Conceptual Model Evolution of the Tauhara Geothermal Reservoir from 1960-2020

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ABSTRACT

At the early stages of reservoir exploration the conceptual model for the geothermal resource is of necessity simple. As a reservoir is developed the conceptual model will be refined as new spatial and temporal information becomes available from additional drilling and extended monitoring of the reservoir response to production and reinjection. Pressure response of the early exploration wells at the Tauhara reservoir, drilled in the 1960s some 5-10 km distance from production areas at Wairakei (first power generation 1958), indicated the existence of a relatively shallow and laterally extensive hydraulic connection between the Tauhara and Wairakei reservoirs. The pressure difference between the reservoirs implied that part of the Wairakei hot recharge was derived from Tauhara. Over time, the conceptual model has evolved, incorporating data from new, deeper wells, together with geophysical surveys, and the reservoir response to changing volumes of production and reinjection fluids. The evolution of the conceptual model for the Tauhara reservoir over the last 60 years is presented along with the current understanding of the nature of the interconnections between Wairakei and Tauhara.

1. INTRODUCTION

The purpose of this paper is to present the evolution of the conceptual understanding of the Tauhara reservoir (Figure 1) which lies in the Taupo Volcanic Zone (TVZ), Central North Island of New Zealand. Tauhara has the unusual attribute that it is hydraulically connected to another geothermal reservoir: Wairakei (5-10 km distance to the NW). In publications and reporting, Wairakei and Tauhara are commonly referred to as the Wairakei-Tauhara geothermal system; this also provides ease for regulatory management. However, the conceptual model is that of two geothermal reservoirs with separate upflows and strong interconnectivity, as further elaborated in this paper.

Tauhara, Wairakei and Rotokawa are three adjacent geothermal reservoirs located immediately north of Lake Taupo (Figure 1). At the present time a combined total of more than 500 MWe is being generated from these three reservoirs. Exploration wells had been drilled in each of these reservoirs by the 1960s and the +60 years of subsurface monitoring since then provides a unique insight into the subsurface links between the three reservoirs. Based on geophysics, geochemistry and pressure data, each reservoir is interpreted to have separate deep recharge (Rosenberg et al, 2010), with interpreted upflow temperatures of 275°C for Wairakei and >300°C for Tauhara. Despite Rotokawa and Tauhara being about 10km to the east and south-east of Wairakei, respectively, up to 1998 Tauhara showed a strong pressure response while the Rotokawa reservoir showed no pressure response to fluid extraction at Wairakei (e.g. Bixley et al., 2009). Rotokawa has been observed to be a separate geothermal reservoir which exhibits large pressure contrasts between production and injection areas and a high degree of reservoir compartmentalization (Clearwater et al., 2016).

Much of the conceptual understanding of Tauhara is reliant on its response to operations at Wairakei due to the hydrological connection between them. This paper presents Tauhara reservoir changes in relation to the changing nature of the Wairakei production-injection operations. To help document the evolution of the conceptual understanding of the reservoir over time (+60 years), reservoir classifications based on geology and reservoir pressures are introduced (Section 2). The development history of the reservoir is divided into four periods to reflect the significant reservoir changes (Section 3).

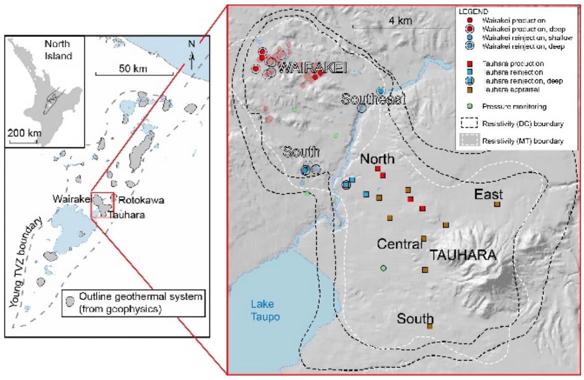

Figure 1: Left: Regional map of the Taupo Volcanic Zone (TVZ) showing location of geothermal systems including area of study (red rectangle); right: Wairakei (to the north-west) and Tauhara (to the south-east) geothermal fields showing well locations as of 2019.

2. RESERVOIR CLASSIFICATION

For the purposes of this paper the Tauhara wells and reservoir have been categorised into "shallow" and "deep" (Table 1; Figure 2) based on geology and reservoir information. Changes to shallow and deep reservoir are the focus of this paper. Changes in the groundwater aquifers above the shallow reservoir (see Table 1 for definition) resulting from pressure change, boiling and formation of steam zones have been extensively documented (Henley and Stewart, 1978; Allis, 1983) and are beyond the scope of this paper.

Geological models of the Wairakei and Tauhara reservoirs have evolved over time, from Grindley (1965), through Steiner (1977), Rosenberg et al., (2009), Bignall et al. (2010) to Rosenberg (2017), which readers can refer to for further detail on geological characteristics given in Table 1.

Table 1 Summary of reservoir units as in this paper. Refer to Figure 2 for geological cross section with geological units. For more information on geological characteristics, refer to Rosenberg et al. (2009). mGL = meters below ground level.

