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AN INTERPRETATION OF THE DILUTION AT WAIRAKEI

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Abstract

The hydrology of the Wairakei borefield is characterized by an initial pressure drawdown followed by two distinct increases in dilution. The dilution is the result of the lateral inflow of essentially fresh water at two different levels in the system. The deeper and hotter inflow occurs at a depth of about 1000m and has a temperature of 220°C. A shallower inflow occurs at a depth of about 450m and has undergone considerable cooling from about 220°C to 190°C since the mid 1970s as a result of exploitation.

The source of the increase in sulphate content in the reservoir fluid since exploitation began is not associated with the dilution, but is instead the result of a corrosive reaction between the reservoir rock and geothermal gases in the steam zone.

Introduction

Wairakei is undoubtably one of the most well studied geothermal systems in the world, and yet its hydrology is poorly understood. However, the availability of over 30 years of production well discharge chemistry has allowed the determination of some aspects of the pre-exploitation hydrology and subsequent changes in response to exploitation.

The determination of the behaviour of the hydrology at Wairakei is an important indication of how other fields around the world may behave as they come into production.

Pre-exploitation Fluid Chemistry and Hydrology

Establishing the.pre-exploitation fluid chemistry is an important aspect in determining the pre-exploitation hydrology and thus the nature of the natural system. However, the interpretation of the early well discharge chemistry prior to about 1964 must be done with caution as many of the techniques used then (Ellis et al. 1968, Klyen 1982) were still in their developmental stages. For this reason some of the most important aspects of the chemistry are also the most difficult to resolve.

The easiest way to determine major changes in hydrology, such as the degree of boiling or dilution, is to determine changes in the concentration of a conservative ion such as chloride. Ideally it would be best to calculate the downhole chloride concentrations using the silica geothermometer to indicate downhole temperatures. However, the silica geothermometer can not be applied to fluids analysed prior to 1964 which have surface silica concentrations in excess of 500mg/kg. This is due to departure from the calibration for the silicomolybdic acid method used (Hahon 1964).

Therefore, as a first step, well data from the earliest reliable analyses, 1958-1961, are examined for variations in chloride concentration at atmospheric pressure. Data used here is from the compilation of Henley et al. (1984). In order to avoid the effects of evaporative concentration in the weir box, only wells with discharge enthalpies less than or equal to liquid saturation at their maximum downhole temperatures are included.

At Te Mihi only two wells, WK207 and 215, had discharge enthalpies at, or less than, the maximum downhole temperature of 265°C and this indicates fluid in this area contained between 2400 to 2480 mg/kg Cl^- at atmospheric pressure between 1960 and 1963.

In the western borefield chloride concentrations were slightly lower, many wells discharged fluids with a maximum chloride value at the surface of 2298 mg/kg Cl⁻, although, most were between this value and about 2240 mg/kg Cl⁻. Further eastwards at the eastern borefield chloride concentrations were still lower at about 1850-2200 mg/kg Cl⁻ at atmospheric pressure. It appears, therefore, that chloride concentration decreases from west to east

Although it is not possible to use silica temperatures to evaluate downhole concentrations in this early period, an attempt has been made using discharge enthalpies to indicate downhole temperatures. Once again only wells with discharge enthalpies less than or equal to the maximum measured downhole temperatures have been used. These are plotted (Figure 1) on a temperature-chloride diagram (Truesdell and Fournier 1975).

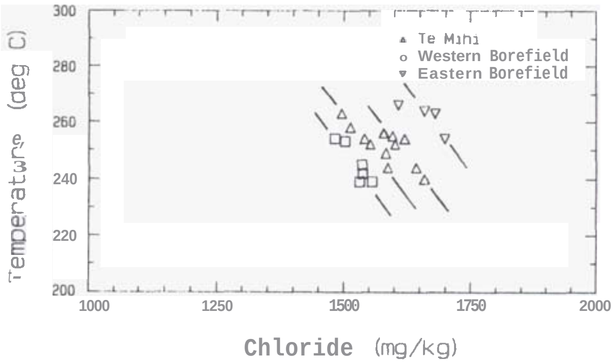

Figure *1.* Graph of downhole temperature *vs* downhole chloride concentration. Temperatures are based upon measured discharge enthalpies. Dashed lines indicate steam *loss* trends.

