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RECENT COMPUTER MODELLING OF THE OHAAKI GEOTHERMAL SYSTEM

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A large three-dimensional numerical model of Ohaaki geothermal system has been developed at the University of Auckland in collaboration with Contact Energy Limited (and its predecessors) over many years. The model is calibrated against data from the natural state, the well testing period, the recovery period and the production period. Recently the model was reviewed and re-calibrated to improve the match between model results and measured data. The production history data was also updated to the end of 2004. A match between model results and the production history was obtained for the enthalpy and carbon dioxide content of individual wells and for reservoir pressures. Matching the carbon dioxide content of individual wells required further adjustment to the carbon dioxide flux in the natural state model. A significant improvement to the match of the model results with the production data was obtained with the 2006 model compared to the previous (2004) model.

1. INTRODUCTION

The Taupo Volcanic Zone (TVZ) is a 12,000 km^2 zone of predominantly rhyolitic volcanic activity, which extends north-east from Mt Ruapehu to White Island 50 km off the coast (Figure 1). The Ohaaki geothermal system is on the eastern margin of the TVZ. The Waikato River bisects the Ohaaki system, dividing it into the West Bank and East Bank areas (Figure 2).

Drilling commenced at Ohaaki in 1965, with a total of 44 wells drilled between 1966 and 1984. There was an extended period of well testing and recovery up to 1988, when the Ohaaki Geothermal Power station was commissioned. The maximum capacity of the plant is 116 MW$_e$. The total number of wells drilled by 1999 was 49 well. Three new wells were drilled in 2005

Three computer models of the Ohaaki geothermal system are discussed in the present paper. The first, called here the 2001 model, is the computer model as it existed in 2001 and as described by Newson, and O'Sullivan (2001). In 2003 and 2004 a finer grid was set up, the model grid was better aligned with possible faults in the Ohaaki area and the permeability structure was based on a three-dimensional geological model developed by GNS. Thus the rock structure used in this 2004 model, more closely matches the geological strata than earlier 2001 model. The shallow groundwater data was also reviewed to give a better representation of the top surface of the model. The 2004 model was described in Zarrouk et al. (2004).

The third model, called here the 2006 model, resulted from a recent review and re-calibration of the 2004 model. The aim was to improve the match between model results and measured data. This was done by changing the heat, mass and CO_2 input at the base of the model and by adjusting the permeability structure.

The 2006 model was refined near some of the production wells on the west bank of the Waikato River to allow better well-by-well matching. The production history data was also updated to the end of 2004.

2. OHAAKI GEOTHERMAL SYSTEM

The natural heat flow of the Ohaaki system is thought to be around 100 MW (Allis, 1980), but there is some uncertainty in this figure because the discharge into the Waikato River was not well quantified. The resistivity boundary at ~ 500 m is NNW-SSE trending, and all the surface activity is within this area. The most significant feature is the Ohaaki Pool, which in the natural state discharged boiling neutral chloride water at approximately 10 *l/s*, precipitating silica sinter around the perimeter of the pool.

Located on the eastern margins of the TVZ (Figure 1) the basement at Ohaaki is down-faulted to the north-west. Two major basement scarps have been drilled, but little permeability has been found in the basement. However, higher temperatures associated with sections of the faults indicate the existence of limited permeable pathways for upflow of geothermal fluid (Wood, 1995). The rocks overlying the basement are a sequence of volcaniclastic sediments, interspersed with predominantly rhyolitic and dacitic volcanic domes and flows. Permeability in both the volcanic rocks and the volcaniclastic sediments is highly variable, and related to internal fracturing or to the contacts with bounding formations.

The Ohaaki Rhyolite which outcrops in the south-west of the field is the main conduit for cold surface water inflows to the reservoir. The shallow Huka formation generally acts as an impermeable cap on the field, but still has local permeable zones.

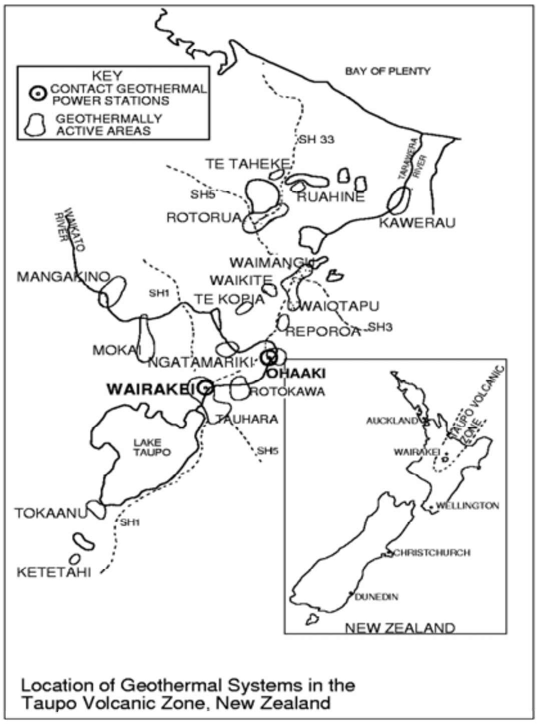

Figure 1. Map of the TVZ and the location of Ohaaki geothermal system.

