Geothermal Surface Features at Geyser Valley, Wairakei, New Zealand

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ABSTRACT

Geothermal surface features such as hot springs and geysers represent the heat and mass flow through the top boundary of the geothermal system. As such, these flows can be affected by changes in the subsurface system. At Wairakei, there was a clear trend of declining chloride concentration and reduction in flow of Geyser Valley springs, which is correlated with the volume of fluid extracted from the reservoir, which began in 1951. By the early 1970’s the liquid spring flows had ceased completely, and were replaced by steaming ground.

This study interprets the major anion chemistry from nineteen springs to identify two groups of springs. The results show that the initial fraction of reservoir water is higher in Group A springs than in Group B. Over time Group A springs all show a relatively regular dilution trend in which the deep reservoir liquid is progressively diluted with the intermediate aquifer fluid, and then by the zero chloride groundwater. Group B springs also have an initial feed from the deep aquifer, but are more likely to show a sharp increase in dilution by zero chloride water. This is likely to be condensed steam because of the presence of sulfate in the spring water.

1 INTRODUCTION

The local groundwater system and surface geothermal features such as geysers, boiling pools, mud pools, and steaming ground at Wairakei, New Zealand, have been strongly affected by 60 years of fluid extraction from the underlying Wairakei geothermal reservoir.

This study re-examines early data collected from Geyser Valley, Wairakei between 1951and 1968. This time frame was chosen because this is the period of maximum rate of drawdown in reservoir pressure, from the natural state starting point. Our reasons for re-examining the early data are to:

- Derive information on feed depths for the springs, in order to assist the development of a conceptual model of the Wairakei Geothermal Field.
- Look at these changes with respect to future environmental monitoring programs.
- Generate some quantitative input data for a large scale numerical model of the Wairakei –Tauhara Geothermal system.

We investigate variations in spring chemistry over time, including chloride, sulfate, bicarbonate, boron and sodium concentrations. We use a mixing model based on spring chloride to understand the contribution of various aquifers to the total spring water, and to develop models of the depth and nature of the sources feeding the Geyser Valley springs.

2 BACKGROUND

2.1 The Wairakei Geothermal Field and Geyser Valley

In its initial state the Wairakei geothermal reservoir was liquid-dominated and at boiling point for depth, with a base temperature of around 270°C, with three main areas of surface activity: Geyser Valley, Karapiti, and Alum Lakes. In total 831 springs were mapped (Gregg and Laing, 1951). These springs represent the natural state heat and mass flows from the Wairakei reservoir.

The subject of this paper, Geyser Valley (Figure 1), is an incised valley located at the north-eastern edge of the Wairakei Geothermal Field. In a geological sense Geyser Valley is a unique part of the Wairakei Geothermal Field, as the Superficial Deposits, which consist of recent alluvium and tephra, have been eroded away exposing the Oruanui Formation, which is thicker than elsewhere in the area. The Oruanui Formation, a series of partially welded ignimbrite and tuff, unconformably overlies the low permeability Huka Falls Formation (HFF). In the northern and eastern parts of the system, in the natural state, there was a thin steam layer immediately below the HFF. This formation is cut in places by several faults, or in the case of Geyser Valley, the middle clay layer is missing completely, allowing the upward movement of chloride water and steam through the rock matrix and possibly also through faults (Figure 13; Bixley et al., 2009, Rosenberg et al., 2009).

Fluid production from the Wairakei reservoir began in 1951. Production from the liquid reservoir caused pressure drawdown and boiling in the reservoir, resulting in an enlarged steam zone within the lower Huka Formation (Bixley et al., 2009). The chemistry of the springs at Geyser Valley was predominantly high chloride, neutral pH, sinter-forming springs, indicating a high proportion of reservoir water (Glover, 1996, 2000). As the amount of fluid extracted from the Wairakei reservoir increased, the chemistry of the springs at Geyser Valley changed, and the spring chloride content declined, as did the mass and heat flow rate. The effect of production at Wairakei on the surface features has been well documented by Glover and Stewart (1996), Glover (1998), Glover and Hunt (1998), White and Hunt (2005), and Glover and Mroczek (2009). Brown et al., (1988) and Glover and Stewart (1996) identify

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fluids which were increasingly diluting the Wairakei surface features since the start of production. Unfortunately, early changes in Geyser Valley spring chemistry and flows were not attributed to reservoir fluid production, and there was no planned sampling program in place to monitor the features.