It would appear that the system can be subdivided into three broad zones: Te Mihi, the western borefield, and the eastern borefield. Each zone is characterized by a distinctive temperature-chloride trend, the Te Mihi zone is the most concentrated. Fluids at the western borefield contain about 100-150 mg/kg less chloride than Te Mihi, whereas fluids at the eastern borefield contain about 200 mg/kg less Cl⁻ than at Te Mihi.

The total variation in chloride concentration suggests a minimum of 12% dilution at the eastern borefield compared to Te Mihi and 6-9% at the western borefield. The maximum temperature-chloride trend at the western borefield is 1595 mg/kg Cl⁻ at 255°C, and this equates with the earlier maximum observed surface chloride concentration of 2298 mg/kg.

These trends are taken to indicate, as near as possible, the pre-exploitation hydrology. In examining changes that have occurred since this period the western borefield maximum temperature-chloride trend of 1595 mg/kg Cl⁻ at 255°C has been used as the initial value against which subsequent increases in dilution have been assessed.

Changes due to Exploitation

After 1964 it is possible to use the silica geothermometer with confidence (Hahon 1964) and this is used here to calculate the downhole temperature of the wellbore fluid and thus changes in the hydrology due to exploitation. The particular geothermometer used here is the iterative geothermometer of Fournier and Potter (1982). Given that the silica analysis has an accuracy of ± 15 mg/kg (Mahon 1964), then the geothermometer has a precision of ± 2.5°C at 250°C.

Allowances have been made where the measured discharge enthalpy is greater than the calculated downhole temperature indicating that additional steam has entered the well. Where the difference exceeds the precision of the well discharge enthalpy determination of ± 50 kJ/kg (Grant et al. 1982) then it is assumed that extra steam is present. The uncertainty arising from the silica analysis is small in comparison, being 7 kJ/kg at 250°C and has been ignored here.

The detection limit for additional steam entry into the well is, therefore, about 2% by mass at 250°C, entry of steam in quantities less than the detection limit can result in apparent decrease in well bore chloride concentration of up to 50mg/kg at 1595 mg/kg and 255°C - an apparent 3% dilution. Some of the dilution prior to 1970 is of this order, however, subsequent dilution was much greater.

The changes that have occurred in the borefield hydrology as a consequence of exploitation can be conveniently summarized by examining the data for well WK48 (Figures 2,3,4,). The changes in behaviour of the hydrology can he subdivided into *3* distinct periods.

The first period occurred between 1958 and 1965, the major feature was the occurrence of a substantial,

