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COMPUTER MODELLING OF THE OHAAKI GEOTHERMAL SYSTEM

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SUMMARY – 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. This was done by changing the heat input at the base of the model and by adjusting the permeability structure. However, although the deep temperatures obtained in the re-calibrated model were closer to those indicated by deep drilling, the shallower temperature profiles, in general, needed further improvement. Model refinements are being worked on to further improve the match.

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.

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.

The second model, called here the 2001/04 model, resulted from a recent review and re-calibration of the 2001 model. The aim was to improve the match between model results and measured data. This was done by changing the heat input at the base of the model and by adjusting the permeability structure. However, although the deep temperatures obtained in the re-calibrated model were closer to those indicated by deep drilling, the shallower temperature profiles, in general, needed further improvement.

Therefore it was decided that a more refined model was required to improve the match between model results and measured data. The new model, called here the 2004 model, has more and smaller blocks to allow better well-by-well matching. Also the model grid is better aligned with possible faults in the Ohaaki area and the permeability structure was based on a three-dimensional geological model developed by IGNS. Thus the rock structure used in the 2004 model, more closely matches the geological strata. The shallow groundwater data was also reviewed to give a better representation of the top surface of the model.

A complete range of results for the 2001/04 model are presented here but the 2004 model is still under development and only a few preliminary results are shown.

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.

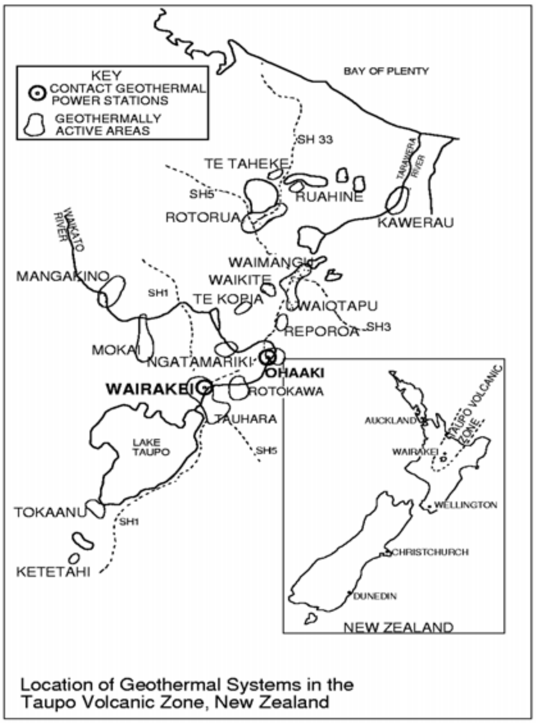

Figure 1. Map of the TVZ and the location of Ohaaki geothermal system (From Newson and O'Sullivan, 2001)

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. The Waiora formation below this is regarded as an aquifer, but has 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 the cooling the discharge 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 Ohaaki rhyolite monitoring wells have declined, and it is thought that a cold down-flow in Ohaaki rhyolite has been responsible for the cooling of several shallow production wells since 1988.

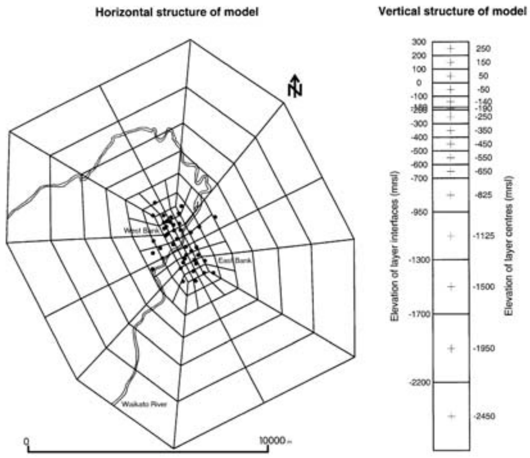

Figure 2. Grid structure for the 2001 and 2001/04 models, showing the location of the wells and the Waikato River.

3. THE 2001/04 RESERVOIR MODEL

The block structure used in both the 2001 model and the 2001/04 model is the same (shown in Figure 2) and the modelling approach is very similar. There are 128 blocks per layer, and 16 layers (2048 blocks in total), extending to a depth of 2700m below sea level. The land surface at Ohaaki is approximately 300m above sea level. The choice and orientation of the grid structure (Figure 2) was dictated by the resistivity boundary. The 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 reinjection 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 the early 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 most recent deviated deep wells drilled in the early 1990's. The wells do not all 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 and pressure changes).