Figure 1: Map showing location of springs, wells, and power stations on the Wairakei Geothermal System.

3 DATA DESCRIPTION AND ANALYSIS

3.1 Introduction

Information on the natural state conditions of the activity in Geyser Valley comes from travel guides and from regional mapping programs undertaken by New Zealand Geological Survey geologists. By the late 19th century, Geyser Valley at Wairakei, with its extremely active geothermal features, was identified as a tourist destination of great beauty. Travel guides at the time describe many of the geothermal springs and geysers in extremely colorful prose, although unfortunately the descriptions were somewhat unsystematic. Among other sources, a catalogue of photographs from Wairakei in 1899 is available from the Boileau Family Album, whose digitized photographs are available on the Australian National Library website (http://www.nla.gov.au/); these show silica sinter-precipitating geysers and hot pools, some of which are shown in Figure 3.

The first coordinated mapping and sampling of Geyser Valley springs was by Gregg and Laing in 1951 (Gregg and Laing, 1951) as part of a survey of geothermal springs of the entire Wairakei – Tauhara area. This study uses chloride and spring appearance data from this dataset. We have assumed that the data from this 1951 sampling is undisturbed ‘natural state’ data from the Wairakei system.

There is unpublished data on spring chloride between 1951 and 1962 (Wilson, 1975), but the next systematic records from Geyser Valley are in 1962. Glover (1965) reports analytical results for 19 springs selected for a chemical and physical monitoring program from 1962 to 1965. This sampling program is the source of much of the data used in this study. Other studies by Thompson (1957), Wilson (1975) and Laing (1951) also report chloride concentration data from selected springs in this period and hence the chloride concentration dataset is the largest, with data from 22 springs.

However, no one spring has a continuous and consistent set of all reported parameters. Because of this, and the small number of springs sampled, it is challenging to explain spring behavior over time, or identify any patterns related to spring location or elevation. However, we can clearly define the existence of two separate groups of springs (Group A and B) based on the Cl - SO₄ - HCO₃ ternary diagram. We have then investigated the behaviour of these springs with respect to the change in chloride concentration over time. A simple mixing model uses the measured chloride concentration and attributes the fractions of source water required to achieve this.
Figure 2: Geyser Valley Springs, spring names and grouping of springs.

Figure 3. The Great Wairakei Geyser and the Twins Geyser (from the National Library of Australia Archives). These are clearly neutral pH, silica-saturated chloride water, depositing silica sinter in the vicinity of the features.

3.2 Cl-SO$_4$-HCO$_3$

Spring water chloride, sulfate, and bicarbonate are shown on a ternary diagram in Figure 4. This plots composition for each spring and for each sampling time. There are two clear groups; Group A, where the data spans from the high chloride apex along an almost constant sulfate composition of 0.1; and Group B, spanning the chloride apex to the SO$_4^{2-}$ apex with very little HCO$_3^-$. Because each spring has from two to five data points over time, it is possible to see the evolution of spring composition over time with respect to chloride, sulfate and bicarbonate. All the springs evolve towards reduced chloride, but Group A springs evolve towards bicarbonate with little change in sulfate, while Group B springs evolve towards sulfate water with very little bicarbonate.

It may be that Group A springs tend to be at a higher elevation than Group B (Figure 2), but the small sample makes any definite correlation with elevation inconclusive.
Figure 4. Ternary plot of chloride, bicarbonate, and sulfate for the springs. (a) Two groups of springs are clearly visible: Group A, where each individual spring trends away from the chloride apex toward bicarbonate with very little addition of sulfate; and Group B, where each spring trends over time towards the sulfate apex, with decreasing chloride, and very little addition of bicarbonate. The arrows show general composition trends over time for each group. There are two springs which remain clustered at the chloride apex, namely S180 and S190. (b) The arrows show the trends over time for each spring.

3.3 Other chemical trends
In addition to the above differentiations between Group A and Group B springs, the graphs below show that the differentiation goes beyond chloride, bicarbonate and sulfate and includes:

- Decreasing sodium with time (Figure 5 (a)), with Group A having an initially higher sodium concentration. This could indicate an initial influence of high sodium peripheral waters (Mroczek pers. comm., 2014). Decreasing chloride-boron ratios over time (Figure 5(b)), with Group A showing less of a drop over time than Group B. This indicates a rapid decrease of deep water influence in Group B, and a more constant deep water influence with Group A (a Cl/B ratio of 80 is the average for the Wairakei reservoir, Mroczek pers. comm., 2014).

