The Lihir Open Pit Gold Mine Revisited

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THE LIHIR OPEN PIT GOLD MINE REVISITED

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SUMMARY – In a previous workshop (White *et al*. 2000) 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 metres 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 deep and more than 30 geothermal wells, a number of steam relief and 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 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.

1. 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).

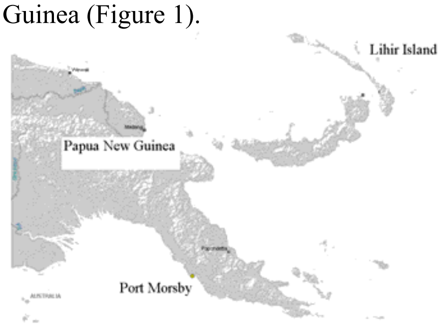

Figure 1 Location map

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.

All depths in this paper are given in meters with respect to a reference level (mRL) where 1000 mRL is mean sea level.

2. CONCEPTUAL MODEL

The conceptual model for the shallow part of the geothermal resource remains much the same as that detailed in White *et al*. 2000. 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.

Pressure measurements in recent wells in the Kapit region (see Figure 2) show pressures below cold hydrostatic at depth, but above about 960 mRL 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.

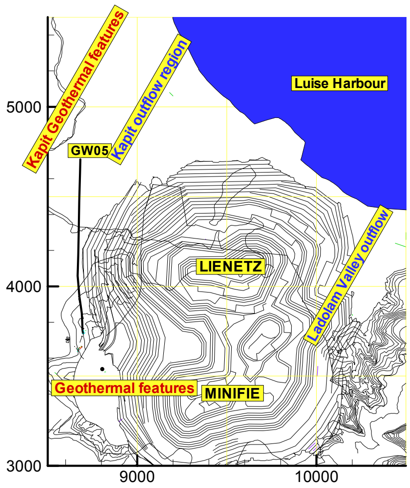

Figure 2: Map showing pit locations and major features of importance to conceptual model.

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 (2000) 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 better match 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 location 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 and northern boundaries of the high-temperature resource. Low permeability, cool formations are assumed to lie outside the structure of enhanced permeability.

3. MODEL DESCRIPTION

We have used the simulator TOUGH2 (Pruess 1999) to model the reservoir. An important change from previous models is that the grid 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.

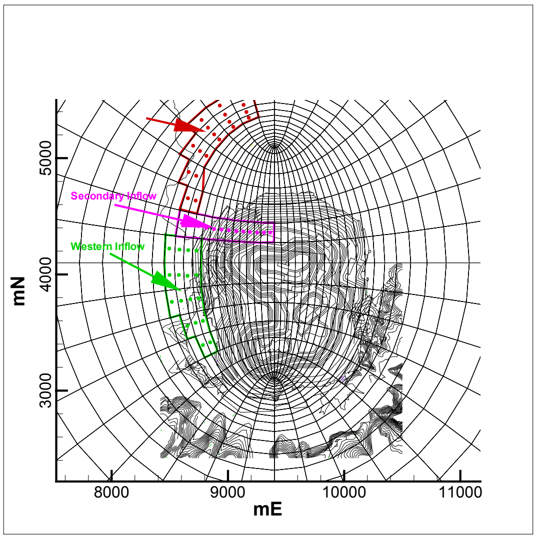

Figure 3: A portion of the TOUGH2 grid

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 elements and applying an appropriate boundary condition.