The Waiora formation below this is regarded as an aquifer, but within it there is no apparent pattern in the permeability distribution (Wood, 1995). Low permeability siltstone and volcanic flows, separate the Waiora formation from the Rautawiri Breccia, which is also considered to be an aquifer rock, particularly at its upper and lower contacts. Below this lies impermeable ignimbrites, minor lava flows, sediments, and the greywacke basement.

The deep temperature reversals found in some wells indicated that there is some contact with groundwater in the west. Permeability on the east is limited laterally and vertically. The Ohaaki system is open to surface groundwater, particularly through the near-surface, high permeability Ohaaki rhyolite in the west.

The effects of mass withdrawal on surface features became apparent during the early well testing period, when discharge ceased from the Ohaaki Pool. The discharge had recommenced by 1986 although ceased again shortly after electricity generation commenced. Separated geothermal water was discharged to the Ohaaki Pool and this resulted in cooling of the shallow aquifers. In order to prevent cooling the discharge of separated geothermal water was reduced to an absolute minimum and the base of the Ohaaki Pool was sealed to prevent down-flows (Clotworthy et al, 1995).

Subsidence indicated that a pressure decline had occurred in the basal Huka formation in the late 1960's. Despite a recovery in reservoir pressure, there was no rebound from the subsidence, and it has continued during the production period (Allis et al, 1997).

Pressures at the base of the Huka Formation reflect the drawdown in the underlying Ohaaki rhyolite. Water levels in monitoring wells in the Ohaaki rhyolite have declined, and it is thought that a cold down-flow in the Ohaaki rhyolite has been responsible for the cooling of several shallow production wells since 1988.

3. THE 2004 RESERVOIR MODEL

The block structure for the original 2001 model is shown in Figure 2. There are 128 blocks per layer and 16 layers giving a total of 2048 blocks.

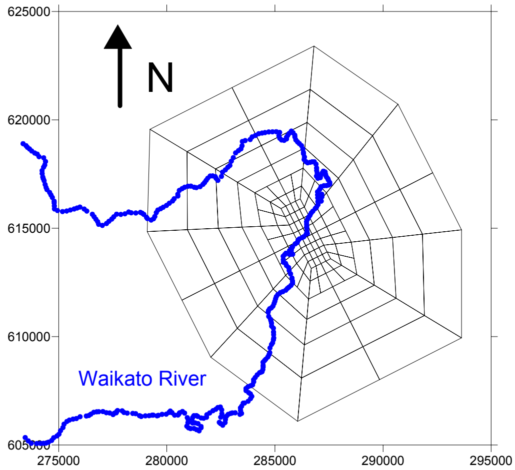

Figure 2. Computational grid for the 2001 model.

The land surface at Ohaaki is approximately 300m above sea level. The small rectangle of blocks at the centre of the model corresponds to the area inside the resistivity boundary, and is referred to as the 'reservoir blocks'. The two rings surrounding the reservoir blocks contain most of the injection and marginal, or unproductive, wells. The large blocks beyond the marginal blocks are the recharge blocks.

The surface of the model is taken to be the water table, which varies from block to block but is fixed with respect to time. Data on the water table surface was obtained from shallow monitoring wells.

The boundary conditions at the model surface are fixed at atmospheric values, and allow a flow of heat and mass across the model surface. The lateral boundaries of the model are closed. The reservoir blocks at the base of the model have hot water injected at 345°C. In some blocks carbon dioxide gas is also injected. The marginal blocks have a conductive heat flow, but no mass flow. The remainder of the blocks have a low background heat flow.

All the wells are vertical except the three deviated deep wells drilled in the early 1990's plus two more recent wells drilled in 2005. Not all wells feed from the same depth and many of them have more than one feed zone. The approach to multiple feed wells has been to assign a fixed proportion of the mass flow from the well to each depth.

The calibration process involves changing a few parameters, then running the model and checking the results. Calibration requires several iterations to achieve a match of model output to field data.

In the first stage of model calibration the natural state behaviour of the system is matched. The location and magnitude of the deep inflows, and the permeability structure are adjusted to obtain a good match to the natural state temperature profiles in the wells. In the second stage of calibration further changes to the model structure are made to achieve a good match to the past history (well enthalpies, pressure changes and CO_2 mass fractions).

3.1 Improvements included in the 2004 model

The block structure used in the 2004 model is shown in Figure 3. There are 366 blocks per layer, and 18 layers (6588 blocks in total), extending to a depth of 2700m below sea level.

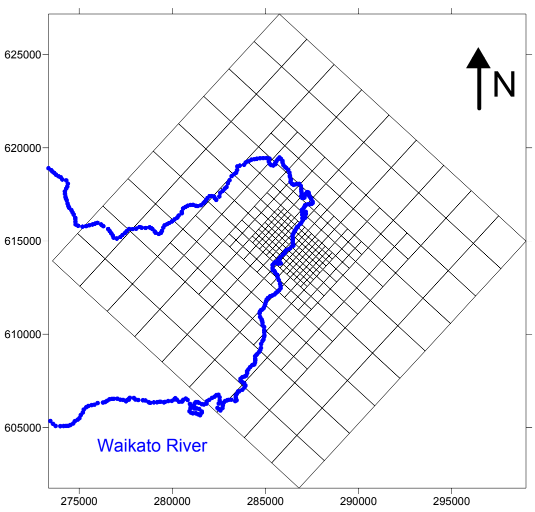

Figure 3. Computational grid for the 2004 model.

