A COMPUTER MODEL OF ROTORUA GEOTHERMAL FIELD

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ABSTRACT

A new computer model of the Rotorua geothermal field is described. It differs from previous models (e.g. Burnell and Kissling, 2005) by having a much finer layer structure in the shallow zone thus making it possible to more accurately represent shallow temperatures and pressures and surface activity.

Two models have been set up: UOA Model 1 with a minimum block size of 250m x 250m and UOA Model 2 with a minimum block size of 125m x 125m. The calibration of UOA Model 1 is well advanced, using both manual methods and inverse modelling, and a good match to surface activity and shallow temperatures has been obtained. Calibration of UOA Model 2 is still in progress.

1. INTRODUCTION

Rotorua Township is located in the Taupo Volcanic Zone (TVZ) in the North Island of New Zealand (Figure 1). The TVZ was created a long time ago by the subduction of the Pacific Plate under the Australian Plate (Wilson *et al*., 1995; Milner *et al*., 2002). Based on the dominant rock type the TVZ can be subdivided into three regions as shown in Figure 1a. In the northern and southern sectors andesite is dominant while rhyolite is dominant in the central sector where Rotorua lies (Houghton *et al*., 1995; Milner *et al*., 2002).

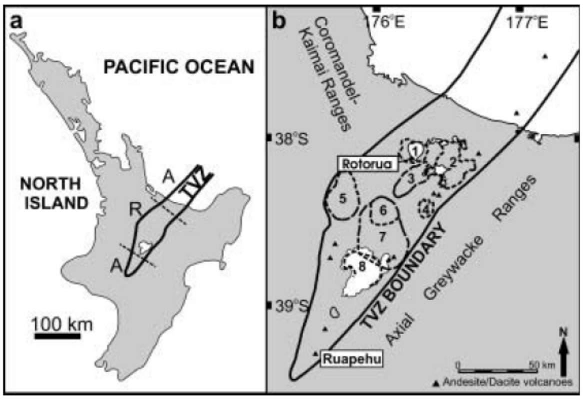

Figure 1: Location of the Rotorua geothermal field (from Milner *et al*., 2002)

Rotorua is one of many calderas in the TVZ (Figure 1b) and was created through the eruption of the Mamaku Ignimbrite at ca 225 ka (Shane *et al*., 1994; Houghton *et al.,* 1995; Black *et al*., 1996; Milner *et al*., 2002). Because of its dominant collapse style, the Rotorua caldera is classified as a down-sag structure (Walker, 1984; Milner *et al*., 2002).

The area of the Rotorua geothermal system is about 12 km^2 (Wood, 1992) and it is famous for its natural surface features which are concentrated in three locations, namely: Kuirau Park in the north, Whakarewarewa in the south, and Government Gardens and Ngapuna in the east (Figure 2). Perhaps the most famous feature is the Pohutu Geyser at Whakarewarewa. It is one of the largest geysers in New Zealand that still exists at the present time (Scott and Cody, 2000). Geysers are not a common natural phenomenon worldwide and so it is very important to preserve Pohutu and the other Rotorua geysers.

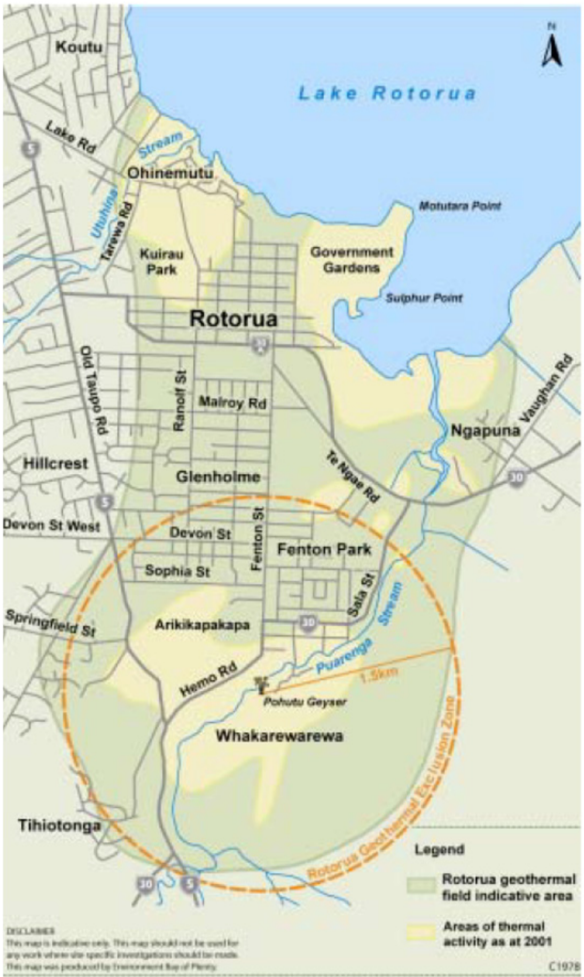

Figure 2 Surface features in Rotorua City (from Gordon *et al*., 2005)

Exploitation of geothermal energy at Rotorua has been occurring since 1920, however, between 1967 and 1986 there was a significant increase in the number of wells that were drilled and the mass flow withdrawn (Scott and Cody, 2000). These events triggered changes in the natural surface activity in the late 1970s, especially in the geysers at Whakarewarewa and flowing springs in other areas across the city. It was suspected that the main reason for the changes was the uncontrolled utilization of the resource by geothermal wells. There were hundreds of wells of various depths drilled in Rotorua. Figure 3 shows the distribution of the wells across the city in 1985. Before that time, there were no regulations to control the utilization of geothermal energy in Rotorua. Residents could easily establish their own geothermal system without notifying the local council, and they could extract an unlimited amount of geothermal fluid with no obligation to re-inject the geothermal fluid back into the earth.

