THE OHAAKI DEEP RESERVOIR

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1 ABSTRACT

The original exploration wells drilled on the West Bank section of the Ohaaki reservoir in the 1960s proved a very productive, high temperature resource at 450-1100m depth. Since production started a significant part of this resource has been invaded by cooler waters, reducing or stopping production in many wells.

During 2005-2007 a deep makeup well program was undertaken to restore the lost production. Twelve new wells were drilled; nine of these being deep wells located on the West Bank targeting permeability below the original production zones at 450-1100m. These deep wells proved an extension of the productive reservoir on the West Bank down to 2,400m depth with temperatures up to 307°C. In retrospect, such an extension of the reservoir was implicit from the exploration wells drilled in this area during the 1960s, as many of these wells developed strong two-phase upflows while shut-in.

After production from the new deep wells started in 2008, the deeper part of the reservoir developed a separate pressure regime about 40 bar lower than that in the overlying “intermediate” production aquifer. Maintaining production from the deep reservoir provides several challenges due to the large pressure drawdown and “cool” interzonal flows in some wells which have feedzones in the different aquifers. This paper outlines the development and evolution of the Ohaaki West Bank reservoir since production started in 1964.

2 INTRODUCTION

Field exploration and development at Ohaaki has continued over more than 40 years, with the level of activity influenced by government policy, uncertainty in the resource potential, effects of reinjection and influx of cooler fluids. Geoscientific exploration work commenced in the early 1960’s and indicated a potential resource area of up to 10 km^2 (Figure 1). The level of drilling activity with time is shown on Figure 2. The first well, BR1, was drilled in late 1965 and although this well encountered high temperatures, the overall permeability was poor and production could not be sustained. The second well, BR2, was the discovery well, with temperatures of 280 °C and high production rates, capable of generating more than 14 MW$_e$ (via 8-5/8” production casing). Twenty-five more wells were drilled and tested from 1965 – 1971. During this time there was extensive production testing, largely from the West Bank wells, at a flowrate equivalent to about 30 MW$_e$. Most of the wells at this time were drilled to about 1200 m maximum depth with the bulk of the production being derived from 450-1100 m depth. One well had been drilled to 2,400 m, but although finding temperatures up to 300 °C, permeability was insufficient to sustain production. At this time the proven productive resource area was about 3 km^2.

Development drilling continued on intermittently until 1988 when the 116 MW$_e$ plant was commissioned and 45 wells had been completed.

Production testing had indicated a decline at a rate of 14% per annum could be expected and at the time of commissioning the plant in 1988 sufficient reserve capacity was available for two years’ operation without makeup drilling. By 1993 the effects of invasion of cooler water were being seen in the shallower part of the production areas together with returns of reinjected water in some production wells. Most of the reinjection was relocated outfield at this time but influx of cool fluids continued to impact many of the shallower-feeding (<600 m) production wells.

In 1995 a deep drilling program was undertaken with the objective to explore the resource potential below the proven production zones at 1100 m. Three deviated wells were drilled across the structural trend to vertical depths of 2,000 m. No significant permeability was found in the greywacke “basement” on the East Bank, but high temperatures and reasonable permeability were identified in the deep volcanic formations underlying the West Bank. In 2005 a development drilling program was undertaken with 12 additional wells completed by 2007. Nine of these wells were deep production targeting high temperatures below 1500 m depth on the West Bank. In 2009 two further deep makeup wells were drilled.

3 PRODUCTION HISTORY

The Ohaaki field development and production history has been summarized by Clotworthy et al, 1995 and Lee and Bacon 2000. The location of the current West Bank production wells together with BR2 (abandoned in 1998) are shown on Figure 1.

Generation was maintained at ~100MW$_e$ from 1988 until the end of 1993 when the available steam supply fell below the rate required for full load conditions. From 1993 the production decline rate was reduced by gradually lowering production and separation pressures and after 2001 by regular well workovers to remove calcite scaling. Never-the-less, by 2006 generation had declined to 40 MW$_e$.

Following the 2005-2007 deep drilling programme, five new wells were commissioned and generation increased to 65MW$_e$. However from 2009 the station output again declined and despite continuing workovers to remove calcite scale and two additional deep makeup wells the output is currently 45-50 MW$_e$.