Reservoir	Definition	Geological characteristics	Operational areas (Figure 1, Figure 2)
Groundwater aquifers	Superficial layer above cap of reservoir (nominally 0-200 mGL). Includes cool groundwater aquifers, thermal aquifers and surface thermal manifestations. Permeability is mainly formational.	Unconsolidated volcanic deposits and alluvium and shallow ignimbrites (S)	
Cap	Low permeability layer between superficial aquifers and shallow reservoirs (nominally 200-350 mGL). Some permeable intercalations of volcanic breccia may host liquid and two-phase zones locally within production areas.	Fine lacustrine deposits with some intercalations of volcanic breccia	
Shallow reservoir	Two-phase or dry-steam reservoir toward the top of production areas (nominally 250-600 mGL), otherwise two-phase or liquid reservoir (600-1250 mGL). High permeability (mostly formational; fracture-permeability also present)	It includes lavas, volcanic-hydrothermal breccias and volcanic-clastic deposits. Lavas are dominantly rhyolitic and typical targets for production and reinjection	Wairakei production, Southeast Wairakei reinjection, North Tauhara production
Deep reservoir	Liquid reservoir (>1250 mGL to 3,000 mGL). Formation permeability present locally. Fracture-permeability increasingly important.	Typically volcanic deposits older than 300 ka and younger than 2 Ma (Rosenberg, 2017), including welded and unwelded ignimbrite, rhyolite and andesite lava and undifferentiated volcanic-clastic deposits.	Wairakei North production, Wairakei Southeast reinjection, Wairakei South reinjection, Tauhara North reinjection
Basement	Low permeability reservoir. In effective terms, top of basement is bottom boundary of productive reservoir.	Pre-volcanic greywacke and argillite. Not yet drilled in the Wairakei and Tauhara areas (within drilled depth of ~3 km). Its existence at depths greater than 3 km is inferred from geophysics and geology of neighbouring geothermal fields of the TVZ.	
Outfield	Any part of the reservoir outside the reservoir boundary (See Figure 1). Characterised by "cold-hydrostatic" pressure gradient.		

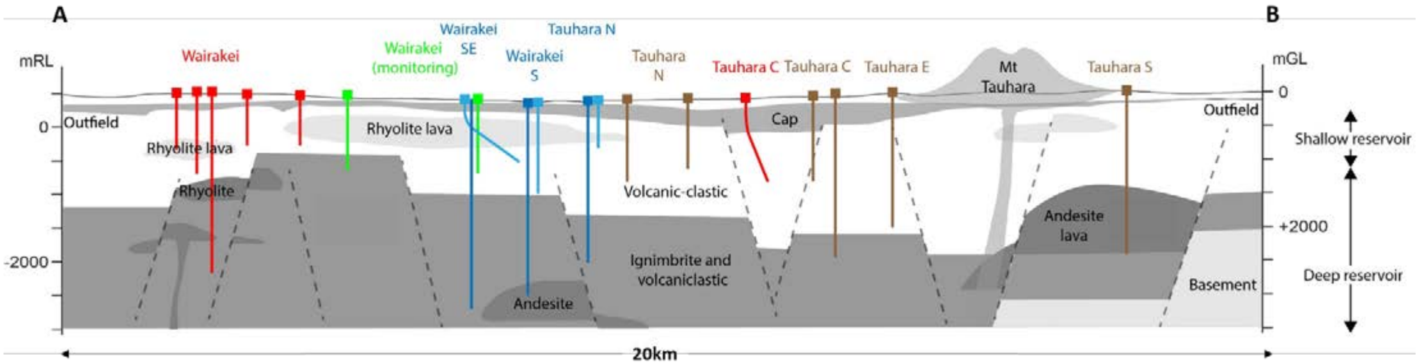

Figure 2: Reservoir classification as in Table 1 illustrated in vertical cross section along A-B direction as shown in Figure 4, together with well data as of 2019, 0mGL referenced at 400mRL (see Figure 1 for geographic distribution).

3. DEVELOPMENT AND OPERATIONAL HISTORY

Figure 3 illustrates pressure trends with time of the liquid reservoirs for both Tauhara and Wairakei. Correlations of pressure trends with production and reinjection history are further explored in this section. The following operational periods are defined (and shown in Figure 3):

- **Period I: pre-1985** Large scale production at Wairakei started in 1956, peaked at ca. 75 Mt/year in 1964 and subsequently levelled off at ~45 Mt/year. In this period there was no reinjection, no development at Tauhara, and pressure decline was observed across both Wairakei and Tauhara;
- **Period II: 1985-1998** Fluid extraction at Wairakei was maintained at about 45-50 Mt/year while reservoir pressures in both fields stabilized; there was only intermittent short-term injection tests, but overall no reinjection.
- **Period III: 1998-2011** Large-scale (mostly shallow) infield reinjection was introduced in the Wairakei Southeast area at about 15 Mt/year (Figure 1, Figure 3), leading to a pressure recovery in wells in both reservoirs. At Tauhara, a relatively small scale development of 7 Mt/year was commissioned in 2010 for electricity generation. Towards the end of this period, small scale reinjection trials commenced at Wairakei South (Figure 1);
- **Period IV: 2011-Present** The extraction rate at Wairakei increased rapidly over two years (2012-2014) to > 90 Mt/year (almost double the previous rate) while reinjection increased to about 50 Mt/year, with reinjection spread between shallow and deep reservoirs (Figure 1, Figure 3).

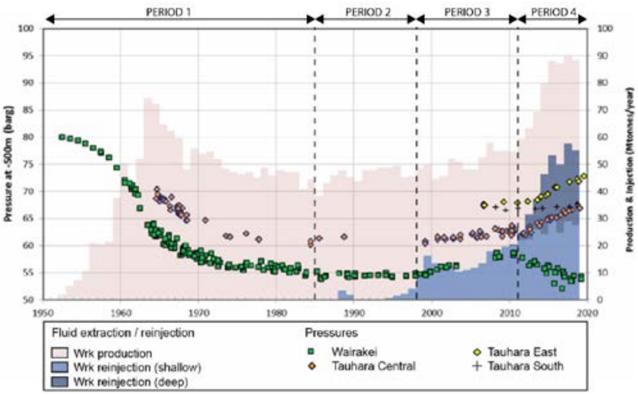

Figure 3: Pressures in Wairakei and Tauhara reservoirs 1950-2020, including development periods as described in text. See Figure 1 for geographic areas. Feedzone pressures for wells have been reduced to a common elevation of -500m relative to sea level (about 900m depth) using the measured reservoir gradient of 0.081 bar/m shown on Figure 6.