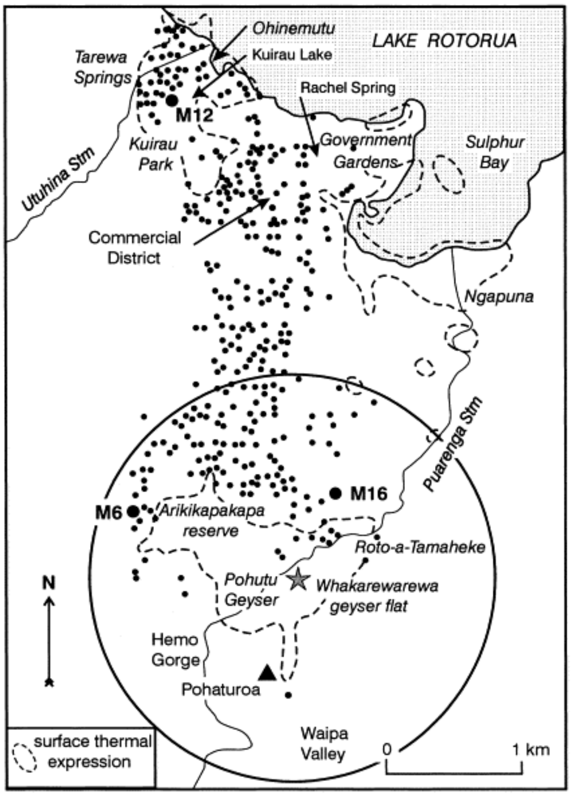

Figure 3. Distribution of geothermal wells in Rotorua City in 1985 (Scott and Cody, 2000)

During the period from 1986 to 1992 the Bay of Plenty Regional Council (BoPRC) introduced a bore closure program requiring all bores within a 1.5 km radius of Pohutu Geyser (shown in Figures 2 and 3) and bores owned by the NZ Government to be closed. The BoPRC also encouraged the use of reinjection wells instead of the discharge of the waste hot water to the atmosphere or to soakage in shallow holes. These actions seem to have been successful and ever since 1992 the pressure of the reservoir has been increasing over time.

2. COMPUTER MODELLING

Used together with an extensive monitoring programme, computer modelling has been one of the key tools for studying the likely future behaviour of the Roturua geothermal field. Back in the 1980s a simple model was used to predict the likely effects of the bore closure program (Grant *et al.*, 1985). Since that time modellers from Industrial Research Limited (IRL) have set up two computer models, the first in the 1990s (Burnell, 1992) and the second in the 2000s (Burnell and Kissling, 2005; Burnell 2007a,b). The present study builds on the second IRL model (called here IRL Model 2), but is different in four respects:

- Our models cover a larger area (Figures 4, 5 and 6)
- They have been rotated to line up with the major structures (shown in Figure 7)
- They are deeper and have a much finer layer structure (Figure 8).
- They incorporate the shallow unsaturated zone and the top of the models follows the topography, whereas for IRL Model 2 the top is set at an assumed simple water table.

On the other hand IRL Model 2 was calibrated with both natural state and production history data whereas our study does not consider the second stage of production history matching.

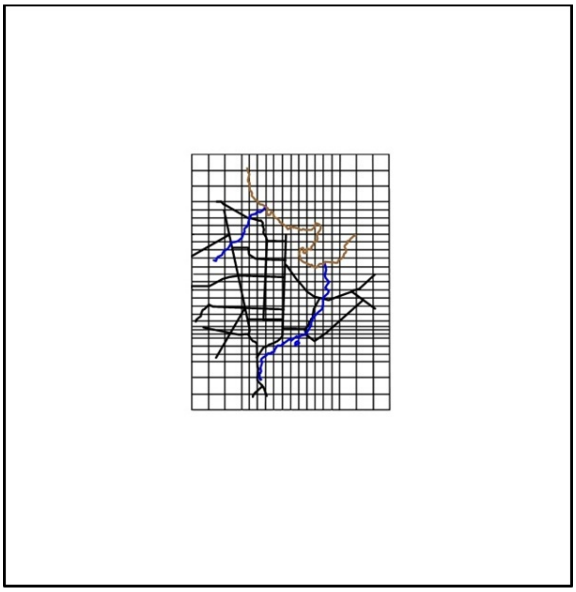

Figure 4. Grid layout for IRL Model 2.

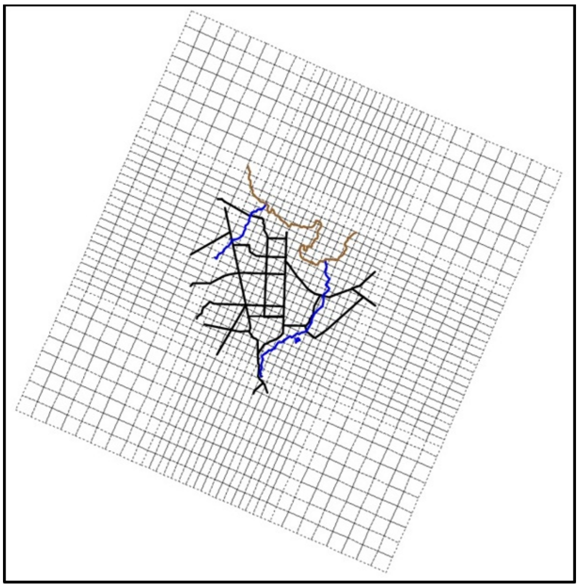

Figure 5. Grid layout for UOA Model 1.

