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DILUTION AND BOILING IN THE WAIRAKEI FIELD DUE TO EXPLOITATION 1959-1982

K.L. Brown, R.W. Henley, R.B. Glover, E.K. Mroczek, and H. Plum

Geothermal Research Centre, DSIR, Wairakei, New Zealand

ABSTRACT

Chemical data obtained from production and exploration wells during exploitation of the Wairakei Geothermal field are reviewed and interpreted in conjunction with physical data for the field. Two processes have dominated the chemistry during exploitation; (a) adiabatic boiling due to depressurisation and (b) dilution due to blowdown of near surface steam heated waters. Adiabatic boiling dominated the period up to the mid I960[1]s and was accompanied by the development of extensive steam-dominated zones in the upper part of the field. As pressure stabilised due to a reduction in the amount of mass discharge, dilution became dominant. These trends are monitored by assuming a simple boiling/dilution model which allows easy comparison between different wells and between the same well in different years.

The dilution trends for the main production area show that the cooler surface waters flow preferentially along fault systems and the cooling effect of these diluting waters is reflected in lower silica temperatures in these areas. The water discharged in 1982 from the production areas of the Wairakei field is diluted by about 7% compared with fluid discharged in 1961, and the 1961 fluid is diluted by about 14% compared with what is believed to be the deep recharge fluid.

The current dilution trends are expected to continue, but with the large size of the available reservoir, and the decline in mass withdrawal for power production, the rate of dilution should be reduced.

INTRODUCTION

The exploration and consequent development of the Wairakei geothermal field has been central to both the evolution of geothermal technology in New Zealand and to the interpretation of the chemistry of geothermal fluids in general. This paper examines the chemical changes which have occurred as a consequence of the massive withdrawal of hot water for power generation over a 30 year period.

Concentration changes of conserved components such as chloride are important as indicators of the principal processes affecting the fluid; boiling, dilution or conductive heat transfer, and geothermometry also provides important information. In assessing changes in the chemistry and hydrology of the field, problems arise due to the lack of definitive chemical data for the undisturbed state of the field; neither sampling and analysis techniques, nor physical measurements were fully developed until later. Thus the early data are reviewed to obtain an estimate of the "deep" water feeding the field. Data for the succeeding 30 year period are used to assess the gross changes in the production field. This data analysis must filter out the chemical changes induced by local boiling and vapour loss. A technique is therefore proposed which permits comparison of data from individual wells and the field as a whole so that conclusions can be drawn concerning the principal changes and their relative rates.

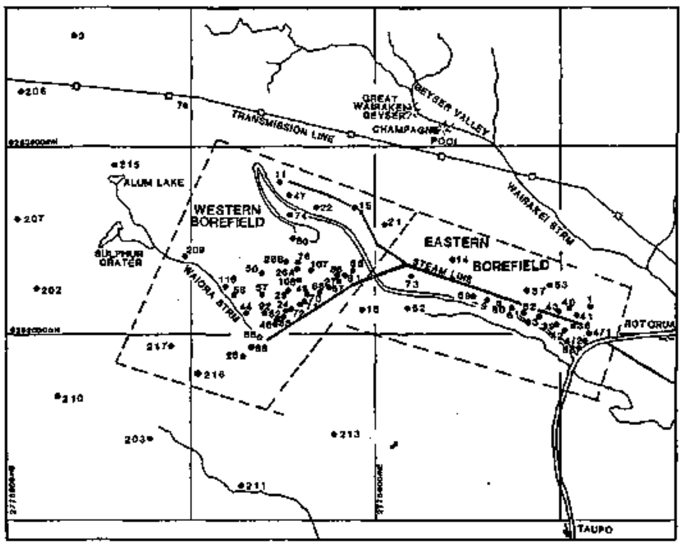

Figure 1: Map of the production area of Wairakei geothermal field.

For reference, Figure 1 shows the location of thermal features and wells in the production area. Early in the history of Wairakei, an Eastern and Western production field were distinguished and these sector names are retained.