3.1 Field Enthalpy

The discharge enthalpy trends since the plant was commissioned in 1988 are plotted on Figure 3. During the 1968-71 testing period the West Bank wells had shown a strong enthalpy increase as pressures in this part of the resource declined with resultant boiling and formation of two-phase conditions. One well even produced only steam for a brief period. At this time many of the West Bank wells developed strong internal two-phase upflows when shut-in. In 1971 all production wells were shut. Several wells developed relatively cool downflows (220-230 °C) and the two-phase zone collapsed due to influx of these cooler fluids and pressure recovery.

After restarting power production in 1988 reservoir pressures again declined but the overall West Bank enthalpy showed little change from the initial value of 1200 kJ/kg (Figure 3). This is due to a combination of cooling through influx of shallow fluids and limited boiling in some wells. Subsequent changes in overall enthalpy and gas content for West Bank wells reflect production well selection rather than changes in the reservoir. Between 1998-2000 several of the wells worst affected by cooling were shut and in 2008 new deep high temperature wells were brought online.

The East Bank wells have followed a more conventional response of enthalpy to reservoir pressure drawdown, with development of two-phase zones and segregated steam zones near some wells, with a resultant increase in enthalpy over the first two years' operation (Figure 3). However after 1990 the overall discharge enthalpy of the East Bank wells followed a decreasing trend as the influx of shallow cool fluids began to dominate. Overall the total field enthalpy remained between 1200-1400 kJ/kg up to 2007 when the new deep wells were brought online.

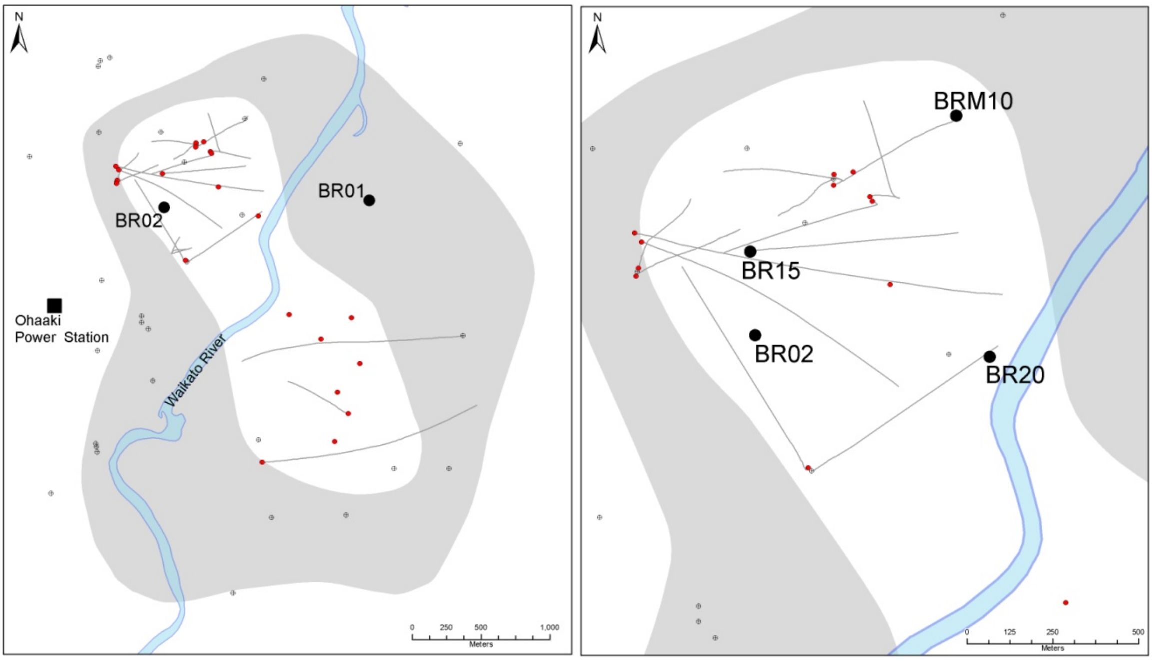

Figure 1: Map of the Ohaaki geothermal field. The left map is the Ohaaki field showing the field boundary. The outer boundary is defined by the DC resistivity and the inner boundary is the 270 ˚C isotherm at -600 masl which outlines the productive area of the field at this depth. There are distinct differences in the characteristics of the eastern and western wells, particularly the fluid chemistry and for convenience the field is divided into two zones with respect to the Waikato River: the West and East Banks. The right map is a close-up of the West Bank showing the well tracks of the deep production wells and other shallower wells referred to in the text.