3.1 Improvements incorporated in the 2001/04 model

The 2001 model had a relatively high heat and mass input into the upflow zone ($135MW_{th}$) 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 2001/04 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 2001/04 model for a typical East Bank well is shown in Figure 3. For the West Bank the model

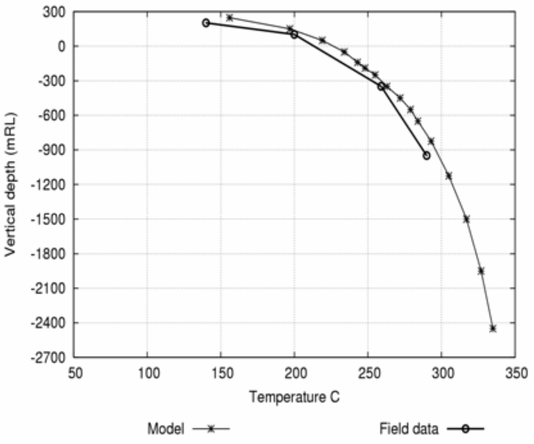

Figure 3. Temperature profile for a typical East Bank well

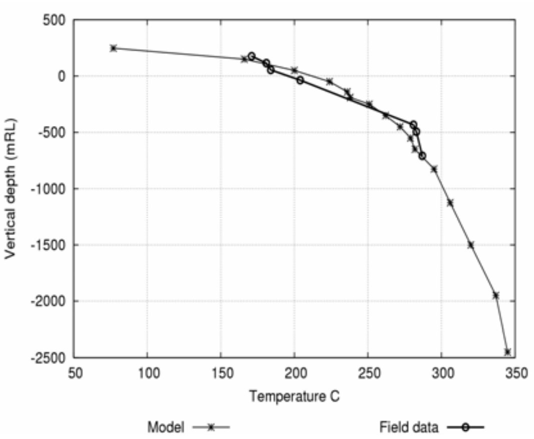

Figure 4. Temperature profile for a typical West Bank well

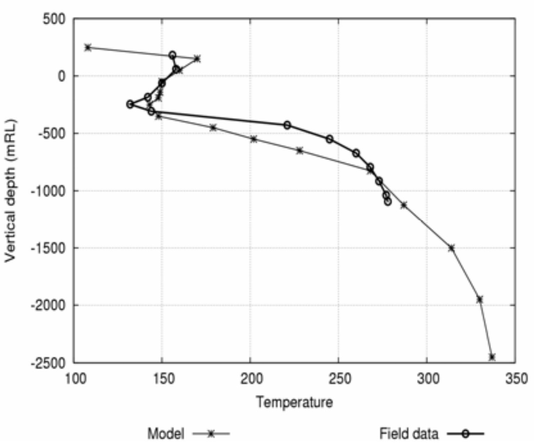

Figure 5. Temperature profile in a well on the margin of the reservoir

temperatures all show similar profiles, and give a good match to field data (see Figure 4).

For wells on the margins of the reservoir the modified model gives deep temperatures that are closer 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 5. It became clear from our efforts to improve some of these temperature profiles that a finer model grid is required.

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 2001/04 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 6 to 11.