CHEMICAL DATA

Chemical data for the well discharges have been reported in a number of published and unpublished reports from 1960 to 1970. These data have been compiled into a database which includes available chemical data for natural features and early exploration wells. The database was compiled using a modified version of the GEODATA computer program (Truesdell and Singers, 1971, Palmer, 1977). The program is designed to recalculate surface water and steam analysis to aquifer conditions assuming a single feed in the well. The recalculation is performed at the silica geotemperature (Mahon, 1966, Fournier and Rowe, 1966) and where enthalpies determined by physical measurements and from the enthalpy of water at the silica geotemperature are within 10%, the discharge enthalpy is assumed equal to the enthalpy of water at the silica temperature for the calculation of single phase aquifer chemistry.

In many wells, measured enthalpies greatly exceed those of water at the respective silica geotemperature suggesting addition of aquifer steam to the total discharge of the well. In those cases, GEODATA calculates the coexisting steam and water compositions which would be present at the silica temperature and assumes an equilibrium distribution of gases between the two phases. Such excess enthalpy wells have been discarded in the discussion of aquifer chemistry changes.

CHEMISTRY OF THE UNDISTURBED FIELD

Isotope evidence shows that prior to exploitation, the Wairakei field was in a steady state against which the effects of exploitation can be assessed. The fluid encountered in production wells at >400 m depth is a near neutral pH, alkali chloride (<1650 mg/kg Cl) which is presumed to have been derived from buoyant upflow. A conventional enthalpy/chloride mixing diagram, Figure 2, with waters of the shallow aquifers (from a compilation of Glover (1977)) shows that the data are bounded by two mixing patterns of either unmineralised water of zero chloride and enthalpy, or steam heated waters at about 155°C such as these encountered in WK3 and WK5. Identification of these fluids is not easy. Well WK107 is in the centre of the Western borefield and in 1976 experienced a downflow of water at about 150°C. Downhole chemical samples contained about 300 mg/kg chloride. We have therefore assumed that the primary diluting fluid contains 300 mg/kg chloride and has a temperature of 150°C. The reference mixing line passing through these points is shown in Figure 2.

The highest temperature wells suggest that the principal upflow lies to the west of the present production field. This appears to be at about 265°C with an initial chloride of 1680 mg/kg. Boiling of this fluid with steam loss leads to a fluid of 260°C and Cl = 1700 mg/kg flowing into the production field.

DATA REDUCTION FOR PRODUCTION WELLS

Withdrawal of fluid from an aquifer results in local pressure reduction around wells and subsequently to a field wide pressure decline. Boiling of aquifer fluid sometimes occurs and the fluid sampled in production wells is a variable proportion of the mixture of liquid and vapour. Upon such a pressure drop, influx of cooler waters can occur, both on the scale of a single well and also field wide. Thus the chemical composition of a well at any particular time may reflect all or some of these perturbations, and a data reduction method is required to compare chemical data from production wells.

With exploitation, the water in the production aquifer is steadily renewed by the inflow of both deep recharge and dilution waters and the well chemistry at any time is related to the proportions of these two components. On an enthalpy-chloride mixing diagram, changes in the "apparent" aquifer composition represented by individual well discharges can be resolved into two components - one giving the relative amount of boiling and the other giving the relative amount of dilution with respect to the original upflow into the field. Changes in the dilution trend then represent changes in the relative proportions of upflow and diluent in the production well feed zones.

Since boiling is a result of both local and fieldwide pressure reduction, it is considered a secondary process in the data reduction. In order to compare chemical data, they are first recalculated to an aquifer condition defined by the quartz geothermometer temperature of the well. These "aquifer" data are then projected on to a reference line, representing field dilution, to obtain boiling corrected chloride concentrations (Cl^1). The data reduction process is illustrated in Figure 3. We have defined the dilution line as passing through the initial fluid composition, H_i = 1134 kJ/kg, Cl_i = 1700 mg/kg and the assumed diluting water H' = 632 kJ/kg, Cl = 300 mg/kg. The sample line passes through the points defined by the liquid enthalpy at the silica geothermometer H_w, and the aquifer chloride concentration Cl_w, and the enthalpy of pure steam at the silica temperature H_s, where Cl = 0. The intersection of these two lines defines the corrected chloride (Cl^1) and corrected enthalpy (H^1). All available data for the Wairakei wells have been examined in this way.