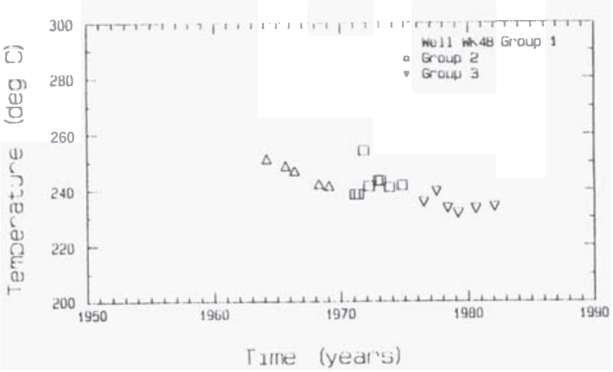

Figure 2. Graph of silica temperature vs time for well WK48

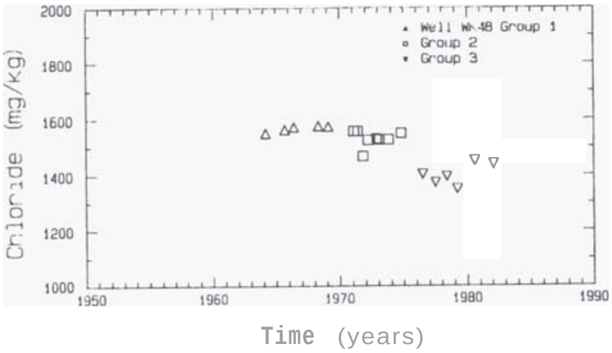

Figure 3. *Graph* of *downhole* chloride *concentration* vs time for well *WK48*

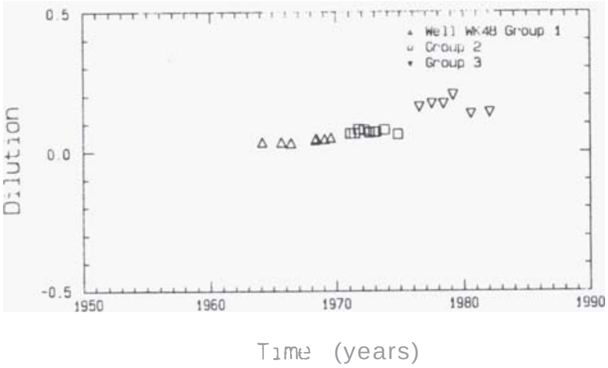

Figure 4. *Graph* of relative *dilution vs* time for well *WK48*

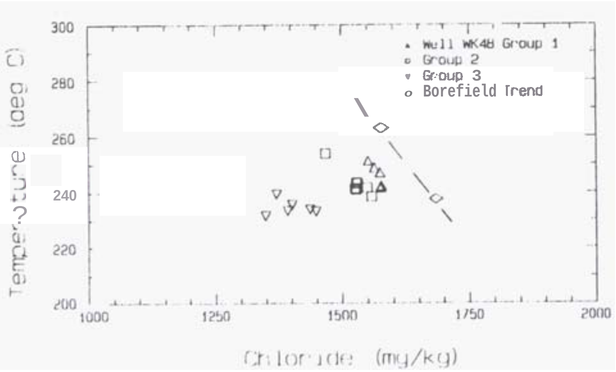

Figure 5. Graph of *silica temperature vs* downhole chloride for *well WK48*

approximately 15-20 bar, pressure drop in the borefield as mass discharge exceeded mass recharge. During this period flashing increased away from the wellbore, probably both horizontally and vertically, and increasing amounts of steam was lost before the fluid reached the well. For well WK48 there is an apparent increase in the solute content of the discharge, but the fluid maintains a constant 3% dilution relative to the borefield trend.

The second period occurred during the early to mid-1970s, when there was a relatively rapid increase in dilution to 6-7% of the borefield trend. This was accompanied in many wells by a small increase in the the wellbore fluid enthalpy.

The third period occurred from about mid-1970 onwards and is characterized by another rapid increase in dilution, this time to 17-20% of the borefield trend for this particular well. More significantly the increases in dilution was accompanied by a decrease in the enthalpy of some of the wells, in the case of WK48, a decrease of 8-10°C.

Although this three stage progression is common at Wairakei, there is significant variation. Some wells, for instance WK81, (Figure 6) show no cooling although they experience up to 12% dilution, thus the diluting component there is as hot as the deep alkali chloride fluid. Whereas in other wells, for example WK74 (Figure 7), the dilutent has become significantly cooler, dropping from about 220°C in 1977 to less than 190°C by 1980. The apparent incompatibility of having both a constant and a decreasing temperature of the dilutent needs to be addressed in any proposed dilution mechanism.

Several attempts have been made to characterize the nature of the dilutent. Brown et al. (1987) considered that dilution was the result of downward percolation of steam heated acid sulphate fluids produced at the near surface. Indeed, most wells show an increase in reservoir sulphate with time which would be consistent with this interpretation. Well WK48 (Figure 8) illustrates such an increase.

