VISUALISATION OF CHANGING RESERVOIR CONDITIONS AT WAIRAKEI

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ABSTRACT

This paper describes the use of the Wairakei 3D geological model to visualise changing fluid conditions within the reservoir. During 50 years of production and reinjection, the Wairakei reservoir has seen many changes. The major changes in the reservoir have been caused by pressure decline in the deep liquid zone due to fluid extraction. Where a capping formation is present, the pressure decline resulted in the formation of segregated steam zones and where the deep reservoir is connected to shallow aquifers, cooler fluids have invaded the productive reservoir. These changes have been closely monitored using physical and chemical methods. Recent development of the Wairakei 3D model has provided an opportunity to integrate some of these changes with the geological model to better understand and visualise the controls on fluid flow within the reservoir.

1. INTRODUCTION

The Wairakei Geothermal Field, New Zealand, was the first high-temperature, liquid-dominated geothermal system in the world to be developed for electricity generation. Figure 1 shows the main production areas of the Wairakei Field, including, from east to west: the Eastern Borefield (EBF), the Western Borefield (WBF), Poihipi and Te Mihi. The latter is now the main production area of the Wairakei Geothermal System. After more than 50 years of production, the Wairakei reservoir has seen many changes: The major effects have been caused by pressure decline resulting in boiling and development of segregated steam zones, and influx of cool fluids into parts of the deeper reservoir (Bixley, 1986; Bixley et al., 2009; Glover, 1977). These changes manifested as changes in well enthalpy, fluid chemistry, gas content and downhole temperatures. From a wider perspective, some of the subsurface changes were also evident as changes in microgravity and ground deformation (Allis et al., 2009; Hunt et al., 2009; Bromley et al, 2009).

Physical and chemical changes of the reservoir have been studied in detail by previous works (as above) using conventional two-dimensional (2D) plotting tools. Over the last four years, collaborative work between Contact Energy, GNS Science and Applied Research Associates (ARANZ) have transpired to develop and improve geothermal three-dimensional (3D) modeling and visualization capabilities. The resulting development of 3D geological models of the Wairakei geothermal reservoir (e.g. Alcaraz et al., 2010) provides a new platform for analysis, integration and visualization of reservoir changes, from a field wide perspective in both space and time. This paper presents the results of some "experiments" using a Wairakei 3D geological model and a review of changes in the Wairakei reservoir from a 3D perspective with emphasis on changes in reservoir temperature and chloride concentration in the WBF. For further information on Leapfrog Geothermal interpolation techniques and cases studies, readers can refer to Alcaraz et al. (2011), Milicich et al. (2010) and Newson et al. (2012).

It is anticipated that additional 3D modeling and visualization work will be undertaken to further refine our understanding of variations in the reservoir.

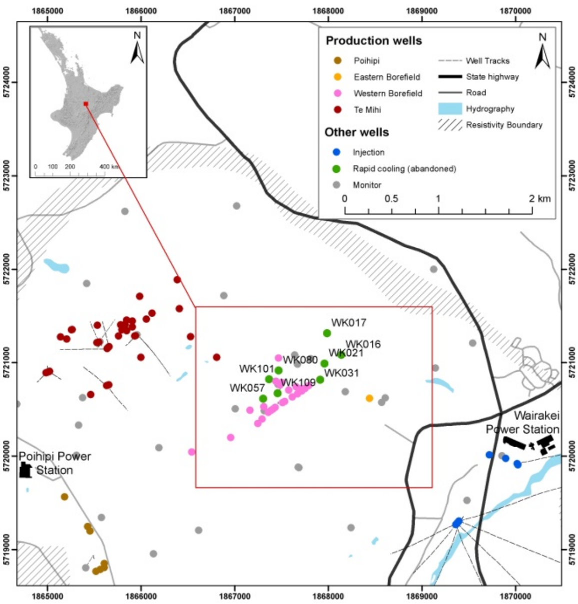

Figure 1: Map of the Wairakei field area under production and reinjection highlighting different production areas. The encased area is the focus area used in this study. See key for descriptions.

