

# MODELLING THE NGATAMARIKI GEOTHERMAL SYSTEM

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## ABSTRACT

The Ngatamariki geothermal field is situated 17 km north east of Taupo. Mighty River Power has announced plans to build an 82 MW power station on the field.

As part of the consent and planning processes, an extensive programme of drilling, testing and modelling was undertaken to provide understanding of the likely response of the field to a development. Analysis of the three new deep wells drilled by Mighty River Power in 2008-9 and the four wells drilled by the New Zealand government in the 1980s, together with recent MT surveys, showed a larger field than was originally defined by the early DSIR resistivity surveys. A conceptual model was developed to encompass the new data collected from the wells and the MT surveys.

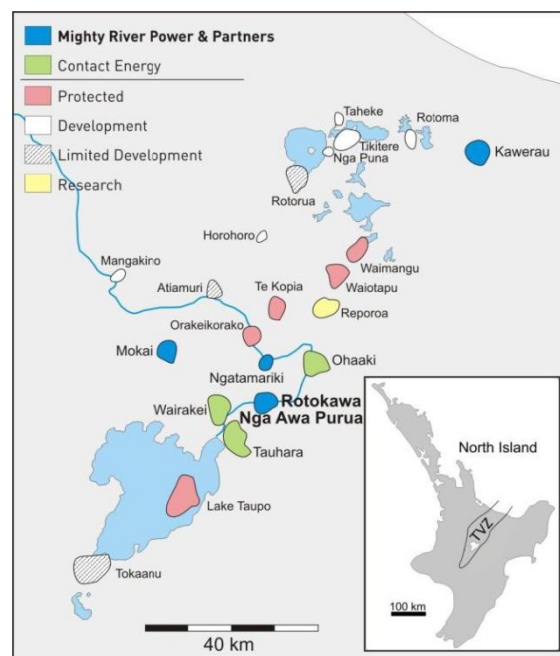
Modelling of the field was undertaken with a full-field dual-porosity numerical model together with a number of simpler process models. The challenge for the numerical modelling was to find parameter values for the model that would provide robust predictions of the field response to development. To help with this challenge, quick-running process models were used to test understanding of the flow processes and the sensitivity of the predictions to the model parameters.

In this paper, we will describe the development of the various numerical models and discuss how the process model informed the full-field numerical model.

## 1. INTRODUCTION AND CONCEPTUAL MODEL.

The Ngatamariki geothermal field is located 17 km north east of Taupo as shown in Figure 1. NM1 was drilled in 1984 by the New Zealand government; it was hot but did not find production permeability. Wells NM2 and NM3 were drilled into hot ( $> 280^{\circ}\text{C}$ ) permeable reservoir while NM4 encountered a conductive temperature gradient and low permeability indicating the northern boundary to the system. Due to the NZ-wide lack of interest in geothermal developments, no further exploration was undertaken throughout the 1990's.

In 2004 the Rotokawa Joint Venture (RJV), a joint venture between Tauhara North #2 Maori Trust and Mighty River Power rejuvenated interest in the field. An MT survey was conducted which suggested a larger resource than was previously defined. Three new deep wells, NM5, NM6 and NM7, drilled during 2008-9 confirmed hot temperatures and permeable reservoir to the south. Well locations and likely resource boundaries are shown in Figure 2.

