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THE LIHIR OPEN PIT GOLD MINE REVISITED

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ABSTRACT

In the last TOUGH2 Symposium (White *et al*., 2003) we described initial modelling of the geothermal system and groundwater in the vicinity of the open pit Lihir gold mine. This mine pit is planned ultimately to reach more than 200 meters below sea level and is being dug into an active geothermal system with some of the area to be mined at boiling-point for depth conditions. Cooling and depressurisation of the geothermal resource associated with the gold mineralisation is an essential part of the mining operation. Previous modelling was based on data from eight deep, deviated geothermal wells completed during 1999 and information from the shallower mineral exploration wells drilled and tested in the 1980's.

Currently the mine is over 150 meters below sea level and more than 30 geothermal wells plus a number of steam relief and new pumped dewatering wells have been drilled. Two power stations have been built to provide a total of 36 MW of electricity for use in the gold refining process. The new geothermal drilling has shown that the productive reservoir beneath the mine pit to be fracture-dominated with a low effective porosity, partially isolated from the shallow reservoir.

This system provides a number of challenges to the modeller with coupling between the groundwater, the sea and the geothermal system all being important and the need to take account of the changing surface topography as the mine pit is deepened.

Use was made of iTOUGH2 running on a cluster of LINUX workstations to aid the fitting of some model parameters. Using this program in a parallel computational environment (Finsterle, 1998) was essential to complete the parameter fitting in an acceptable time.

Recently we have also made use of a new version of Multi-TOUGH2 (Zhang *et al*., 2001), also on a LINUX cluster and this has significantly reduced the processing time required to calculate initial states for some of the large models developed.

INTRODUCTION

The Lihir Group consists of four islands, of which Lihir (or Niolam) is the largest. Lihir Island is located about 700km north-east of the national capital, Port Moresby, and forms part of the New Ireland Province of Papua New Guinea (Figure 1).

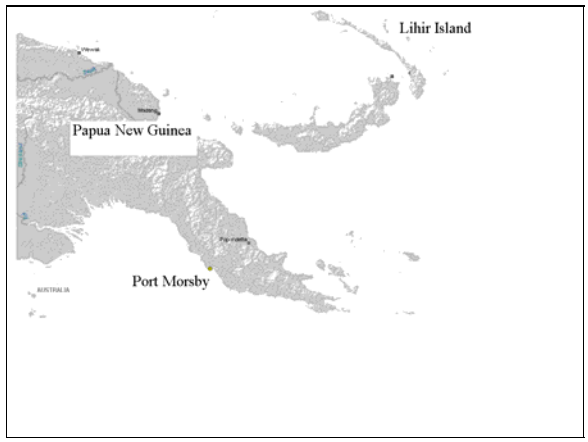

Figure 1. Location map

Lihir experiences a high rainfall, averaging about 3.7 metres per annum, with mean relative humidity of 80%. Air temperature varies between 20 and 35°C. Being situated only 3° south of the equator, Lihir is not subjected to the effects of cyclones. Natural vegetation is predominantly tropical rain forest.

CONCEPTUAL MODEL

The conceptual model for the shallow part of the geothermal resource remains much the same as that detailed in White *et al*. (2003). Recent drilling has increased knowledge about the conditions in the Lienetz and Kapit regions (Figure 2), provided a revised geologic map and significantly altered the conceptual picture of the deep (below 700 mRL) resource.

The shallow Luise geothermal system is seen as a permeable bathtub, surrounded on three sides by low permeability rock [outside the Luise collapse structure boundary], and on the fourth side by the sea. There is a connection between the hot resource and the sea at shallow levels where most of the natural flow exits the system, while at deeper levels the sea is isolated from the geothermal resource by low permeability rock.