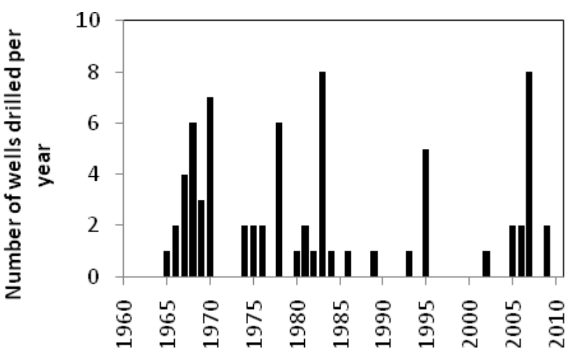

Figure 2: Wells drilled over time at Ohaaki.

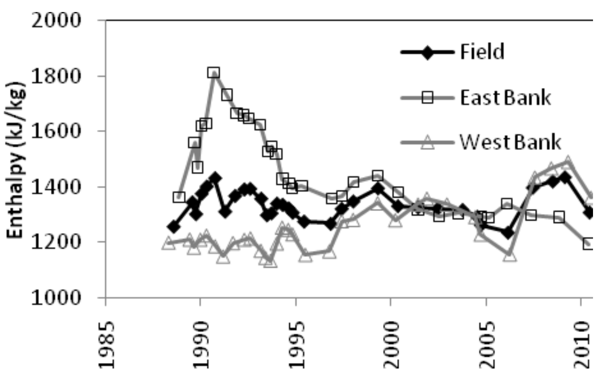

Figure 3: Enthalpy Trends for the Ohaaki field 1988-2010.

4 PRESSURE CHANGES

4.1 West Bank Liquid Pressures

Pressure changes with time at Ohaaki are discussed by Hitchcock and Bixley, 1975, Clotworthy et al, 1995 and Lee and Bacon, 2000. During the 1968-1971 production testing on the West Bank, pressures in this part of the reservoir declined by up to 17 bar, although local zones of greater drawdown developed near some lower permeability wells. Subsequently reservoir pressures gradually recovered until by 1988, just before commissioning the 116 MW plant, the pressures had recovered to 5 bar below the pre-development values.

At this time it had become evident that on the West Bank an aquifer containing relatively cool water (Ohaaki Rhyolite aquifer, 150-200°C) overlay the production reservoir and that this aquifer and the hot geothermal reservoir were in good hydraulic communication. This had been demonstrated by pressure interference testing, tracer testing and by the fact that the hydraulic gradient was continuous between the "aquifers" (Figure 5).

Pressures monitored in the geothermal reservoir and in the overlying Ohaaki Rhyolite aquifer since 1987 are plotted on Figure 4. For simplicity, pressures in only two wells are plotted: BR20 a very permeable well with a major feedzone at 1000 m depth (-708 metres above sea level [masl]) which reflects pressures in the West Bank "upper reservoir"; and BRM10 which has permeability at 250 m depth (+45 masl) in the Ohaaki Rhyolite. Following commissioning of the power plant, pressure in the production reservoir declined, reaching a maximum of 20 bar below the 1987 value by 1994. Since then pressure in the "upper reservoir" has recovered by 10 bar as the production from West Bank wells declined. Pressures in the Ohaaki Rhyolite which overlies the "upper reservoir" on the West Bank followed a similar tend with time and a maximum decline of about 12 bar.

Figure 4: Pressure in BR20 (-708 masl) and BRM10 (45 masl). BR20 data reflects pressure change in the "Upper Reservoir", the West Bank production reservoir up to 2007 and BRM10 data reflects pressure change in the Ohaaki Rhyolite, a relatively cool aquifer overlying the "Upper Reservoir" on the West Bank.