SPATIAL CHANGES IN THE CHEMISTRY

We have focussed on the Western borefield in mapping the spatial changes in Cl' for two reasons. The linear arrangement of wells in the Eastern borefield does not permit satisfactory contouring, and wells in the East tend to draw on shallower aquifers which rapidly developed an excess enthalpy condition.

Figure 4 shows mean corrected chloride concentrations for the years prior to 1961 for the Western borefield. The principal fault systems are

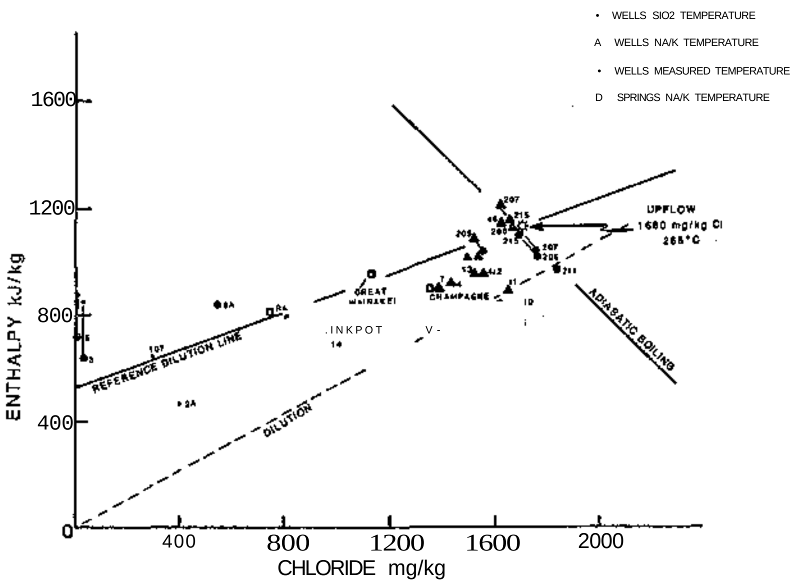

Figure 2: Enthalpy/Chloride relationship for natural features and early wells.

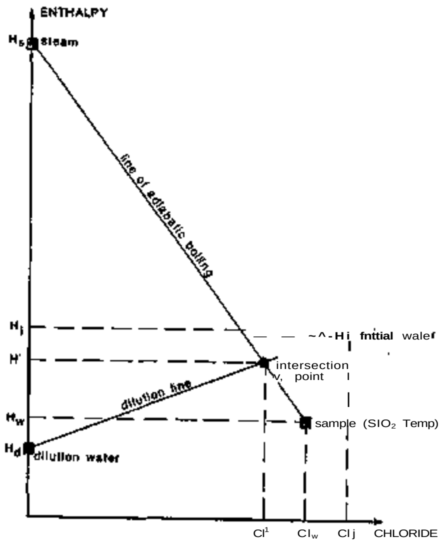

Figure 3: Derivation of CT.

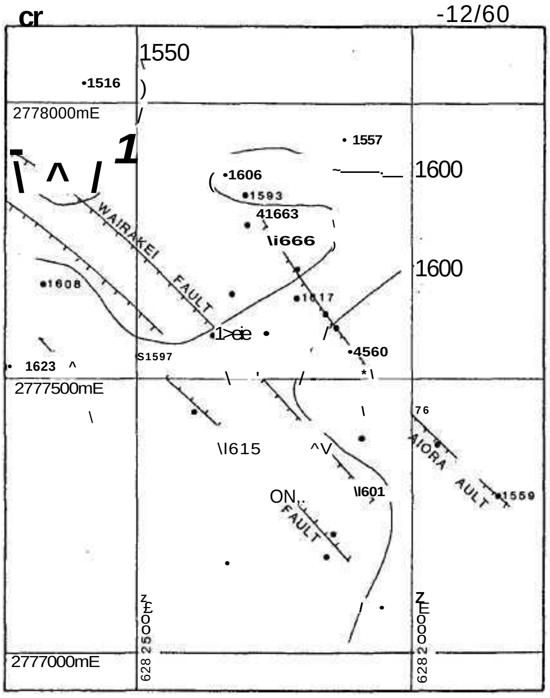

Figure 4: Average CT, Western Borefield to 1960.