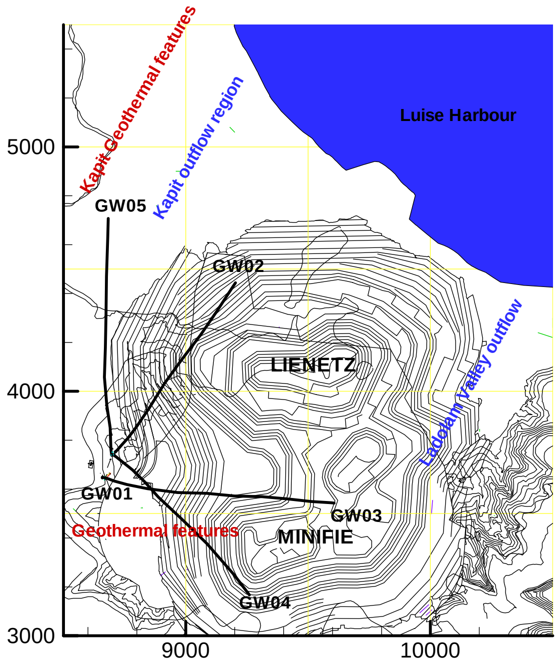

Figure 2. Map showing pit locations and major features of importance to conceptual model.

Pressure measurements in recent wells in the Kapit region (see Figure 2) show pressures below cold hydrostatic at depth, but above about 960 mRL (1000 mRL being the mean sea level) they exceed the pressure in the sea at the same depth. So, the outflow must be at this depth and above. Isotopic measurements suggest that there was minimal cold recharge to the undisturbed geothermal reservoir from the sea at depth even though the hydrostatic pressure is significantly greater outside than inside the geothermal reservoir. Allis (2003) has reviewed all existing geophysical data and believes that magnetic anomaly data indicate a source of deep recharge largely located beneath the Kapit area. There must also be some recharge spread along the western side of the Minifie and Lienetz pits.

The conceptual model of the deep system has been revised significantly in the light of this new information. The key differences between the conceptual model used in modelling described in White (2003) and this work are.

- The area of hot inflow has been extended to include the area beneath Kapit identified in Allis (2003) and recent deep drilling. The enthalpy of this inflow has been increased to match better the high (> 300 °C) temperatures existing in some deep regions of the reservoir.
- The permeable regions below 800 mRL in the current model are more extensive than in the earlier work.

This deeper permeability is somewhat irregular and probably comes from fractured rock rather than the more extensive permeability found in some of the shallow units such as the Boiling Zone. The area of the permeable fractured region is still uncertain but drilling suggests it extends at least at least over the areas ‘inner’ and ‘outer’ in Figure 4. The upflow region is also likely to be fractured.
Previously the Anhydrite Sealed units were treated as being low permeability throughout the reservoir. However some recent drilling and the need to match measured pressure drawdown in the deep parts of the reservoir has required a revision of this. The current model has areas of fracture permeability at depth and permeability in the Minifie shear zone and beneath the planned Lienetz pit.

The geothermal resource is now much better understood than it was but some of the previous uncertainties remain. The most important of these is the full extent of the high temperature resource. Electrical geophysical surveys have been carried out, but provided limited information due to rugged local topography, the massive sulphide orebody and relatively high-salinity groundwater adjacent to Luise Harbour. The southeastern flank of the resource has been proven in some detail by the mineral exploration wells and by the deep wells. However, there is no direct information available to determine reliably the location of the northern and western boundaries of the permeable high-temperature geothermal resource. For modelling purposes, the rim of the Luise collapse structure has been used to locate the western northern boundaries of the high-temperature resource and the work of Allis to locate the upflow which is also taken as the northern boundary of the deep resource. Low permeability, cool formations are assumed to lie outside the structure with enhanced permeability and high temperatures confined within the collapse structure.

A key issue for the mining of the Kapit region is the connection between the permeable areas of the geothermal resource and the sea. The geological model shows Boiling Zone and Silica Clay extending beneath the sea and in the numerical model described here these provide a permeable connection to the sea in the Kapit Region. The poor tidal response of wells in this region does not exclude this connection as the existence of a two-phase reservoir extending beneath the sea will mask any tidal effects.

MODEL DESCRIPTION

As in the models described in White (2003) we have used the program TOUGH2 (Pruess *et al.*, 1999) to model the reservoir. An important change is in the grid now used for these models has been replaced by that shown in Figure 3. This was done in the interests of computational efficiency, accuracy and stability. Although the current model has three times the number of elements of the old model, calculation time is similar.