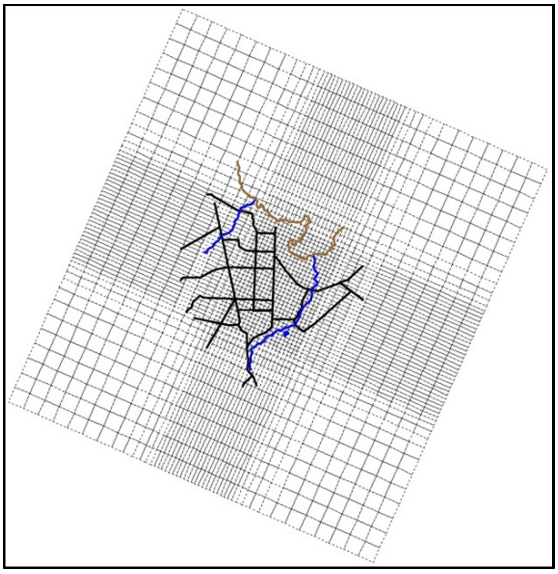

Figure 6. Grid layout for UOA Model 2.

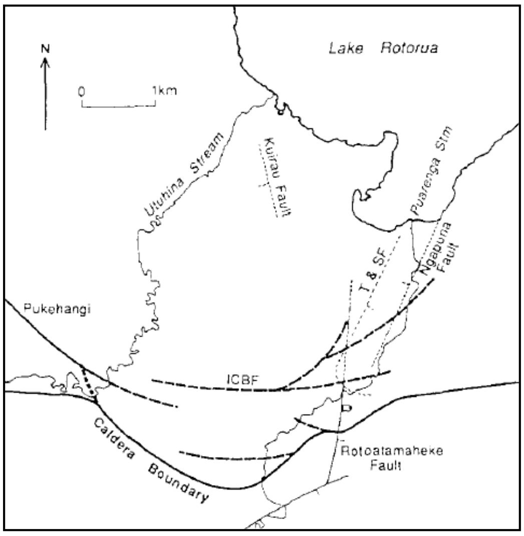

Figure 7. Main faults near Rotorua (from Wood, 1992)

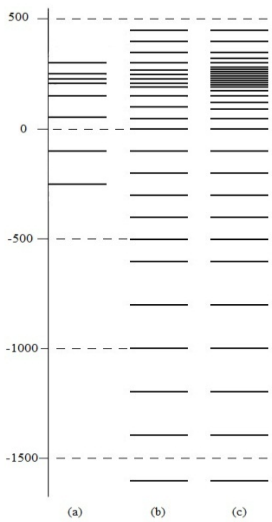

Figure 8. Layer structure for (a) IRL Model 1, (b) UOA Model 1 and (c) UOA Model 2.

Two models are considered here: UOA Model 1, (Figure 5) with a horizontal resolution similar to that used in IRL Model 2, and a higher resolution version called UOA Model 2 (Figure 6). The calibration of UOA Model 1 is well advanced but UOA Model 2 is still under development.

A comparison of the models is given in Table 1.

Table 1. Summary of differences in the models of Rotorua Geothermal Field

Category	Present study: UOA Model 1 & UOA Model 2	IRL Model 2
Grid area	12.4 km x 18.3 km	6 km x 8.5 km
Grid depth	2,000 m	570 m
Blocks (not including atmosphere)	27,217 or 69555	3,550
Orientation (angle to N-S)	23.7^0	0^0
Rainfall rate	1 m/year	1.3 m/year
Infiltration rate	10%	7.5%
Layers	23 or 31	7
Surface	Follows topography & lake bathymetry	Planar water table, 40m lower at the lake

The general aims of reservoir modeling are to set up a computer model which represents the permeability structure, heat inputs and fluid inputs of the real reservoir with reasonable accuracy and then to use the model to simulate the likely future behaviour of the real reservoir for various scenarios over 20 or 30 years. Basically there are four steps in reservoir modelling:

1. Conceptual model building.
2. Natural state modelling.
3. Production history matching.
4. Simulation of future scenarios.

In the case of Rotorua the conceptual model is well developed (Grant *et al*., 1985; Grant, 1986; Burnell and Kissling 2005; Gordon *et al*., 2005; various articles in *Geothermics,* 1992). A sketch taken from the Environment Bay of Plenty Report (Gordon *et al*., 2005) is shown as Figure 9. Thus the present study was able skip the conceptual modelling stage and could start with natural state modelling. Only this stage is reported here. The main changes made to our model, based on the conceptual model and in contrast to IRL Model 2, were (i) to rotate the grid to align it with the major faults and (ii) to introduce a finer layer structure.

One of the aims of our modelling study was to provide a much more detailed representation of the shallow zone at Rotorua and that is why a fine layer structure was introduced.

