THE NATURAL-STATE GEOCHEMISTRY OF THE ROTOKAWA RESERVOIR

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ABSTRACT

The geochemistry and enthalpy characteristics of shallow, intermediate, and deep reservoir fluids have been evaluated as part of a conceptual model update for the Rotokawa reservoir. The ultimate goal is to provide a more comprehensive and in-depth understanding of the nature of fluid origins, upflow, and movement within the system.

Significant gradients in terms of Cl, Cl/B, Na-K-Ca geothermometry, and non-condensable gasses (NCGs) are observed across the field. The deep reservoir fluids also appear to be in disequilibrium with respect to many geochemical systems. Relationships of enthalpy-Cl, major and trace liquid constituents, and NCGs do not easily resolve a unique parent fluid to the system, yet the possibility of one cannot be discounted. An updated conceptual model has been developed on the basis of new understanding which accommodates both possibilities.

The conceptual model incorporates elements of a hot, deep, two-phase upflow which rises and boils, outflowing from the system toward the north. Progressive dilution along the outflow by marginal fluids is largely responsible for the observed geochemical gradients. A large structural feature in the centre of the field provides a zone of enhanced permeability, allowing deep reservoir fluids to rise and boil within an intermediate aquifer. The intermediate aquifer is a complex mixture of gas-rich steam condensates, groundwater, boiled reservoir fluids, and acid-SO_4-Cl fluids from a shallow, steam-heated aquifer in the vicinity of Lake Rotokawa.

1. INTRODUCTION

The Rotokawa geothermal reservoir currently supports 174MW of baseload renewable power generation through the 34MW Rotokawa binary power plant (RGEN), and the 140MW Nga Awa Purua (NAP) triple-flash power station. A total of twelve production wells supply the average daily consented fluid production rate of 60,500t/d. Flashed geothermal brines and steam condensate from the turbines are re-injected to the reservoir through a combination of deep and intermediate depth injection wells.

Mighty River Power Limited has recently completed a conceptual model update of the Rotokawa reservoir which forms the basis of a new numerical simulation model. This model will be used to predict reservoir response to future production scenarios.

Early geochemistry investigations by the DSIR laid the foundation for much of the current conceptual understanding of the geothermal system (Hedenquist et al., 1988). Information available at the time was limited to seven Crown exploration wells. A conceptual model update in 2006 considered wells up to RK18 and focused on natural-state temperatures, pressures, alteration patterns, permeability distribution, and geophysical data (Bowyer, 2006; Bowyer and Holt, 2010). At that time, a comprehensive review of the field-wide geochemistry was not performed. As of 2011, 14 additional deep production and injection wells have been drilled and a significant quantity of additional geochemistry data now exists to help characterize reservoir processes within the Rotokawa system. This paper presents new understandings and conceptual elements of the reservoir which have been developed on the basis of fluid discharge geochemistry from historical and post-production wells and thermal features.

2. NATURAL STATE DATA SELECTION

A review of the available geochemistry data has been conducted involving several iterative screenings designed to filter out the possible effects of production and injection, and select only those data most representative of natural-state reservoir conditions. Additionally, data which appear to have been impacted by drilling or other stimulation by cold water have been eliminated. Data which demonstrate poor ion balance or other indicators of poor data quality have also been removed from the dataset. Only deep reservoir fluid discharges prior to the start of deep injection in late 2004 are considered for the geochemical conceptual model. These include discharges from wells RK1, RK4, RK5, RK6, RK9, RK13, and RK14. Additionally, discharges from intermediate aquifer depth wells RK1X, RK2, RK3, RKM5, RKM6, RK11, and shallow groundwater monitoring wells RKM1, RKM2, RKM3, RKM3, RKNEC are used to characterize the natural-state fluid from these aquifers.

Figure 1 shows the layout of the current steamfield, indicating the locations of deep production and injection wells with respect to the other intermediate aquifer and shallow monitoring wells at Rotokawa.

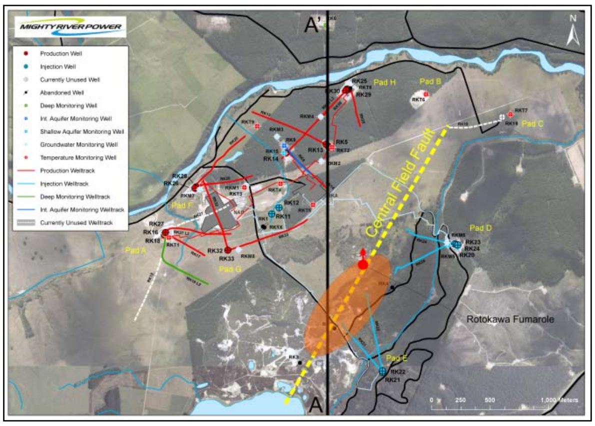

Figure 1: Layout of the Rotokawa steamfield showing deep production and injection wells, intermediate aquifer wells, and shallow groundwater monitoring wells. See text for full description of the conceptual model elements and relationships in cross-section A-A'.

An area of a weakly developed deep reservoir clay-cap, the Central Field Fault (CFF), and the Rotokawa Fumarole are shown in Figure 1. These are important elements of the conceptual model which are graphically depicted in a line of cross section (A-A') and described in detail in Section 6.