4.2 West Bank Deep Aquifer

During the 2005-2007 deep drilling program additional productive resource was identified below the exploited upper reservoir on the West Bank. The wells encountered moderate permeability and high temperatures, up to 307°C, at depths of 1,600-2,100 m. Pressures in the deep wells fell on the same trend as those in the upper reservoir, with a continuous hydraulic gradient from the Ohaaki Rhyolite at 300 m depth down to 2,100 m (Figure 5).

In 2008 five of the new deep West Bank wells were brought on to production. By 2009 downhole pressure surveys showed that there was substantial pressure drawdown in wells with feed zones below 1,500 m (-1200 masl). Pressures were at least 40 bar below the 2007 values. Pressures in the "upper reservoir" (above -1200 masl) showed little change over the same period. Over the last two years the pressure in the lower reservoir appears to have stabilized at 40 bar below the 2007 values.

4.3 Reservoir Structure

The new pressure data, together with historical pressure and temperature changes indicate that on the West Bank the reservoir comprises three main components:

- Ohaaki Rhyolite Aquifer: Contained within the Ohaaki Rhyolite with temperatures 150-200 °C, at depths 100-300 m (elevation +200 to 0 masl). This aquifer is partially isolated from the underlying production reservoir by a thin, but discontinuous, layer of Huka Formation siltstones.

- Upper Reservoir: The "original" West Bank high temperature reservoir. In the natural state temperatures of 240-290 °C at or close to boiling point in the shallower part. Hosted mainly in Waiora Formation and Rautawiri Breccia. Permeability is usually found at depths from 400-1,500 m (elevation -100 to -1,200 masl).