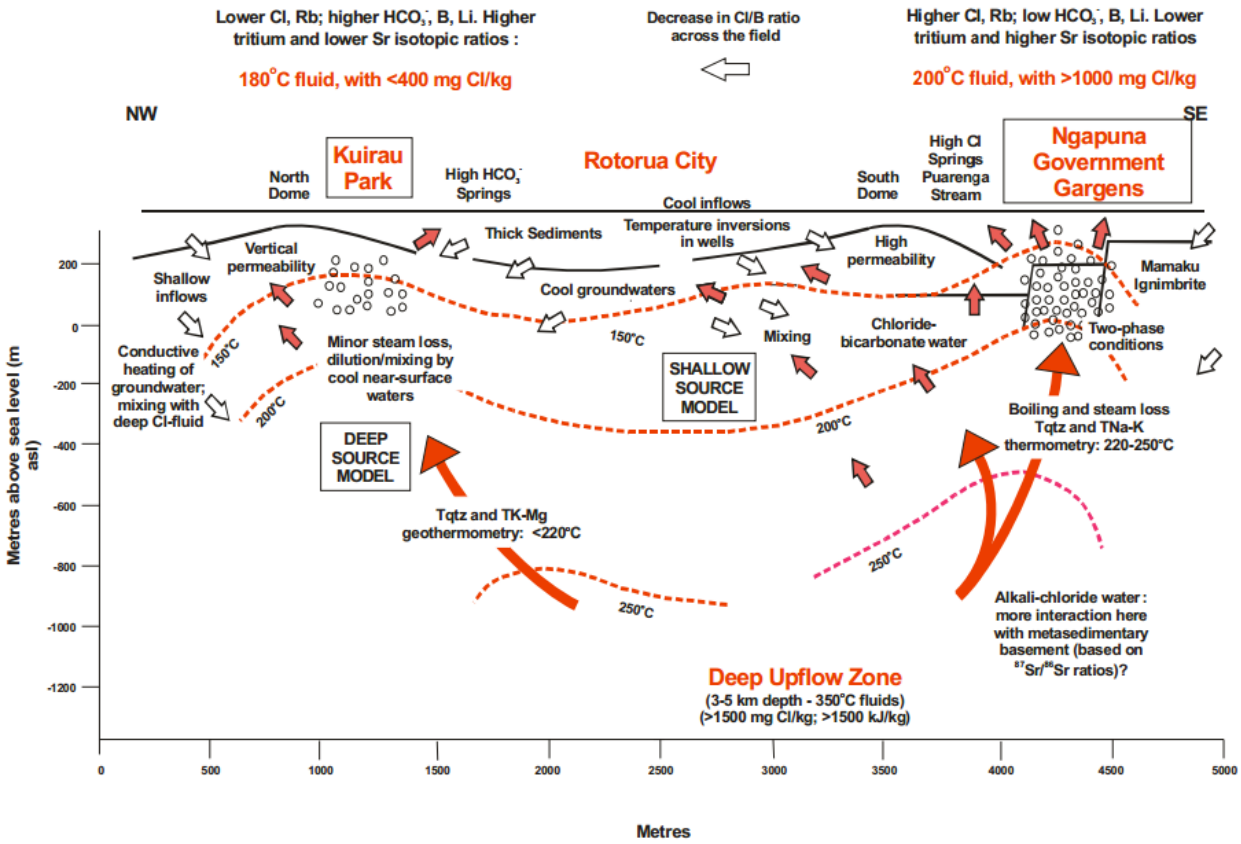

Figure 9. Hydrology of the Rotorua Geothermal field (Gordon *et al*., 2005)

Also the very shallow unsaturated zone was included, requiring the use of EOS4 equation of state (air/water) with AUTOUGH2 whereas the IRL models used EOS1 (pure water with chloride as a tracer) and the top of their models was set at an assumed water table.

3. BOUNDARY CONDITIONS

Top boundary. At the top surface, atmospheric conditions are assigned as the boundary condition: the value of the pressure is 1 bar and the temperature is 150C.

Below the lake surface the pressure is set to the hydrostatic pressure corresponding to the depth of the lake. That is:

$$P = P_0 + \rho g h,$$

where P_0 is the atmospheric pressure, ρ is the water density at 10^0C, g is the gravity acceleration equal to 9.81 m/s^2, and h is the lake depth. The bathymetry of the lake (Figure 10) was retrieved from International Lake Environment Committee Foundation (ILEC). It is a database providing data on lakes worldwide. The mean water level of 280 mRL for Lake Rotorua was sourced from BoPRC (2013).

According to BoPRC, rainfall measurements in Whakarewarewa-Rotorua show that annually the mean rainfall is 1,428 mm, but it varied between 995mm and 1,791 mm in the period 1982-2005. In this study, rainfall is represented by cold water injected into the top of the model. An annual rainfall of 1,000 mm/year and an infiltration rate of 10% are used.

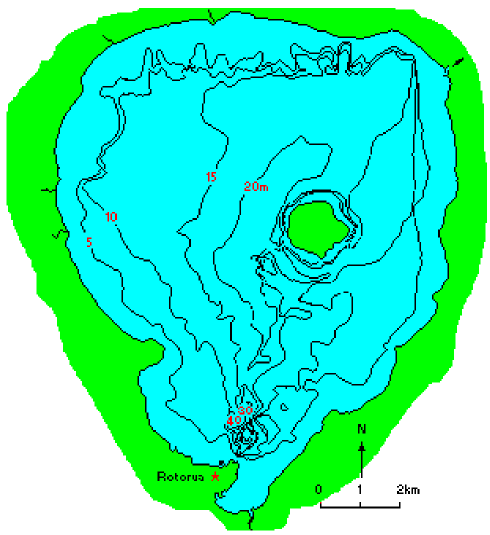

Figure 10. Bathymetric map of Lake Rotorua (from www.ilec.or.jp)

Combining the topography information from the land map and Lake Rotorua bathymetry, the surface elevation of the model was set, using pyTOUGH (Croucher 2011), as shown in Figure 11.