2. METHODS

In this study, a 3D geological model was produced using up-to-date geological information (Figure 2). For a recent description of stratigraphy, readers can refer to Bignall et al. (2010). The stratigraphic logs of Wairakei contain a high degree of detail, including distinction of members within Huka Falls Formation (Upper, Middle and Lower) and Waiora Formation (members Wa1 to Wa5). For this study, Huka Falls Formation members were modeled separately, but it was impracticable to do so with the Waiora Formation. Although Waiora Formation complexities are not reflected in our 3D model, they are relevant for this study as discussed in Section 3. Other aspects of 3D modeling worth highlighting include:

1) Types of geological units: Broadly speaking, Leapfrog allows the modeler to specify “stratigraphic” units and “intrusions”. The former is used to model units which are laterally extensive (typically all but lavas). “Intrusions” have the ability to cut through adjacent units, and they are the practical choice for units of local extent (e.g. lavas, Mid Huka Falls stratigraphic unit);
2) Anisotropy: In general, the geometry of regional stratigraphic units or units penetrated by a high number of wells are best constrained by data only. In the case of units of local extent (e.g. lavas), or where data points are scarce, horizontal anisotropy was adopted for selected units (e.g. Karapiti 2a Rhyolite, Waiora Valley Andesite, Mid Huka Falls);
3) Structures: Faults were used to model large-scale stratigraphic discontinuities. The approximate location of fault planes is interpreted and modeled from stratigraphic offsets in drill-hole data; the orientation (dip and strike) of such faults is inferred from surface fault traces (e.g. GNS active fault database) and known tectonic regime (e.g. Rowland et al., 2010). Significant stratigraphic offsets are only found in deep units (namely, Wairakei Ignimbrite and Tahorakuri Formation). Accordingly, faults were deliberately “stopped” at the interface of the Waiora Formation and the Huka Falls Formation.

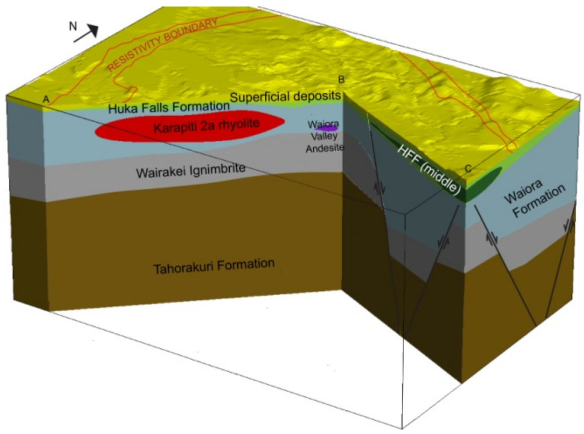

Figure 2: A geologic model of the Wairakei production and reinjection area with the stratigraphy of wells created using the Leapfrog Geothermal 3D modeling program. Area is sectioned along the Western Borefield (A – B) and the Eastern Borefield (B-C).

Spatial predictions of temperature were produced using selected downhole temperatures of the Wairakei field. The goal was to obtain a dataset representative of the early (pre-1975) stage of the productive reservoir. Because some wells have been abandoned and new wells drilled throughout the history of Wairakei, with significant temperature changes occurring during 1958-1975 (Figure 3), data selection unavoidably contains a degree of bias associated with different sampling populations. To minimize these artifacts, interpreted rather than measured reservoir parameters were used for spatial predictions.

Of particular interest are temperature inversions within the productive reservoir, which can be indicative of either lateral outflows or shallow inflows of cold water. The latter occurred to a large degree in some WBF and EBF wells, adversely affecting productivity and the useful life of these wells (referred to as “rapid cooling” wells in Figure 1). In order to model the geometry of such cooling zones, 3D volumetric representations were developed, with top and bottom constrained by downhole temperatures (Figure 5). These 3D volumes are modeled in a way analogous to geological modeling, using “intrusions” with horizontal anisotropy. Rapid cooling can be conceptually understood as dilution of deep, high-chloride reservoir fluid by a shallow, low-chloride steam-heated fluid (e.g. Bixley et al., 2009; Glover and Mroczek et al., 2009).

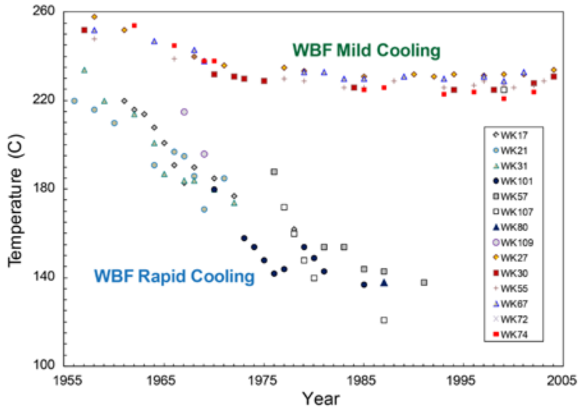

Figure 3: Graph of historical wells located in the Western Borefield showing temperature decline over time. Note the existence of wells with rapid cooling (below) and mild cooling (above).