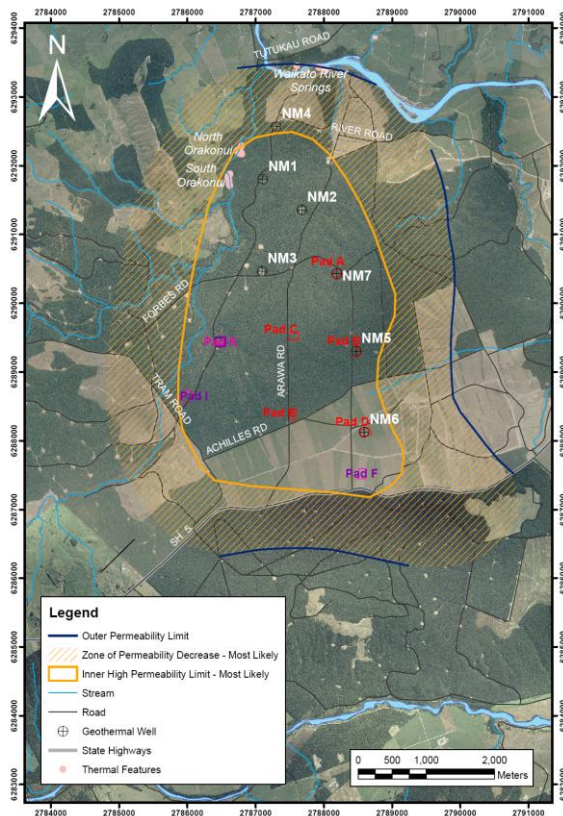


**Figure 1: Location of the Ngatamariki geothermal field**

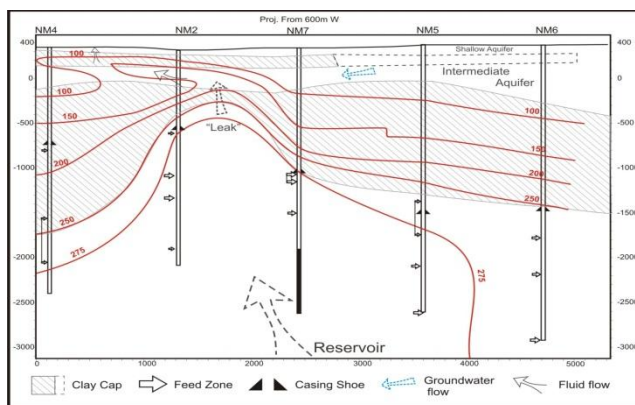
The information obtained from these new wells and the MT survey was incorporated into an updated conceptual model of the field described in (Boseley, Grant, Burnell, & Rickets, 2010). This conceptual model is summarized in Figure 3, showing a deep andesitic reservoir separated from an intermediate aquifer (mainly rhyolite and vitric tuff) by a hydrothermally altered clay cap.

Deep reservoir fluid flows up and out into the intermediate aquifer via a permeable gap in the clay cap. Groundwater flows north through the intermediate aquifer and mixes with deep reservoir fluid and meteoric water and exits to surface via a number of hot springs, with some interaction with a small shallow aquifer located above the intermediate aquifer. There are some indications of a deep outflow to the south-east of the system. Temperature and chloride contours locate the connection between the deep reservoir and the intermediate aquifer close to NM2 and NM3. The temperatures of the deep wells indicate that the hot upflow into the system is close to NM7.

Numerical modelling of the reservoir was undertaken to provide understanding of the likely response of the reservoir to development. A goal of the model was to represent both the deep geothermal reservoir and the shallow intermediate aquifer.



**Figure 2: Ngatamariki well locations and resource boundary**



**Figure 3: Ngatamariki conceptual model summary**

## 2. DESCRIPTION OF NUMERICAL MODEL DEVELOPMENT

### 2.1 Single porosity model

The initial numerical model of the reservoir was focused on understanding the likely response to development of the field. It was a single porosity TOUGH2 model with 27 layers and 33,966 grid elements and achieved very reasonable matches to measured temperatures and pressures. Results from this model identified cold downflows from the intermediate aquifer as a risk to any development of the reservoir. As a consequence it was decided that any development plans should include 100%

reinjection to reduce the pressure drawdown and minimise the likelihood of a cold downflow.

A subsequent review of development options with 100% injection identified thermal breakthrough from injection as a significant risk to the project. At this stage, it was realised that a single porosity numerical model was not suitable for assessing this risk, and it was decided to undertake the risk assessment using a dual porosity numerical model together with simpler process models.