Because the temperature and pressure are fixed at the base of the lake it acts as an "open" boundary with cold water able to flow freely into the model from the lake, or warm water out of the model into the lake.

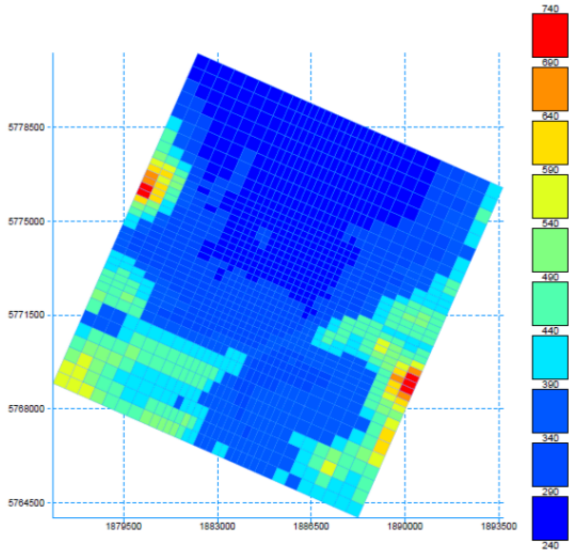

Figure 11. Elevations of top surface of UOA Model 1.

Side boundaries. All the side boundaries are assumed to be closed, which means that there is no heat or mass coming into or going out of the system.

Base boundary. There is some deep inflow of very hot water at the base of the model and elsewhere a conductive flow of heat of 80 mW/m^2 is applied. A comparison of the deep inflow of hot water used in IRL Model 2 and the calibrated version of UOA Model 1 is given in Table 2.

Table 2. Comparison of deep inflows

Area	UOA Model 1		IRL Model 2	
	Mass t/day	Temp (^{0}C)	Mass t/day	Temp (^{0}C)
Kuirau Park	2509	260	2,420	200
Ngapuna Stream	6,290	260	17,300	220
Whakarewarewa	13,567	250	30,320	200

The mismatch between the deep inflows given in Table 2 is to be expected for two reasons: first, in IRL Model 2 they are applied at an elevation of -250mRL whereas for UOA Model 1 they are applied much deeper, at -1600mRL The temperatures in UOA Model 1 at an elevation of -250mRL are lower than the base temperatures and the flows are somewhat larger, both effects coming from the extra convective entrainment of cold water. The second reason for the mismatch is the fact that UOA Model 1 has not been calibrated with production data and the permeabilities and flows may be too small. Past experience has shown that multiplying all permeabilities and all deep inflows of mass by the same factor leaves the natural state temperatures almost unchanged, while having a large effect on pressure drawdown during a production history simulation. The permeabilities used in IRL Model 2 seemed to be very high and they were significantly reduced in UOA Model 1 (see Table 3), but possibly by too much.

Table 3. Comparison of permeabilities in IRL Model 1 and UOA Model 2 (permeability in milli-Darcies)

	IRL Model 1			UOA Model 2			
Rock-type	x	y	z	Model code	x	y	z
Ignimbrite	660	980	200	IGNIM	52	110	13
North Ignimbrite	100	1000	20	NIGNM	5	5	2
South Ignimbrite	100	20	50	SIGNM	9.8	19	5.2
East Ignimbrite	500	500	50	EIGNM	42	52	5
West Ignimbrite	500	500	10	WIGNM	49	49	10
Sediment	100	100	50	SEDIM	8	11	54
West Sediment	500	500	50	WSEDM	50	58	9.7
Aquaclude	10	10	1	AQUAC	10	1	1
				AQUAD	10	1	5
Rhyolite	4800	150	10000	RHYOL	722	483	7.6
				RHYOM	4.8	55	2.9
				RHYON	482	374	12.7
Greywacke				GREYW	1.1	1.0	1.0
ICBF	100	1	100	ICBF	100	13	27
ICBF lower	100	100	100	ICBFL	1.4	6.6	7.9

4. NATURAL STATE MODELLING

The aim of our study was to re-calibrate the natural state model by varying the permeability distribution and deep inflows of heat and mass so that the model results matched field data. Three kinds of field data were used:

- The location and magnitude of surface heat and mass flows in the three main geothermal areas at Whakarewarewa, Kuirau Park and Ngapuna (see Figure 12).
- Temperature contours at 180 masl derived by Wood (1985), shown in Figure 15.
- Downhole temperature profiles for 155 wells from Ministry of Works reports held by the Geothermal Institute and from electronic records obtained from BoPRC (Ady Candra and Zarrouk, 2013).

An initial permeability structure was assigned to our model by interpolation and extrapolation of the structure used in the IRL 2004 model and then adjustments were made to improve the match of the model results to the field data. In the first stage of calibration manual methods were used while in a second stage inverse modelling using PEST (Doherty, 2003; Doherty *et al*., 1994) was applied.