3. MAIN AQUIFER UNITS AND HYDROCHEMICAL CHARACTERISTICS

The Rotokawa geothermal system broadly comprises three main hydrostratigraphic units:

1. Shallow Aquifer – A shallow groundwater system consisting of a blanket of steam-heated, acid sulphate-Cl springs and diffuse neutral-Cl discharges, mixing with cold groundwater. This unit is hosted predominately in the shallow surface deposits, Oruanui formation, and the Parariki Breccia overlying the Huka Falls formation.

2. Intermediate Aquifer – An aquifer comprising a complex mixture of downward migrating fluids from the shallow system, boiled deep reservoir brines migrating upward through an area of a weakly developed reservoir clay cap (between RK1 and RK3; Figure 1), steam condensates, and conductively and/or steam-heated marginal groundwaters, variably enriched in CO_2 and H_2S and corrosive in nature. The intermediate aquifer is mainly hosted within the Waiora Formation and the Haparangi Rhyolites.

3. Deep Reservoir – A deep (below ~-500 to -700 mRL), hot (300-340°C), neutral-Cl (850-450ppm), geothermal reservoir with very large geochemical gradients from south to north with respect to Cl, Cl/B, non-condensible gasses (NCG), and liquid geothermometry (T_{Qtz} and T_{NKC}). The deep reservoir is partially capped by a smectite rich clay zone variably hosted in the Wairakei Ignimbrite and the basal layers of the Waiora Formation. The main permeable reservoir is hosted within the Rotokawa Andesite, Waikora Formation, Tahorakuri Formation, and the underlying basement greywacke.

3.1 Shallow and intermediate aquifers

Fluid interactions and conceptual model elements relevant to the shallow and intermediate aquifers are graphically depicted in Figure 2.

The fluid interactions in the intermediate and shallow aquifers are complex. This largely arises from upwelling deep reservoir fluids ([1]) which exploit enhanced permeability created by a weakly developed deep reservoir clay cap ([2]) and the central field fault (CFF) in the area between Lake Rotokawa and RK1/RK1X. These permeable features allow deep reservoir fluids to rise into the intermediate aquifer and boil ([1] and [3]). In the process the fluids lose CO_2 and proportionally retain more of their soluble H_2S. H_2S-rich steam condenses into shallow groundwater creating the extensive area of acid-SO_4-Cl fluids around Lake Rotokawa ([4]). Some component of deep reservoir brine ([5]) must reach very shallow levels as evidenced by the significant Cl component of the acid-SO_4-Cl springs (520ppm avg. Cl; New West Pool). These fluids partially drain back downward to generate advanced argillic alteration in RK4/RK2 ([6]).

Some of the rising boiled fluids appear to inject large quantities of CO_2 and H_2S into steam condensates formed at the base of the Huka Falls fm. and Parariki Breccia ([7]). Downward migrating, oxygenated groundwaters, conductively heat and mix with these steam condensates ([8]). The mixing process oxidizes and removes the H_2S in the form of soluble SO_4, leaving behind highly corrosive, carbonic acid-rich fluids ([7]). These fluids are responsible for the casing breaks and/or corrosion in RK1, RK2, RK3, RK4, RK5, and RK9.