4. PERIOD I (pre-1985)

4.1 Operations

In the early stages of exploration, surface geophysics, geochemistry and geology are used to identify the critical elements needed to develop a conceptual model that can be used for well targeting (Cumming, 2016). At the time of early drilling at Wairakei, there was no proven experience with geophysical exploration methods. Hence, the approach to reservoir development was somewhat pragmatic, guided in first instance by the distribution of surface thermal features and subsequently by drilling results. Exploration drilling at Wairakei started in 1950 and by 1956 large scale production testing (>20 Mt/year) had been undertaken. In the first decade of production, fluid extraction was focussed in a small area of about 1 km^2 in the eastern part of the field, which progressively expanded to the north-west (Figure 4A). The fluid extraction rate quickly increased and reached a peak rate of 73 Mt/year in 1963. After this the extraction rate gradually declined and stabilised at about 45 Mt/year from 1975. No reinjection was practiced in this period.

By the early 1960s direct-current (DC) resistivity surveys had identified a potential resource at Tauhara (Banwell and Macdonald, 1965) and four appraisal wells were drilled to evaluate the resource potential from 1964-1967 (Figure 4A).

4.2 Reservoir

The Tauhara appraisal wells encountered maximum temperatures close to 255°C at 600-800m depth, except for the southernmost well which found higher temperatures (275°C at 900mGL).

From routine downhole pressure measurements it was soon apparent that although these wells were up to 10 km away from the Wairakei production area, the reservoir pressures at Tauhara were declining at the same rate as at Wairakei (Figure 3), but were about 5 bar higher than the Wairakei pressures. At the time, the explanation for the pressure offset of 5 bar was not clear: it could have been due to a timing lag as the pressure signal spread from Wairakei to Tauhara, a simple drainage effect as fluid drained from the margins of the reservoir toward the pressure sink at Wairakei, or it could be accounted for by a U-tube effect due to slightly different reservoir temperatures and a deep pressure connection. The pressure difference between the two fields of 5 bar was maintained from 1965 to 1985.

Nevertheless, the clear pressure communication between Wairakei and Tauhara cemented the concept of extensive horizontal (formation controlled) permeability with a connection in the shallow reservoir being favoured.

4.3 Geophysical Investigations

When the Tauhara appraisal wells were drilled in the 1960s, geophysical methods to delineate geothermal resources were in their infancy. A DC resistivity field survey had been undertaken over part of the Tauhara field in the early 1960s, which in retrospect roughly outlined the shallow reservoir in Northern Tauhara (Banwell and Macdonald, 1965). Together with geology and the extensive surface manifestations, this survey was used to assist in locating the four Tauhara appraisal wells drilled at that time.

Over the next decades (1970s to 1990s) the geophysical boundary of Tauhara was refined by further DC resistivity surveys (Risk, 1984, Risk 1994 to produce the DC boundary shown in Figure 4A.

4.4 Heat Flow and Natural Recharge

Before development at Wairakei, the natural heat flow at Tauhara was estimated to be about 100MWth (Allis 1983). This heat flow was evident as neutral chloride springs and geysers, heated groundwater and steaming ground. The pre-development deep recharge to Tauhara cannot be accurately determined as there was most likely significant subsurface

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heat discharge, particularly to the north of the reservoir. However, allowing for possible hot subsurface outflows and assuming deep recharge temperature of >275ºC, the natural state deep recharge rate at Tauhara would have been in the order of 100 kg/s (3 Mt/year). Production at Wairakei with the resultant decline in deep pressure at both Wairakei and Tauhara resulted in the cessation of all thermal features reliant on boiling, pH neutral chloride fluids. At the same time, the heat output at all steam-heated thermal areas at Wairakei increased while only steam-heated features in the northern half of Tauhara increased (Allis et al., 1989); the features in the southern half were unchanged.

4.5 Conceptual Model

Healy and Hochstein (1973) coined the term "outflow" to describe horizontal flow in marginal parts of a geothermal reservoir, having noted well temperature inversions in some geothermal reservoirs of New Zealand and Chile. Allis (1983) used a similar concept to describe the northern part of the Tauhara reservoir. The 275ºC maximum temperature measured in the southernmost appraisal well suggested this well was the closest of the four wells to the deep recharge or upflow. A small temperature inversion at the bottom of the well, however, suggested the southernmost well was still within an outflow implying a deep recharge zone further to the southeast. In the natural state this outflow supported the surface discharges of hot chloride springs and geysers along the Waikato River in Tauhara North (Figure 5A). As the outflowing fluid continued to move to the north toward Wairakei it interacted with the Wairakei outflows as evidenced by wells in the Wairakei East and Southeast areas.

Pressure decline and declining surface activity in the northern part of the Tauhara reservoir area in response to production from Wairakei indicated that there was a strong hydraulic connection connecting the two reservoirs. At this time the location of the boundary between the two reservoirs was somewhat unclear, and was generally assumed to be near the Waikato River. The absence of any change to the surface thermal features in the southern part of Tauhara suggested there may be parts of the reservoir less well connected to Wairakei.

The vertical connectivity to shallow depths with the observed changes to surface manifestations and lateral connections across >5km distances from NW to SE allowed some interpretation about fluid movement between the reservoirs, with Wairakei production understood to be drawing some fluid over from the Tauhara reservoir. Understanding of the deep recharge was limited, and, as drilling had not yet tested the reservoir margins, there were uncertainties as to the nature of the lateral reservoir boundaries.