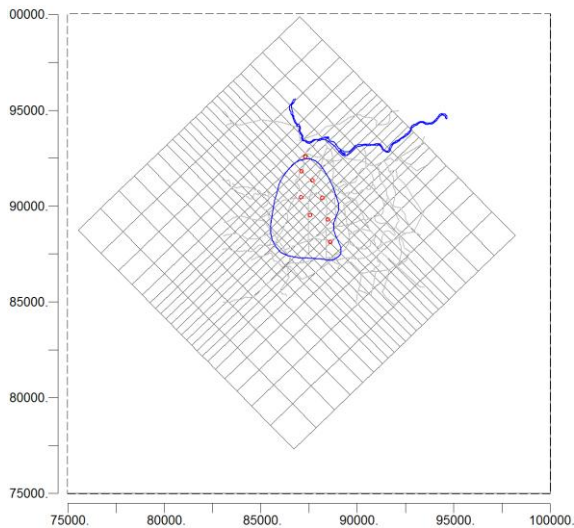
The reasons why a single porosity model is not suitable for assessing injection breakthrough are worth discussing in more detail. Reservoir rocks can be conveniently grouped into high permeability, high porosity fracture and low porosity, low permeability matrix. Fluid flow through a geothermal system is dominated by flow through the fractures whereas the interaction between matrix and fracture is a key control on heat transfer. Typically, in response to production, fracture pressures will drop and induce fluid to flow out of the matrix and into the fracture. The size of the flow from matrix to fracture will affect the magnitude of pressure drop, the amount of boiling and the enthalpy of the produced fluid. In the case of Ngatamariki, where all produced fluid will be injected back into the reservoir, the fracture pressure will remain high which may lead to limited fluid flow between fracture and matrix. In this case, the main heat transfer mechanism for heating the cooler injected fluid will be conduction from the matrix rock. This may allow cooler injected fluid to travel long distances through the fracture without significant heating, increasing the risk of thermal breakthrough at the production zones.

Single porosity models average the flow properties of the matrix and fractures over the scale of a model grid block and are unable to accurately estimate the heat transfer processes between the matrix and the fractures, and hence such phenomena as thermal breakthrough. On the other hand, dual porosity models treat the fracture and matrix separately and provide better estimates of thermal breakthrough. Further complexity can be added by using the multiple interacting continua (MINC) functionality in TOUGH2 which separates the matrix up into additional layers (Pruess, Oldenburg, & Moridis, 1999).

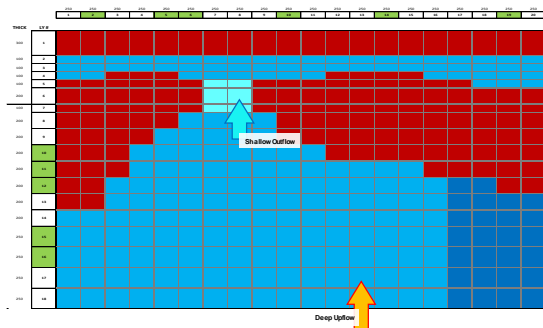
### 2.2 Dual porosity and process models

A dual porosity model of the Ngatamariki reservoir was developed, covering an area of 16 square kilometres and extending from the ground surface down to -5000 mRL (Figure 4). The model was split into 26 layers with a total of around 15,000 grid blocks. Model parameters were adjusted to get reasonable matches to initial state temperature and pressure; and to interference tests when NM7 was flowed.

Simultaneously, a simpler process model with around 5040 grid blocks was developed to be a reasonable match to the measured Ngatamariki temperatures and pressures. The process model, depicted in Figure 5, was developed to enable quick exploration of flow processes in the reservoir and to test the sensitivity of the predictions to the model parameters.



**Figure 4: Model horizontal grid for the dual porosity model. The closed blue curve is the approximate resource boundary, and the red dots are wells and well pads.**

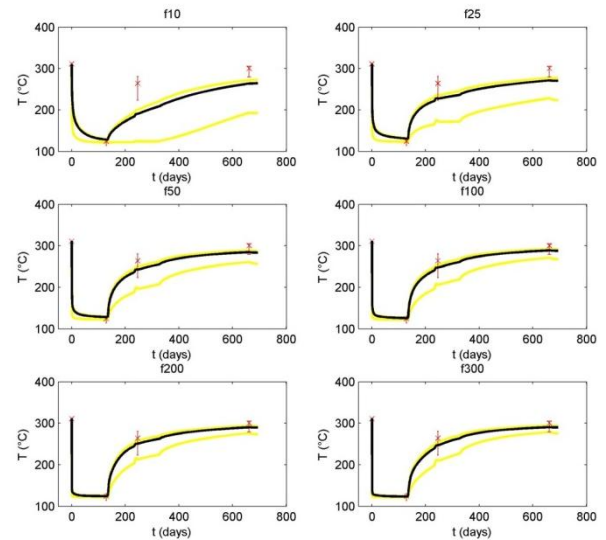


**Figure 5: Vertical view of the process model showing a simple structure with blue indicating permeable rock and red indicating the impermeable clay cap and ground surface.**