Figure 5: (a) Sodium concentration over time for Group A and B springs; (b) Chloride-Boron ratios over time for Group A and Group B springs. Na concentration in ppm.

3.4 Physical nature of springs
The springs referred to in this study include clear pools, turbid pools, geysers and mud pots (Figure 2). Interestingly Group A springs are dominantly geysers, where as Group B springs are dominantly clear pools (Figure 6). This indicates that Group A pools have a hotter (and therefore possibly deeper) source than Group B.
Figure 6: Proportion of surface feature type for each group

3.5 Spring Chloride

The natural state chloride concentration varies between 750 & 1860 mg/kg. Some springs show an early decrease in chloride concentration (S55, S59, S174, S198) while others (S97, S190, S205, S232) show little change until around 1960. It is difficult to determine why some springs showed a delay in decreasing chloride, as there is no clear pattern concerning location and elevation of these springs. Many of the springs show short term increases in chloride, with some showing extreme increases (i.e. S50, and S113) (Figure 7). Increases in chloride could be caused by the spring response to reservoir processes, groundwater pressure, pool evaporation, or measurement errors. We have decided to use all the data, because of the difficulty of defining an ‘unacceptable’ variation in the data.

Figure 7. All chloride concentration data for Geyser Valley springs, 1950 to 1970. Springs which are not in the Cl-SO4-HCO3 dataset are S113, S174, and S201.

3.6 Chloride Mixing and Dilution model.

The measured chloride concentration of each spring, and the chloride concentration of the subsurface aquifers feeding the spring, are used to identify the proportions of reservoir liquid and diluting fluid in the spring water. Chloride concentration data for the subsurface aquifers feeding the springs is taken from Brown et al (1988), and Glover and Mroczek (2009). The reservoir liquid at source has 1700 mg/kg of chloride (Brown et al, 1988), which is 2429 mg/kg when corrected for adiabatic steam loss. The diluting fluids are suggested by Glover and Mroczek (2009) to be either:

- steam-heated waters or groundwater (0 mg/kg Cl; 150 °C or 10 °C, respectively), or
- dilute chloride water (300 mg/kg Cl, 10 to 200 °C). This water may have a component of dissolved CO2.

The mixing model is for two liquids only. Hence the feeds to the springs are subject to two conditions:

1. If the spring chloride concentration is > 300 mg/kg then the mixing is between the deep reservoir and 300 mg/kg chloride liquids. In Equation (1) and (2) below, $x$ is the fraction of water and $C$ is the chloride concentration. The subscripts res, 300, and spr indicating reservoir water, 300 mg/kg chloride water, and spring water, respectively.

$$x_{res} = \frac{(C_{spr} - C_{300})}{(C_{res} - C_{300})}$$  (1)
2. If the spring chloride concentration is < 300 mg/kg, then the reservoir contribution is assumed to be zero, and the mixing is between the 300 mg/kg chloride liquid and zero chloride water. In Equation (3) and (4), \( x \) and \( C \) are as above, with the subscripts 300, 0, and \( spr \) indicating 300 mg/kg chloride water, zero-chloride water and spring water, respectively.

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x_{300} = 1 - x_{\text{res}}
\]

\[
x_{300} = \frac{C_{\text{spr}}}{C_{300}}
\]

\[
x_0 = 1 - x_{300}
\]

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**Figure 8:** Schematic diagram showing the fluid mixing theory. Used Glover & Mroczek (2009) as ref for values/depths

### 3.6.1 Natural state proportion of reservoir liquid in spring water

The early (1951) proportion of reservoir liquid is positively correlated with whether the Spring is in Group A or Group B indentified above. For Group A springs, the fraction of reservoir liquid in the spring water is always greater than 0.6. Conversely, for Group B, the fraction of reservoir liquid in the springs is less than or equal to 0.6. This is shown graphically in Figure 9. The two springs which are shown in orange are those which do not trend, in the original Cl-SO\(_4\)-HCO\(_3\) diagram.