The envelope of pressure response for the Wairakei-Tauhara reservoir as understood in 1985 is shown in Figure 4A. This is based on temperature distribution, pressure drawdown and changes to surface manifestations. The lateral extent covered was about 10-12 km with the majority of deep production wells drilled to less than 1,200m depth. As can be seen in Figure 4A this represented a relatively small portion of the reservoir to that which was explored at the time. A cross section interpretation is given in Figure 5A showing the limited knowledge of the two reservoir in 1985. This cross section reflects the natural state conceptual model of the reservoir.

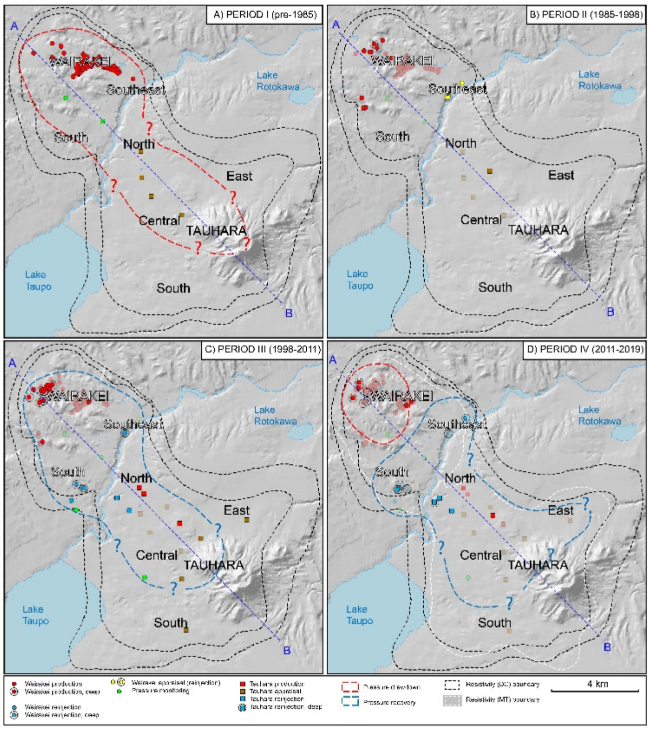

Figure 4: Envelope of pressure drawdown based on well pressure and changes to surface thermal manifestations based on data available until (A) 1985, (B) 1985-1998, (C) 1998-2011 and (D) 2011-2019. DC Resistivity boundary after Risk (1984) and Risk et al. (1994). MT Resistivity Boundary as of 2010. A-B cross section direction used for concept models shown for reference. Legend abbreviations: WRK = Wairakei; TAU = Tauhara. Not all WRK monitoring wells shown.

5. PERIOD II (1985-1998)

5.1 Operations

During 1985-1998 new production wells were drilled at Wairakei North (liquid reservoir) and Wairakei West (dry-steam reservoir) areas. Due to progressive decline in production at Wairakei East, the overall impact of new production on the average extraction rate was minor (maintained at about 45 Mt/year), with reservoir pressures remaining relatively stable. Several appraisal wells were drilled in the Wairakei Southeast area and tested for reinjection capacity (Figure 4B).

In Tauhara Central, only one appraisal well was drilled during this period into the shallow (<500m) reservoir encountering similar temperatures compared to previous appraisal wells of Tauhara Central. As such there was limited additional information provided regarding the extent of the Tauhara reservoir during this period.

5.2 Conceptual Model

The stabilization of pressures at Wairakei and Tauhara indicated the production had reached an equilibrium with recharge into reservoir. This allowed the analysis of the nature of the recharge to be performed. A mass balance using the well flows and chloride flux together with microgravity and pressure change demonstrated that by 1990 the natural hot recharge at Wairakei of about 12 Mt/year (400 kg/s - Allis, 1981) had increased by about three times to about 35 Mt/year and that the remaining recharge of about 10 Mt/year comprised cooler, shallow aquifer fluids (Brown et al., 1987). Some of the cool recharge was entering the Wairakei reservoir vertically via the conduits that had originally supported the chloride springs in the eastern margin of the field. By analogy, similar cool recharge was thought to be entering the Tauhara reservoir via the chloride springs in North Tauhara. The 5 bar pressure difference between Tauhara and Wairakei was considered to result in a flow of hot reservoir fluids from Tauhara to Wairakei in the shallow reservoir (400-800m depth), perhaps diluted to some extent by the cool fluids flowing down into the reservoir through the original natural spring conduits.

The conceptual model of the Tauhara reservoir remained relatively unchanged during this period with the exception of the shallow interactions with surface manifestations in the northern part of the reservoir (Figure 5B). The southern manifestations continued to remain unchanged during the period.

6. PERIOD III (1998-2011)

6.1 Operations

During this period there were a number of operational changes across both the Wairakei and Tauhara reservoirs as well as some supplemental drilling.

At Wairakei:
Production quantities increased slightly and production wells continued to migrate toward the north-western part of the reservoir as older wells in the east failed, with the majority of production still obtained from less than 900m depth;

- Appraisal drilling programs were conducted from 2003 provided further information on the reservoir structure (via reservoir temperature, pressure and fracture logging).
- Additional reinjection wells (1200-3000m depth) were drilled at Wairakei South and Wairakei Southeast.
- Large-scale shallow reinjection of separated geothermal water commenced at Wairakei Southeast. By the end of this period ~30% of produced fluids were reinjected at shallow depth (400-900m).