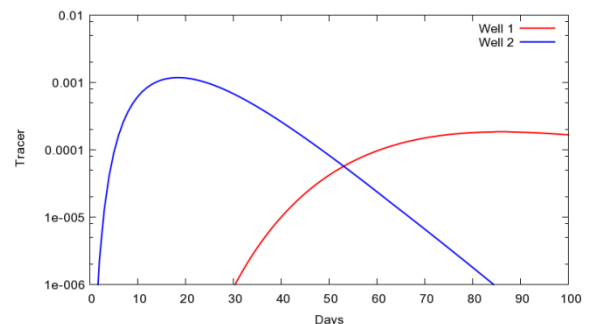
### 2.3 Constraints on fracture spacing and fracture permeability

Natural state measurements do not provide good constraints on the parameters describing the interaction between matrix and fracture. These are key parameters controlling the predictions of a dual porosity model.

With no production history at Ngatamariki, data was found from a neighbouring field where a well was used as a cold condensate injector for 3 months. The consequent cooling and heat up from this test provided some data with which to constrain the fracture spacing parameter. As can be seen in Figure 6, the well cooled from 300 °C to 120 °C during condensate injection before heating up over the following months. This test was modelled with a dual porosity process model, and the best fits to the data were found with a fracture spacing of around 100m. The same field also offered a tracer test which provided estimates of the fracture permeability - Figure 7.



**Figure 6: Results showing the match of a simple radial model to the cooling and heating of the well in response to condensate injection. The different figures show results for different fracture spacings. The black lines show the mean temperature over the depth of the well, with the yellow lines indicating the maximum and minimum temperature found in the well. The red lines summarize the measured temperatures, with the cross marking the mean and the maximum and minimum temperatures indicated by the extent of the line.**



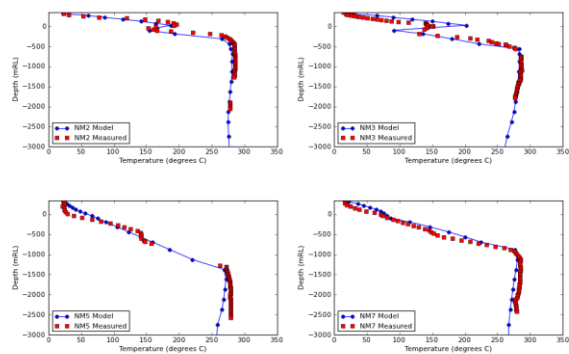
**Figure 7: Model tracer returns for injection of tracer for 2 days at 2 different wells 1300m apart. In the field returns were detected after 1 day and 40 days respectively.**

## 3. RESULTS

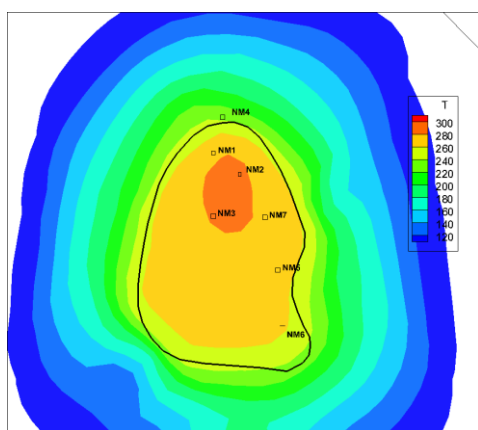
### 3.1 Natural state match

The natural state temperatures of the dual porosity model are shown in Figure 8 and Figure 9, demonstrating a close match to measured well temperatures. Because of the potential for cold downflow from the intermediate aquifer it was important that the model accurately represents the intermediate aquifer. The temperature profiles shown in Figure 8 show that the model reproduces the temperature inversions that are seen in NM2 and NM3.





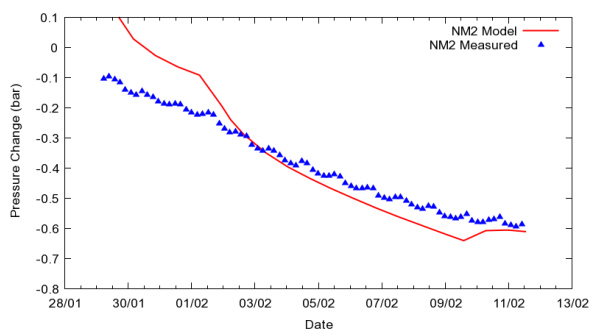
**Figure 8: Dual porosity model matches to natural state temperature profiles. The blue curves are the model temperatures and the red dots are the measured temperatures.**



**Figure 9: Contours of the dual porosity model natural state temperatures at -1500 m.**

### 3.2 Interference Tests

In addition to matching the natural state temperatures, some short term interference tests were performed in the reservoir. In early 2010, NM7 was discharged for 11 days and the pressures in NM2 were monitored. This test was reproduced in the numerical model and the match is shown in Figure 10. This is a reasonable match for a field-scale reservoir model.