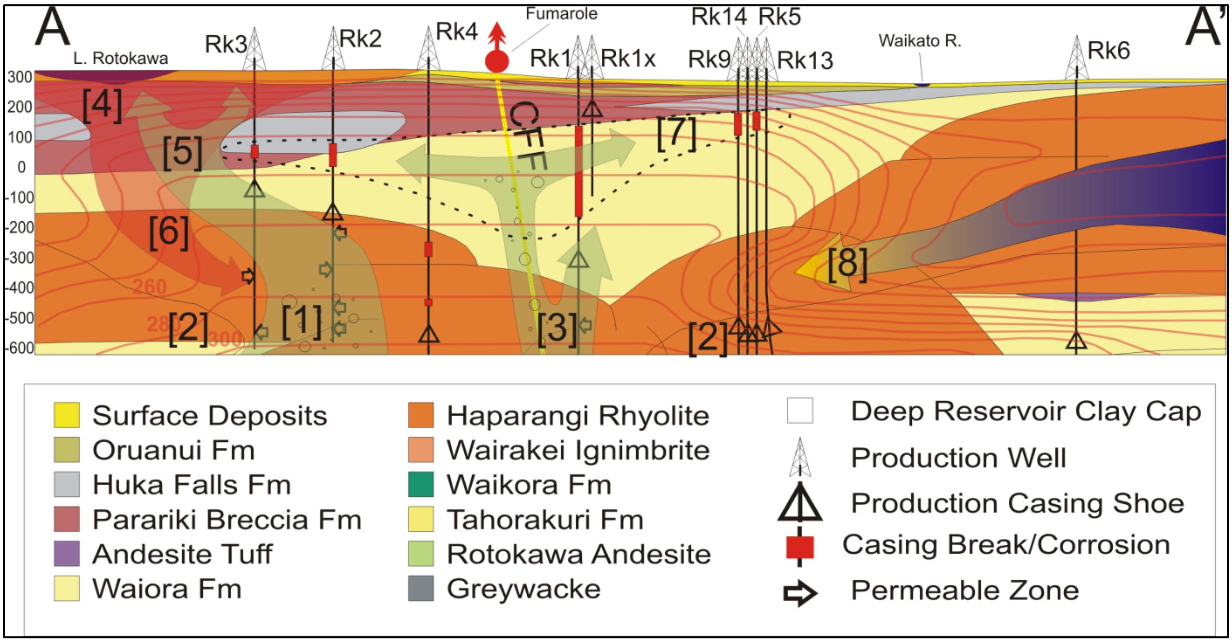

Figure 2: N-S cross section through RK2, RK5, and RK6 with wells RK1, RK3, RK4, RK9, RK13, and RK14 projected onto section A-A' (see Figure 1). The trace of the Central Field Fault (CFF) and its relationship to the Rotokawa Fumarole are also projected onto section. Conceptualized fluid flow pathways are indicated by arrows and specific reservoir processes are numbered in brackets and referred to in the text.

4. DEEP RESERVOIR

4.1 Summary of early work and steamfield development

Early work on the Rotokawa reservoir geochemistry highlighted large differences in geochemical constituents found between the southern and northern sectors of the deep reservoir (Hedenquist et al., 1988). The classification of the reservoir into two broad geochemical groups; Rotokawa North (RN) and Rotokawa South (RS), was introduced by Giggenbach (1995). At that time, RN wells consisted of RK1, RK5, RK6, and RK8 while RS wells were RK2, RK3, and RK4. Of the RS wells, only RK4 was completed within the deep reservoir, however the lack of a competent clay cap in the area of RK2 and RK3 allowed these wells to directly produce rising fluids from the deep reservoir in the RS area.

Starting in 1997 the steamfield was expanded to support RGEN and later NAP operations. In the process, a series of production wells (RK9-RK18 and RK25-RK33) were drilled along a NE-SW structural axis which forms the modern production field (Figure 1). RGEN injection was entirely into the intermediate aquifer from start-up in 1997 until late 2004, at which time it was shifted to deep edge-field wells RK16 and RK18, and ultimately to RK20 in the southeast. With the expansion of NAP, additional deep injection wells (RK21-RK24) were drilled along a NE-SW striking structural axis in the southern portion of the reservoir near RK4 (Figure 1). These deep injection wells were not sampled and therefore, the only available geochemistry for deep reservoir fluids are from historical RK2, RK3, and RK4 discharges.

Geochemically, RK2, RK3, and RK4 are not only different from each other, but also very different from RN. Because of this, there has been long-standing ambiguity as to whether the deep reservoir is supplied by one geochemical parent fluid, or that two or more different parent fluids supply RN and RS separately.

4.2 Geochemical Gradients

The geochemistry of deep fluids at Rotokawa indicates that the reservoir is poorly mixed. Reservoir Cl, Cl/B, Na-K-Ca geothermometry (T_{NKC}), and non-condensable gasses (NCGs) all show significant gradients across the field from the southeast to the northwest. The gradients tend to be perpendicular to the main NE-SW structural axis of the production field and the TVZ. Along this structural axis, geochemical variation is minor. Similar, though less extreme gradients have been observed at Broadlands-Ohaaki (Christenson et al., 2002).

Figure 3 shows an example of this gradient in an isochemical contour map of deep reservoir Cl. B, NCG, and T_{NKC} all show nearly identical patterns. In the south, reservoir fluids are high in Cl, B (51ppm; RK4), and NCG (1.8 wt% in total discharge; RK4). RK2 and RK3 produce fluids containing on average about 1900ppm Cl and as much as 62ppm B. RK2 discharges contain as much as 4.7 wt% NCG in total discharge, while RK3 is much lower with only 0.38 wt% NCG. High Cl and B contents are probably reflective of local boiling conditions in the natural-state reservoir. The large difference in RK2 and RK3 NCGs, despite their otherwise similar geochemistry, indicates that RK2 taps a two-phase fluid along a deep upflow, which subsequently loses gas and steam to form RK3 fluid. Figure 2 shows this conceptual model element ([1]) and its influence on RK2 and RK3. In the absence of a competent deep reservoir clay cap (Figure 2; [2]), it is difficult to achieve the high NCG concentrations and reservoir steam fractions (>75% excess steam) observed in RK2 without a deep, two-phase fluid source.

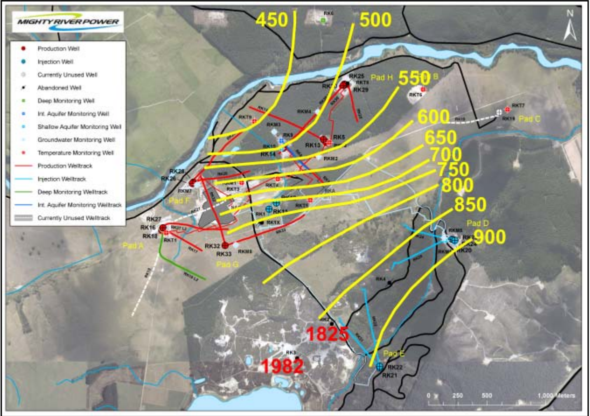

Figure 3: Isochemical contour map of deep reservoir Cl. RK2 and RK3 are not contoured but their individual Cl values are shown in red. Contours in the SE are based upon RK4.

