EXPANDING THE BOUNDARIES AT KAWERAU: NEW DATA FROM THE TE AHI O MAUI PROJECT

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ABSTRACT

The Te Ahi o Maui drilled one production well (TP-1) and two injection wells (TI-1, TI-2) in 2016, and then in 2017 side-tracked TP-1 (TP1-ST), and drilled a second production well (TP-2). These wells were drilled for a new 25 MWe power plant development on the western side of the Kawerau reservoir.

The geology encountered in these wells was largely as expected, with greywacke basement deepening to the north and west. The clay cap, as defined by methylene blue results, is at 200-500m in the production wells, and up to 650 m in the injection wells. There is evidence of both NE and NW striking faults in this area, with all formations below the Matahina Ignimbrite offset between TP-1 and TP-2 by an inferred NW striking fault.

Very good permeability was found in four of the five wells, mostly occurring between Kawerau Andesite and the top of greywacke basement. The highest temperatures (up to 265°C) were seen above greywacke, with an inversion beneath. Temperatures are higher than expected in the injection wells. These higher temperatures and good permeability in the injection wells that were sited beyond the previously recognized resistivity boundary indicate an extension of the deep geothermal system in this part of the field.

1. INTRODUCTION

Te Ahi O Maui Limited Partnership (TAOM) is a joint venture between Eastland Generation and the owners of the A8D block on the western side of the Kawerau geothermal field, in which the well KA22 was drilled in 1977. TAOM has drilled new wells and constructed a 25 MWe binary power plant to utilize the geothermal resource beneath the A8D block. This paper presents new information about the Kawerau geothermal system that was obtained from those wells.

2. DRILLING

In 2016, TAOM drilled one production well (TP-1) and two injection wells (TI-1, TI-2). In 2017, TP-1 was side-tracked (TP1-ST), and a second production well (TP-2) was drilled. The well tracks of the new wells, and the location of KA22 are shown on Figure 1. Depths in this paper are mostly given relative to ground level or to sea level.

2.1 Injection wells

Two injection wells were drilled in 2016 from the TI wellpad in the northwest of the A8D land block. TI-1 was completed on 24 August 2016 and TI-2 was completed on 29 July 2016.

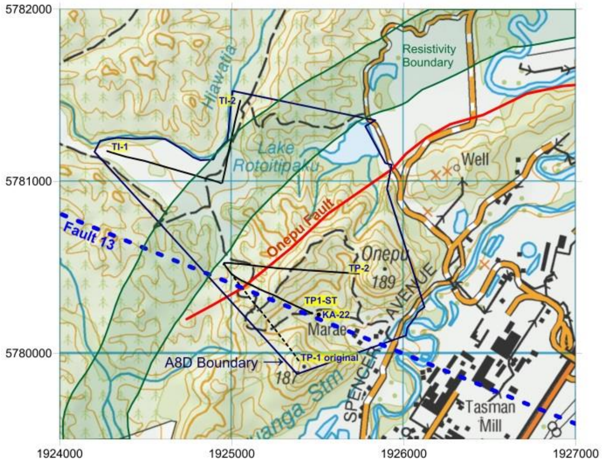

Figure 1: Location map, showing TAOM wells within the A8D land block at Kawerau and the resistivity boundary (from Milicich *et al* 2013, after Allis 1997).

TI-1 was drilled to a total depth of 1986 mMD (1799 mVD) with 9-5/8" casing and 7" slotted liner, and found major permeability at 1230-1310 mMD (1147-1222 mVD). Minor permeability was found at 1450-1485 and 1530-1570 mMD.

TI-2 was drilled to a total depth of 1981mMD (1868 mVD) with 9-5/8" casing and 7" slotted liner and found major permeability at 1230-1390 mMD (1145-1285 mVD) and minor permeability at 1470-1600 mMD. The good permeability in both injection wells was somewhat surprising, as these were drilled outside the resistivity boundary of the field.