**Figure 10: Match of the model to NM2 pressure response to NM7 discharge in early 2010.**

### 3.3 Dual porosity model scenarios

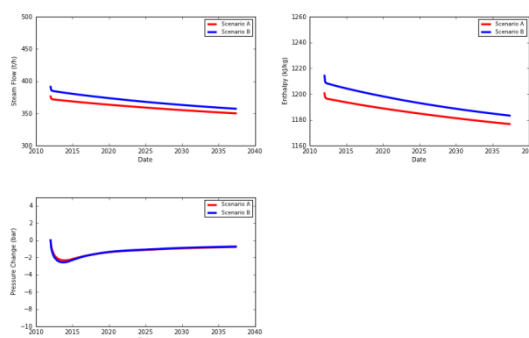
The calibrated numerical model was used to run numerous forecasting scenarios, in an attempt to determine the optimal development option and assess risks. The scenarios considered different production and injection well locations and amounts of produced fluid. An important part of this forecasting was understanding the range of the predictions that would result from model aspects that were not well constrained by the field data. The process model played a key role with this.

The scenarios were constructed using wells on deliverability, where the deliverability model was calibrated from the output of wellbore modelling. The model was run for 25 years and the different scenarios were compared using the predicted steam flow from the field.

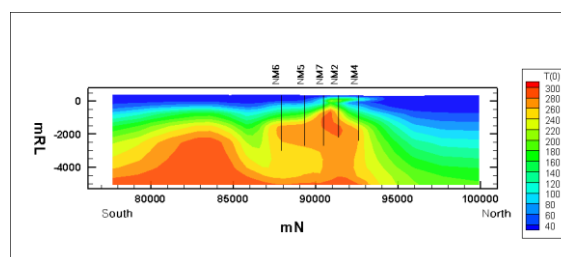
The results demonstrated that the required steam flow could be maintained over a 25 year period with only a small enthalpy drop. The result of the running the different scenarios suggested that it was feasible to setup the field with a production area between NM7 and NM5 and the injection area to the north of NM1.

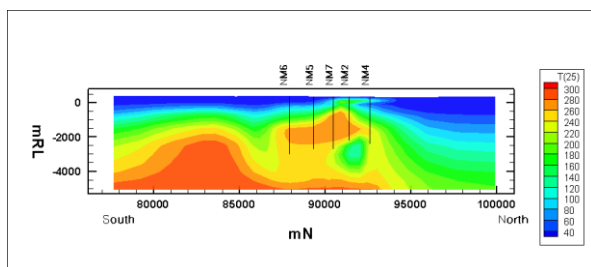
Examples of the model output are shown in Figure 11. In this scenario, there is a decline in enthalpy and hence steam flow as a result of cooler injected fluid encroaching on the production area. Figure 12 shows fracture temperatures in a north-south slice through the field from the natural state and after 25 years production. The cooling seen in the second figure is from injection deeper than the production levels of around -1500 mRL.

The model was also used to investigate the possibility of inducing a downflow of cold water from the intermediate aquifer. In all development scenarios with 100% injection, such a downflow did not occur. However with only 75% injection, some scenarios did show a downflow as seen in Figure 13.