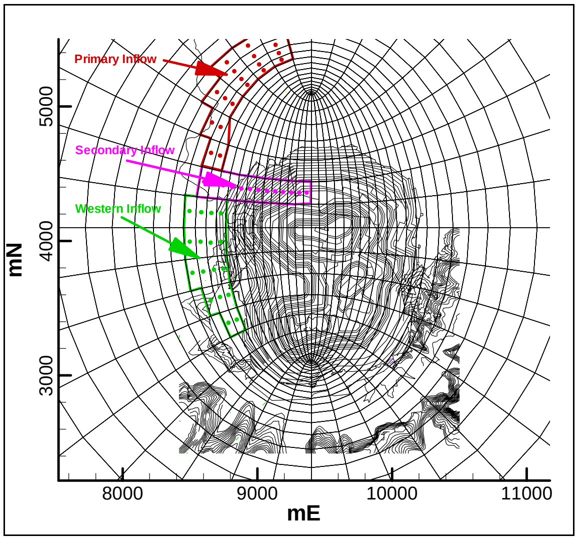

Figure 3. A portion of the TOUGH2 grid

The horizontal resolution generally varies between 50 and 500 meters with the fine resolution over the geothermal system and mine area. For simulations involving the proposed Kapit pit, resolution in the sea wall was improved to 20 meters. Two different vertical resolutions were used, a coarse resolution model, with a vertical resolution above 700 mRL of 40 m, and a fine resolution model which has a resolution of ten meters above 700 mR. The coarse model contains more than 16,000 elements and the fine resolution model more than 45,000 elements. The earth surface topography is modelled both above and below sea level by removing elementa and applying an appropriate boundary condition.

The geology and hydrology of the area are approximated by the integrated finite difference method (IFDM). The IFDM treats the reservoir as being composed of a large number of elements (or blocks) and calculates the flows between these blocks, and average temperatures, pressures, CO_2 content and saturations within each block. Similarly, any production and injection well location is defined only to the dimension of the block containing the well. The size of these blocks therefore determines the resolution of the model.

ROCK PROPERTIES

The shallow geology (above 700 mRL) in and around the mine pit and the Kapit area has been defined in some detail by the mineral exploration drilling. It was necessary to divide the Anhydrite Sealed unit of the geologic model into three distinct units of different permeability to allow different permeabilities in the Minifie Shear zone, beneath the Lienetz pit, and at depth in the area of productive geothermal wells, and a general region of low permeability at depth.

In some of the modelled areas where subsurface information was not available, the rock type assigned was extrapolated from observed data. This is particularly true in the area of the model extending beneath the sea.

Outside the caldera structure and beneath the sea there is little information available on the geology or permeability. The rapid increase in groundwater levels and the existence of perched aquifers at the margins of the caldera structure suggest low permeability and all rock outside this area is assigned to a single rock type.

In the undisturbed state the hydrostatic pressures within the geothermal resource and in the sea are balanced at about 850 - 960 mRL. Below this level, pressures beneath the sea exceed the geothermal fluid pressures. The reservoir fluid chemistry and isotopic analysis indicates that the connection to the sea at depth is poor. As in earlier models the permeability between the sea and the geothermal system has been adjusted to reduce cool recharge flowing from the sea. This is in keeping with the retrograde solubility of anhydrite ($CaSO_4$) with increasing temperature. Heated seawater is expected to precipitate anhydrite, and the permeability of any connection between the sea and the hot reservoir would be expected to diminish over a period of time. At shallow levels where hydrostatic pressure in the geothermal reservoir slightly exceeds seawater pressure, the flow direction is from the reservoir to the sea and the shallow rock types (defined by exploration) determine the permeability of this connection.

Below 700 mRL within the caldera the rock is divided into four types:

inner - a very high permeability zone of fractured rock, this region is largely defined as an envelope of the highly productive geothermal wells
outer - a moderate-high permeability region of fractured rock
downflow - a low permeability region which allows a small amount of cooler vertical recharge to the deeper parts of the reservoir.

anhydrite sealed - a low – moderate permeability region within the caldera for which there is no evidence of significant permeability.

In the Ladolam Valley, measurements of tidal efficiency showed the wells communicated through a zone of high permeability. The well temperature profiles indicate this was also an area with high infiltration of cool near-surface waters. In this area a high permeability has been assigned irrespective of the rock type. Although poor tidal efficiencies have been measured in the Kapit region these should not be taken as indicating no permeable connection with the sea as the two-phase nature of the reservoir in this region make interpretation of tidal efficiencies difficult.