As mentioned, the T_{NKC} gradient pattern is very similar to Cl, B, and NCG. T_{NKC} follows a constant gradient from high temperature in RS (RK4; 320°C) to low temperature in RK6 (260°C). In most cases, T_{NKC} temperatures are cooler than either silica (T_{Qtz}) or measured formation temperatures. Because T_{NKC} is a ratio geothermometer, it is not as susceptible to boiling or dilution effects and should more faithfully reflect the overall distribution of reservoir temperatures. However, T_{NKC} equilibrates much more slowly than T_{Qtz} and therefore these temperatures do not necessarily indicate local reservoir temperatures but rather may have "memory" of a more distal reservoir condition.

The fact that T_{NKC} is slow to equilibrate; is significantly cooler than T_{Qtz} and measured formation temperatures; and demonstrates a cooling trend toward the north, suggests that the deep reservoir fluids are progressively diluted northward by a cooler, marginal fluid. Furthermore, the fact that T_{NKC} temperatures are so much lower than measured formation temperatures indicates that the fluids are out of equilibrium with the feldspars upon which the T_{NKC} geothermometer is based. The root causes of this behavior are not well understood and warrant further study.

These characteristics are somewhat difficult to reconcile with the preferred model of progressive dilution by deep, heated groundwater from the north. Analogous dilution in other geothermal fields is generally accompanied by cooling, which is not observed in Rotokawa. The implications of these characteristics to the conceptual model are explored in Sections 5 and 6.

4.3 Liquid and gas geochemistry

Significant effort has been made in the literature to resolve the geochemistry of the Rotokawa system to a single geochemical source fluid on the basis of liquid, gas, and isotope geochemistry. Early interpretations of enthalpy-Cl relationships first identified the difficulty in relating RK2/RK3 to RK4 and to northern reservoir fluids through more typical reservoir processes and conditions. This is summarized in Section 5.1 below. Hedenquist et al. (1988) demonstrated that, on the basis of a CO_2/H_2S boiling model, it is possible to relate all reservoir fluids to a common geochemical parent. However, subsequent work by Giggenbach (1995) pointed out the difficulty in using

CO_2/H_2S to distinguish end-member fluid compositions because of their relatively similar vapour-liquid distribution coefficients. Instead, Giggenbach (1995) explored the Rotokawa data through the H_2O-CO_2-Cl ternary system and proposed on this basis that the system is fed by more than one distinct geochemical fluid source for RN and RS.

The larger and more comprehensive H_2O-CO_2-Cl dataset now available suggests that it is in fact possible to relate Rotokawa reservoir fluids to a single geochemical parent through a combination of reservoir dilution and boiling processes. However the possibility of multiple fluid sources cannot be ruled out. Thus, ambiguity remains as to exact origin of the deep reservoir fluids.

Despite this uncertainty, some important characteristics of the deep reservoir fluids are evident from N_2-He-Ar gas data. Figure 4 shows a plot of these natural-state reservoir gas data, including data for the Rotokawa Fumarole (see fumarole relationship to CFF in Figure 1 and Figure 2).

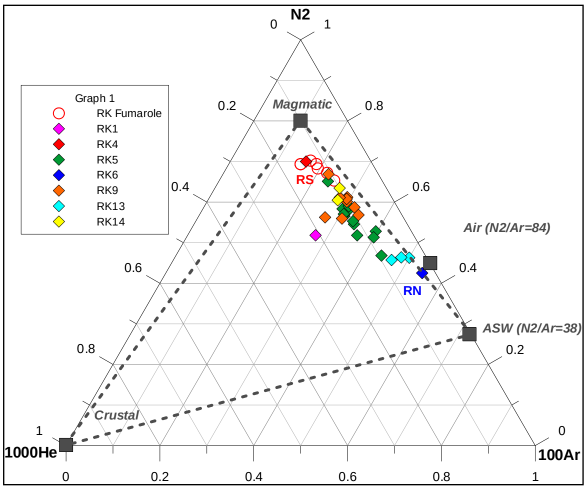

Figure 4: N_2-He-Ar ternary diagram for the Rotokawa Fumarole and natural-state deep well discharges (adapted from Hedenquist et al., 1988).

N_2/Ar ratios progressively decrease from RK4 > RK9 > RK14 > RK5 > RK6. These data demonstrate scatter along a mixing line between a RS (RK4) end-member and air-saturated groundwater (ASW; $N_2/Ar=38$), such that RK6 represents a mixture of nearly 75% ASW to 25% RK4 fluid. This is consistent with overall NCG degassing trends and other geochemical indicators suggesting progressive dilution of the deep reservoir toward the north by a marginal deep groundwater (Section 4.2).

N_2/Ar ratios for the Rotokawa Fumarole are similar to RK4 and on this basis, the fumarole appears to be more strongly correlated with south-eastern and southern reservoir fluids. CO_2/Ar-H_2/Ar relationships additionally define a direct connection between the fumarole gasses and these deep reservoir fluids, presumably through the CFF and associated structures.