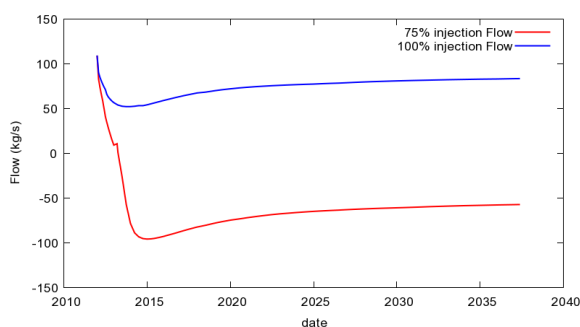


**Figure 11 Model prediction of reservoir steam flow, enthalpy and pressure change beneath the leak**



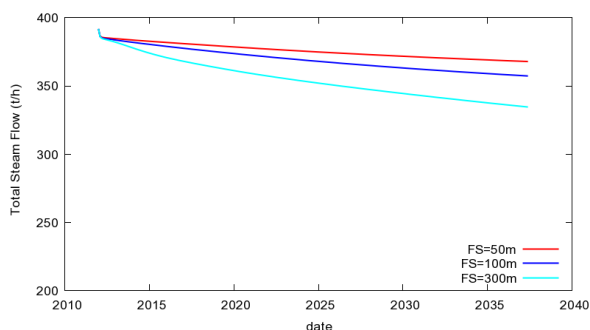


**Figure 12: Fracture temperatures in the model in a north-south slice through the field in the natural state and after 25 years production**



**Figure 13: Flow between the geothermal reservoir and the Intermediate Aquifer with 75% vs. 100% injection scenarios. A positive value signifies an outflow from the reservoir and a negative value is a downflow.**

The fracture spacing used in the model was obtained from a test in a neighbouring field, so the applicability to Ngatamariki was subject to some uncertainty. The sensitivity of the numerical model to the fracture spacing was assessed by running the model with a range of fracture spacings. Figure 14 shows the effect of fracture spacing on the steam flow. Even with a pessimistic fracture spacing of 300m, the reduction on the steam flow is only of the order of 5%.



**Figure 14: Total steam flow under a variety of fracture spacings.**

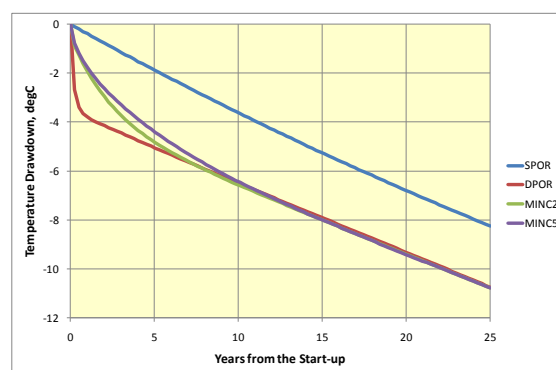
### 3.4 Process model sensitivities

In addition to the range of scenarios considered in the full field model the process model was also used to test the sensitivity of the results. The process model which was smaller and less complicated provided a convenient way of

testing model features together with the sensitivity of the model parameters.

An example of a model feature is the nature of the reservoir matrix and fractures. The process model was used to compare a single porosity model, a dual porosity model with a single matrix block and dual porosity models with 2 and 3 matrix layers. Figure 15 shows the temperature change in the production region for these different models. There is a significant difference between the single porosity and various dual porosity models, whereas the main difference between the dual porosity models occurs in the first 4 years.

The process model was also used to test the fracture spacing, with temperature cross-sections shown in Figure 16. With a larger fracture spacing the cooling front from the injected fluid extends closer to the production wells. This plot also demonstrates that the cooler denser injected fluid tends to stay deep in the reservoir.



**Figure 15: Process model temperature change in the production region with additional MINC layers. Legend indicates a single porosity model (SPOR), dual-porosity (DPOR), then a two and three layer MINC model (MINC2 and MINC3, respectively).**

As in most geothermal systems the base of the permeable reservoir at Ngatamariki is not well constrained. In order to determine the impact of different assumed reservoir depths the process model was calibrated to initial state data with reservoir bases at -3000 mRL and -5000 mRL. A comparison of the model results for a production scenario is shown in Figure 17. This shows that the smaller reservoir has a slightly larger initial pressure drawdown with reducing drawdown as production continues. The interpretation of this result is that the long term pressure response is controlled by the intermediate aquifer pressures and is less dependent on reservoir conditions.

Interestingly there is a significant difference in the modelled temperature response, with the smaller reservoir decreasing by 11 °C after 25 years production while the large reservoir only decreased by 5 °C. In the larger reservoir the denser cooler injected water disperses through the reservoir at depth while the smaller reservoir has less room to disperse this injected fluid so there is a greater effect on production temperatures.