At Tauhara:
- A series of mid-depth (1000-1250m) wells and deeper appraisal wells (1900-2500m) were drilled from 2006 to provide more information on the extent of the high temperature resource.
- Production started between 2008-2010 for industrial heat use and electrical generation. Both developments used 100% shallow reinjection of produced fluids (~7 Mt/year) located in the northern part of the reservoir (Figure 1).

6.2 Reservoir

Immediately after starting reinjection in southeast Wairakei in 1998 pressure began increasing in all the monitored wells in both Wairakei and Tauhara reservoirs, with a total increase of 3 bar by 2009. Toward the end of this period the reservoir pressures started to stabilise and data measured at this time from Wairakei and Tauhara wells was used to define the infield pressure-elevation gradient down to 3000m depth (Figure 6). The new appraisal wells also proved much higher temperatures than had previously been encountered at Tauhara Central (290-320°C).

New pressure data showed that both Tauhara and Wairakei reservoirs had the same vertical pressure gradient of 0.081 bar/m (hot water gradient for 231ºC), even though the actual reservoirs temperatures were somewhat higher (230-270ºC at Wairakei and 250-300ºC at Tauhara). The plot also shows that for each reservoir the pressure gradient is consistent throughout the whole depth range in all the measured wells, indicating there was very good vertical permeability in each reservoir with no significant permeability barriers.

At this time it was also noted that well pressures for the reinjection area at Wairakei South, conventionally assigned to the Wairakei reservoir, fell on the Tauhara pressure trend, rather than the Wairakei trend (Milloy and Lim, 2012). Downhole fluid samples from two wells at Wairakei South also indicated by their Cl/B ratios and isotope analysis that they were related to Tauhara fluids rather than Wairakei. A further clue to the permeability structure at Tauhara is that two of the appraisal wells at Tauhara East and Tauhara South had pressures significantly higher (~5 bar) than the trend seen in all the other Tauhara wells (Figure 6).

6.3 Geophysical Investigations

A downhole seismic network was commissioned 2009 to provide high-resolution seismic monitoring. By 2011, a reasonable picture of background (baseline) microseismicity had been produced at Wairakei South and Tauhara North. At around the same time (2010), magneto-tellurics (MT) surveys were undertaken across Wairakei and Tauhara to resolve the three-dimensional resistivity structure. Using the criteria outlined in Sepulveda et al. (2014), a revised geophysical reservoir boundary was obtained (Figure 4C), which was a good match with the DC resistivity boundary between 0-400 m.

6.4 Conceptual Model

System Upflow

The new deep appraisal wells indicated that the deep recharge at Tauhara was much hotter (>300ºC) and covered a larger area than had been previously considered and was most likely located further east, close to the eastern margin of the field (Rosenberg et al., 2010). The recharge concept outlined in Section 4.2 for the 1985-1998 period was revised to move the deep recharge zone further to the east and increase the temperature from ~275°C to >300ºC.

Wairakei-Tauhara Boundary

The 2009 pressure-elevation plot (Figure 6) shows the Wairakei South and the deep Wairakei Southeast well pressures falling on the Tauhara trendline. Therefore these wells lie within the Tauhara reservoir, rather than Wairakei. Accordingly the deep boundary separating Wairakei and Tauhara was moved northeast to separate the Wairakei production area from the Wairakei South reinjection area. The position of Wairakei Southeast reinjection wells is more complicated. The deep wells belong to Tauhara based on the pressure trend correlation, while the shallow wells remain closely linked to Wairakei (as demonstrated by the response of some shallow wells here to production in the 1950s) and still retaining a highly probable link to Tauhara as this area is close to the Wairakei-Tauhara shallow connection zone.