Both RK4 and the Rotokawa Fumarole appear to have affinities with a magmatic N_2/Ar fluid signature (Giggenbach, 1986). A magmatic fluid component to the system is consistent with other characteristics of the geochemistry data. Most notably, the RS fluids are not in equilibrium with respect to the Fischer Tropsch-HSH2, y-T gas geothermometer grid. Similar behavior has been observed in the Philippine Mahanagdong system which was attributed by Siega et al. (2000) to the presence of magmatic, acid-SO_4 fluids.

5. ENTHALPY-CHLORIDE RELATIONSHIPS

5.1 Early observations

The Rotokawa reservoir chemistry (Crown wells RK1 to RK6) was initially evaluated on an enthalpy-Cl plot by the DSIR (Hedenquist et al., 1988). The data were corrected to reservoir conditions on the basis of T_{Qtz}. Figure 5 is an adaptation of the enthalpy-Cl plot from the DSIR report which shows the well data available at that time, and the early interpretations of the enthalpy-Cl relationships.

This diagram shows the complexity in relating the various geothermal waters in the field to each other. The authors observed what appeared to be a dilution trend ([1]) from RK5 and RK6 (RN) toward steam-heated groundwater discharged from RK2 ([2]) following a casing break (RK2CB). They drew a steam loss line ([3]) to RN to accommodate the possibility that RK5 and RK6 are entirely independent from the remainder of the reservoir. However the initial interpretation was that the dilution line to a ~180°C steam-heated groundwater like RK2CB ([2]) was controlling the RN deep reservoir chemistry and that RK4 had boiled from a higher enthalpy, higher chloride parental fluid common to both RK4 and RN ([4]).

The authors highlighted the complexity in explaining a direct relationship between RK2 and RK3 to the rest of the reservoir. The dilution line ([1]) they proposed could be projected back to the RK3 steam-loss line ([5]), however, assuming a liquid parent ([6]), this would have an unreasonably high enthalpy (1950 kj/kg; close to the critical point for water). Instead, they proposed that either the parent fluid from which RK4 originated had boiled and conductively heated in a complex way ([7]) to produce RK3, or there was an independent source fluid (e.g., a magmatic vapor condensate) for RK2 and RK3 which would lie somewhere along a steam-line connecting to RK3. A separate parent supplying fluid independently to RK2 and RK3, and at the same time isolated from RK4 and the rest of the reservoir is hard to explain, and these initial observations highlight the ambiguity surrounding the origin of the reservoir fluids.

Consideration of the geochemistry data now available demonstrates that a very large number of potential fluid mixing pathways in enthalpy-Cl space can be devised to explain the origins of the fluids (both as single- and multiple-parent sources), and few of these relationships are simple.

5.2 Single parent geochemical system

An alternative enthalpy-Cl mixing model proposed for the system invokes a fundamentally different reservoir process to explain the fluid chemistries of the deep reservoir. Figure 6 shows the proposed mixing pathways in this alternative model.

The system is proposed as a single-parent geochemical source ([1]) with an inferred two-phase upflow ([2]) supplying fluid from depth, however the parent liquid is cooler (~340°C) than [6] in Figure 5. 340°C is close to measured liquid temperatures in RK22 and its postulated existence is therefore more easily explained than a near-critical point fluid. As in Figure 5, RK2 and RK3 are generated by boiling and steam-loss from a two-phase parent ([3]). The parent liquid ([1]) mixes with a very hot

(~290°C), conductively heated groundwater ([4]) to generate the full array of deep reservoir fluids. RK4 fluids ([5]) tend to lie just below the [1]-[4] mixing line and this may reflect localized boiling and cooling of the RK4 fluids due to the restricted permeability in that well.

Large volumes of very hot, conductively heated marginal fluids are problematic under long-lived, steady-state reservoir conditions. The mixing relationships proposed here suggest a transient reservoir condition which could have developed in response to a catastrophic eruption and/or depressurization event. This concept is discussed in more detail in Section 6.

A fair degree of uncertainty still exists as to which of the many possible enthalpy-Cl mixing models is likely to be correct. However, considering that the simplest models are often the most defensible, a preference is given to one which assumes a single geochemical parent source. Given the difficulty in explaining >~360°C reservoir temperatures, lack of evidence for mixing a ~180°C steam condensate in the deep reservoir, and geologic evidence indicating the Rotokawa system may be very young, additional preference is given to the enthalpy-Cl mixing model in Figure 6.