The orientation of the 2004 model grid was chosen to better line up with what are thought to be strikes of dominant faults in the system.

An extra two layer were added in the 2004 model to give a more gradual transition to the thin layer representing the contact zone at the base of the rhyolite (see Figure 4).

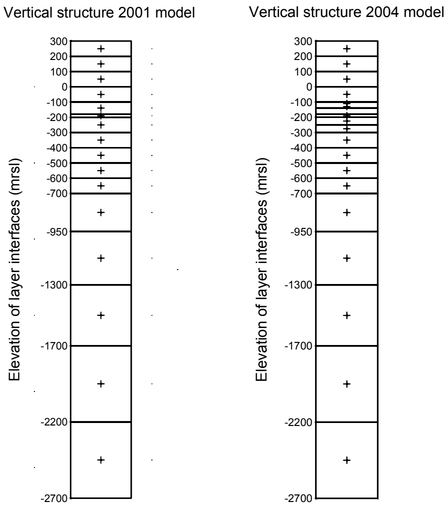

Figure 4. Comparison of the layer structure for the 2001 model and the 2004 model

The 2004 model had a relatively high heat and mass input into the upflow zone ($116MW_{th}$) compared to the estimated natural heat output of around $100MW_{th}$. Nevertheless, the model results showed cooler temperatures than the measured values in some production wells, particularly on the periphery of the reservoir. The high heat input also resulted in boiling temperatures in the shallow part of the centre of the reservoir, thus suppressing cold lateral inflow. Therefore the model was not able to match the temperature inversions and the formation of a shallow steam condensate layer. In the 2004 model changes in the heat and mass input (reduction in the reservoir blocks and increase in outer rings) at the base of the model were made. This was accompanied by some changes to the permeability structure, to widen the upflow zone.

The natural state temperature profile obtained with the 2004 model for a typical East Bank well is shown in Figure 5.

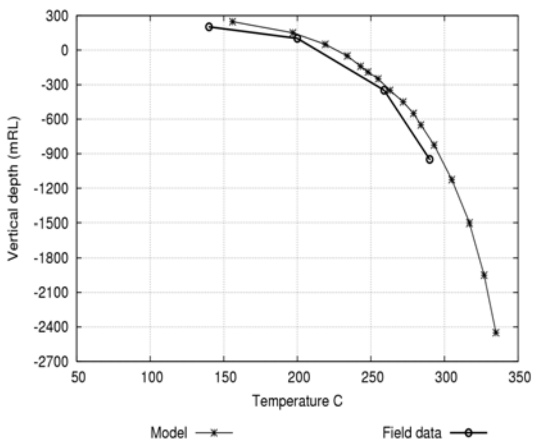

Figure 5. Temperature profile for a typical East Bank well (2004 Model).

For the West Bank the model temperatures all show similar profiles, and give a good match to field data (see Figure 6).

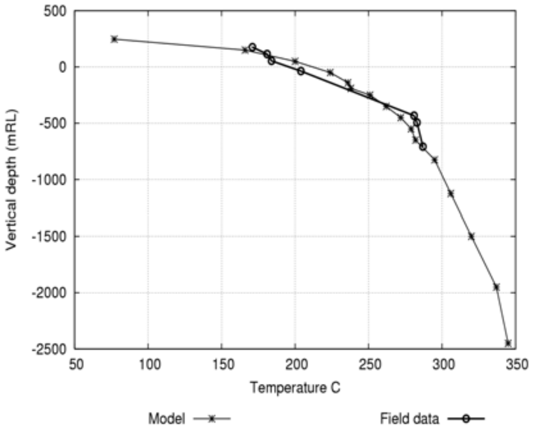

Figure 6. Temperature profile for a typical West Bank well (2004 Model).

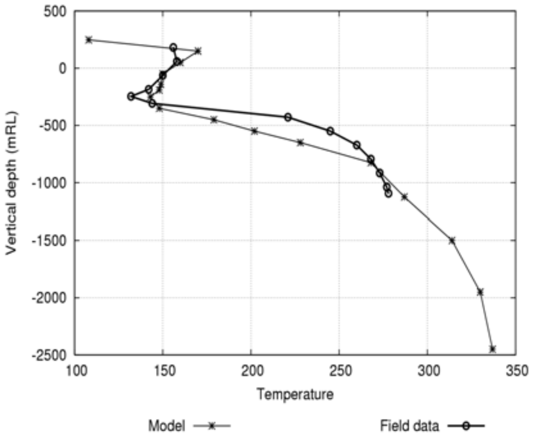

Figure 7. Temperature profile in a well on the margin of the reservoir (2004 Model).