However, although there is a positive relationship between increasing sulphate concentration and time, and a positive relationship between increase in

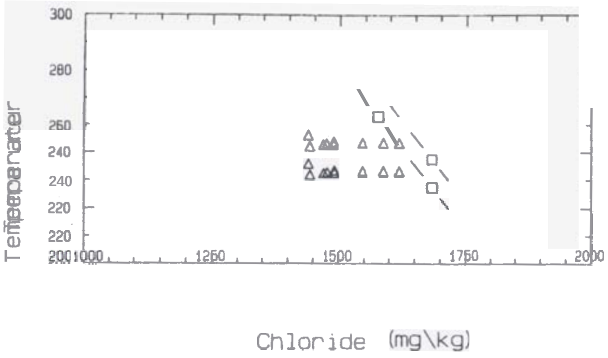

Figure 6. Graph of silica temperature vs downhole chloride for well WK81.

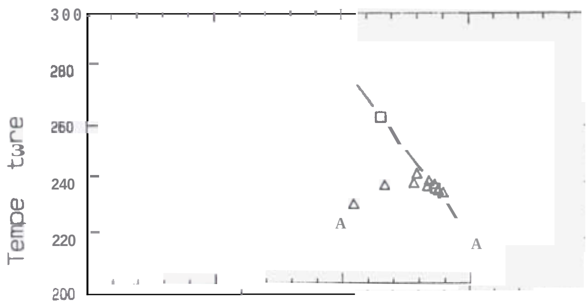

Figure 7. Graph of silica temperature vs downhole chloride for well WK74

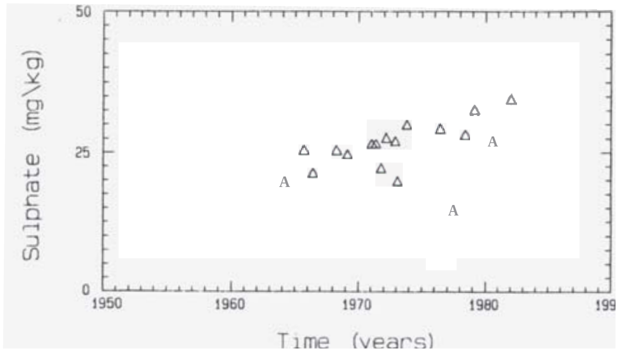

Figure 8. Graph of downhole sulphate concentration time for well WK48.

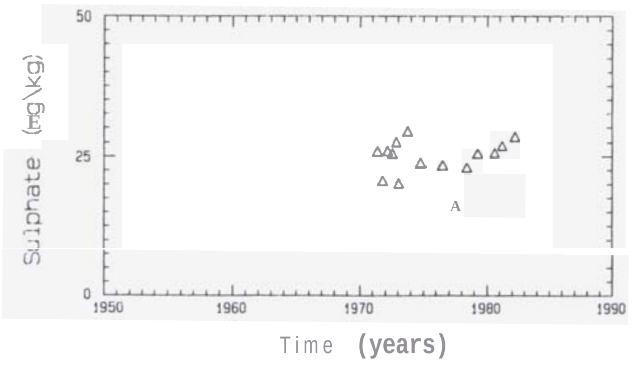

Figure 9. Graph of downhole sulphate vs time for well WK47

dilution and time, there is no causal relationship between increase in sulphate and increase in dilution. Well WK47, which shows little (1-2%) or no dilution compared to the borefield trend, best illustrates this point (Figure 9). Despite the lack of dilution it still displays an increase in sulphate comparable to many of the more strongly diluted wells. The same results can be drawn from other essentially undiluted wells such as WK74 and 116. From a simple sulphate mass balance consideration a dilutent with 600 to 1000 mg/kg SO_4^{2-} is required to account for the observed increase in sulphate from about 19 mg/kg to about 28 mg/kg with 1-2% dilution. The highest sulphate values in Wairakei fluids are, however, several instances of 70-90 mg/kg SO_4^{2-} recorded from the shallow wells WK9, 14, and 15, and the deeper well WK56. Given these values, shallow waters simply can not account for the observed increase in sulphate values in the undiluted wells. Moreover, the sulphate values for the shallow wells are more commonly about 50 mg/kg SO_4^{2-}, so that even if solutions of this concentration reach the deeper upflow, they are precluded as a source of sulphate by mass balance considerations for wells with less than 20% dilution, Few wells exceed 20% dilution. Thus an alternative source for the increase in sulphate and, therefore possibly, also the increase in dilution must be found.