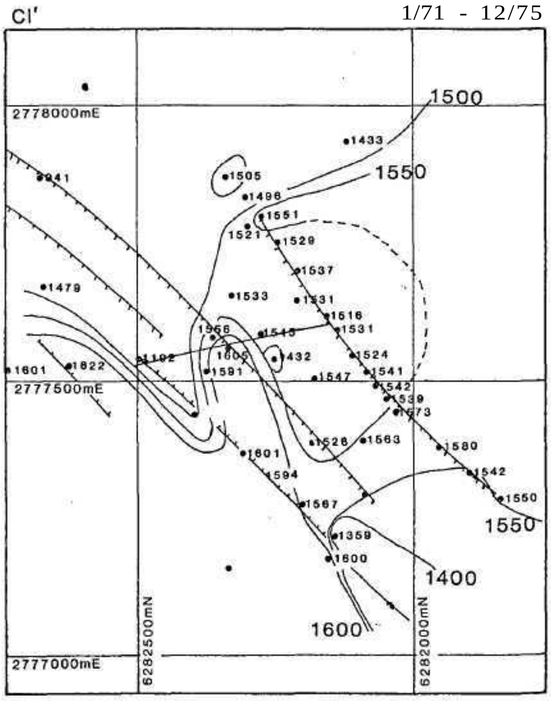

Figure 5: Average CT, Western Borefield 1971-1975.

also shown. Within the constraints of the available data, there is an even distribution, although some dilution occurs in the northeast, trending eventually to the relatively dilute chloride natural discharges in the Geyser Valley.

Figure 5 shows the same area for the years 1971-1975. Dilution trends are becoming apparent and the strong effect of structure is clear with cool water tongues penetrating along the Kaiapo and Wairakei faults. By 1975, the Western borefield was dominated by discharges of relatively more dilute waters containing corrected chloride declines of 50-100 mg/kg in most wells.

The data for 1981-1982 are shown in Figure 6. Declines of 100-200 mg/kg in Cl' are evident in many wells corresponding to enthalpy declines of 40-80 kJ/kg relative to the original state of the field. These data also highlight the southern and western parts of the reservoir as the principal recharge regions. The arrow symbols show tracer first-arrival data from McCabe et al (1983) based on injection tests in the late **1970**'s and early 1980's. These confirm the chloride patterns derived independently. Contoured maps of silica geotemperatures show similar trends.

GROSS CHANGES IN THE AQUIFER

The average chloride function for the Western borefield, weighted according to annual well discharges is shown in Figure 7. There is considerable scatter in the data due to wells being taken off production or unable to sustain production pressures, however, some trends are clear. From 1959 to 1963 there is an almost constant average chloride function of --1585 mg/kg indicating negligible dilution of the water discharged. This is consistent with the formation, during this period, of a steam zone in the upper part of the reservoir, formed by a drop in the level of fluid (Allis, 1981). From 1965 onwards, there is a definite dilution trend evident. The data for 1981 and 1982 have an average Cl' of 1497 mg/kg and this corresponds to a drop of 5.6% since 1959-1963. If