High concentrations of chloride (1000’s of ppm) in geothermal fluid is commonly associated with deep geothermal recharge in a reservoir (Nicholson, 1993). Dilution of geothermal fluid is evident when chloride concentrations decline (100’s of ppm). Accordingly, chloride can provide an independent indication of the degree of cooling. At Wairakei, measured chloride is corrected for secondary processes (such as multiple steam separation) and projected onto a hypothetical dilution line between reservoir and steam-heated fluid end members to correct back to a baseline, following the methodology described by Brown et al. (1988) and Glover and Mroczek (2009). The corrected chloride, referred to as chloride tick (Cl’), is routinely calculated at Wairakei for key monitor wells. In this study, Cl’ was modeled using conventional 2D interpolation techniques (i.e. Kriging; Figure 4). 2D maps of Cl’ were then integrated with 3D models of cool zones and used to further constrain such 3D geometries, as detailed in Section 3. Both numeric models of temperature and volumetric models of reservoir zoning were then integrated with the 3D geological model (Figure 6 and Figure 7).

3. RESULTS AND DISCUSSION

3.1. Cooling zones from a three dimensional perspective

WBF wells exhibited varying degrees of cooling during the earlier stages of production. Based on the magnitude of cooling, wells can be grouped into two categories: rapid cooling (for example WK101, WK017) and mild cooling. The magnitude of the temperature drop with time for these categories is shown in Figure 3. From these graphical representations of temperature patterns in wells along with

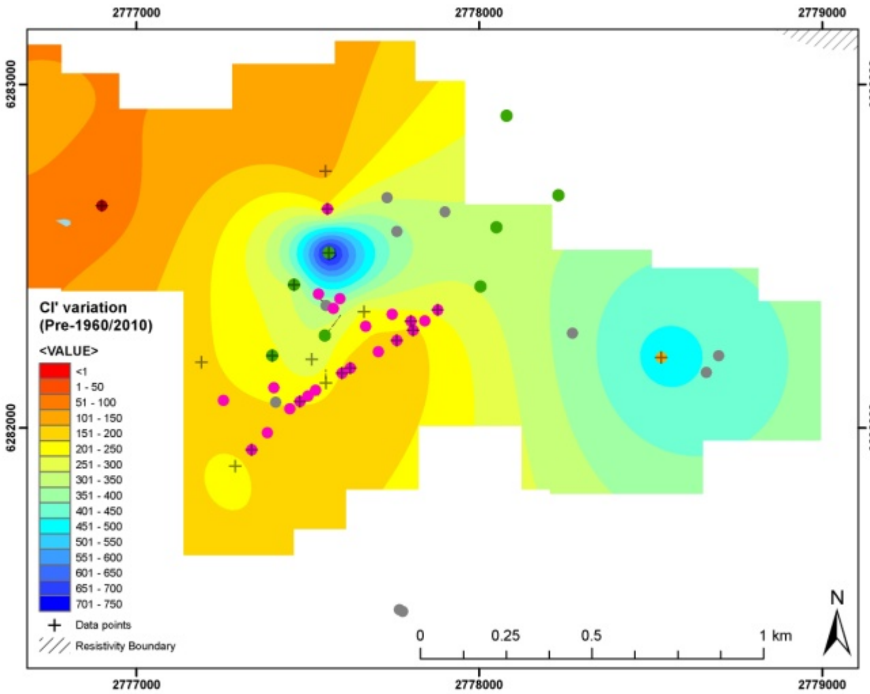

Figure 4: Map of variation in Cl' for the period pre-1975 to 2010. Contours of the change in Cl' at 50 mg/L intervals. Refer to Figure 1 for the general key (i.e. well status, resistivity boundary).

