C was recorded near the bottom of the well. The chloride concentration in the deep water at the permeable zone was approximately 1300 ppm but the discharge of the well was so small that there is some doubt as to whether this was a true undiluted (from drilling fluid) sample. If this concentration is representative of this depth, then there is a reversal of the chloride gradient somewhere between 700 and 1500 m.

Figures 3 and 4 show the deep chloride concentrations in the waters supplying the six wells studied. Results from 1964 onwards were calculated using the silica temperatures and the discharge enthalpies of the wells. Values previous to 1964 were estimated from a combination of measured temperatures, discharge enthalpies and integrated information available from wells in each specific area of the system. Most particularly, the trends in chloride values at atmospheric pressure and boiling point for each well were used for this assessment. Silica temperatures were not used, as silica concentrations analysed before 1964 were low and not accurate enough for the estimations. It is difficult to assess the accuracy of the deep chloride concentrations as there are a number of variables involved in the calculations. Early results suggested that an accuracy of ±15-20 ppm was possible and that differences of up to 40 ppm could not be interpreted as a real change. Trends with time appear to be more significant thana comparison of individual values.

The relationships between deep chloride concentrations and silica temperatures and between trends in deep chloride concentrations and time were discussed by Hahon (1964* and 1975) and Mahon and Finlayson (1972). Two trends in deep chloride concentrations with time are frequently recognised. Decreases in chloride Concentration frequently result when drawdown of water allows water of lower temperature (not cold) and chloride content to enter a well's discharge. Increasing chloride

FIGURE 3: Deep Chloride vs Time, Wells 24, 27, 47 and 72, Wairakei Borefield.



concentrations occur when hot water undergoes evaporation at a level above that expected from iso-enthalpic expansion. This evaporation occurs when heat io transferred conductivity from the rock to the water as the water migrates towards a well.

The mort interesting deep chloride trends were observed in wells 24, 27, 41 and 12. Deep chloride concentrations increased in these wells, peaking in 1968 in well 24, in 1912 in well 27, from 1914 to 1980 in well 41, and from 1966 to 1968 in well 72. The increase in well 24 was less significant than the increases in the other three wells. After peaking the chloride concentrations in wells 24, 27 and 12 decreased to values below their 1960 to 1964 levels. The concentrations of well 41 remained high and showed no significant decrease over the monitoring period. The increases in well 21 and 12 occurred after the period of maximum drawdown while that in well 41 occurred both during and after this period.

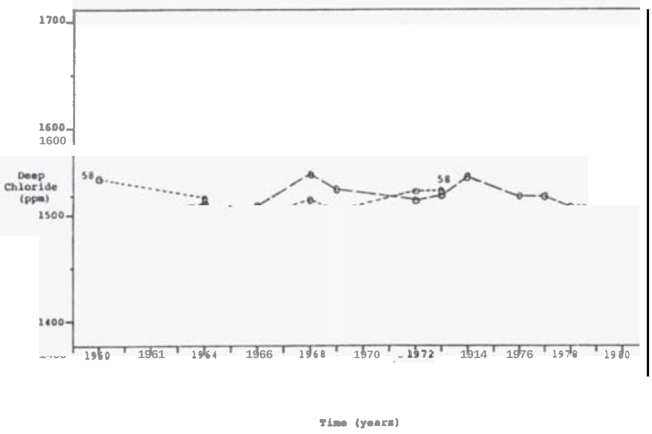
Within the period of maximum pressure drawdown, resulting mainly from a fall in deeper water levels, water from higher levels in the system was drawn down into rocks of higher temperature than that of the water. Although the kinetics of conductive heat transfer are slow, a combination of isoenthalpic and isothermal fluid expansion could occur. This infers that evaporation of water is higher than that expected from simple iso-enthalpic fluid expansion.

As indicated earlier, the chloride concentrations below 300 m are relatively constant. Waters undergoing evaporation in a near constant temperature environment or through exposure to a higher temperature environment, will concentrate the water soluble constituents, such as chloride, to a lesser or greater extent depending on the amount of evaporation. If the silica temperature represents the true water temperature, and this is controlled by local pressure, then the overall effect is for the water temperature to remain relatively constant or to decrease while the deep chloride concentration increases.

This trend of decreasing water temperatures with increasing deep chloride concentrations was seen over the monitoring period in wells 24, 27, 12 and 41. Whereas the thermal buffering in wells 24, 21 and 12 appeared to decrease with time, this was not apparent in well 41. It is possible that a rapid fall in water level in the vicinity of this well, at an early date, allowed considerable amounts of shallower water to undergo evaporation as they passed into hotter rocks. This concentrated water was of sufficient volume to enable a supply to be maintained to well 41 for a considerable period of time after pressures had stabilized. Thermal buffering does not appear to have been significant in the eastern production field during the monitoring period.

The lower deep chloride concentrations apparent along the Waiora and Wairakei Faults during 1978-1980 could be indicative of one or two mechanisms or a combination of both. Shallower water of lower chloride content than that occurring in the constant chloride gradient zone could have been drawn down in the producing horizons of wells 24, 21 and 72. Alternatively, water from deeper levels of lower chloride content (cf result from well 121) could have increasingly been added to the discharges of these wells. There is no other chemical evidence to substantiate that the latter was occurring although if mixing of shallower and deeper water was taking place it would have been difficult to recognise chemically.

FIGURE 4: Deep Chloride vs Time, Wells 39 and 58, Wairakei Borefield, New Zealand.



Allis (1981), on the basis of mass and heat balance calculations, suggested that the inflow of hot (260°C) water into the production field from deeper (>700 m) levels increased until the mid 1960's, after which a gradual decline occurred. Although there is some evidence for this from the silica temperatures, the trend in deep chloride concentrations is not definitive enough to prove or disprove this hypothesis.

SUMMARY

The deep waters supplying the wells at Wairakei have steadily decreased in temperature over the period 1964-1980. Deep water temperature. assessed from silica geothermometry appear to give a satisfactory commentary on the actual conditions existing at depth and the method appears to be acceptable for monitoring purposes.

Trends in silica supply water temperatures and deep chloride concentrations at Wairakei suggest that the system has been thermally buffered by the extraction of heat from the hot rocks by the migrating water.. This buffering mainly occurred after the major pressure drawdown in the system had occurred and was more apparent in the western production field than in the eastern field. Between 1978-1980 there was some evidence that shallower water (from 280–300 m) was entering the discharge of some of the major western production wells. An alternative possibility was that deeper water of lower chloride concentratio (1300 ppm) was becoming increasingly available to these wells.

ACKNOWLEDGEMENTS

The silica temperatures and deep chloride values used in this paper were calculated from the large body of chemical and physical data collected from the Wairakei wells over the years by staff of Chemistry Division, D.S.I.R. and of Ministry of Works and Development at Wairakei. We wish to acknowledge their contribution to this paper

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