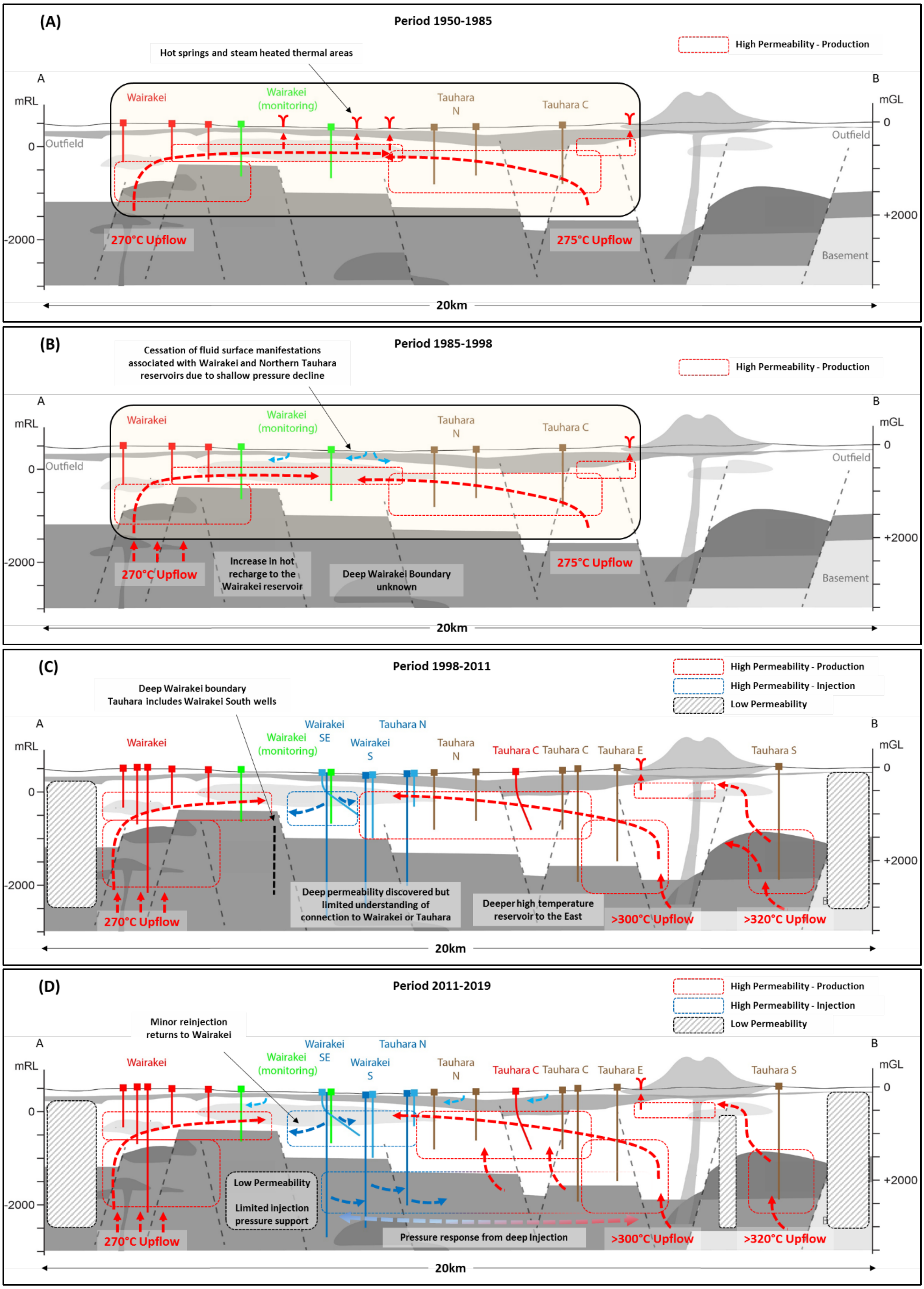

Figure 5: Conceptual Models: (A) 1950-1985 Natural State, (B) 1985-1998, (C) 1998-2011 and (D) 2011-2019. Cross Section A-B shown on Figure 4.

Permeability

All of the deep injection wells (>2400m) drilled in this period encountered high permeability at 2200-2500m. These wells are spread over all three injection locations and lead to the idea that there may be some stratigraphic or formational control on the deep permeability. At this time there was insufficient data to evaluate any pressure response related to deep injection as there had been no sustained injection.

The 3 bar pressure recovery between 1998 and 2011 demonstrated that reinjection at shallow and intermediate depths from Wairakei Southeast was providing pressure support (in equal amounts) to both Wairakei and Tauhara reservoirs. This response was consistent with the concept of widespread horizontal permeability interpreted from pressure drawdown resulting from production at Wairakei (in previous periods). While geochemical evidence pointed to minor reinjection returns from Wairakei Southeast to Wairakei production (shallow reservoir, eastern margin mainly), the cooling at Wairakei was still dominated by intrusion of cooler fluid from above the production reservoir.

The approximate envelope of the Wairakei and Tauhara reservoirs as understood by the end of the 2011 (based on pressure drawdown and pressure recovery following Wairakei Southeast reinjection) is shown in Figure 4C. This area is marginally larger than the pressure drawdown area of Figure 4A reflecting the extended coverage of new wells, rather than an expanded area of pressure change. The updated conceptual model is shown in Figure 5C.

7. PERIOD IV (2011-2019)

7.1 Operations

At Wairakei:

- Appraisal drilling continues until 2013, supporting further expansion of production to the northwest and to greater depths. Fluid extraction rate increased from about 50 Mt/year to almost 90 Mt/year by 2015 (Figure 3).
- Reinjection also increased significantly during this period; from 15 Mt/year to 50 Mt/year with about 60% of reinjection by 2019.
- Increased reinjection volumes are part of a major shift in the reinjection strategy of increased reinjection from shallow injection, mostly at Wairakei Southeast, to approximately 50:50 shallow and deep injection spread across all the injection areas. The Wairakei South area increasingly became the focus with approximately 65% of the total injection as of 2019.

At Tauhara:

- Operations remained the same as the previous period (7 Mt/year production; 100% reinjection), except for a shift from 100% shallow to 30% shallow and 70% deep reinjection.

7.2 Reservoir

The Wairakei and Tauhara reservoir pressures responded very differently to operational changes in this period. Pressures in Tauhara Central deviated from the decreasing pressure trend of Wairakei wells, having previously followed them (with a 5 bar offset for the previous >50 years). In 2011 the rate of pressure build-up at Tauhara increased from about 0.2 bar/year to 0.7 bar/year, while at Wairakei began to decline once more at about 0.5 bar/year (Figure 3).