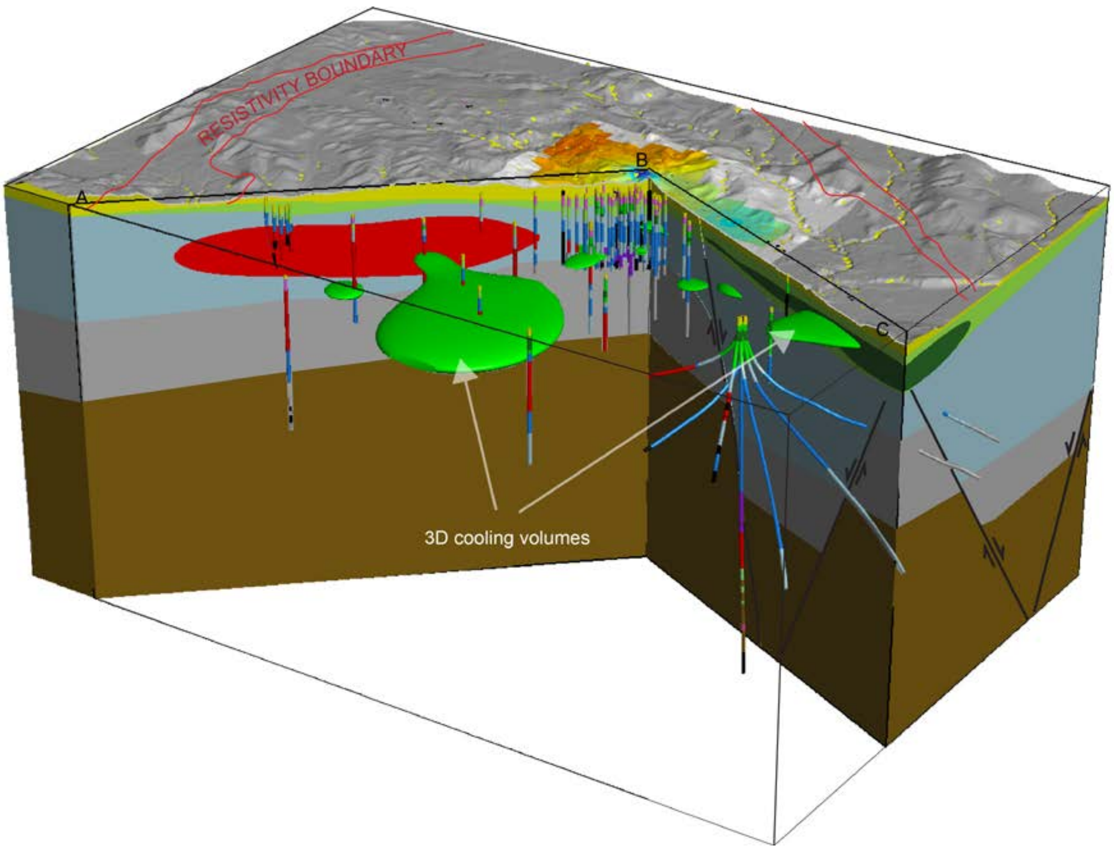

Figure 5: A geologic model of the Wairakei production area with 'cooling zones' (as green volumes indicated). The model is sectioned along the Western Borefield (A – B) and the Eastern Borefield (B – C). The resistivity boundary of the Wairakei Geothermal Field is shown in red. Wells and their stratigraphy are also represented. Chloride tick difference as in Figure 4 draped onto topography.