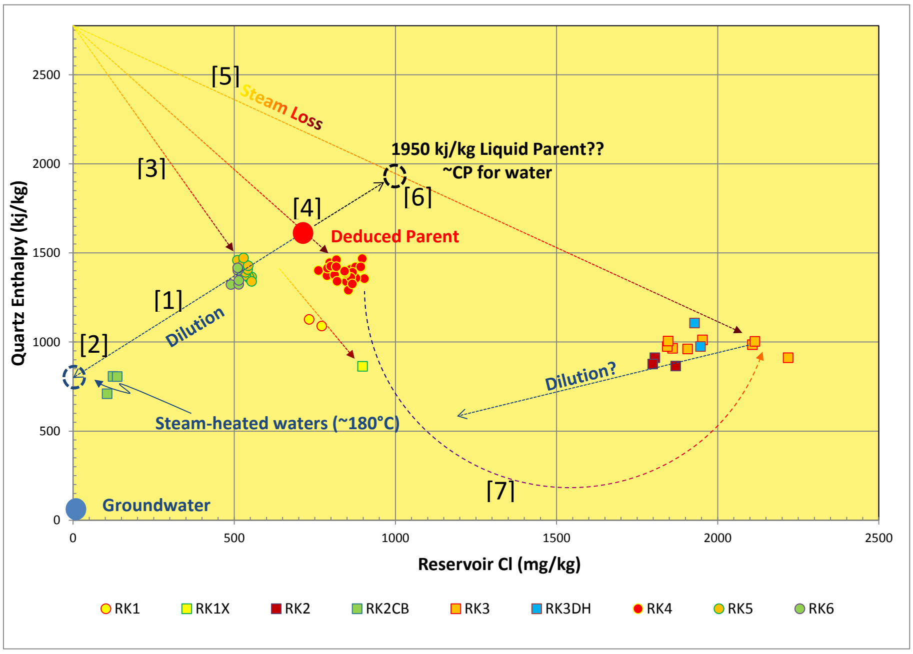

Figure 5: Reservoir corrected enthalpy-Cl relationships for Rotokawa wells (modified after Hedenquist et al., 1988). Numbers in brackets refer to specific reservoir processes as discussed in the text.

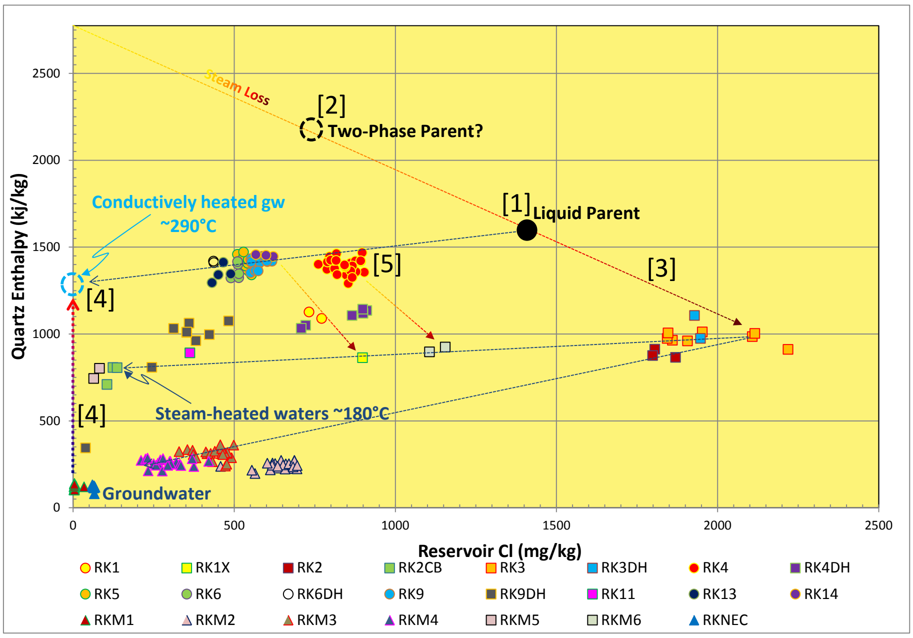

Figure 6: Reservoir corrected enthalpy-Cl relationships for Rotokawa wells. All available natural-state reservoir fluids are shown. The proposed mixing lines and arrows reflect reservoir processes within a multiple-parent geochemical system. Numbers in brackets refer to specific reservoir processes as discussed in the text.

6. CONCEPTUAL GEOCHEMICAL MODEL

A conceptual model has been developed which accommodates the possibility of both a single- and multiple-parent geochemical fluid source, as well as the potential for steady-state and transient reservoir conditions as previously mentioned. This model maintains consistency with the proposed enthalpy-Cl mixing relationships and with the overall reservoir geochemistry data. A cross section of this conceptual geochemical model along the section line A-A' (see Figure 1) is presented in Figure 7.

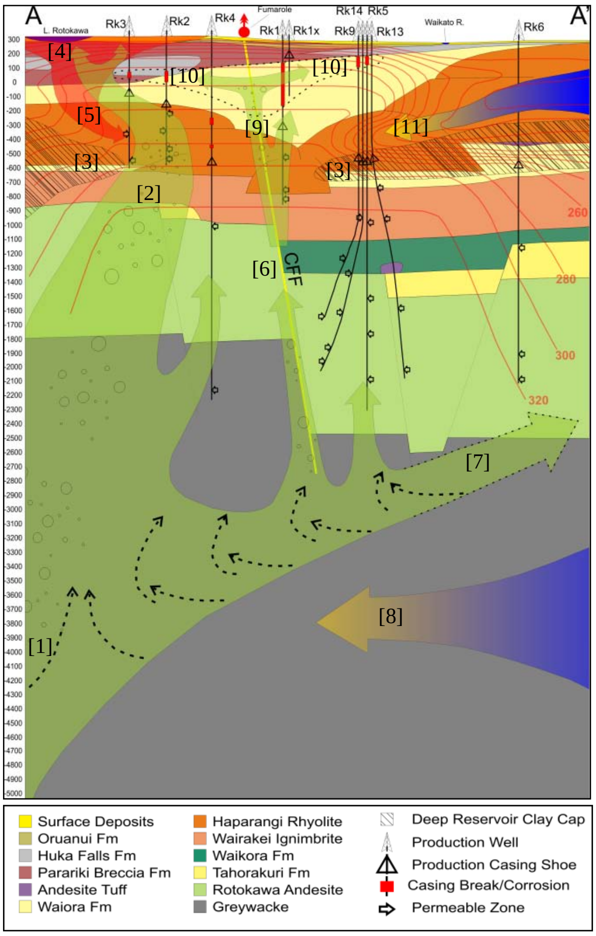

Figure 7: Rotokawa conceptual geochemistry model cross section. The trace of the Central Field Fault (CFF) and its relationship to the Rotokawa Fumarole are also projected onto section. Conceptualized fluid flow pathways are indicated by arrows and specific reservoir processes are numbered in brackets and referred to in the text.