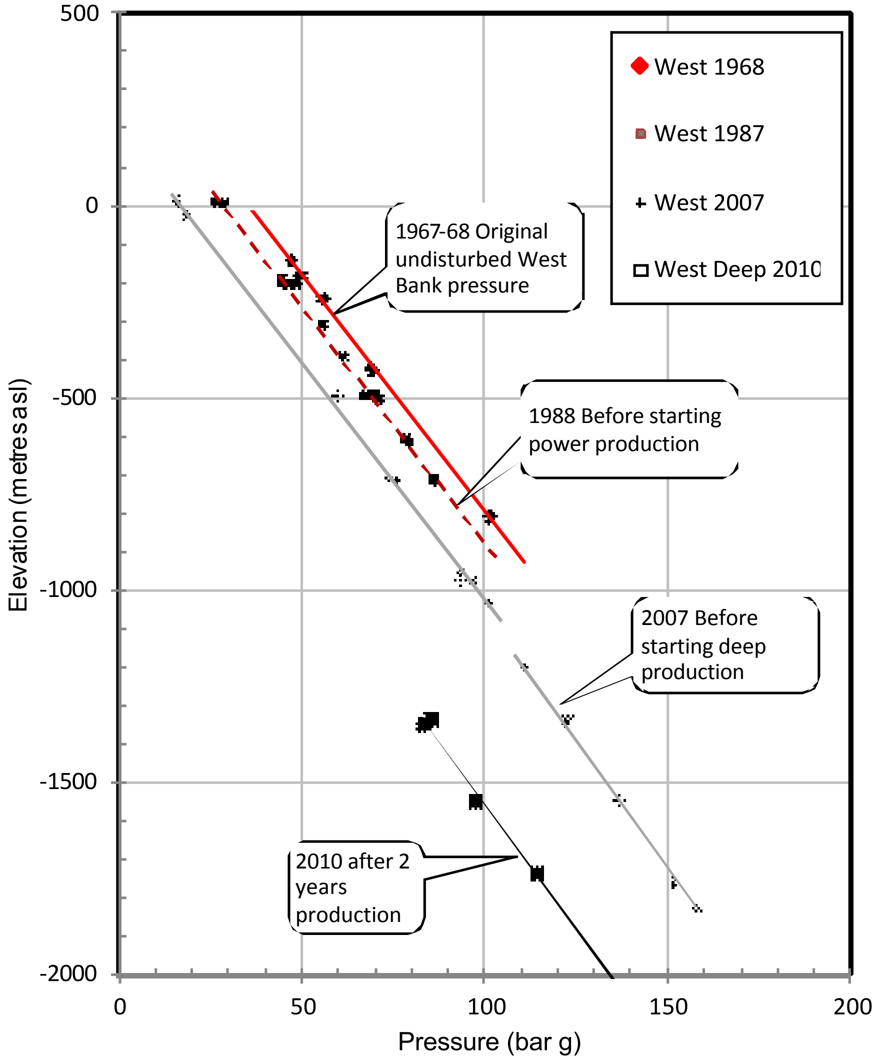

Figure 5: Pressure trends for the West Bank wells

- Deep Reservoir: Found in volcanic formations in West Bank area below 1,500 m depth (elevation below -1200 masl). Moderate permeability with original temperatures close to 300 °C.

The 2005 deep drilling programme showed that on the West Bank the high temperature permeable reservoir extended down to at least 2,200 m below surface (BR15 had been drilled down to 2,400 m in 1968, but while having temperatures more than 300 °C, it had insufficient permeability to sustain production).

5 COOLING

5.1 West Bank Shallow Reservoir

Many of the older West Bank production wells have shown extreme cooling. As mentioned above following the 1968-71 field production test, several of these wells developed cool downflows which continued from 1971 until about 1980, at which time reservoir pressures had recovered sufficiently that the "geothermal" pressures could balance the pressure in the shallow cool reservoir overlying this part of the resource. This cooling is controlled by the local stratigraphy where the very permeable Ohaaki Rhyolite, containing "cool" fluids at around 200 °C, overlies the high temperature reservoir, separated by a thin, but discontinuous layer of low permeability Huka Formation siltstones (Wood et al, 1998).

BR15 (which was shut-in until it was redrilled in 1996) is a good example of cooling in the Upper Reservoir. Between 1988 and 1996 temperatures at 550 m (behind the cemented casing) declined from 250 to 190 °C (Figure 6). Several other nearby production wells showed similar temperature declines eventually being abandoned when they could no longer sustain flow.

5.2 West Bank Deep Reservoir

The deep production wells drilled in 2007 are cased to around 1100 m to reduce as far as possible the effects of cooling in the upper reservoir. This has generally been successful but some wells have feedzone temperatures as low as 220 °C as deep as 1100 m (Figure 7). Where wells have encountered feed zones in both the upper and deep reservoirs, the additional pressure drawdown in the deep reservoir results in a pressure imbalance and downflow. This may have two effects: either the well will not flow if the temperature of the downflow is too low, or the cooler upper feedzone dominates and the deeper high temperature zone cannot produce.