Source of the Sulphate

The most likely source of sulphate is the oxidation of H_2S present in the deep fluid. The rapid increase in sulphate prior to 1970 suggests that the increase may be associated with the pressure drawdown and the formation of the steam zone across the field (Bolton 1970). It is known from the behaviour of geothermal gases (Glover 1977, Giggenbach 1980) that H_2S will preferentially partition off with the steam that escapes to the steam zone. The positive steam pressure within the steam zone means oxygen is most unlikely to be entrained into the zone and is thus unlikely be the major oxidant. This leaves virtually one other contender, Fe^{3+}, which is present in the reservoir rocks.

Within the steam zone CO_2, which has preferentially partitioned off with the steam, will be absorbed into any condensate or residual pore waters, producing a slightly acidic environment.

$$CO_2 + H_2O = HCO_3^- + H^+$$

This weakly acidic solution is capable of leaching cations from the rock, amongst these will be Fe^{3+} and Fe^{2+}.

Both Fe^{2+} and Fe^{3+} can react with any dissolved bisulphide ion present.

$$8Fe^{3+} + HS^- + 4H_2O = 8Fe^{2+} + SO_4^{2-} + 9H^+$$

$$Fe^{2+} + 2HS^- = FeS_2 + 2H^+$$

The reduction of Fe^{3+} produces sulphate, hydrogen ion and Fe^{2+}. The resultant Fe^{2+} and any already present in the rock can further react to produce iron sulphide and additional hydrogen ion. So, although the reaction may be slow at the onset, due to the weak nature of the carbonic acid, the additional hydrogen ion produced as a result of the reactions with bisulphide will produce a much more aggressive solution, further enhancing the leaching capabilities of the solution, and thus further fueling the reaction.

This dynamic local production of hot sulphuric acid has important ramifications to casing integrity, especially in "gassy" systems. It also explains the previous enigma of the occurrence of acid sulphate fluids at depth (1400m) in Philippine geothermal systems (Cope et al. 1985).

Confirmation that the reactions do occur is made possible by detailed analysis of the iron oxidation state in the reservoir rocks (Youngman 1988). There is, at Wairakei, a reciprocal relationship between decrease in Fe^{3+} and increase in Fe^{2+} even though the total amount of iron does not change, indicating a simple redox process. Furthermore, there is a general increase in FeS_2 with increase Fe^{2+} indicating that bisulphide is fixed by Fe^{2+}.

It appears that the concentrated sulphate solution "drips" back into the deep alkali chloride fluid, however, its concentration in the deep fluid appears to be controlled by a saturation equilibrium. For instance, sulphate values in WK47 (Figure 9) rarely exceed about 28mg/kg SO_4^{2-}. The most likely saturation reaction that could explain this is that between sulphate and Ca^{2+} precipitating calcium sulphate (anhydrite). In fact, WK48 (Figure 10) shows a reciprocal relationship between sulphate increase and Ca^{2+} decrease. However, note that this diagram can only indicate the general trend as anhydrite solubility is also sensitive to temperature which can not be indicated here.