The conceptual model incorporates elements of a hot, two-phase upflow in the south under the Lake Rotokawa area, to depths of more than 4km ([1]). These two-phase fluids rise [2] in a vigorous upflow in the Lake Rotokawa area under RK2 and RK3. As the fluids boil adiabatically and rise through the weakly developed clay cap between RK3 and RK1X ([3]), they lose CO_2 and proportionally retain their more soluble H_2S and B. H_2S- and B-rich steam condenses into shallow groundwater creating the extensive area of B-rich, acid-SO_4-Cl fluids around the lake ([4]) which partially drain downward ([5]) through permeable features ([3]) in the vicinity of the central field fault (CFF; [6]) to generate the advanced argillic alteration sequences observed in RK4 and RK2. Deep reservoir fluids outflow toward the north ([7]) where they are progressively diluted by a conductively heated (or steam-heated) deep groundwater ([8]). This deep, marginal, diluting fluid, discussed in the enthalpy-Cl plots of Section 5, is responsible for the large geochemical gradients sampled by the wells from the south to north.

The central field fault (CFF; [6]) provides a zone of focused permeability allowing deep reservoir fluids to rise and boil, partially exiting the system at the surface through the Rotokawa Fumarole. Some of this fluid injects high concentrations of CO_2 and H_2S ([9]) into steam condensates formed at the base of the Huka falls Fm. and Parariki breccias ([10]). Downward migrating, oxygenated groundwater ([11]) is conductively heated and mixes with these steam condensates. The mixing process oxidizes and removes the H_2S in the form of soluble SO_4, leaving behind highly corrosive carbonic acid rich fluids ([10]). These fluids are responsible for the casing breaks and/or corrosion in RK3, RK2, RK4, RK1, RK9, and RK5.

6.1 Transient reservoir state

As indicated in Section 5.2, an alternative interpretation of the reservoir is possible based on enthalpy-Cl relationships, which would have a fundamentally different implication for the origin of dynamic fluid movement in the reservoir. In cross section, the conceptual model describing fluid flow and reservoir processes for this alternative would appear similar to Figure 7 and the dilution element ([8]) would need to be very hot (~290°C; see Figure 6; [4]). The difficulty in maintaining a flow of dilute, ~290°C fluids under steady-state conditions was noted in Section 5.2, and its existence would strongly suggest a transient reservoir condition.

Evidence of geochemical disequilibrium is consistent with a transient reservoir condition as opposed to the steady-state condition usually assumed for the geochemistry of natural-state geothermal reservoirs. Geologic evidence supports the suggestion that the reservoir may be in a state of geochemical disequilibrium. Collar and Browne (1985) report on geologic evidence for at least eight large hydrothermal eruptions in the southeastern part of the field in the last 20,000 years, the latest as recent as 3700 years ago, with the possibility of smaller eruptions since the deposition of the Taupo Pumice 1800 years ago. These eruptions would have subjected the reservoir to episodic de-pressuring events, triggering field wide boiling. Evidence of boiling events is preserved in the common presence of bladed calcite and chalcedony (re-crystallized from boiling-induced deposition of amorphous silica), widely distributed throughout the reservoir. Surface water recharge following these eruptions and reservoir de-pressuring events may, in part, explain geochemical disequilibrium in the reservoir fluid.

An alternative way to interpret the conceptual model and cross section in Figure 7 is as a “snapshot” of major transient changes occurring in a reservoir that has been significantly shifted out of thermodynamic equilibrium. A geologic mechanism is proposed to explain the origin of this transient condition. This alternative model assumes a recent eruption (e.g. the one produced Lake Rotokawa) is the cause of a catastrophic reservoir depressurization event. In response to an eruption event like this, a significant pressure gradient would have developed between groundwater in the Haparangi rhyolites and a radically under pressured deep reservoir. This would have allowed cold, dilute fluids to flood into the reservoir on a massive scale. These fluids would have encountered what likely was either relict hot rock from a pre-eruption geothermal system, and/or possibly rock that was and is experiencing transient heating in response to deep magma injection. Deep magma injection under RS would be consistent with N_2/Ar ratios for RK4 and the Rotokawa Fumarole, and an associated thermal disturbance could easily have triggered hydrothermal eruptions shifting a steady-state system into a state of disequilibrium.