Figure 4 shows the location of the different rock types defining the deep geothermal reservoir between –250 mRL and 0mRL and Figure 5 is an example of a layer in shallow reservoir rock types where rock types are largely defined by the LMC geologic model.

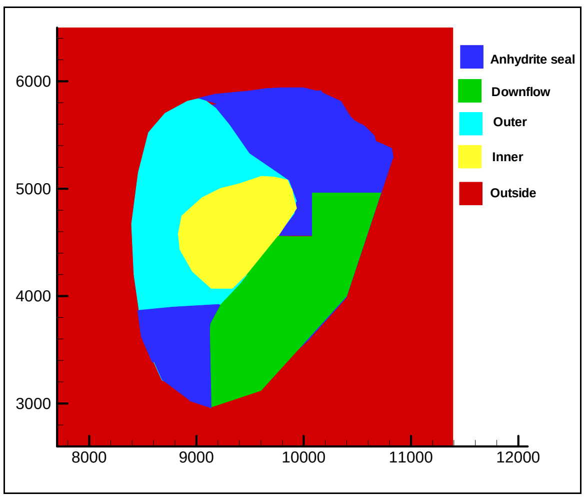

Figure 4. Deep permeability structure

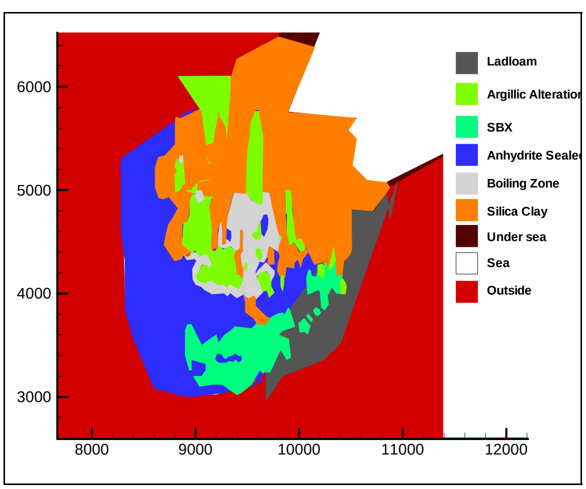

Figure 5. Typical shallow permeability structure

There are now sufficient measurements to allow permeability estimates to be made over a much wider area of the reservoir than previously. A number of interference and pressure rundown tests have been performed on wells in the Lienetz and Kapit regions. Many of these have been analyzed and provide permeability-depth estimates for Boiling Zone and Silica Clay units in these regions. Good estimates of the permeability above RL 700 meters have been obtained by matching pressure drawdown of the monitor wells in response to production from dewatering wells and geothermal production. Using iTOUGH2 (Finsterle 1999). There was good agreement between permeabilities estimated using this method and those calculated from the interference tests.

Permeabilities in the deep reservoir were also estimated using iTOUGH2 (Finsterle 1999) to match pressure drawdown in the geothermal wells. Deep pressures were surprisingly sensitive to shallow dewatering, indicating a much better connection between the shallow and deep parts of the field than previously believed. The best estimates of permeabilities are a compromise between matching the initial state of the field and matching the pressure history. Generally those judged to have good reliability have been refined using inverse modelling producing results consistent with interference test data.

BOUNDARY CONDITIONS

The base of the model, at –500 mRL, is mostly defined as a no fluid-flow boundary. A heat flow of 0.15 W/m^2 is applied to all elements of the bottom layer of the model. This represents heat conduction from hotter rock at depth. The value chosen has been found to be appropriate for other geothermal areas. In addition to the heat flow there is hot fluid recharge into some of the bottom elements in the areas shown in Figure 3. The flow rate and enthalpy for each of the regions shown in this figure is given in Table 2

Table 1: Flow rate and enthalpy at the base of the model

Region	Flow Rate (kg/s)	Enthalpy (kJ/kg)
Primary	58	1680
Secondary	13.4	1230
Western	17.3	1100
Total	88.7	133 MW

The vertical sides of the model are assumed to be no-flow boundaries as it is believed that the areal extent of the model is sufficient to include the whole catchment likely to contribute recharge to the geothermal system and that these boundaries are sufficiently far away from the geothermal system for this to be a reasonable choice of boundary condition.