2.2 Production wells

Two production wells were planned to be drilled from the TP wellpad on the western side of the A8D block, but the first well did not obtain commercial productivity and was side-tracked prior to drilling the second production well. The original TP-1 was completed on 23 June 2016 and the side-track (TP1-ST) was completed on 24 August 2017. The second production well, TP-2, was completed on 28 September 2017.

TP-1(original hole) was drilled to a total depth of 1903mMD (1706 mVD) with 13-3/8" casing and 9-5/8" slotted liner and found only minor permeability at 1250-1450 mMD (1155-1321 mVD) and 1480-1580 mMD.

TP1-ST (side-track) reached a total depth of 1554 mMD (1368 mVD) with 9-5/8" production casing below 605 mMD and 7" slotted liner. Major permeability was located at 950-

1000 mMD (901-1199 mVD), and minor permeability at 1380 mMD.

TP-2 reached a total depth of 1893 mMD (1657 mVD) with 13-3/8" production casing and 9-5/8" slotted liner. Major permeability was located at 1280-1330 mMD (1159-1199 mVD), with a secondary zone at 1710-1720 mMD (1503-1511 mVD). Minor permeable zones were found at 1350-1360, 1220-1235 and 1000 mMD.

3. GEOLOGY

3.1 Lithologies

The lithologies encountered in the TAOM wells were largely as described from elsewhere in the Kawerau geothermal field (*e.g*. Milicich *et al*, 2013, 2015), comprising rhyolitic and andesitic extrusives, rhyolitic intrusives, pyroclastic deposits and sedimentary units overlying greywacke basement.

Intrusive rhyolites were observed cutting Tahuna Formation sandstones at shallow levels (~350-460 mMD) in TP-2, and cutting greywacke in TI-1 and TP-1. The depth to basement increases to the north and west, from -1175masl in TP-1 to below -1300masl in TI-1. In general, the best permeability and highest temperatures were found between Kawerau Andesite and greywacke basement, in ignimbrites of the Raepahu and Te Teko formations. A schematic summary log is presented in Figure 2 for TP-1 (original), which is representative of the wells drilled, and had cuttings returns for most of its' depth.

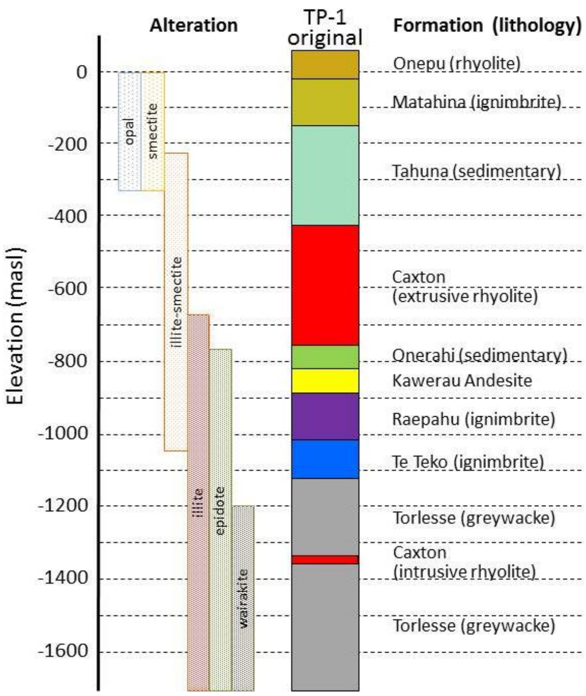

Figure 2: Summary log of TP-1 (original), showing the formations and lithologies (right), and the distribution of selected alteration minerals (left).

3.2 Alteration

Alteration is also similar to that documented in other wells in the Kawerau geothermal system, with minerals like opal, cristobalite, smectite, zeolites and marcasite observed at shallow levels, then a zone of interlayered clays, to illite, epidote and wairakite in the deepest samples (Figure 2). Quartz, calcite, chlorite and adularia are common in most depth intervals throughout these wells, and platy calcite crystals were observed in parts of TP1-ST and TP-2. The clay cap, as identified from methylene blue analysis, is at a depth of 200 to 500m in the production wells, and up to 650 m depth in the injection wells.