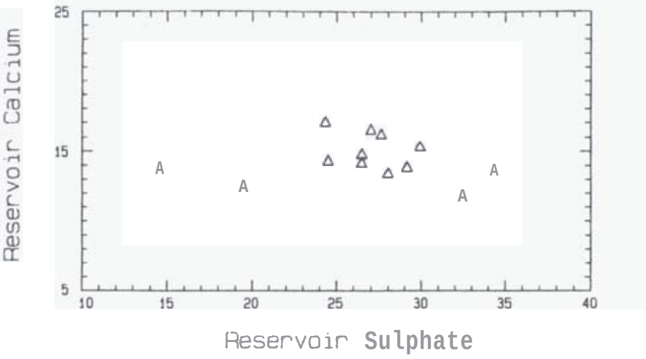

Figure 10. Graph of downhole calcium vs sulphate for well WK48

Given that anhydrite solubility increases with decreasing temperature (Arnorsson 1982). then for a constant reservoir Ca^{2+} content, the maximum amount of sulphate in solution will increase with decreasing temperature. Therefore maximum sulphate concentration can increase due to pressure drawdown. In addition, if dilution reduces the Ca^{2+} concentration in the reservoir fluid prior to sulphate admixture, the maximum sulphate concentration can rise even further. Thus wells that are more dilute and cooler than WK47 can exhibit higher maximum sulphate values, WK48 is a case in point. It is not surprising then that maximum sulphate values at Wairakei have increased in time as there are two processes, dilution and cooling, which favour this.

Origin of the Dilutent

Near surface acid sulphate fluids can not give rise to the observed sulphate values, but this does not preclude them, in the first instance, from being candidates for the increase in dilution. Essentially 4 dilution sources exist.

(a) Near surface acid sulphate fluids

(b) Shallow cold inflow in the Huka Falls Formation unit hu_2

(c) Steam condensate

(d) Deep lateral inflow

The first two options, are probably the source of dilution in several wells such as WK14, 15, 21, in the western borefield and WK9 in the eastern borefield, all of which are shallow, the deepest being 300m deep (Healy 1984b). Dilution by inflow from these shallow aquifers is precluded in deeper wells which show little or no cooling with dilution, but, moreover, it is assumed that this flow is effectively cased out of the deeper wells. Cold downflows within wells have, however, been observed (Bixley 1986), and in two wells, WK107 and 118, the level of inflow at about 130m rsl may be the result of the shallow cold water aquifer., The total known downflow from this level, of about 50kg/s is, however, not sufficient to account for the field wide dilution.

The third option although attractive can be excluded by mass balance considerations. For instance, under the most favourable conditions where the 265°C deep upflow loses all its steam before it reaches the wells at 230°C, a mass fraction of about 8% of the upflow would escape to the steam zone. The steam would continue to rise and cool from its initial value of 2804 kJ/kg at 230°C to 2676 kJ/kg at 100°C, about 5% of the steam fraction would therefore condense out by the time the steam reached the surface. This amounts to about 0.4% of the original mass of the upflow. Thus, even under the most favourable conditions, a condensate could only account for less than 1% of the observed dilution. Clearly we have to discount this as a major mechanism at Wairakei.

This leaves deeper cold lateral inflows as the most probable source of the dilutent. The evidence for the presence of these inflows is 2-fold. The first is the direct physical measurement of temperature inversions in early well measurements at Wairakei. In two recent reviews, Healy (1984a, 1984b) placed some emphasis on the existence of cold lateral inflows in the pre-exploitation and early exploitation system. He considered that a cold inflow existed to the southwest within the Karapiti Rhyolite, and that this inflow entered the western borefield at about sea level. A considerable number of Wairakei production wells have casings which are set just above this level.

The second line of evidence is, at present, indirect and comes from more recent work (Youngman 1988) based upon clay geothermometry. Here, temperature sensitive clays obtained from drillcore record narrow, lower temperature, "inversions" at depth. These low

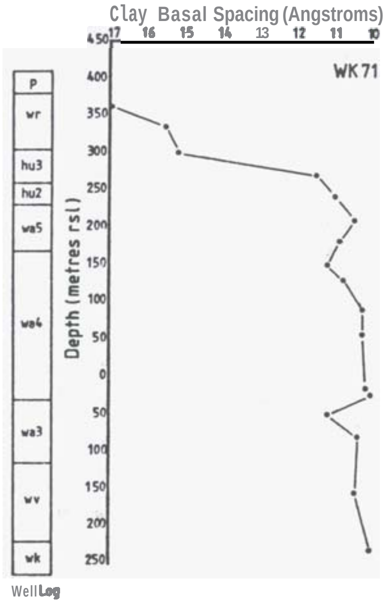

Figure 11. Profile of clay basal spacing downhole for well WK71.