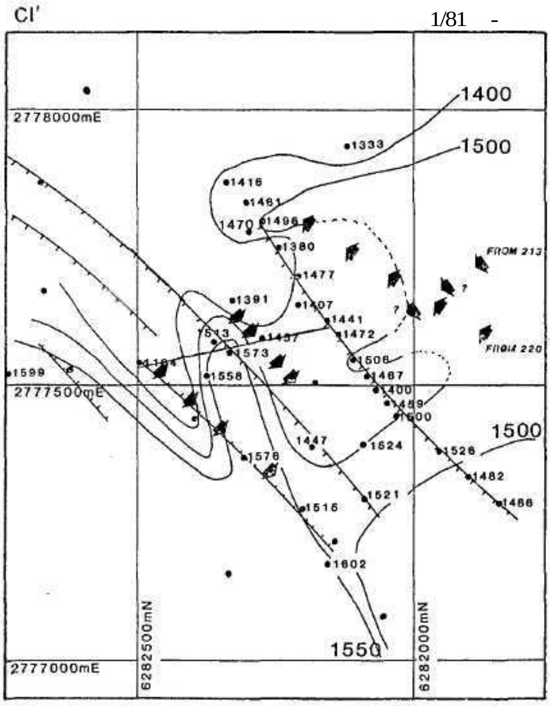

Figure 6: Average Cl', Western Borefield to 1981.

unis dilution is all due to inflow of fluid with a chloride concentration of 300 mg/kg, then 6.8% more of the fluid discharged in 1981/82 consisted of this diluting water than in 1959-1963.

Figure 8 shows the equivalent calculation for the Eastern borefield. The Cl^1 is more or less constant until 1969, implying that there is little or no dilution during this time. This probably reflects production resulting from a drop in the average water level and subsequent formation of a steam zone. In 1970, there is a dramatic drop in average Cl ' indicating production from more dilute fluids. This trend is confirmed in the data for 1981/82 where the average Cl ' is 1437 mg/kg. This represents an increase in dilution of 7.2% by 300 mg/kg Cl fluid over the early years. It would appear that the dilution front which reached the northeastern extremities of the Western borefield in 1963 did not have a significant effect on the Eastern borefield until 1970. However when dilution did commence in the Eastern borefield, it had a more pronouced effect suggesting that the Eastern borefield draws on a proportionately smaller local reservoir than the Western borefield.

CHLORIDE MASS BALANCE

Modelling of the Wairakei field to date has been confined to the use of physical data. The chemical database now permits the development of independent models providing additional boundary constraints. Two endmember models are considered. The first model assumes that the reservoir affected by production is small compared with the amount of fluid extracted. The chloride balance can therefore be expressed as:

$$M_R Cl_R + M_D Cl_D + M_I Cl_I = M_P Cl_P + M_O Cl_O$$

where M and Cl refer to mass fluxes and chloride concentrations and the subscripts R, D, I, P, and 0 refer to deep recharge (R), drainage from the forming steam zone (D), cooler diluting water inflow (I), well production (P), and natural (non-production) outflow (0). The drainage component refers to hot fluid produced from storage in porous rock following pressure decline. For model calculations referring to any chosen year folowing the demise of the natural hot water discharges, $M_Q = 0$, and we also assumed that $Cl_R = Cl_n$. Thus:

$$M_R + M_D + M_I = M_P$$

For any particular year, M_p is known and M_Q can be estimated. Clp is assumed to be constant with time and equal to 1680 mg/kg. Cl j is assumed to be 300 mg/kg and values for Cl_p have been determined. Consequently the equations can be solved for Mj and M_R and the results are:

	1961	1971	1981
Mn (M tonnes/year)	11.1	43.8	26.9
MT (M tonnes/year)	3.7	6.7	5.2
M_I/M_P	8.7%	12.5%	15.0%

It can be seen that the contribution of the surface zone water to the production flow has increased from 8.7% in 1961 to 15.0% in 1981. During the initial period of the field history between 1960 and 1970, the main production was from drainage of the forming steam zone as determined by Allis and Hunt (1986). By 1971, this was essentially completed and the deep system responded with a greater flow of recharge water. By 1981, the contribution from surface waters had increased markedly and this caused declining enthalpy of the production field.