For wells on the margins of the reservoir the 2004 model gives deep temperatures that are close to those indicated by deep drilling. However in some cases the shallower portions of the temperature profiles needs further work and do not match the field data as well as the results shown in Figure 7.

It became clear from our efforts to improve some of these temperature profiles that a finer model grid was required near the west-bank production wells.

In the second stage of calibration the mass withdrawal and injection rates during past production are put into the model and then the model parameters (permeability and porosity) are adjusted to obtain a good match to the production history. The data used in calibration are the pressure responses and the history of discharge enthalpies.

The model enthalpy results obtained with the 2004 model are an improvement on those obtained from the older 2001 model, and the pressures are almost as good. Examples of the model pressures, enthalpies and CO_2 mass fractions in wells and separation plants (SP) are shown, with field data, in Figures 8 to 13.

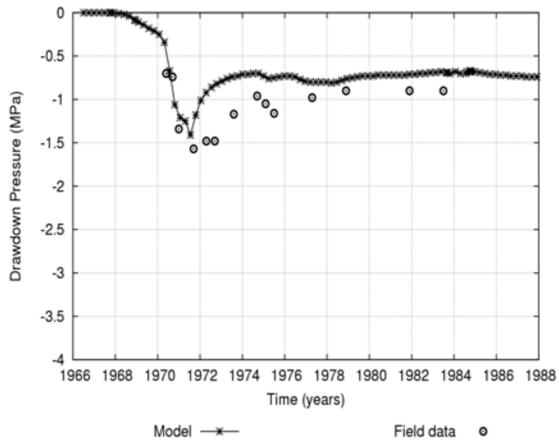

Figure 8. A typical East Bank well, drawdown pressure

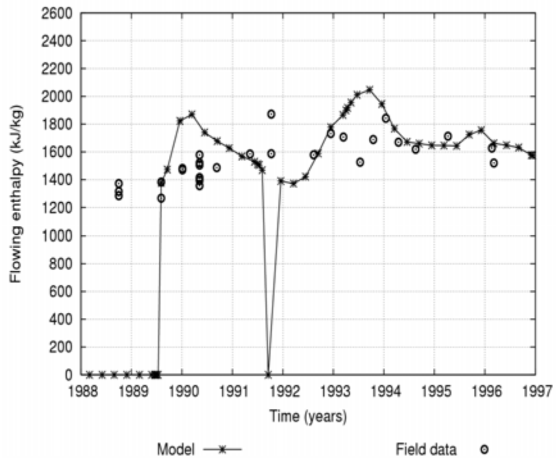

Figure 9. A typical West Bank well, production enthalpy

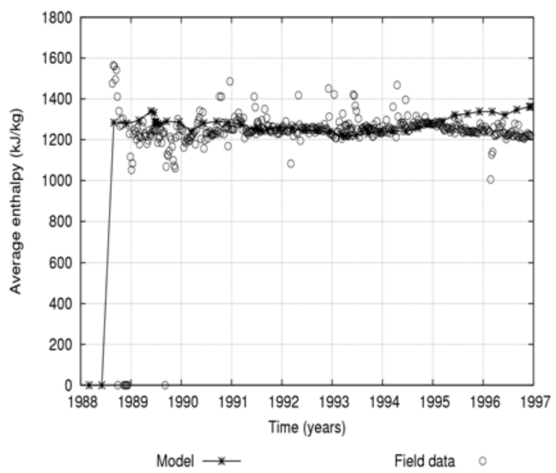

Figure 10. East Bank. SP, average enthalpy

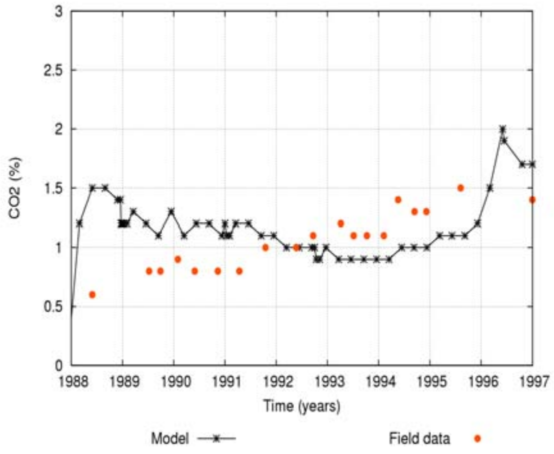

Figure 11. All West Bank wells, average gas concentration

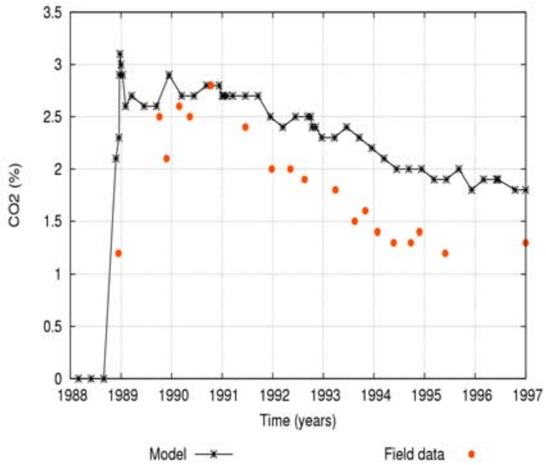