### 3.6.2 Modeled spring source waters over time

The full chloride concentration dataset from each spring is used for calculating the contribution of the source aquifers over time. Here we have used 3 additional springs which did not have bicarbonate and sulfide data (and hence are not grouped into A or B), but did have chloride data allowing them to be grouped based on the initial chloride concentration, as in Figure 9. Below, the proportion of reservoir liquid, 300 mg/kg chloride liquid, and zero chloride liquid is plotted over time for Group A and Group B springs, respectively (Figure 10, Figure 11, and Figure 12).

Over time, both Group A and Group B show a negative trend in the reservoir contribution of chloride over approximately the same time scale, with both groups of springs showing a decline in reservoir contribution (Figure 10). Both groups also initially show a positive trend in the 300mg chloride contribution (Figure 11). By 1963, eight of the eleven Group A springs are >80% intermediate aquifer fluid (Figure 11 (a)). For Group B (Figure 11 (b)) there is less uniformity in the trends. Six of the eleven springs show a sharp decrease, while three of the remaining four still show <80% of this intermediate fluid. Figure 12 shows than for the six springs in Group B (Figure 12 (b)), between 1961 and 1962 there is a rapid influx of zero chloride liquid, whereas with one exception (S113) Group A has a later and lesser extent of zero chloride infiltration (Figure 12 (a)). The 'exception' in Group A, S113, is the spring with initial chloride values which place it at the borderline defining Group A and Group B.
Figure 9. Fraction of reservoir liquid (based on spring chloride concentration) in 1951. The two data points colored orange are those that did not have a clear trend on the Cl-SO$_4$-HCO$_3$ diagram. The dark yellow data points are springs that do not have sulfate and bicarbonate data, and hence are assigned to Group A and Group B on the basis of initial fraction of reservoir fluid.

Figure 10. Proportions of hypothetical deep reservoir liquid for (a) Group A and (b) Group B springs.

Figure 11. Proportions of hypothetical intermediate aquifer (300 mg/kg chloride liquid) for (a) Group A and (b) Group B springs.

Figure 12. Proportions of hypothetical zero-chloride liquid for (a) Group A and (b) Group B springs.

4 CONCLUSION

4.1 Conceptual model

We have combined the geologic model and mixing model (Figure 13) to build a local conceptual model of Geyser Valley in the natural state and after reservoir drawdown. It has demonstrated that the surface features can communicate changes going on in the deeper reservoir, and there was a clear trend of deep reservoir discharge being replaced by more dilute, probably shallower fluids over time. There are two groups of springs which have different response over time to reservoir pressure drawdown. The shallow mixing fluids are different for each group; for Group A the fluids are progressively replaced by the shallow geothermal aquifer and
then by groundwater. Group B, initially has a lower fraction of reservoir water, maybe indicating a slightly lower pressure, and cooler, source. As the reservoir pressure draws down there is a rapid influx of zero chloride water in some springs, and in all, an influx of sulfate, which indicates that the diluting fluid in this case has a component of condensed steam.

4.2 Implications for monitoring
Our conclusions in this study were made using little data from a less-than-ideal dataset. The baseline data does not include a full suite of the major chemical species in geothermal springs, and there is a lack of data for the 10 years after the start of production from the reservoir. This paper, however, has shown that:

- we can gain an understanding of surface feature characteristics using a relatively small amount of data.
- a re-examination of old data has given us new insights into the subsurface processes beneath the Geyser Valley springs.
- the model we have developed is for an area of springs on the margins of the Wairakei geothermal field, however, other springs on other geothermal systems may be suitable for similar method of analysis.

4.3 Modeling data
This study has helped with the identification of feed depths for surface features which can be input into numerical reservoir models, and has given us a better way to represent springs. The activity at Geyser Valley can be represented by two types of spring:

1. One, equivalent to Group A, with three feeds:
   a. A feed source close to 500 m depth.
   b. Another at the base of the relatively thin HFF.
   c. A shallow groundwater feed, which should be above the HFF.

2. Equivalent to Group B, with at least two feeds, and possibly a third:
   a. A feed source above 500 m depth, but still in the geothermal reservoir (Waiora Formation).
   b. A shallow groundwater feed, which should be above the HFF.
   c. Possibly another at the base of the HFF as for the Group A springs, although this may not be as important here.

![Figure 13: Conceptual model of Geyser Valley showing geology, approximate spring locations, and conceptualized fluid mixing.](image-url)
5 ACKNOWLEDGEMENTS

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6 REFERENCES