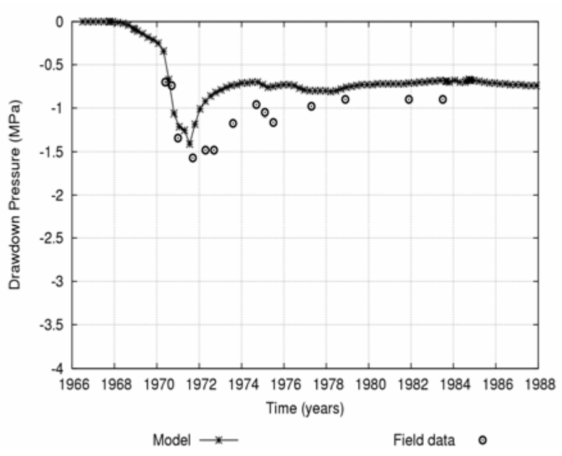

Figure 6. A typical East Bank well, drawdown pressure

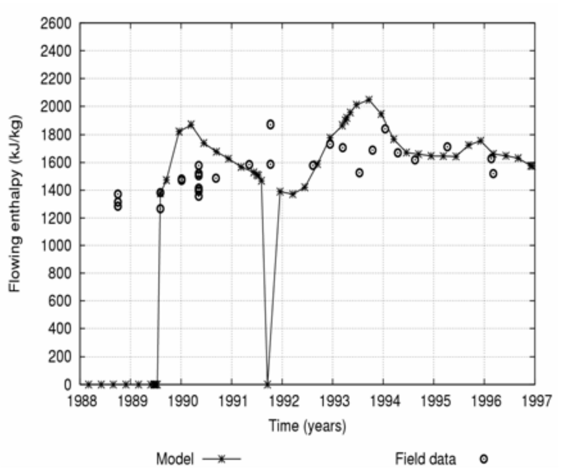

Figure 7. A typical West Bank well, production enthalpy

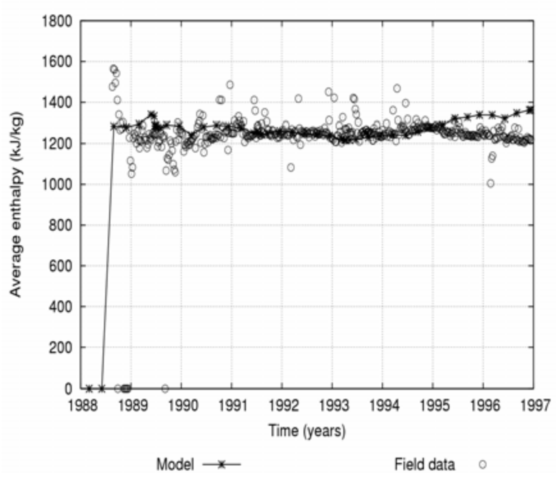

Figure 8. East Bank. SP, average enthalpy

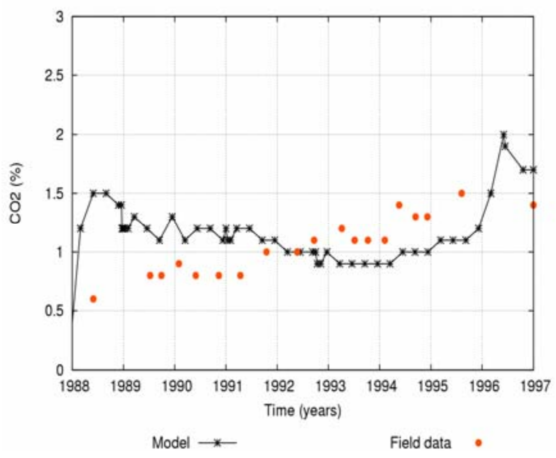

Figure 9. All West Bank wells, average gas concentration

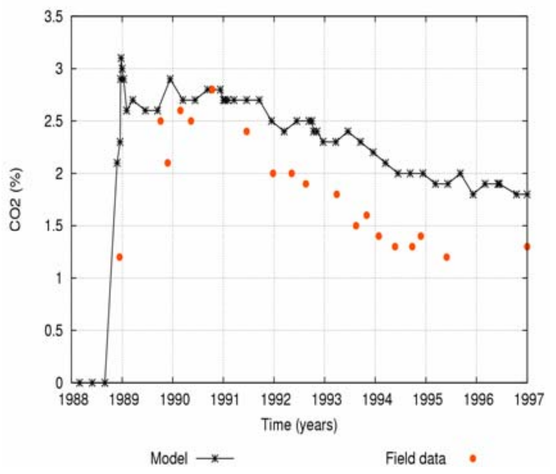

Figure 10. All East Bank wells, average gas concentration

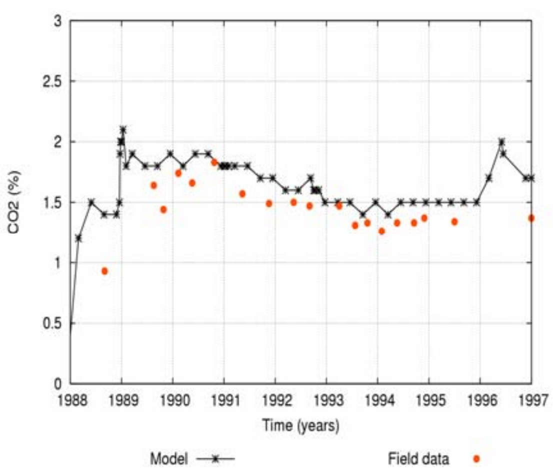

Figure 11. Gas fraction in total production

4. THE 2004 RESERVOIR MODEL

Because of the difficulties experienced with the 2001 model and the 2001/04 model, particularly in matching the temperature profiles in the wells to the west of the model, with temperature inversions, we decided to set up a model with a finer grid structure (Figure 12). It will be referred to as 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. The revised grid contains 366 grid blocks per layer and covers a total surface area of (18 *km* × 18 *km*, see Figure 12). The layer structure is similar to the 2001 model except for two extra layers that were introduced. These were added to give a more gradual transition from the thin layer representing the contact zone at the base of the Rhyolite. The layer structures are compared in Figure 13.