Detailed petrology studies indicate that at least some of the epidote at depth is corroded and may not be in equilibrium with the current conditions (*i.e*. fluids may have cooled since the epidote formed).

3.3 Structures

The greywacke basement at Kawerau is believed to be step-faulted on northeast and northwest trending normal faults, and generally downthrown to the north. Most of those faults are not visible at the surface, as they are buried beneath younger volcanic and alluvial deposits (*e.g*. Milicich *et al*. 2013). They have only been inferred from well data, and hence are poorly located. The only well defined and accurately located structure is the NE trending Onepu Fault, which passes through the A8D block (Figure 1) and was intersected by the production wells. This fault is reported to have moved in the 1987 Edgecumbe earthquake (Berryman *et al*. 1998), and is included in the GNS active faults database. The Onepu Fault was identified in the production wells by total loss zones at close to the predicted depths. Those zones were placed behind production casing because of concerns that they might conduct cool fluids downwards.

One of the NW trending faults was extrapolated westward from the central part of the field to pass just south of the TP wellpad (Milicich *et al*. 2013). Data from the TAOM production wells is consistent with the presence of a north-dipping normal fault at that location, passing between TP-1 (original) and TP-2. The key evidence is that four readily identifiable depositional contacts are all 40 to 60 m deeper in TP-2 (Figure 3). Few of those contacts were seen in TP1-ST, but the contact of Onerahi Formation on Kawerau Andesite is 66 m vertically deeper in TP1-ST compared with TP-1 (original), despite a horizontal separation at that depth of just 84 m.

The timing of movement on this NW fault is constrained by the ages of Caxton Formation, which is offset, and Matahina Ignimbrite, which is not. Based on the ages given by Milicich *et al*. (2013) for these units, this fault moved between 320 and 360 ka., and probably also at some time prior to this.

This NW fault is thought to be largely responsible for the very good permeability that was encountered in the production section of both TP1-ST and TP-2.

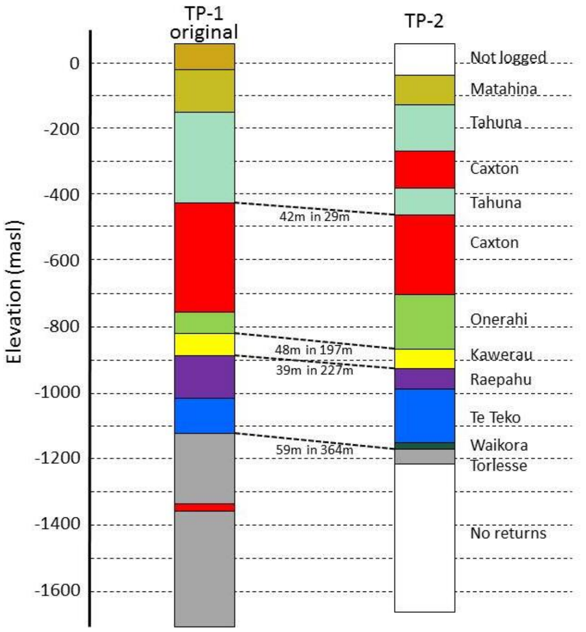

Figure 3: Schematic stratigraphic logs of TP-1 (original) and TP-2, showing formations and differences in elevation against horizontal distance between points for certain marker horizons.

4. RESERVOIR ENGINEERING

4.1 Well Testing

4.1.1 Injection wells

The injection wells were both cased to more than 1110m vertical depth, and both encountered good permeability in the volcanic formations above the greywacke but negligible permeability within the greywacke. The temperatures were unexpectedly high (Figure 4), with the temperature peaks in the formations above greywacke.

The Injectivity Index measured during completion testing was 52 t/h-bar in TI-1, and 39 t/h-bar in TI-2, indicating high injection capacity for both wells. There was minor permeability within greywacke in both wells, but had they been cased into the greywacke it appears that the injection capacity would have been insufficient.