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

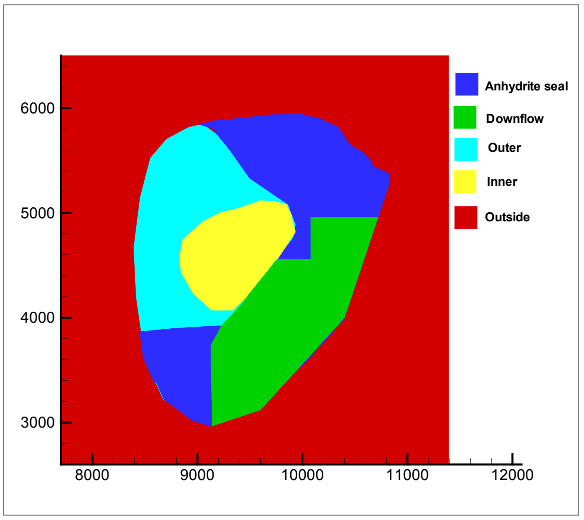

Figure 4: Deep permeability structure

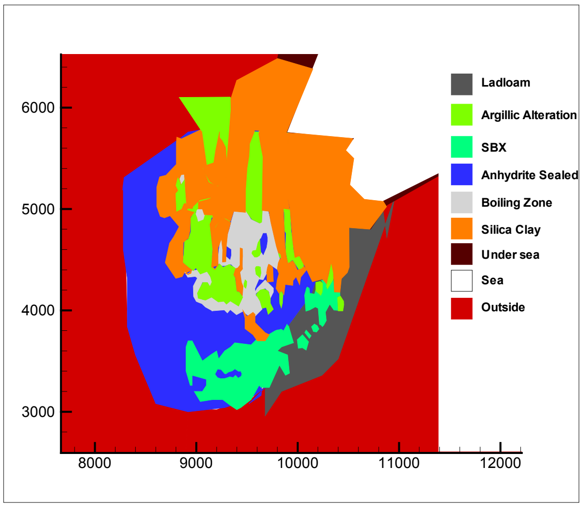

Figure 5: Typical shallow permeability structure

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.

Permeabilities in the deep reservoir were also estimated using ITOUGH2 (Finsterle 1999) to match pressure drawdown in the geothermal wells. The best estimates of permeabilities are a compromise between matching the initial state and matching the pressure history. Generally those judged to have good reliability have been refined using inverse modelling producing results consistent with interference tests.

5. 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 collapse structure, 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.

6. 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.

7. 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 and porosities 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 Figure 6 to Figure 8 contours of calculated temperatures at selected elevations are shown. Measured data are shown on these figures as spot values or contours. 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.

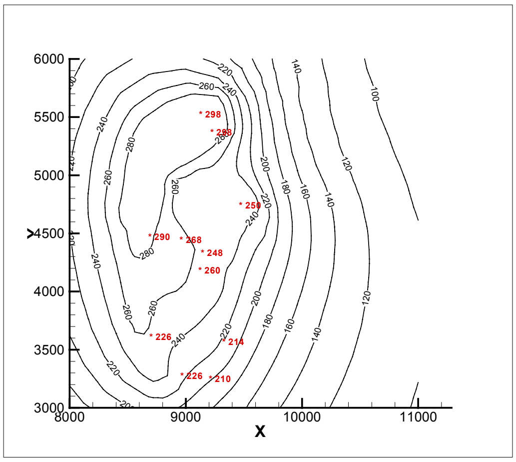

Figure 6: Match to Initial temperatures at 0 mRL, measured values are shown in red

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

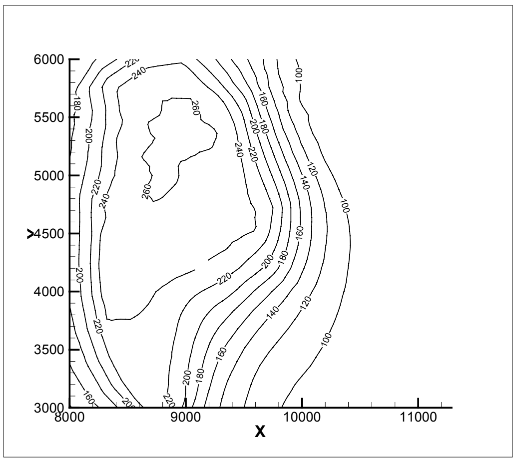

Figure 7: Match to Initial temperatures at 500 mRL, measured values are shown in red.