The upper surface of the model represents the topography of the area. At the ground surface ‘air’ (actually CO_2 gas) with a temperature of 30°C and a pressure of one bar is specified. The surface thermal features in the Kapit area are represented by a pressure dependent ‘sink’.

Cold recharge to the system is largely from rain falling on the surface of the modelled area, with a small amount of deep recharge from the sea. The rain is modelled by adding sources of 30°C water in all the elements at the surface of the model. These sources represent the portion of the rain that infiltrates into the groundwater system and mixes with the upflowing geothermal fluid. The rain does not infiltrate uniformly over the whole model but at different rates in different areas. Infiltration is largely governed by the rock type assigned to surface elements. In the areas of high infiltration (Ladolam valley and Lienetz region) about 55 % of the rain can infiltrate, while in the high ground outside the caldera, 0.1% of the rain is assumed to infiltrate into the groundwater system. Most of this is high ground with steep topography and low permeability and is not expected to absorb rain at a greater rate.

MODEL VERIFICATION

The parameters defining the model are:

- Magnitude, enthalpy and location of the sources representing the geothermal recharge into the system
- Permeability, porosity, specific heat and density of each element in the model.
- Magnitude and location of surface infiltration
- Non-condensable gas content in the deep recharge fluid

These parameters are adjusted until the model calculates an acceptable match to a number of measured or interpreted properties of the system.

The information used in calibrating this model was:

- Temperature and pressure measurements from the shallow mineral exploration wells;
- Pressure and temperature measurements from the deep geothermal wells drilled since 1999;
- Estimated fluid flows through the system. Pressure drawdown resulting from dewatering.
- Pressure drawdown in the deep geothermal system.

STEADY STATE

The first step in the verification of a geothermal model is the simulation of the natural state of the system. This is calculated by setting all boundary conditions, setting initial conditions to arbitrary values and then allowing the system to evolve in time until it ceases to change. Calculated values of pressure, temperature and flows are then compared with measured or estimated values for the field. Parameters defining the model are then adjusted to improve the match between calculated values and measured data and the model rerun. This process is repeated until an acceptable match to measured data is obtained.

Once an acceptable steady state is obtained, then permeabilities are refined by matching the response of the dewatering monitor wells and the deep geothermal system to dewatering and geothermal production. The steady state is then rerun and parameters further adjusted to improve the match to observation.

In Figures 6–10, contours of calculated temperatures at selected elevations are shown. Measured data are shown on these figures as spot values. Over the entire reservoir there is an acceptable agreement between the model results and field measurement. As can be seen from these figures the modelled temperatures compare satisfactorily with values found in the deep wells. At shallower levels, above 800 mRL, there is generally good agreement between the model and observation. The largest discrepancies are in the Ladolam valley region where modelled temperatures are too hot in some areas.

The shallow structure in the Lienetz region is obviously complicated with large variations in temperature over short spatial scales. The cool downflow around 4000m N 9600 mE is represented by the model but some fine-scale detail in this area is absent.

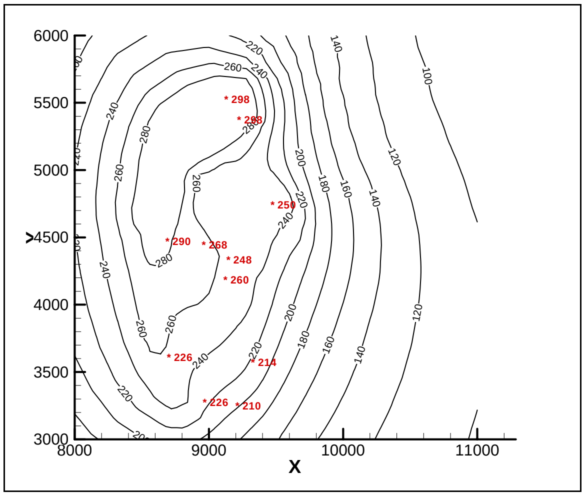

Figure 6. Match to initial temperatures at 0 mRL, measured values are shown in red