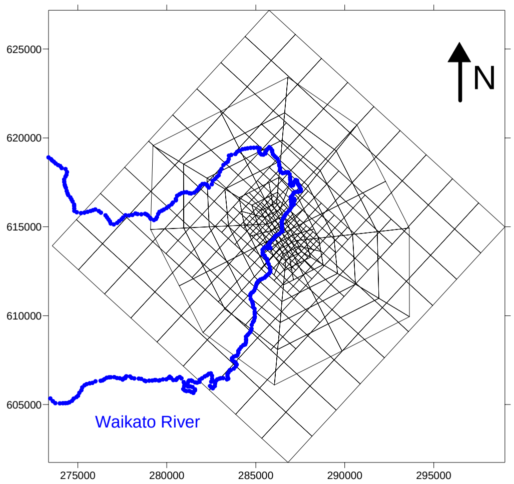

Figure 12. Ohaaki new and old grid structure with the path of the Waikato River.

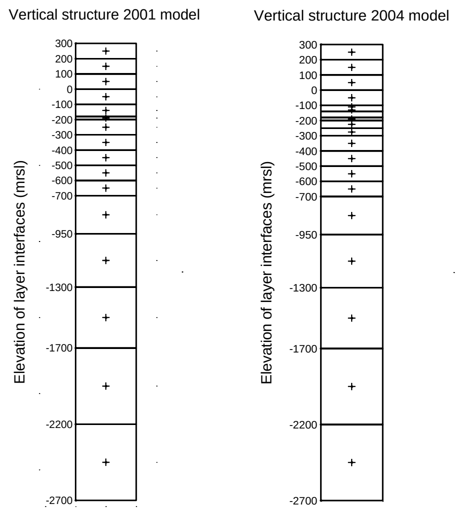

Figure 13. Comparison of the layer structure for the 2001/04 model and the 2004 model

The enlarged portion of the grid (Figure 14) shows that the new grid allows most wells to be allocated to separate blocks.

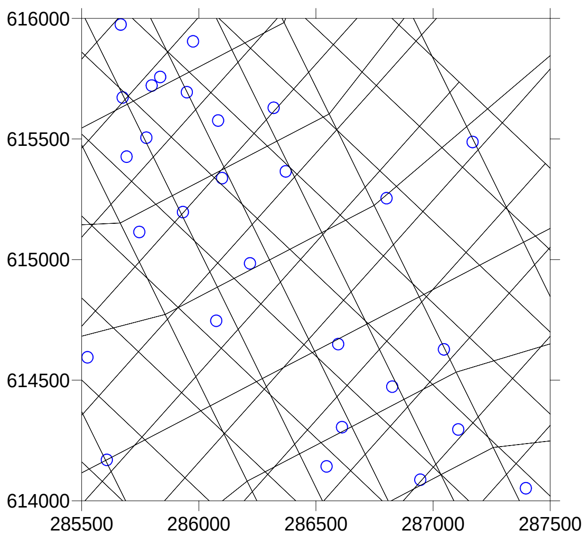

Figure 14. An enlarged portion of the grid for the 2004 model showing the well locations. The grid for the 2001 is superimposed.

A revised surface ground water level was generated using recent data from ground water 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 model surface (Figure 15).

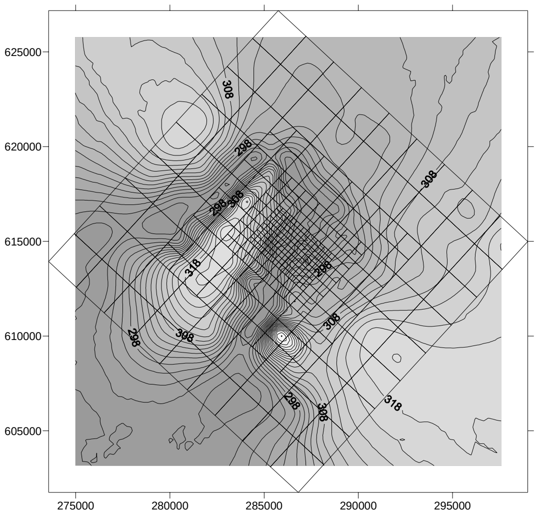

Figure 15. New water surface used with the new grid.

The rock types and permeability structure from the 2001 model were imported into the new 2004 model and the first natural state run produced similar temperature profiles to those shown above. Further refinement to the permeability structure has produced some improvement (as shown in Figure 16 for example) and model development is continuing.