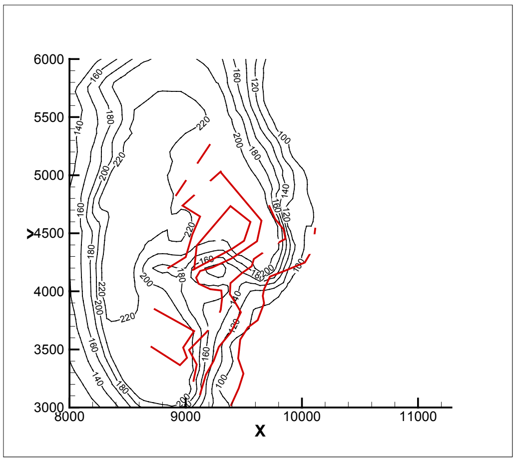

Figure 8: Match to Initial temperatures at 800 mRL, the red lines are estimated contours through measured data.

8. 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 geothermal wells is shown in Figure 9 and monitor bore water levels in Figure 10 and 11.

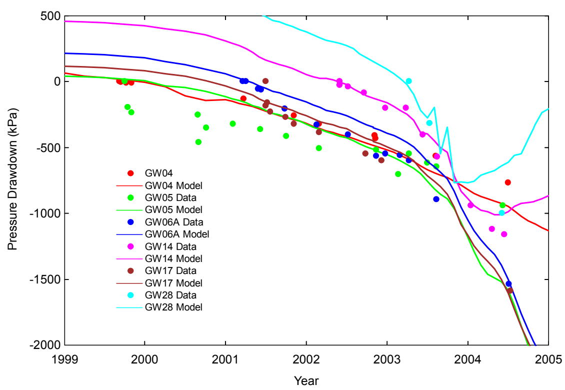

Figure 9: History match of the model to the drawdown in the geothermal wells.

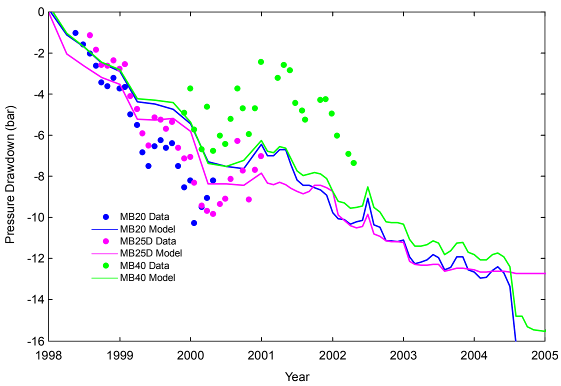

Figure 10: History match of the model to drawdown in the East Minifie region

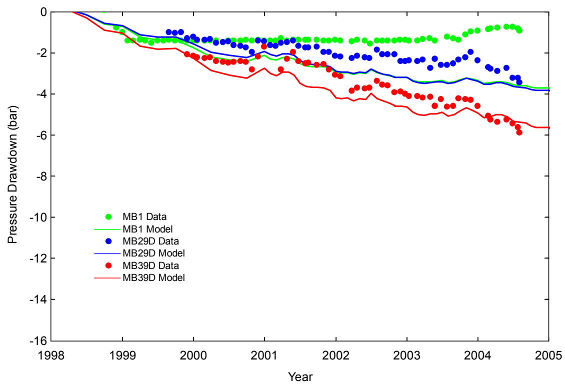

Figure 11: History match of the model to drawdown in the Ladolam Valley

9. CONCLUSIONS

The numerical model of the Luise geothermal resource has been upgraded to incorporate measurement data up to 2005. 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 drawdown in this deep reservoir in response to dewatering and geothermal production is sensitive to shallow permeabilities to the West of the Minifie pit and permeabilities in the deep reservoir itself. This has allowed better estimates of the permeabilities in this region to be made.

10. REFERENCES

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