A second model assumes that the production reservoir is very large and well mixed throughout, so that there is a long residence time in this reservoir. The notation is the same as that for the first model with the addition of M_s and Cl_s which are the mass and chloride concentration of the large production reservoir. It is assumed that Cl_p = Cl^ and that M< is constant, implying rapid mixing of the reservoir. M< has only been constant since 1971, so this model is applicable only to the dilution phase. Again it is assumed that $M_A = 0$. We consider the period 1971-1981. For this it) year period the total flow into the reservoir was $M_j^T + M_R^T = M_p^T$ where the superscript T refers to the total flow for the 10 year period. The total chloride in the production reservoir in 1971 was $M_S Cl_S^{1971}$ and in 1981 was $M_S Cl_S^{1981}$. The difference between these two totals must equal the chloride inflows and outflows, i.e.

$$M_S Cl_S^{1981} - M_S Cl_S^{1971} = M_j^T Cl_j + M_R^T Cl_R - M_p^T Cl_p$$

As well, $Cl_S = Cl_D$, $Cl_O^{1981} = 1490$ mg/kg, $Cl_S^{1971} = 1525$ mg/kg, and $M_p Cl_p$ can be calculated by summing over the 10 year period. Together with the mass balance, there is still not enough information to solve for M_R, M, and M<. However, for a variety of recharge/diTutioSi ratios (M_R/M_T), estimates of the reservoir size can be made (all units are Mtonnes for the 10 year period).

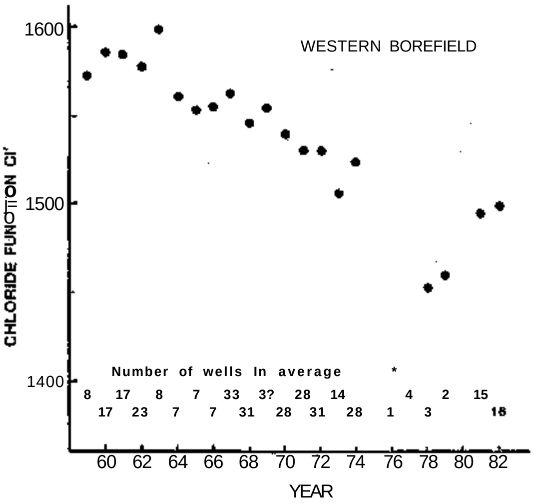

Figure 7. Flow weighted average Cl^1 Western Borefield.

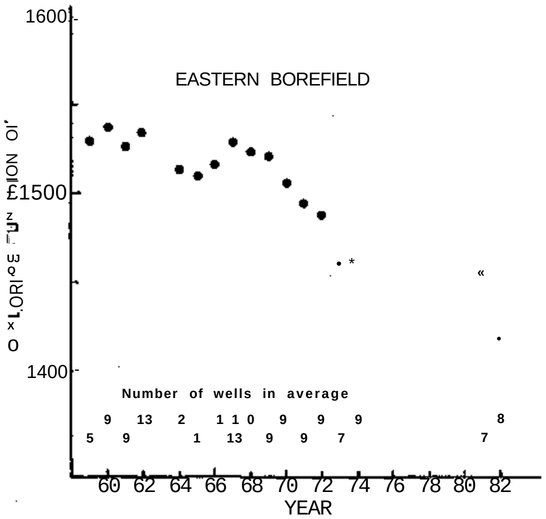

Figure 8: Flow weighted average Cl^1 Eastern Borefield.

M_I^T/M_R^T	M_I	M_R	M_S
6:1	371	62	12469
4:1	346	87	11484
2.6:1	313	120	10182
2:1	288	144	9245
1:1	216	216	6406
1:2	144	288	3567
1:4	87	346	1272
1:7	54	378	0

Since there cannot be a negative mass for the reservoir, the maximum ratio of inflow to recahrge water is about 1:7. Prior to exploitation, M_D was estimated to be around 12 Mtonnes/year (ATI is, I98 }?' If 2\ is assumed that this is constant, then I'.R = *6 and tne mixed reservoir size is estimated to be -10000 Mtonnes.

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