Following the hydrothermal eruption, large-scale groundwater flooding, and re-establishment of hydrostatic pressure conditions, the reservoir would have begun a slow, transient recovery toward equilibrium. Cold dilute fluid input to the system would slow dramatically as pressures equilibrate, and rebounding reservoir temperatures promote the growth of clay-rich alteration assemblages, sealing-off permeable pathways originally exploited in response to the eruption-induced pressure gradient. This volume of cold fluid which flooded the system in a one-time event would conductively heat to ~290°C in response to contacting a large volume of relict hot-rock from the pre-eruption system. Input of a 340°C parent fluid, like in Figure 6 ([1]), would begin to mix with the large reservoir of dilute fluids heating them further, and re-establishing a deep reservoir outflow toward the north (Figure 7; [7]). Considering this model, natural-state conditions as are now currently observed and as have been conceptualized in Figure 7, may not actually be steady-state conditions, but rather a point in time along a transient pathway toward re-equilibration.

6.2 Implications for a reservoir numerical model

The conceptual model presented above is not only consistent with the observations of large geochemical gradients and disequilibrium, but it can also explain the differences between RN and RS without needing a multiple-parent fluid source to the system. A multiple-parent source cannot be discounted as a possibility, but it requires an unnecessary level of complexity, and until evidence emerges that clearly delineates two distinct fluid chemistry sources, the preferred model is one with a single geochemical source fluid.

The preference for a single-parent system in no way precludes the possibility of multiple fluid upflows to the natural state reservoir. In fact, as shown in Figure 7, multiple upflows are conceptualized to explain: 1) two-phase conditions, low Cl/B, and high gas under RS; 2) intermediate aquifer features and the Rotokawa Fumarole in the area of the CFF; 3) high enthalpy fluids feeding the RK5 (and RK17/RK29) area; and 4) hot, yet dilute fluids in the area of RK6.

The conceptual model elements linking these upflows to a singular fluid chemical source is the deep outflow and the mechanism of dilution with marginal fluids ([7] and [8]; Figure 7). Until further exploratory drilling provides additional constraint, there is a fair amount of flexibility in the depths of the outflow ([7]) and dilution ([8]) elements. What is observable from currently explored depths and appears as individual upflows, likely originates from a single deeper reservoir outflow as shown in Figure 7. It is reasonable to model this numerically as individual upflows with the understanding that below a basal boundary condition of the model, there may be a single, connected, deep fluid.

If the pre-exploitation reservoir was in steady-state equilibrium conditions, then relatively complex geochemical processes are necessary to explain the variation in geothermometry, gasses, isotopes, and liquid constituents across the field. This is a very real possibility. But it is important to stress that more often than not, the geochemistry demonstrates equilibrium conditions which cannot be universally applied across the reservoir. Rather it appears that reservoir liquids and gasses are in disequilibrium with each other and with the reservoir rock.

The alternative possibility, as implied in enthalpy-Cl relationships and discussed conceptually, is that the reservoir is in a phase of transient recovery and moving toward equilibrium conditions following a major thermodynamic disturbance, e.g., in response to an eruption event that produced Lake Rotokawa. Figure 8 graphically shows the enthalpy evolution of the geothermal system with respect to these two possible alternatives and to the present-day frame of reference as “natural-state.”

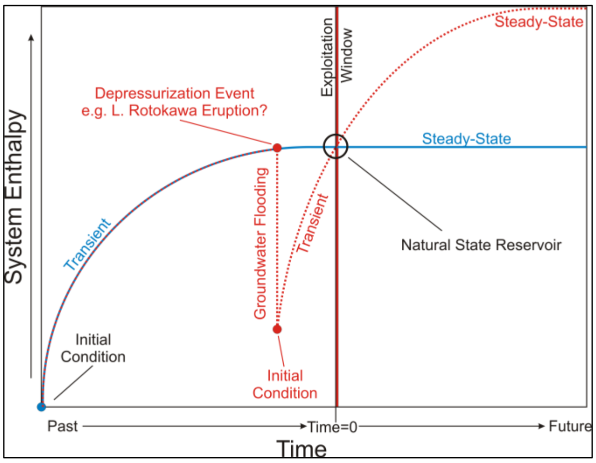

Figure 8: Enthalpy vs. Time conceptualized evolution of the Rotokawa geothermal system showing possible system evolution pathways. The blue curve reflects a system which has evolved uninterrupted to steady-state conditions. The red curve reflects a relict system which evolved in a similar way until a depressurization event (e.g. eruption) produced a major shift in the equilibrium state of the system. Following this event, new initial conditions to the system are established and the system enthalpy follows a transient recovery toward a new steady-state condition. The natural-state reservoir condition is the Time=0, currently observable reservoir.

On Figure 8, baseline reservoir conditions projected into the future will differ depending upon which evolutionary pathway the system is actually following. However, relative to the overall time required for the system to establish steady-state conditions, a ~50-100 year exploitation window (shown in Figure 8 as the thin red rectangle) is insignificant. On the time-scales of practical field development and operations, divergence of the two curves will not significantly impact forward projections of reservoir enthalpy and pressure. Additionally, any difference between the curves will be many orders of magnitude smaller than the transient changes produced in the reservoir as a result of production. Therefore, regardless of which of the two system evolution pathways more accurately reflects the reality of the Rotokawa reservoir, a numerical model that reasonably matches natural-state conditions and reproduces production history will be a robust model for making forward predictions of reservoir performance.

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