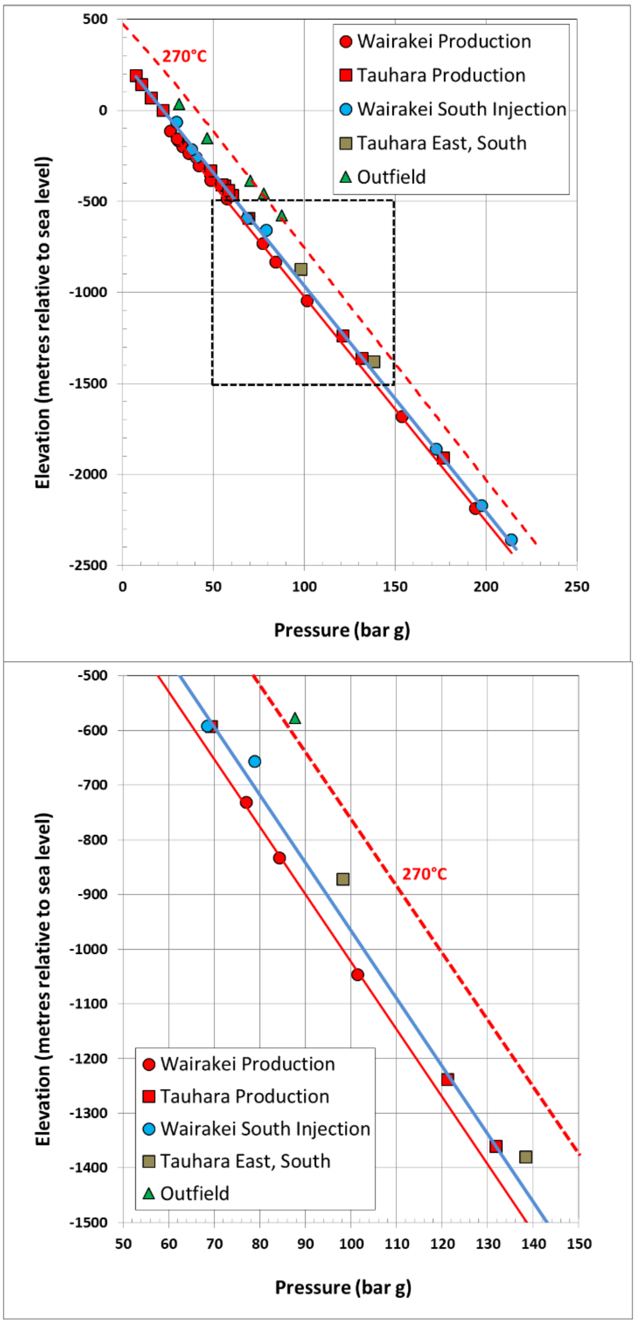

Figure 6: Pressure-elevation plot for Wairakei-Tauhara in 2009. Reference pressure gradient from ground level for hydrostatic and 270°C fluid at saturated conditions shown for reference (dashed blue and dashed red lines, respectively).

This period also showed some new behaviour by the Tauhara East and Tauhara South wells which in 2009 had anomalously high reservoir pressures. Since 2013 pressures in Tauhara East (already a further 5 bar higher than the other Tauhara wells) have increased at the same rate as the main Tauhara trend (Figure 3). This is noteworthy considering the pressures are already above the general reservoir pressure and the significant distance to the Tauhara Central wells. Pressures in

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Tauhara South however, have not changed significantly (Figure 3). An interpreted envelope of pressure drawdown and pressure recovery for Wairakei and Tauhara reservoirs is used to highlight possible areas of communication associated with changes in the production and reinjection strategy of this period (Figure 4D).

The pressure difference measured at 500m depth between Tauhara East and Tauhara Central can be explained by a "U Tube" connection, at 2200-2500m between these area using the hydrostatic gradient for the observed temperatures of 300ºC and 255ºC. A lateral high permeability connection at this depth also fits with feedzone information from the deep wells that shows consistent deep permeability in all wells (Figure 5D).

Tracer testing was completed in 2016 indicating that a small, slow return of fluid from Wairakei Southeast reinjection to Wairakei wells. There were no signs of tracer returns from Wairakei South to Wairakei, nor were there any returns detected at Tauhara from either reinjection areas.

7.3 Geophysical and Geological Investigations (local and regional)

Geoscientific and reservoir information from more than 200 wells in the Wairakei and Tauhara reservoirs and a series of field studies (e.g. MT surveys, microseismic monitoring, formation imaging, fault mapping) have helped refine the conceptual model in regards to:

- Field boundaries: based on the remarkable agreement between "infield" vs "outfield" classifications based on DC/MT resistivity boundary (<400 m) and well reservoir pressures (shallow and deep reservoir) (e.g. as documented in Sepulveda et al., 2014 and this study), the resistivity boundary continues to be the best available representation (and predictor) of the field boundary (both shallow and deep reservoir).
- Formation permeability: using porosity from TVZ core samples as a proxy for formation permeability in the shallow and deep reservoir (Stratford and Stern, 2008), formation permeability can be expected to decrease with depth (average porosity >20% and > 10% in shallow and deep reservoir respectively). In practice, correlation of feed zones and geological logs shows that formation-related permeability is present both within the shallow and deep reservoir.
- Field (tectonic) structure: based on surface fault-mapping (Villamor et al., 2015), formation imaging (Massiot et al., 2013), microseismicity (e.g. Sepulveda et al., 2013, 2015) and geological logging (Rosenberg et al., 2009; Bignall et al., 2010; Rosenberg, 2017), the structural characteristics of Wairakei and Tauhara reservoirs can be summarised as follows:
    - Presence of a primary (dominant) NE-SW trending structural overprint associated with a normal stress regime throughout the reservoir (shallow and deep) (e.g. Rowland and Sibson, 2004; Wilson and Rowland, 2016);
    - Presence of a secondary (less dominant), oblique (i.e. other than NE-SW) structural overprint associated with caldera structures (Rosenberg, 2017), accommodation zones (Rowland and Sibson, 2004), or inherited basement structures. Caldera structures and basement structures are suspected to mainly play a role in permeability of the deep reservoir;
    - Presence of large (typically hundreds of meters) stratigraphic offsets associated with faulting and post-300 ka caldera events in the deep reservoir. Stratigraphic offsets are of lower magnitude in the shallow reservoir due to shorter (geological time scale) fault reactivation history and absent large-scale, caldera forming episodes.