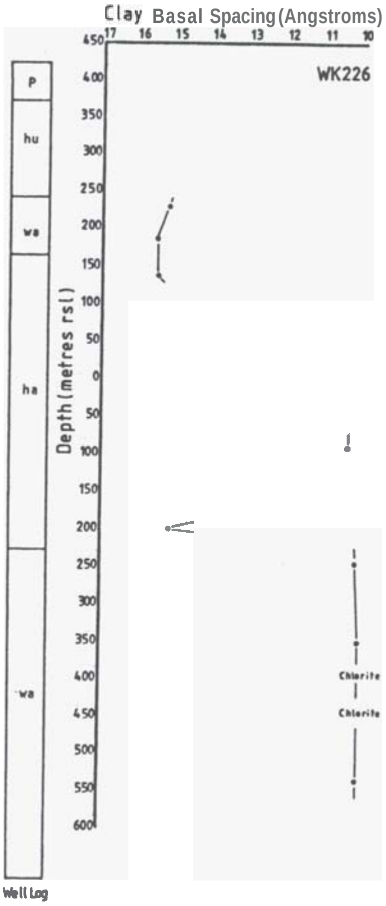

Figure 12. Profile of clay basal spacing downhole for well WK226

temperature intervals correlate very well with the previously described physical measurements. Well WK71 (Figure 11) is an example of the information such a technique can provide. An inversion is indicated at about -50m rsl and another within the upper Waiora Formation at 150m rsl. The upper inversion is just 20m higher than the two high level cold water downflows previously mentioned. Bixley (1986), however, also detected cold water downflows which entered three other wells, WK80, 101, and 213, between -50 and +50m rsl. This corresponds well with the clay evidence for the lower inversion at -50m rsl in WK71. Thus there is good agreement between the clay geothermometry and actual observed cold water entry.

Well WK226 (Figure 12) to the southeast indicates an inversion at about -200m rsl and suggests that the inflow probably warms during its passage into the center of the field, ascending about 100-150m by the time it reaches the western borefield.

A further temperature inversion in the deep well, WK121, (Healy 1984a) indicates that a deeper inflow occurs at about 400m below sea level. Some of the Wairakei production wells bottom hole at about this depth or deeper. It is quite possible that the -400m rsl inflow is reasonably warm with respect to the 230-235°C borefield temperature. A temperature run in WK121 some 1 1/2 years after drilling indicated temperatures of about 220°C at the level of the inversion (Healy 1984a). This is the only reasonable explanation for the hot dilution observed in WK81.

In contrast, the sea level inflow is inferred to be cooler than the deeper -400m rsl inflow, and to have suffered a considerable cooling probably as a consequence of being more heavily drawn upon since the mid-1970s. Bixley (1986) gives a measured decrease from 180-200°C in 1968 to 120-140°C in 1984.

It would seem most probable that the two deeper inflows, one at sea level and one at -400m rsl, are the cause of the variable responses of the different wells with respect to the degree of dilution and temperature of the dilutent.

The fact that they exist in the undisturbed system means that they are a primary element of the hydrology at Wairakei. As they occur as discrete, vertically confined, units it is most probable that the judicious selection of some wells for remedial attention may return their production to former levels if these inflows, especially the sea level inflow, can be cased out.

Conclusions

Sulphate increase in the reservoir fluid is the result of a dynamic reaction taking place between iron in the reservoir rocks of the steam zone and H_2S in the steam. The final concentration of the sulphate in the wellbore discharge is controlled by anhydrite saturation, which in turn depends on the amount of dilution and cooling that the deep upflow has undergone.

The increase in dilution is the result of increased draw off from two lateral unmineralised inflows of variable temperature. They consist of a deep hot inflow at -400m rsl, and a more shallow cold inflow at sea level. The actual enthalpy decline that accompanies an increase in dilution in any particular well depends on the ratio of the two inflows in the mix. The inflows are primary elements of the hydrology at Wairakei and are significant enough to leave a thermal signature in the reservoir rocks of the system.

Acknowledgements

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