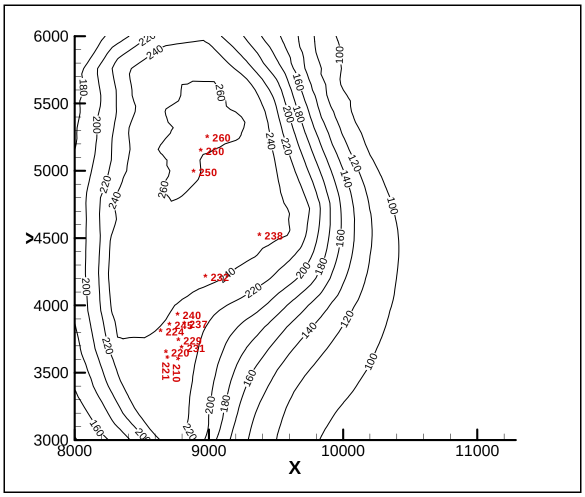

Figure 7. Match to initial temperatures at 500 mRL, measured values are shown in red

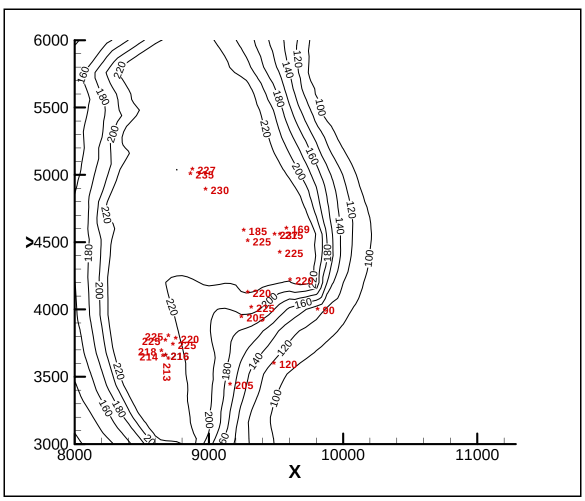

Figure 8. Match to initial temperatures at 700 mRL, measured values are shown in red.

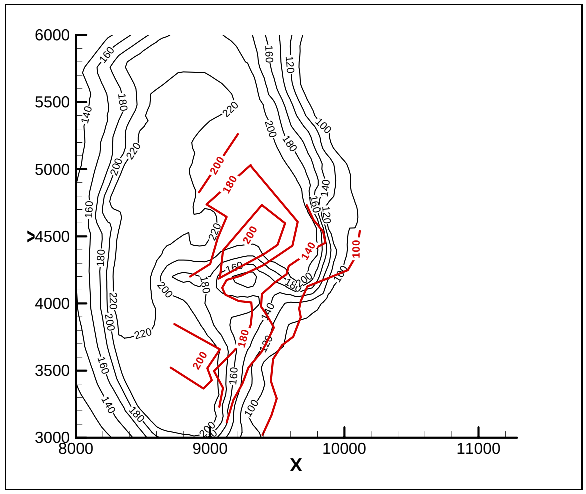

Figure 9. Match to initial temperatures at 800 mRL, the red lines are estimated contours through measured data.

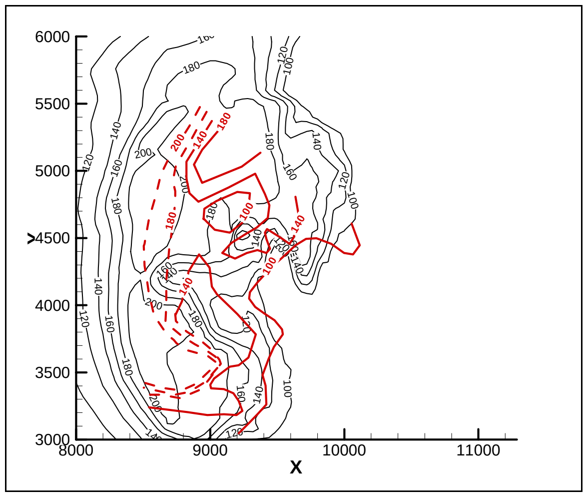

Figure 10. Match to initial temperatures at 900 mRL, the red lines are estimated contours through measured data.

INVERSE MODELLING

The steady state calculation described in the previous section provides a starting point for simulation of dewatering and geothermal production from the field. Comparing calculated pressures and temperatures with measured values gives better estimates of model parameters to be obtained.