5. RESULTS

As shown in Table 3 the calibrated version of UOA Model 1 ended up with lower permeabilities than were used in IRL Model 2. As mentioned above no production history matching calibration of UOA Model 1 has been carried out and it may be that both the deep inflow of mass and the permeabilties should be multiplied by the same factor. A factor of 2 would make the deep mass flows similar but would still leave the permeabilities in UOA Model 1 lower than those in IRL Model 2. Some production history modelling is required for further calibration of UOA Model 2.

The measured surface activity at Rotorua is shown in Figure 12, near surface (top layer) temperatures from UOA Model 1 are shown in Figure 13 and from UOA Model 2 in Figure 14.

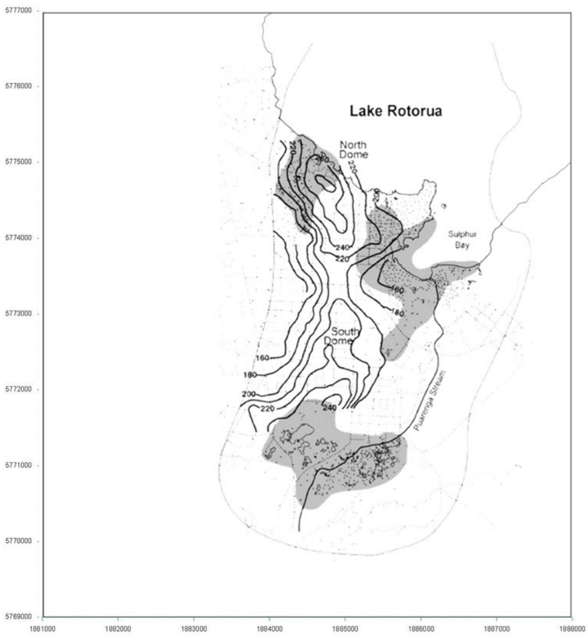

Figure 12. Surface features in Rotorua City after Werner and Cardellini (2006)

UOA Model 1 is not hot enough in the Whakarewarea area or the Kuirau Park area. UOA Model 2 is better in the Whakarewarewa area but is similarly too cold at Kuirau Park. Both models have hot zones in the correct locations on each side of Sulphur Bay at the Government Gardens and Ngapuna but the areas may not be quite large enough.

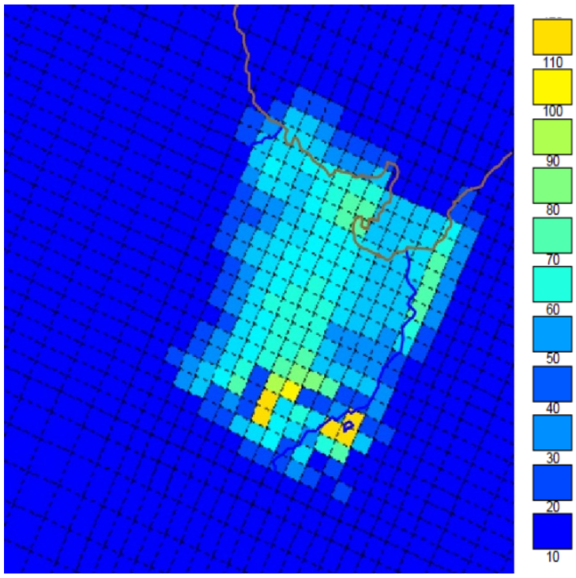

Figure 13. Near-surface temperatures, UOA Model 1.

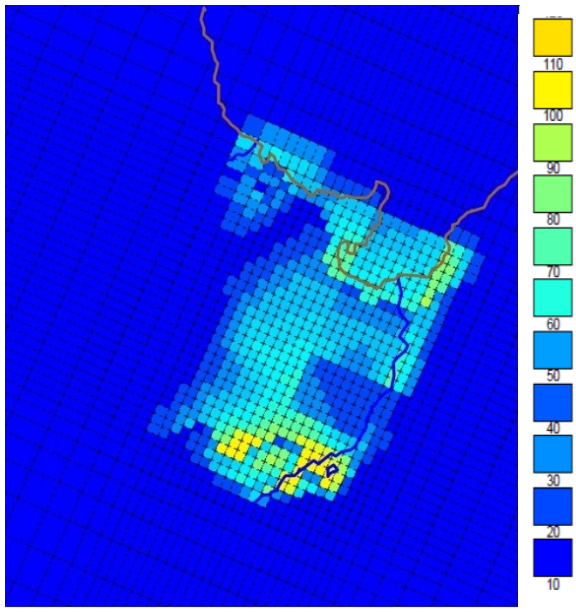

Figure 14. Near-surface temperatures, UOA Model 2.

Temperature contours at 180 masl based on measured data (Wood, 1985) are shown in Figure 15 and UOA Model 1 results for 190 masl (centre of layer 9) are shown in Figure 16. The values of the temperature in the model at this elevation are correct but the extent of the hot zone beneath Whakarewarewa is too large. The data shows more inflow of cold water from the west than is present in the model.