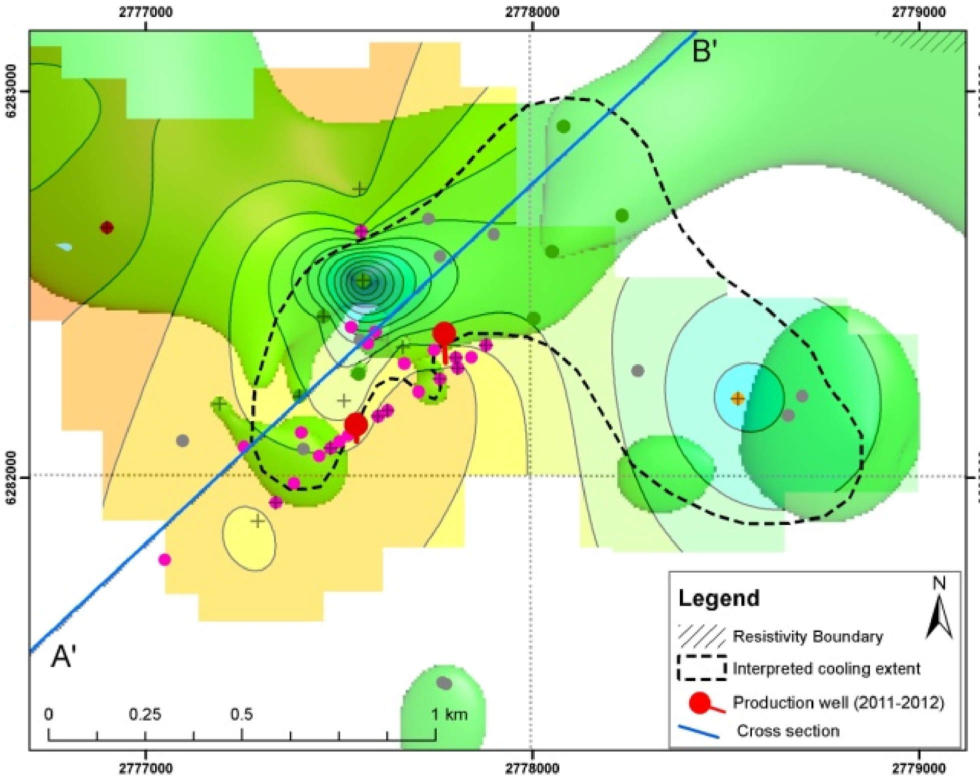

Figure 6: A map of cooling zones overlaid with Cl' variation in the Western and Eastern Borefields. Refer to key in Figure 1 and Figure 4 for well type reference. The dashed line indicates the interpreted extent of cooling in the area. Map also shows the location and deviation of two production wells recently drilled in the WBF. A cross section is created from A' to B' and is displayed in Figure 7.

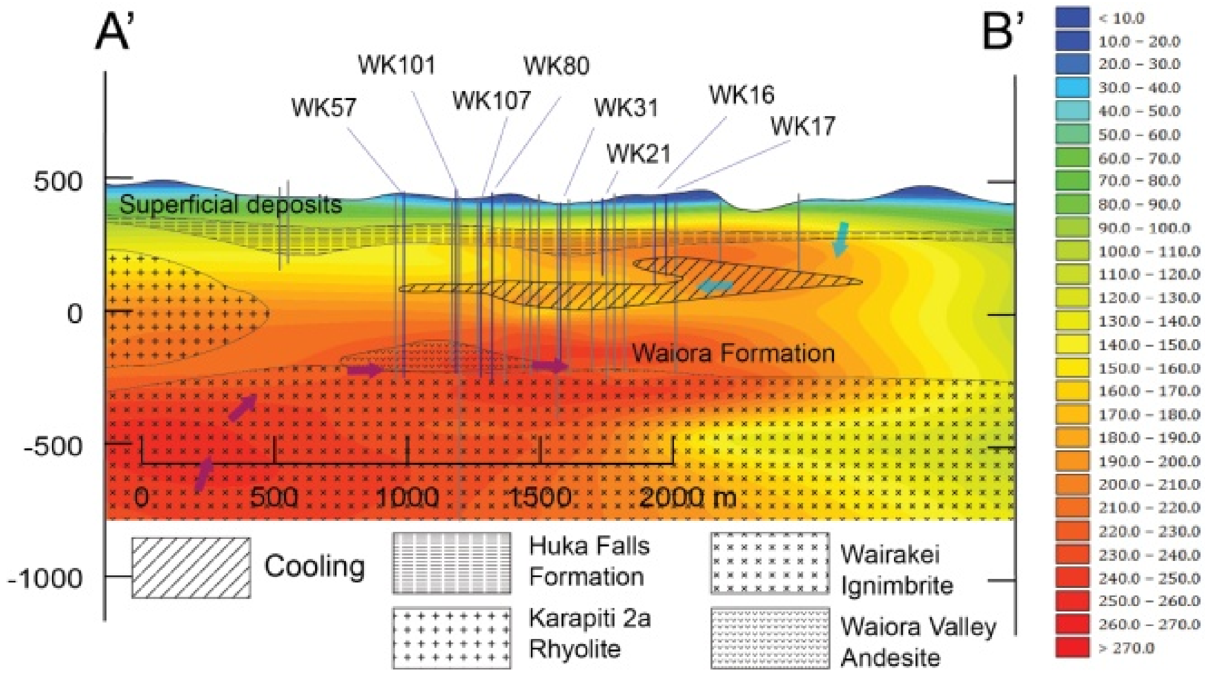

Figure 7: A cross section of the Western Borefield showing the locations of rapidly cooled wells, stratigraphy, temperature predictions at 10°C intervals (from 3D model), and projected 3D cooling volumes. Fuchsia arrows indicate an area of major upflowing fluids and blue arrows indicate an area of cool inflowing fluids.

temperature inversions seen in other well statistics from 1958 up to 1975 a 3D model was created (Bixley, 1986; Brown et al., 1988; Glover, 1977). It should be noted that several wells represented in Figure 3 through to Figure 7 were abandoned over the years as a consequence of rapid cooling combined with other detrimental processes such as calcite scaling and casing deterioration.