The procedure used was to model the dewatering and geothermal production over the period from September 1997 to March 2005. This produced estimates of the pressure drawdown at each of the monitor and geothermal wells. The permeability of regions affecting the calculated pressure drawdown was adjusted to improve the match to measurement and the process repeated. This procedure used the inverse modelling program iTOUGH2, which repeatedly adjusts parameters until an optimum match to measurement is obtained. In some cases this was aided by manual adjustment of parameters. Not all model parameters can be adjusted in this manner as some parameter estimates are insensitive to available measurements. The calculated match to monitor bore water levels is shown in Figure 12-15 and geothermal wells in Figure 11.

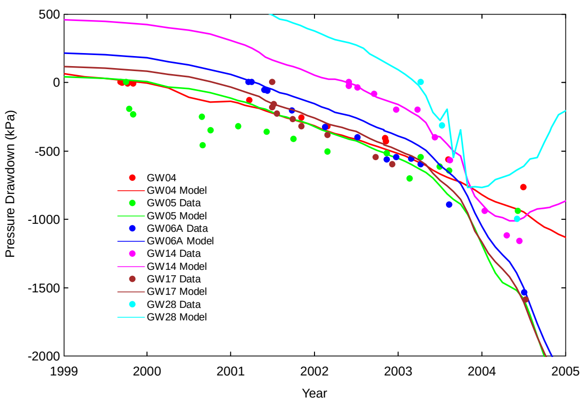

Figure 11. Match of the 2005 Phase 7 Model to the drawdown in the geothermal wells.

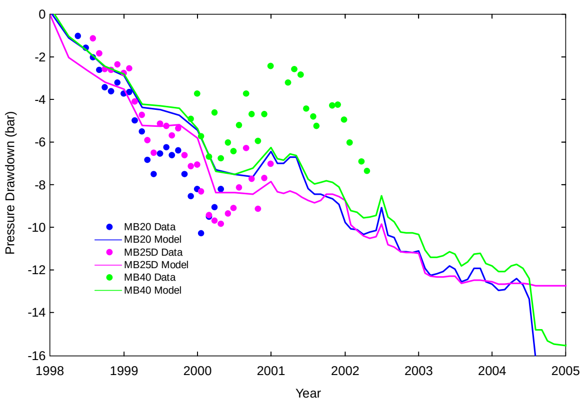

Figure 12. History match of the 2005 Phase 7 Model to drawdown in the East Minifie region

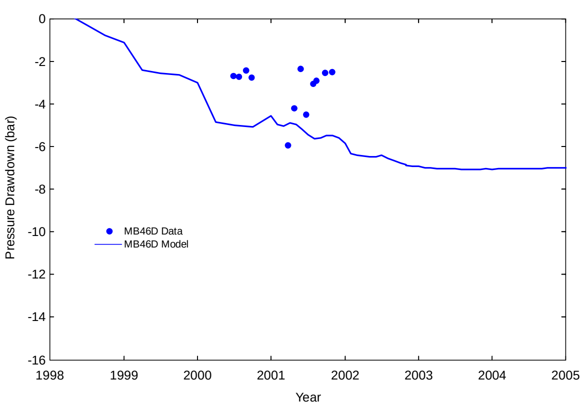

Figure 13. History match of the 2005 Phase 7 Model to drawdown in the Bridge Area

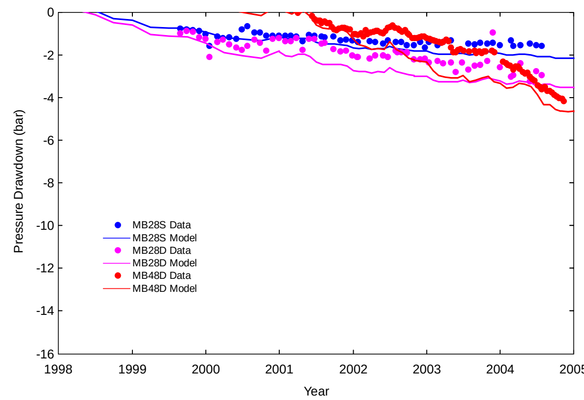

Figure 14. History match of the 2005 Phase 7 Model to drawdown in the East Lienetz area