Figure 12. All East Bank wells, average gas concentration

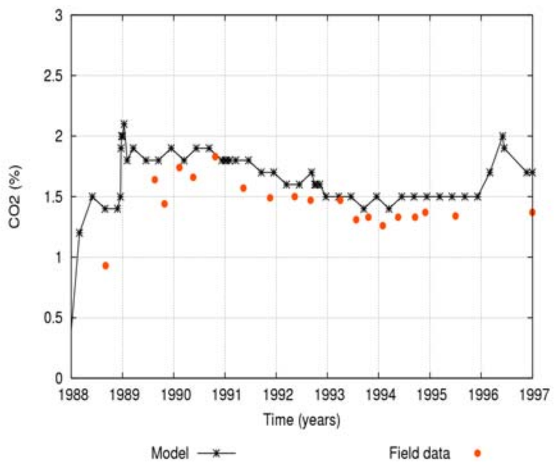

Figure 13. Gas fraction in total production

4. THE 2006 RESERVOIR MODEL

4.1 Model structure

Because of the difficulties experienced with the 2004 model particularly in matching the temperature profiles in the wells to the west of the model, with temperature inversions and where multiple wells are located within the same grid block, we decided to set up a model with a finer grid structure (Figure 14). It will be referred to as the 2006 model.

The revised grid contains 393 grid blocks per layer and covers the same area as the 2004 model (18 *km* × 18 *km*, see Figure 14). The layer structure is to the same as the 2004 model (see Figure 4).

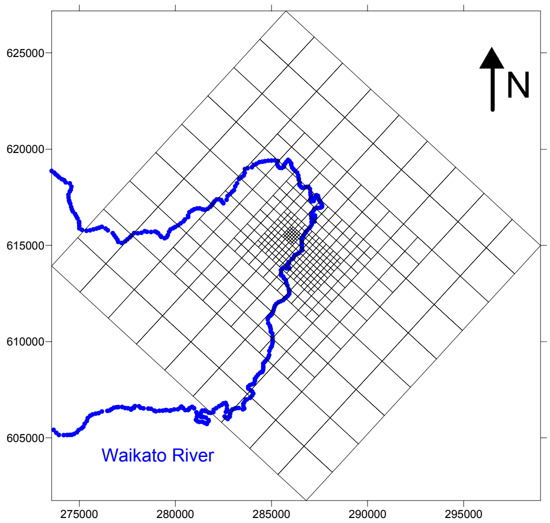

Figure 14. Computational grid for the 2006 model.

The enlarged portion of the grid (Figure 15) shows that the new grid allows most wells to be allocated to separate blocks. This is an improvement on the 2004 model.

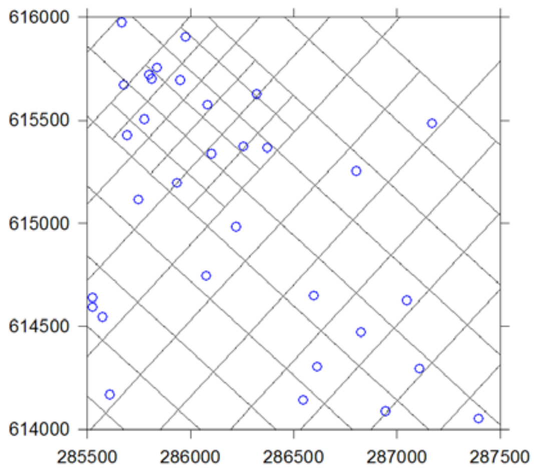

Figure 15. An enlarged portion of the grid for the 2006 model showing the well locations.

A revised surface groundwater level was generated using recent data from groundwater wells, both in Ohaaki and the surrounding area. The Waikato river water level (averaged over the year) was also included in the new water surface. This resulted in a better representation of the groundwater level which is used as the model surface (Figure 16).

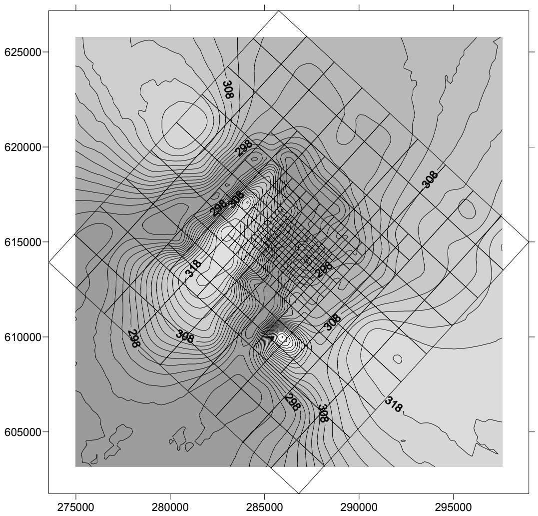

Figure 16. Water surface used in the 2006 model.