4.1.2 Production Wells.

TP-1 (original) was cased deep (-1092masl), and had an Injectivity Index during completion testing of 6 t/h-bar, indicating low permeability. The Productivity Index on discharge was measured as 1.3 t/h-bar, with a flow of 98 t/h at a non-commercial wellhead pressure of 4.9 barg after 9 hours.

After sidetracking, TP1-ST Injectivity Index was 107 t/h-bar, indicating very high permeability which was confirmed with a flow of about 700 t/h at a wellhead pressure of 19.7 barg. The pre-flash temperature was 264°C.

The TP-2 Injectivity Index was 79 t/h-bar, indicating good permeability. However, on discharge in November 2017 the enthalpy and wellhead pressure were low. A flowing survey (Figure 5) showed a low temperature inflow near 1500 mVD of 192°C. A decision was therefore taken to abandon the lower section of the well and in February 2018 it was cement-plugged back to 1450 mMD (1296 mVD). On re-discharge in May 2018 the pre-flash temperature was 236°C (Figure 5), compared to 210°C previously. However, the mass flow was lower than expected, at about 180 t/h at 8 barg wellhead pressure.

The combined output of the two production wells (TP1-ST and TP-2) is in excess of the steam requirement for the 25 MWe power plant.

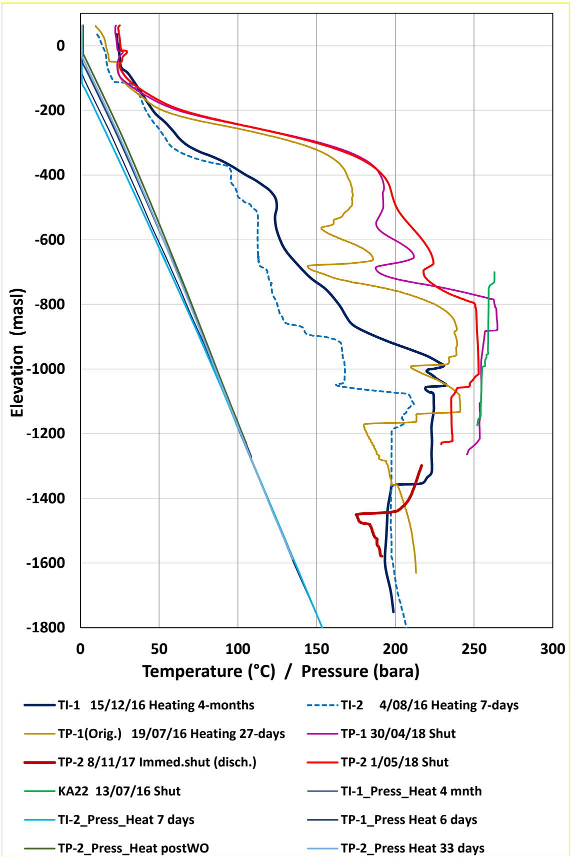

Figure 4: Most recent temperature and pressure profiles of TAOM production and injection wells.

4.2 Reservoir Conditions

The volcanic formations immediately above the greywacke provided generally good consistent permeability.

None of the production wells found useful permeability in the greywacke basement; permeability was very low in TP-1 (original), and in TP1-ST only the deepest zone of minor permeability might be in greywacke (total losses in Kawerau Andesite mean that the depth of greywacke in this well is uncertain). In TP-2, the zone of good permeability at 1505 mVD was producing low temperature fluid (192°C). The injection wells likewise did not find useful permeability within the greywacke. It appears that there is much lower fracture density within the greywacke formation in the marginal outflow areas of the field compared to the central high temperature zone tapped by the Mercury production wells and some NTGA wells.