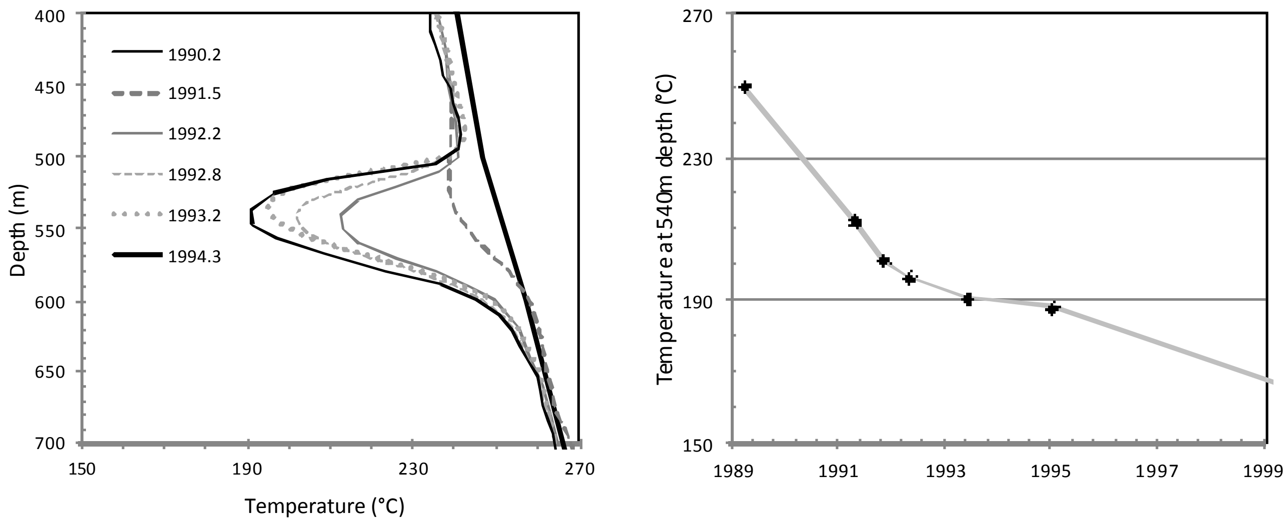

Figure 6: BR15 Temperature change at 550m 1990-1995. At this time BR15 was cased to 1066 m, so these changes reflect real change in the formation outside the wellbore.

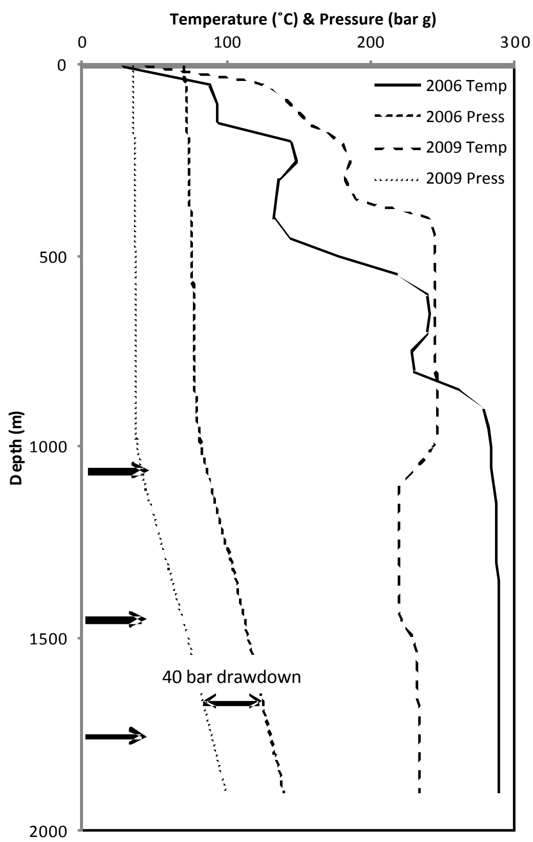

Figure 7: Temperature profile for a well with permeability in the "Upper Reservoir" at 1100m, and the "Deep Reservoir" at 1450m. A downflow between these two feedzones was identified by spinner profiles. The higher temperature profile was measured in 2006 before the pressure drawdown developed in the "Deep Reservoir". The arrows represent the feedzones identified from the completion test.

The deeper cased wells which have feedzones below 1500 m have not yet been affected by cooling or dilution and are now producing from two-phase conditions that have developed in the deep 300 °C reservoir (probably local to the wellbore). There is some evidence that the Rangitaiki Ignimbrite, 300-500 m thick in this part of the reservoir forms at least a partial barrier to the migration of cooler fluids from the upper reservoir to the deep reservoir (Wood et al, 1998).

6 BR2

As mentioned earlier, BR2 was the discovery well for the Ohaaki field and subsequent deep exploration has shown it was located close to the most productive part of the deep reservoir. BR2 was drilled to 1034 m, with a maximum temperature of 280 °C at bottom. Within a month of completion the well developed a strong interzonal upflow, which was seen in all downhole surveys 1966-1970. Similar upflows were seen in other West Bank wells at that time and in retrospect it is implicit that there was a deeper extension of the resource. One deep well was drilled to 2,400 m in 1968, and although it encountered temperatures over 300 °C, permeability was poor, and no further deep drilling was done in the West bank area until 1995.

7 CONCLUSION

Pressure drawdown on the West Bank production area at Ohaaki has resulted in the invasion of the original high temperature productive resource (Upper Reservoir) with cool waters from the overlying Ohaaki Rhyolite aquifer. Most of the original wells producing from the Upper Reservoir have now been abandoned and replaced by deeper wells producing from temperatures close to 300 °C below 1,200 m depth. The productive reservoir has now been extended down to 2,300 m (-2,000 masl) and there still remains potential to obtain deeper production to maintain generation if this can be done economically.

8 ACKNOWLEDGEMENTS

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