A new rock structure was used in the model, which identifies the rock-types in the TOUGH2 data file with the geological strata. This was achieved by allowing multiple permeability values for each of the 11 basic rock-types. Thus a record of the geological structure is preserved in the reservoir model, while allowing the detailed permeability structure to be adjusted.

4.2 Natural state model

The rock types and permeability structure from the 2004 model were imported into the new 2006 model and the first natural state run produced similar temperature profiles to those shown above.

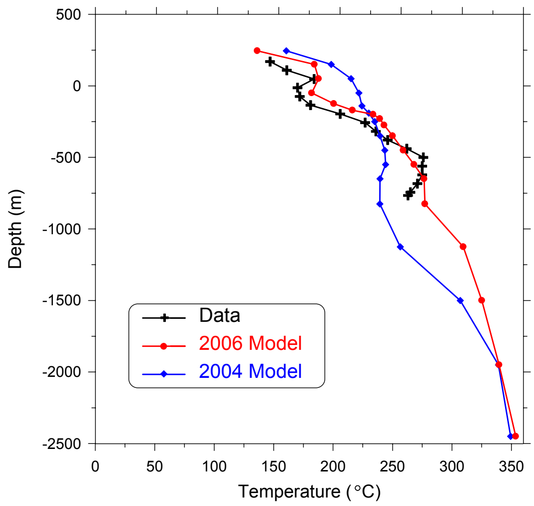

Figure 17. Comparison of results between the 2004 model and 2006 model. Temperature vs depth.

Further refinement to the permeability structure has produced some improvement in matching temperature data (as shown in Figures 17-25, for example). Most of the temperature profiles in the reservoir area were reasonable for the 2004 model. Some improvement has been achieved with the 2006 model, for example Figure 17 and Figure 18.

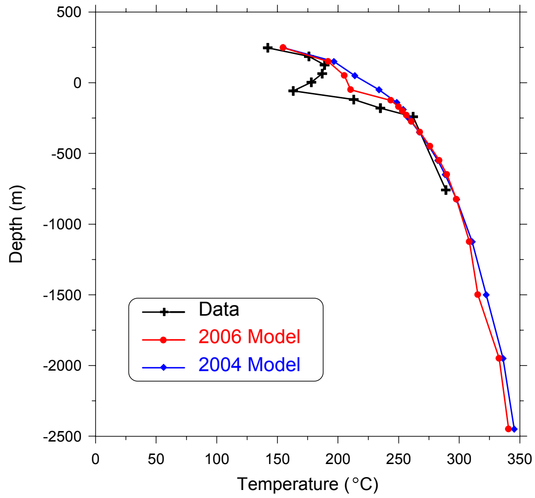

Figure 18. Comparison of results between the 2004 model and 2006 model. Temperature vs depth.

In most cases a better match has been obtained for wells that are at the edge of the reservoir (boundary wells). The plots for two wells at the south and south-west of the field are shown in Figure 19 and Figure 20, respectively.

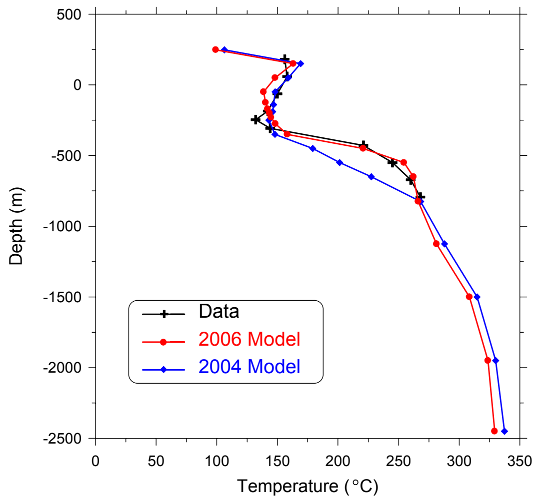

Figure 19. Comparison of results between the 2004 model and 2006 model. Temperature vs depth.

Similarly the temperatures are improved at the north-east (Figure 21), the north (Figure 22) and the north-west (Figure 23 and Figure 24). The large inversion in the west of the field is now reasonably matched (see Figure 24). Some fine tuning of the model is continuing to further improve all the matches of model results to measured temperature vs depth.

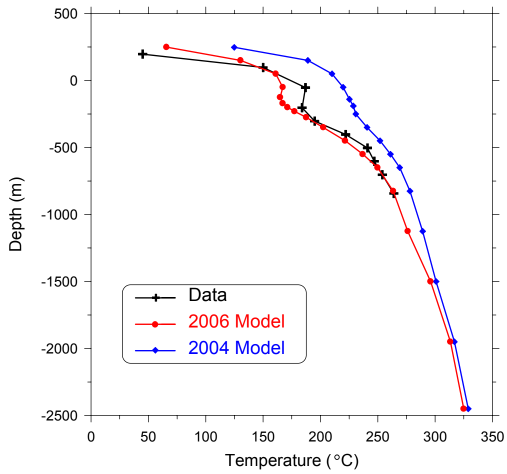

Figure 20. Comparison of results between the 2004 model and 2006 model. Temperature vs depth.