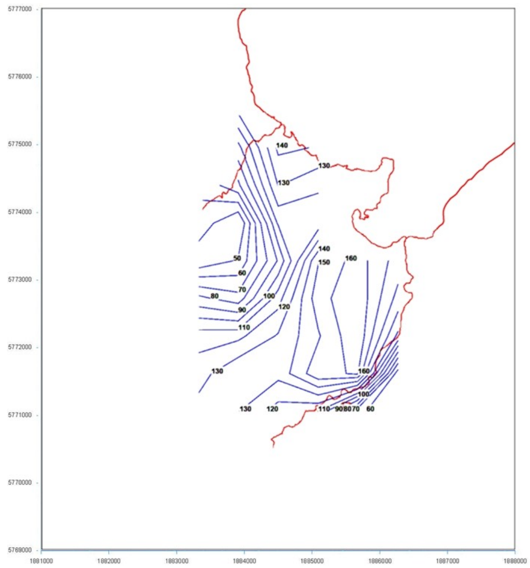

Figure 15. Temperature distribution at 180mRL, after Wood (1985)

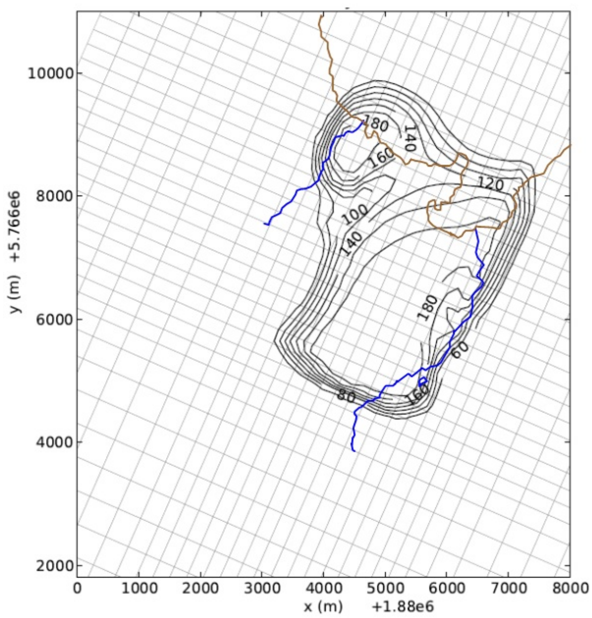

Figure 16. Temperature contours at 190mRL for UOA Model 1.

Three plots of down-hole temperatures are shown in Figures 17-19. They are for wells in the north, centre and south of Rotorua, respectively. The match between the model results and the data is good, but the wells are all shallow and thus the data extends over a limited range in elevation.

Similar plots were made for 130 different wells and most show a similar quality of match between the model results and the data. Further runs of PEST are being made to further improve the model.

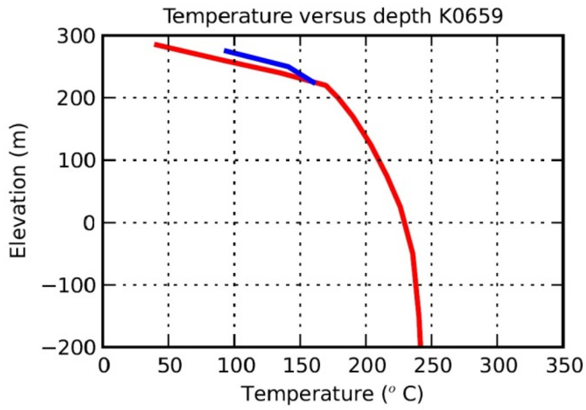

Figure 17. Down-hole temperature for well 659: blue for data, red for model results.

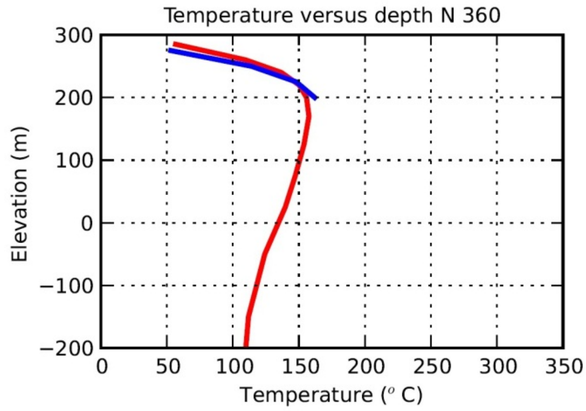

Figure 18. Down-hole temperature for well 360: blue for data, red for model results.

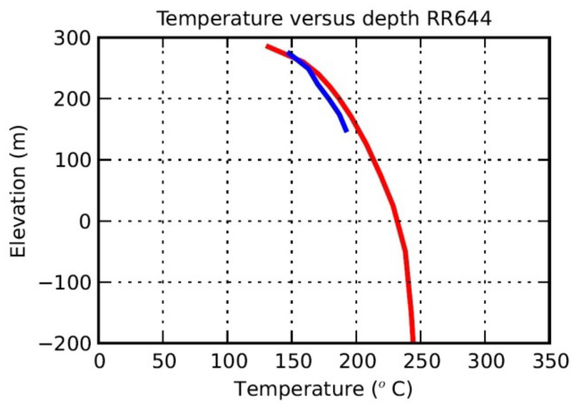

Figure 19. Down-hole temperature for well 644: blue for data, red for model results.

6. CONCLUSIONS AND RECOMMENDATIONS

A start has been made on developing models that have the potential to represent the shallow zone of Rotorua with good accuracy. Manual methods and inverse modelling have been used to calibrate UOA Model 1 against surface activity, temperatures at 180mRL and downhole temperatures from

~130 shallow wells. Further calibration to improve the natural state model is required and production history matching is also required for model calibration. The even more detailed UOA Model 2 is being developed in parallel.