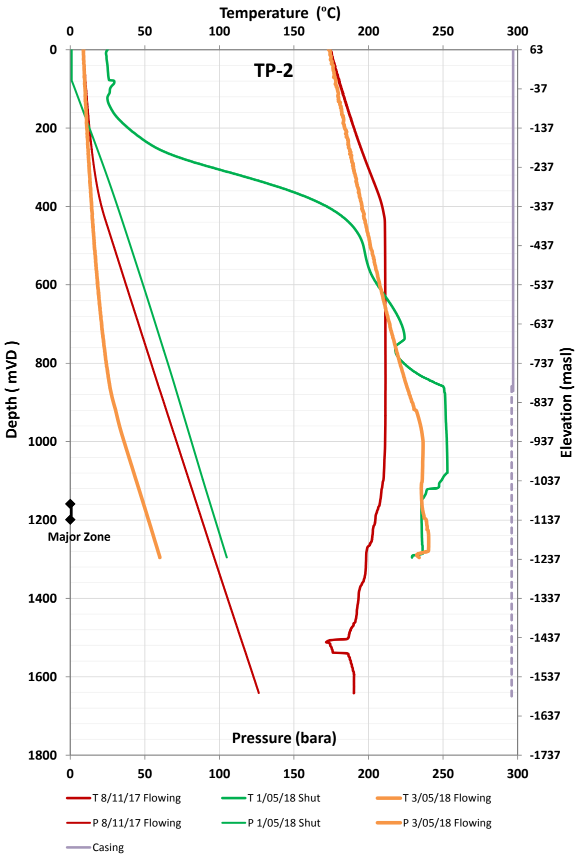

Figure 5: TP-2 flowing surveys before and after plugging below 1395 mVD plus static survey.

Narrow temperature inversion zones were seen in TP1-ST and TP-2 at similar elevations of about -700 masl (Figure 4) which are attributed to intersection with the Onepu Fault. Initially there was concern that the fault might be allowing a downflow of cooler groundwater, but temperatures have almost recovered at TP-2 and are still recovering at TP1-ST so this now appears unlikely. It is possible that production may induce downflow in this area, but that is considered unlikely because there is a good pressure connection between the production and injection areas, so the pressure drawdown will be limited.

There is a zone of sharply lower temperature (175°C) between -1445 and -1470 masl in TP-2, within the greywacke. The source of this lower temperature water is not clear. There is a downflow of groundwater near well KA31 (Milicich *et al*, 2015), located just outside the TAOM area to the southeast; however this cool fluid is more likely to flow east towards the pressure sink created by deep production wells. The other possibility is that there is a deep lateral recharge from the west. The Kawerau geothermal system has open boundaries and the conceptual model of the field is that deep lateral recharge is responsible for the limited pressure drawdown experienced.

Well KA22 is currently being used as a pressure monitor well and in 2016 it had experienced a drawdown of only about 2.7 bar between 2004 and 2016, during the period when the extraction rate from the reservoir had a substantial increase. Since 2016 the pressure at KA22 has shown a minimal increase. The pressure response of KA22 to brief test discharges of TP-1 and TP-2 was likewise minimal, with a decline of less than 0.1 bar.

The injection wells were targeted to be outside the field resistivity boundary. One unexpected factor affecting future management of the TAOM wells is the likely good connection between the injection wells and the deep production zones shown by the similar pressure profiles (Figure 4). Fortunately the major production zone in TP-1 is at 300m higher elevation than the permeable zones in the injection wells. Monitoring of production well chemistry and tracer tests will be used as the basis for adaptive management of injection.

5. CONCLUSIONS

The temperatures and permeability encountered in the two injection wells, TI-1 and TI-2, indicate that the Kawerau geothermal field extends further west than the resistivity boundary would suggest.

Very good permeability in TP1-ST and TP-2 is associated permeable ignimbrite units above greywacke, and with a NW-SE oriented fault, which moved between 320 and 360 ka.

The Kawerau geothermal field has experienced inflows of cooler water via downflows and lateral recharge and these are likely to affect the long term management of the Te Ahi O Maui production and injection wells. The original hot outflow past the injection wells may have reversed with large scale production from the field.

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