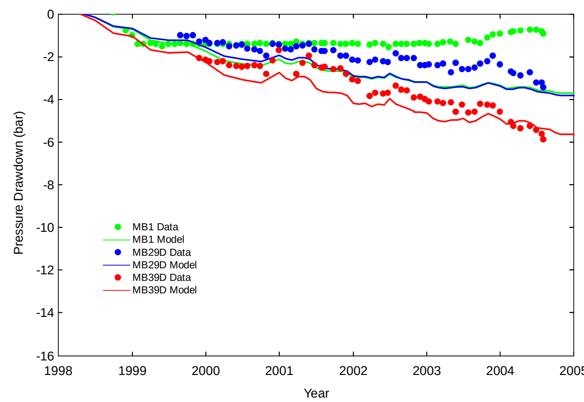

Figure 15. History match of the 2005 Phase 7 Model to drawdown in the Ladolam Valley

It is also useful to compare calculated values with measured values while also providing information about the location of the measurements. In Figure 16 we ignore depth and plot the difference between calculated and measured shallow pressures in March 2005. This figure illustrates a generally good correlation between measured and calculated pressures over the whole area for which data are available. Figure 17 provides a comparison between measured temperatures at 880 mRL. Again the match is acceptable although the model may over estimate temperatures in the east.

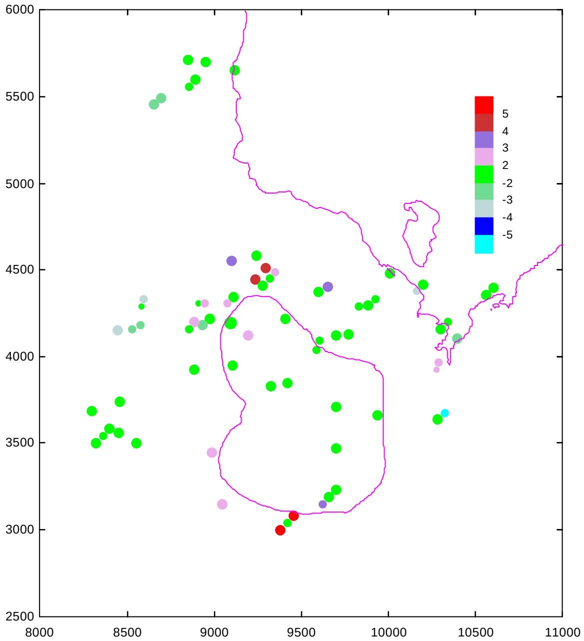

Figure 16. March 2005 Pressures. Plot of differences between calculated pressures and measured pressures (in bars) in March 2005. Each coloured circle represents a pressure difference in the range shown in the key. A positive number means that the model pressure is too high. The magenta curve shows the pit at 1005 mRL in March 2005.

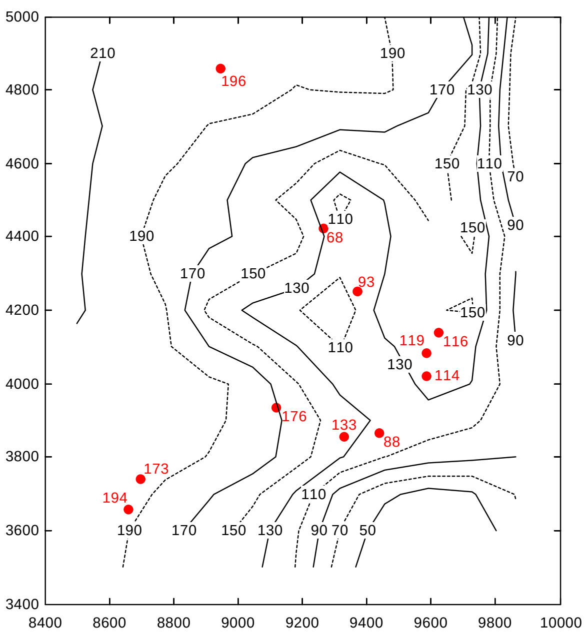

Figure 17. Comparison between measured temperatures (red) and model results (contours) at RL880 in March 2005.

CONCLUSIONS

The numerical model of the Luise geothermal resource has been upgraded to incorporate measurement data up to September 2003. The new model has significantly higher temperatures than earlier models and a more extensive permeable area at depth to the North and West of the mined area. Calculation of pressure draw down in this deep reservoir in response to dewatering and geothermal production are sensitive to shallow permeabilities to the West of the Minifie pit and permeabilities in the deep reservoir itself. This has allowed a better estimate of the permeability in this region to be made.

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