Figure 5 depicts the geometry of cooling areas in a 3D space, as defined by temperature data for the period 1958 to 1975. This cooling zone model is overlaid on our geologic model for comparison (from Figure 2). Although these volumetric cooling zones require further refinement, Figure 5 indicates further reservoir properties can be successfully modeled as volumetric bodies in Leapfrog, transposed on to other models and visually compared to other reservoir properties.

Using Figure 5 some comparisons with stratigraphy and areas showing possible cooler zones with geology indicates most cooler areas occurred within the Wairoa Formation, as well as along the margins of shallow rhyolites (Karapiti 2a Rhyolite) and Mid Huka Falls Formation which is a stratigraphic layer found extensively through the EBF that was thought to act as a productive aquifer which cooled and depressurized during the initial years of production (Bignall et al., 2010 and Bixley, 1986, Glover, 1977). Waiora Formation and Mid Huka Falls Formation also hosted local steam zones, with horizontally confined cool fluid inflows recognized above and below steam zones. This reservoir stratification, consisting of steam zones sandwiched by cool aquifers is explained by the occurrence of thin, relatively impermeable sedimentary layers interspersed within the Wairoa Formation as described by Grindley (1965) and Bignall et al. (2010). A detailed cross section view of cooling is shown in Figure 7.

3.2. Comparisons with chemical variations

Figure 4 shows contoured values of the change in Cl’ for the period pre-1975 to 2010, referred to as ΔCl’ for simplicity. Two lows in ΔCl’ can be identified, one centred in the WBF and another one in the EBF. It is worth noting that Cl’ measurements offer only a partial coverage of WBF area and poor coverage in the EBF. The Wairakei production and reinjection area has over 200 wells but only around 60 of these are or have been used for production. Many have been used for monitoring or reinjection purposes (which are frequently peripheral wells) and thus little chemical data for these wells usually exists. A bias of data is present as many production wells are concentrated in areas (such as the WBF). However, the lack of Cl’ information can be supplemented by examining the distribution of rapid cooling wells and extent of 3D cooling volumes as in Figure 5. A re-interpreted area of rapid cooling is shown in Figure 6, whose outline is primarily defined by the location of ΔCl’ lows and rapid cooling wells, and secondarily dictated by the outline of 3D cooling volumes. The fact that 3D cooling volumes locally extend beyond the re-interpreted area of rapid cooling shows that 3D cooling volumes encompass both rapid and mild cooling.

Understanding the extent and magnitude of cooling is an important component of well planning in the WBF. While cool fluid inflows adversely affected productivity of a number of wells in the WBF and EBF, the productive life of some wells within the perimeter of rapid cooling was prolonged by casing off cooling horizons. This was the case for wells WK101 and WK107 (locations shown in Figure 7). Both wells showed rapid cooling in the earlier stages of production and successfully returned to production in the 1980’s by isolating cool inflows. Recent drilling at the WBF offered an opportunity to test our conceptual understanding of cooling processes. Because of existing steamfield infrastructure, the accessible land for drilling was limited. With that constraint in mind, two wells were planned with relatively deep casing (relative to bottom of cooling) and deliberately deviated outwards from the rapid cooling areas (Figure 6). Both wells were successfully completed.

3. CONCLUSIONS & FUTURE WORK

This paper describes the utility of 3D integration of reservoir parameters, including geology and reservoir changes (temperature and chloride), at the WBF in Wairakei. It demonstrates how such an integrated approach has the potential for efficient multi-dimensional data analysis and assessment of data strengths and weaknesses.

This is a work in progress and considerable further development is anticipated, including further refinement of the WBF models presented here and expanding the modeled fluid conditions across the complete reservoir incorporating the steam zones in the southwestern and Te Mihi areas, plus localized steam zones within the WBF. This may further improve how we manage and monitor production fields in a newer, more informed way in the near future.

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