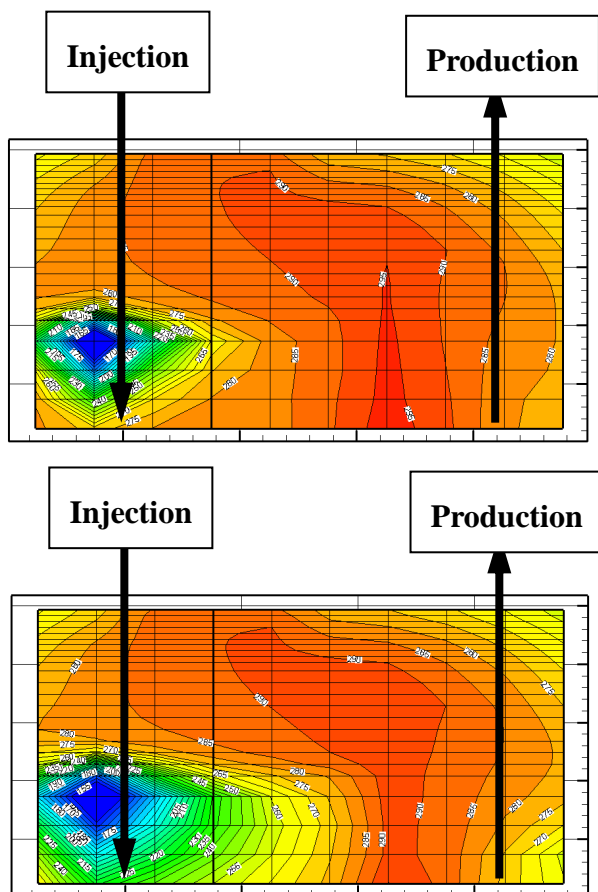


Figure 16: Temperature after 25 years of production with fracture spacing of 50 m (top) and 300 m (bottom)

#### 4. CONCLUSIONS

Numerical modelling of the Ngatamariki system required coordinated interaction from a variety of disciplines including geology, geophysics, reservoir engineering, mathematical modelling and management. Initial modelling suggested possible risks for the development of the field. This focused efforts on appropriate representation of thermal processes with a dual porosity model, and a comprehensive investigation of the process model.

Much of this work was set against of the backdrop of reducing and understanding the uncertainty of field predictions and managing potential development risks. The main limitation in the modelling effort was the lack of data. The field has not been produced so there is minimal interference data and all wells were drilled in a relatively narrow south-east to north-west corridor.

Through the sensitivity analysis, both the full field and simpler process models indicate that the performance of the models is very sensitive to the heat exchange characteristic of the rock (i.e.: fracture spacing). In addition, the process model also indicates that the model performance is affected by the thickness of the reservoir (e.g.: 3400m vs. 5400m).

The process model was an invaluable tool in increasing our confidence in the full-field simulation results and this approach will be incorporated into our future modelling efforts.

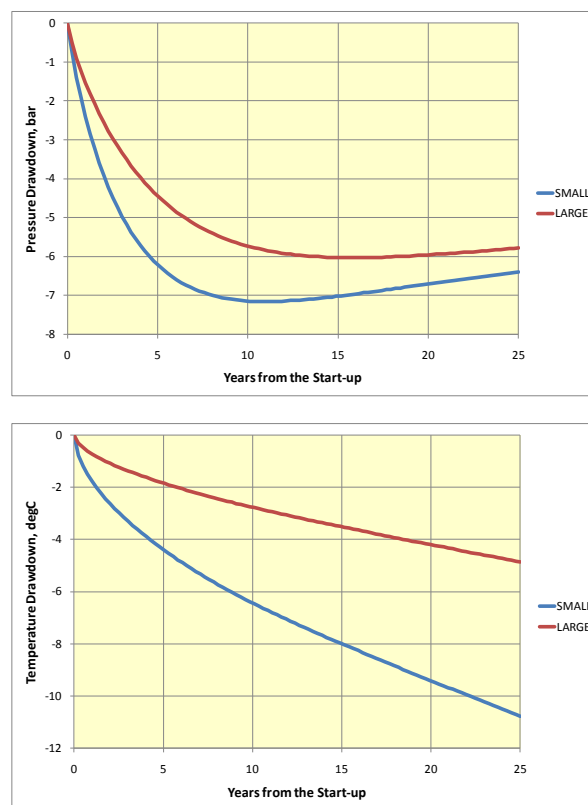


Figure 17: Pressure and temperature with a process model with reservoir base of -3000 m (SMALL) and -5000 m (LARGE).

#### ACKNOWLEDGEMENTS

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