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REFERENCES

Ady Candra, S. and Zarrouk, S.: Testing Direct Use Geothermal Wells in Rotorua, New Zealand. *Proc. 35th New Zealand Geothermal, Workshop, Rotorua*, New Zealand (2013).

Bay of Plenty Regional Council.Lake Rotorua Water Level. Retrieved 30/04/2013, from http://monitoring.boprc.govt.nz/MonitoredSites/cgi-bin/hydwebserver.cgi/sites/details?site=238&treecatchment=26 (2013).

Black, T.M., Shane, P.A.R., Westgate, J.A. and Froggatt, P.C.: Chronology and paleomagnetic constraints on widespread welded ignimbrites of the Taupo Volcanic Zone, New Zealand. *Bull. Volcanol., 58*, 281-287 (1996).

Burnell, J.G.: Modelling mass, energy and chloride flows in the Rotorua geothermal field. *Geothermics, 21* (1/2), 261-280 (1992).

Burnell, J.G.: Rotorua geothermal reservoir modelling part 2: scenario modelling. *Industrial Research Limited Report to Environment Bay of Plenty*, February, 2005 (2005).

Burnell, J.G.: Rotorua geothermal reservoir modelling 2006: heat exchanger scenarios preliminary report. *Industrial Research Limited Report to Environment Bay of Plenty*. May, 2007 (2007a).

Burnell, J.G.: Rotorua geothermal reservoir modelling 2006: heat exchanger scenarios and exclusion zone assessment final report. *Industrial Research Limited Report to Environment Bay of Plenty*. July, 2007 (2007b).

Burnell, J., & Kissling, W.: Rotorua geothermal reservoir modelling part 1: Model update 2004. *Industrial Research Limited Report to Environment Bay of Plenty*. February, 2005 (2005)

Croucher, A. E.: PyTOUGH: a Python scripting library for automating TOUGH2 simulations. *Proc. 33rd New Zealand Geothermal, Workshop*, University of Auckland, Auckland, New Zealand (2011).

Doherty, J.: *Version 5 of PEST Manual*. Watermark Numerical Computing, Brisbane (2003).

Doherty, J., Brebber, L. and Whyte, P.: PEST: Model-independent parameter estimation. Watermark Computing, Corinda, Australia, 122 (1994).

Geothermics. Rotorua Geothermal Field, New Zealand. Special Issue of Geothermics, 21(1), (1992).

Gordon, D. A., Scott, B., & Mroczek, E. K.: *Rotorua geothermal field management monitoring update: 2005*. Environment Bay of Plenty Environmental publication 2005/12 (2005).

Grant, M.A., McGuiness, M.J., Dalziel, S.R., Razali, Yunus and O'Sullivan, M.J.: A model of Rotorua geothermal field and springs. In: *The Rotorua geothermal field - Technical report of the monitoring programme 1982-1985*. Ministry of Energy, Wellington (1985)

Grant, M.A.: The response to exploitation of Rotorua geothermal field. *Proceedings 11th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford , California, 271-275 (1986)

Houghton, B.F., Wilson, C.J.N., McWilliams, M.O., Lamphere, M.A., Weaver, S.D., Briggs, R.M. and Pringle, M.S.: Chronology and dynamics of a large silicic magmatic system: Central Taupo Volcanic Zone, New Zealand. *Geology, 23*, 13-16 (1995).

Milner, D., Cole, J., and Wood, C.: Asymmetric, multiple-block collapse at Rotorua caldera, Taupo Volcanic Zone, New Zealand. *Bulletin of Volcanology, 64*(2), 134-149 (2002).

O'Sullivan, M.J.: *AUTOUGH2 Notes*. Geothermal Research Software., Department of Engineering Science, University of Auckland (2000).

Pruess, K.: TOUGH2: A general-purpose numerical simulator for multiphase nonisothermal flows, Lawrence Berkeley Lab., California USA (1991).

Scott, B. J. and Cody, A. D.: Response of the Rotorua geothermal system to exploitation and varying management regimes. *Geothermics, 29*(4), 573-592, (2000)

Shane, P., Black, T. and Westgate, J.: Isothermal plateau fission track age for the paleomagnetic excursion in the Mamaku Ignimbrite, New Zealand, and implications for late Quaternary stratigraphy. *Geophys. Res. Lett., 21*, 1695-1698, (1994)

Walker, G.P.L.: Downsag calderas, ring faults, caldera sizes and incremental caldera growth. *J. Geophys. Res., 89B*, 8407-8416, (1984).

Werner, C. and Cardellini, C.: Comparison of carbon dioxide emissions with fluid upflow, chemistry and geologic structures at the Rotorua geothermal system, New Zealand. *Geothermics, 35*(3), 221-238. doi:10.1016/j.geothermics.2006.02.006, (2006).

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lamphere, M.A.,Weaver, S.D. and Briggs, R.M.: Volcanic and structural evolution of Taupo Volcanic Zone: a review. *J. Volcanol. Geotherm. Res., 68*, 1-28, (1995)

Wood, C.P.: Geology of the Rotorua geothermal system. *Geothermics, 21*(1), 25-41, (1992).

Wood, C.P.: Geology of Rotorua Geothermal Field. In: *The Rotorua geothermal field -Technical report of the monitoring programme 1982-1985*. Ministry of Energy, Wellington (1985).