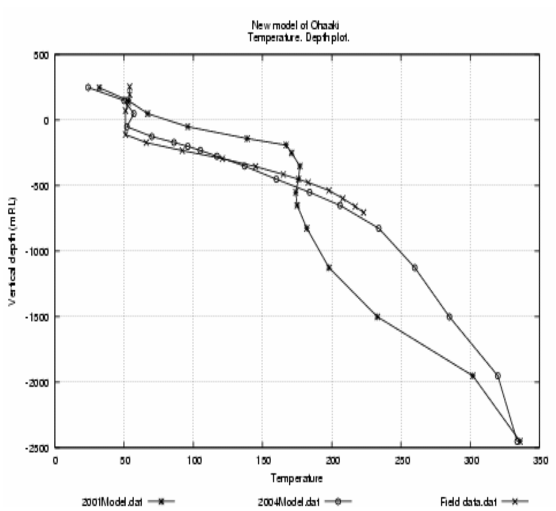

Figure 16. Comparison of results between the 2001 model and 2004 model. Temperature vs depth grid.

4.1 Geological Model

A 3-D geological model was prepared by Paul White of IGNS specifically to match the block centres of the 18 layers used in our revised reservoir model. This geological model is based on available geological data (Figure 17). The geological model covers a smaller area and therefore some extrapolation of the geology was required (see Figure 18).

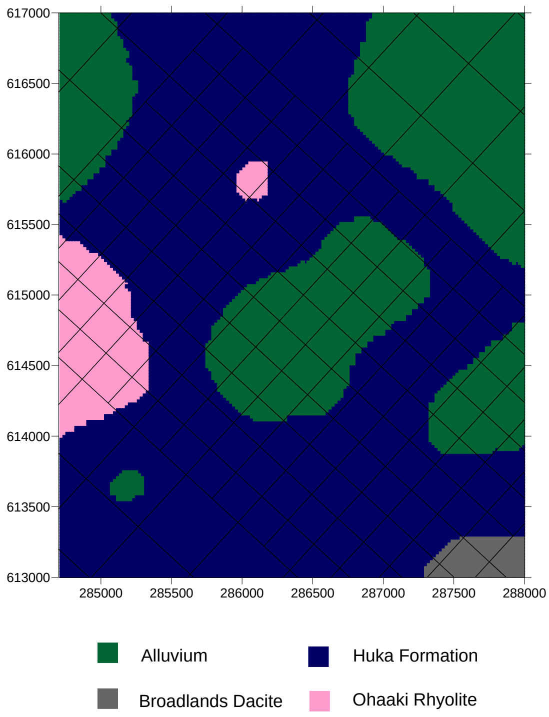

Figure 17. Geological model of the first layer (250 m asl)

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. This resulted in more than 150 rock types in the 2004 model.

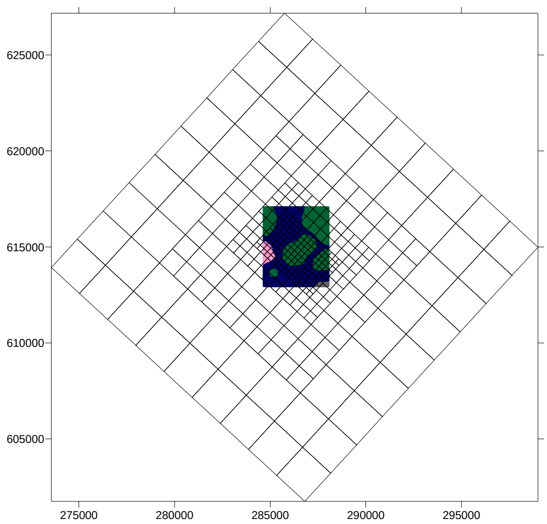

Figure 18. Geological model overlayed on the new grid.

4.2 New Version of MULGRAPH

Dr. Adrian Croucher (Geothermal Group, Department of Engineering Science) has implemented several new features in

MULGRAPH (the University of Auckland graphical interface for TOUGH2.2, O'Sullivan and Bullivant, 1995). One option that is useful for dealing with the Ohaaki models allows the plotting of temperature and pressure profiles in deviated wells. Other new features include: the inclusion of the well locations and well tracks in the geometry file and better zooming capability.

4.3 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 periodically untaken 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.

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, 1993; Finsterle et al., 1997) to assist with model calibration.

5. FUTURE WORK

Work is continuing with the calibration of the 2004 model. It is expected that it will soon be available to assist Contact Energy Ltd. with field management decisions.

6. ACKNOWLEDGMENT

The authors would like to thank Contact Energy Limited for their support and for the kind permission to release recent modeling results.

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