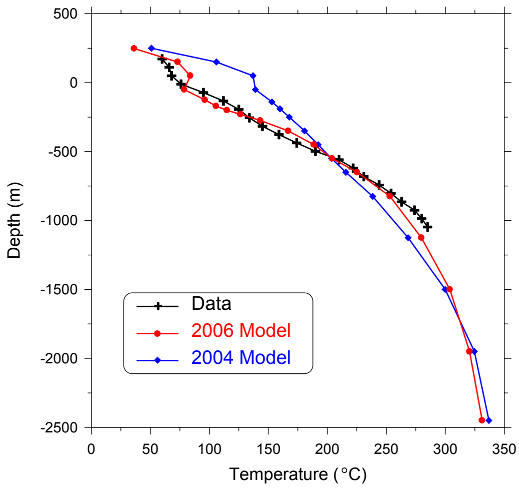

Figure 21. Comparison of results between the 2004 model and 2006 model. Temperature vs depth.

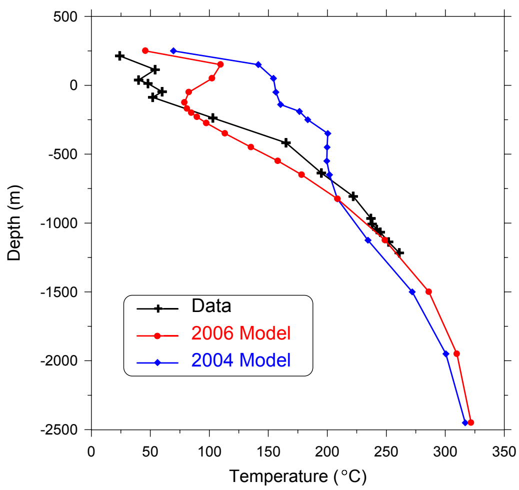

Figure 22. Comparison of results between the 2004 model and 2006 model. Temperature vs depth.

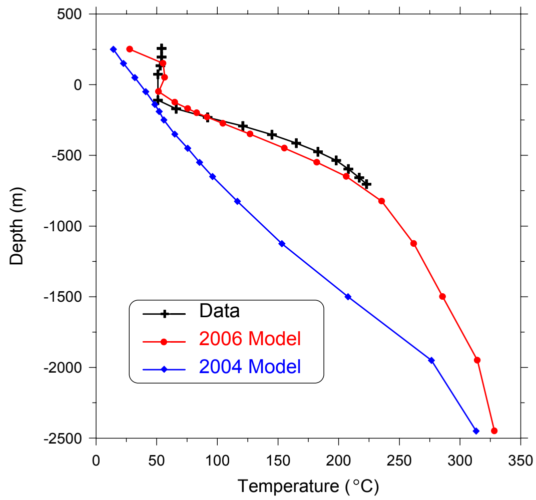

Figure 23. Comparison of results between the 2004 model and 2006 model. Temperature vs depth.

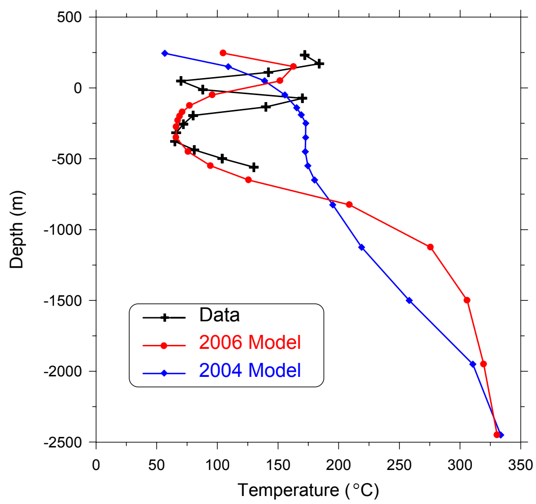

Figure 24. Comparison of results between the 2004 model and 2006 model. Temperature vs depth.

4.3 Production history

The 2006 model also produces a better match to the production enthalpy and the carbon dioxide content for some, but not all, of the individual wells (not shown) and to measured pressure changes (not shown). The enthalpies for three of the separation plants are shown in Figures 25-27. As shown in Figure 25, the 2004 model matches the field data better than the 2006 model up to 1997 (the end of the simulation period for the 2004 model). The 2006 model matches the field data quite well until the separation plant was decommissioned.

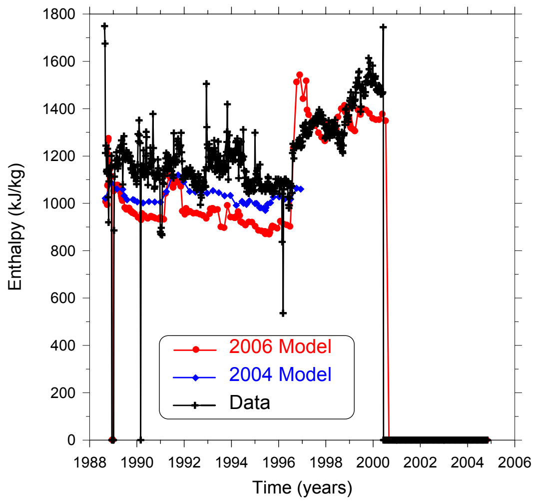

Figure 25. Comparison of results between the 2004 model and 2006 model. Enthalpy vs time.