7.4 Conceptual Model

A revised conceptual model for Tauhara as of 2019 is presented in Figure 5D. The key aspects of the current conceptual model reflect:

- Pressure trend data which shows a diversion of response between Wairakei and Tauhara wells which appears to be in response to increased production and deep injection associated with operations at Wairakei.
- The evidence that deep pressure support resulting from injection at Wairakei South and potentially Wairakei Southeast is far reaching across the Tauhara field further to the SE.
- An extensive zone of deep permeability from Tauhara East across Tauhara North and including the Wairakei Southeast and Wairakei South reinjection areas.
- Strong pressure communication throughout the vertical and lateral extent of the Tauhara reservoir with the exception of Tauhara South.
- A compartmentalized deep reservoir with limited injection pressure support to Wairakei and stronger pressure support to Tauhara.
- Shallow communication remaining as understood from the 1960s from Wairakei through to Tauhara North.

System Upflow

The concept of separate upflows to Tauhara East and South gained more support with the lack of pressure response in the South (Figure 3). While the concept of lateral flow from SE toward the NW at 400-800m depth in the reservoir still holds true today, a second much deeper connection below 2000m must also be present. This is largely supported by the pressure response observed at Tauhara East.

Boundary Conditions / Recharge

Wairakei is an anomaly in the global geothermal context. It is a mature reservoir with a large estimated natural hot recharge (~400kg/sec, 12 Mt/year) which has since been estimated to have tripled in response to pressure drawdown, limiting the drawdown and buffering cool inflows which might otherwise have been drawn into the reservoir from either above or from the sides. Tauhara is estimated to have had roughly 25% of the natural hot recharge estimated at Wairakei and most temperature degradation is localised and attributed to cold intrusion of shallow fluids rather than cooling of deep recharge. The lateral boundaries to both Wairakei and Tauhara reservoirs would appear to be low permeability, limiting the ingress of peripheral cooler fluids into the reservoir. This is supported by drilling results at the reservoir margins and the lack of significant temperature decline in these wells over more than 50 years.

Reservoir permeability

Pressure data shows that Wairakei and Tauhara are two separate reservoirs with strong communication at shallow and intermediate depths. Effects of early production at Wairakei (mostly shallow reservoir) were far reaching with pressure drawdown extending through Tauhara North to Central and

East areas. The effects of early Wairakei Southeast injection (1998-2011, mostly shallow reservoir) were similarly extensive across the whole reservoir. Pressure effects from more recent deep injection at Wairakei Southeast and Wairakei South appears more compartmentalized, with Wairakei South and Tauhara (North, Central and East) showing the strongest communication.

With regards to the deep Tauhara reservoir, the first downhole pressures measured in Tauhara South and East in 2008 fell on a similar trend, about 5 bar higher than all the other Tauhara wells (Figure 6). At this time this was interpreted as Tauhara East and Tauhara South wells being representative of the pressure domain near the margin of the reservoir. However, since 2008 the Tauhara South pressures have not changed, while Tauhara East has followed the increasing trend seen in all the other Tauhara wells.

Taken together, the lack of change in the surface thermal features in Tauhara South coupled with the lack of pressure response in there, appears to confirm the hypothesis of Allis (1989) that Tauhara South forms a separate compartment of the reservoir. This type of compartmentalisation is also evident at the Rotokawa reservoir to the north of Tauhara (Clearwater et al., 2016). The 5 bar offset in Tauhara East now appears to confirm that there is an extensive zone of deep permeability at 2200-2500m extending from Tauhara East back toward the Wairakei South and Southeast injection areas. While there are also indications of deep permeability in the production areas in the northern part of Wairakei, the deep communication between Wairakei South and Wairakei North is less evident.

Evidence for formational permeability in shallow and deep reservoirs, combined with evidence in favour of a dominant NE-SW structural direction, and evidence in favour of deep reservoir pressure compartmentalisation support the concept of deep structures acting both as channels and barriers for fluid flow. This dual behaviour of faults is less evident in the shallow reservoir where horizontal permeability is large and linked to permeable formations.

8. SUMMARY

A growing understanding of the reservoir has been gained thanks to the introduction of injection, extended reservoir monitoring and new appraisal tools. This has consolidated the view of strong communication between the two reservoirs at shallow and intermediate elevations, but also demonstrated a greater degree of compartmentalization with increasing depth. This compartmentalization is not only evident between the Wairakei and Tauhara reservoirs but also within Tauhara itself, with the southern part of the reservoir showing the highest temperatures, relatively invariable surface manifestations and stable reservoir pressures over the past 60 years. Compartmentalisation in the nearby Rotokawa reservoir has been seen to have had a significant influence on the management of the reservoir. In Tauhara there is now strong evidence that there are multiple upflows driving fluid through the reservoir at intermediate and shallow elevations.

The evolution of the conceptual model of the Tauhara reservoir has been facilitated through expanded drilling campaigns alongside the changes in operation at nearby Wairakei over the past 50 years. The absence of either would have meant a significantly different understanding of the two reservoirs. Deeper wells across the reservoirs have brought new information on responses; be it pressure, temperature or chemistry changes. Although the development of a conceptual model requires many types of supporting data, measured pressure responses have been the most significant tool in helping distinguish different reservoir behaviours. The unique information at Tauhara is the period of increasing pressure from which an extensive zone of deep permeability has been indicated.

From a reservoir management perspective, the understanding of the response of the reservoir to reinjection with respect to both pressure and temperature is critical to the effective and sustainable development of the resource. While Tauhara has not been produced to the extent of Wairakei, the large swings in reservoir pressure (10-20 bar) have not caused notable degradation of temperatures in the productive reservoir. Pressure support from deep reinjection provided across long distances with little or no degradation in reservoir temperature in production areas is viewed as a significant advantage in the context of adaptive management of the reservoir. At the time of writing an appraisal well drilling program had commenced at Tauhara which will most likely lead to further refinement of the conceptual model in due course.

This study further reinforces why conceptual models should be considered as being live and in a constant state of adjustment and modification, providing an evolving foundation for field management and the calibration of numerical simulation models.

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