For Figure 26 both models match the field data well. The 2006 model again matches the separation plant data for 1997-2005 very well.

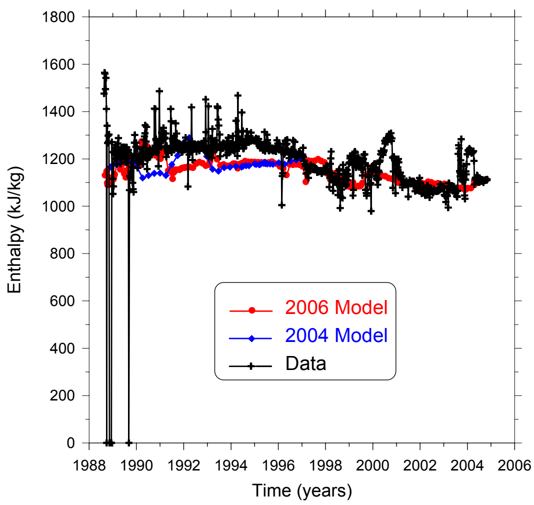

Figure 26. Comparison of results between the 2004 model and 2006 model. Enthalpy vs time.

Neither model matches the early enthalpy peak for the separation plant of Figure 27. The enthalpy for the 2006 model is too low for, 1997-2005 but the downward trend is correct.

Some further calibration of the 2006 model is being carried out by looking at the well-by-well enthalpies and adjusting parameters to improve the match.

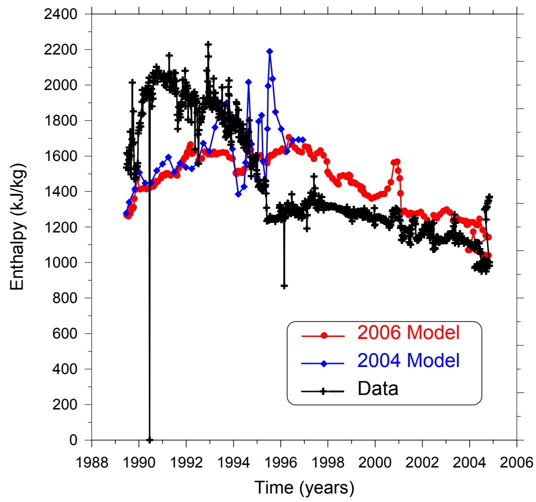

Figure 27. Comparison of results between the 2004 model and 2006 model. Enthalpy vs time.

4.4 Difficulties

At Ohaaki the production rate and average enthalpy at each separator is measured but these quantities are not continuously measured at each well. Therefore for history matching the well-by-well histories are constructed from the separator data and the periodic output tests on individual wells. The production for each multi-feed well is further broken down by assigning the total flow rate proportionally to each feed. Neither of these two allocation processes is precise. Unfortunately the enthalpy response of the model is quite sensitive to the flow rate and thus errors in the synthetic well-by-well production rates lead to incorrect model enthalpies.

A particular problem was met in the calibration of the natural state model of Ohaaki which we have not encountered in modelling other fields. In some cases a small change in the permeability structure resulted in a model block wishing to change from a two-phase state to compressed hot-water. This type of phase change is not usually a problem in a model but in the case of the Ohaaki model the high CO_2 content sometimes makes it difficult and the natural state simulation takes a very large number of time steps to complete, or may not reach completion. Unfortunately this problem has made it difficult to use the inverse modelling code ITOUGH2 (Finsterle, 1997) to assist with model calibration.

The calibrated model is currently being used to model various future scenarios for Ohaaki

6. ACKNOWLEDGMENT

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7. REFERENCES

Allis, R.G., Carey, B., Darby, D., Read, S.A.L., Rosenburg M., and Wood, C.P. (1997) Subsidence at Ohaaki Field, New Zealand, *Proc. 19th New Zealand Geothermal Workshop*, The University of Auckland, pp. 9-16.

Clotworthy, A.W., Lovelock, B., and Carey, B. (1995) Operational history of the Ohaaki geothermal field, *Proc. the World Geothermal Congress, 1995*, pp.1797-1802.

Finsterle, S. (1993) ITOUGH2 User's Guide Version 2.2, Report LBL-34581, Lawerence Berkeley Laboratory, University of California.

Newson, J.A. and O'Sullivan, M.J. (2001) Modelling the Ohaaki Geothermal system. Proc. 26th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, pp. 186-192.

Wood, C.P. (1995) Basement geology and the structure of TVZ geothermal fields, New Zealand, *Proc. 18th New Zealand Geothermal Workshop*, The University of Auckland, pp. 157-162.

Zarrouk S.J., O'Sullivan, M.J. and Newson, J.A. (2004). Computer Modelling of the Ohaaki Geothermal System. *Proc. 26th New Zealand Geothermal Workshop*, University of Auckland