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Magneto-telluric (MT) surveys in a challenging environment at Lihir Island, PNG

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ABSTRACT

Since an initial pilot power development of 6 MW was commissioned in 2003, the geothermal resource at Lihir Island in Papua New Guinea has been progressively developed to power gold mining operations with present capacity at about 56 MW. A desire to further expand power generation led to the execution of Magneto-Telluric (MT) surveys of the system in 2004 and 2007. These surveys were conducted under challenging conditions that included active mining operations centred on the geothermal resource and extreme terrain across much of the survey area. There was reason to also suspect an extension of the geothermal resource to sea and this was reinforced by a survey of shallow seafloor temperatures made in 2007.

After successfully using 3D inversion in 2004 to model MT data collected on coastal areas, the 2007 survey therefore added more coastal measurements to improve coverage of the resource that extends under the Luise harbour. The coastal part of the survey included measurements in shallow water on the coastal platform at low tide. Despite the high temperatures and very high salinity of the reservoir waters, the main reservoir of the Lihir geothermal system presents a high resistivity feature lying beneath a typical layer of high conductivity due to argillic alteration in the shallow part of the system – the "clay cap". The extent of the clay cap has helped indicate the extent of the system beyond the area that was originally proven by drilling and used to support the initial power development. Subsequent delineation drilling guided by the MT survey results has significantly extended the area of proven high temperature resource.

The experience at Lihir strengthens the concept that the conductive hydrothermal clay alteration cap is a strong geothermal indicator even with high salinity reservoir fluids and demonstrates that MT surveys are an effective tool for guiding step-out delineation drilling of fields already under development.

1. INTRODUCTION

Lihir Island is located in Papua New Guinea which is around 900 km northeast of the capital city of Port Moresby (Figure 1). The geothermal resource in Lihir is situated within a large open pit gold mine consisting of three adjacent pits (Minifie, Lienitz and Kapit sectors). Lihir Gold Limited is a major gold producer with an estimated gold resource of 36.3 million ounces including 21.8 million ounces in ore reserves. The mine has been operating since 1997 and has produced more than 7 million ounces of gold. The gold production capacity will be increased to 1 million ounces per annum starting in 2012 from 771,000 ounces in 2008.

The geothermal system at Lihir was initially mapped from the extent of surface manifestations and temperature data from mineral investigation corehole drilling. This enabled understanding of how the upper part of the system may be de-watered to allow mining operations to proceed. It resulted in a strategy for drilling a combination of shallow and deep wells to reduce the reservoir pressure and dewater and cool the shallow parts of the geothermal system where mining would occur. Over 100 steam relief wells were drilled in potential geothermal areas starting in 1998 at a depth of at least 100 m to depressurise the steam zone found at the shallow part of the reservoir (Villafuerte et al., 2007).

Once mining operations were successfully commissioned, and as the hydrothermal system became better understood, more attention was given to the potential for using the geothermal production from the resource for power generation. Geothermal power generation in Lihir commenced in April 2003 through the operation of 6 MWe non-condensing pilot plant. Due to the successful operation of this plant and the increasing cost of heavy fuel oil, Lihir Gold Limited commissioned a 30 MWe power plant in July 2005 and a further 20 MWe power plant in March 2007 which increased the geothermal power plant capacity to 56 MW.

Figure 1: Location map of Lihir Island in the New Ireland province of Papua New Guinea.

Prior to 2004, geophysical surveys were conducted only for mineral exploration in Lihir and had been quite localized within the Luise caldera. Only aeromagnetic surveys in 1987-1988 extended across and beyond the Luise caldera.

In 2004, based on the success of the initial pilot geothermal power generation, a decision was made to increase geothermal power production and this required a better understanding of the deep geothermal system. To meet this objective, a Magneto-Telluric (MT) survey was undertaken to determine the extent of the geothermal system. This indicated that the system extended much further north which was then proven by step out drilling.

A supplementary MT survey was conducted during May and June 2007 to further delineate the extent of the geothermal reservoir and to assess the geothermal potential of other areas on the island.

Both MT surveys were completed within a challenging environment covering an active open pit gold mining area, an operating geothermal steam field, rugged jungle terrain and coral coastline adjacent to a very deep ocean. The mining operations involve regular drilling, excavation, blasting, dewatering wells with downhole pumps and truck movements. The geothermal operation includes producing wells, steam pipelines, and operating power plant. The terrain rises to 600m elevation within 1 km of the coast, and the sea deepens rapidly beyond the Luise harbour, reaching 500 m depth within 2 km of the coast and 1000 m depth within 6 km.

The geothermal reservoir is generally enclosed within a 6 km by 4 km Luise caldera located within a steep terrain and possibly extends towards the sea.

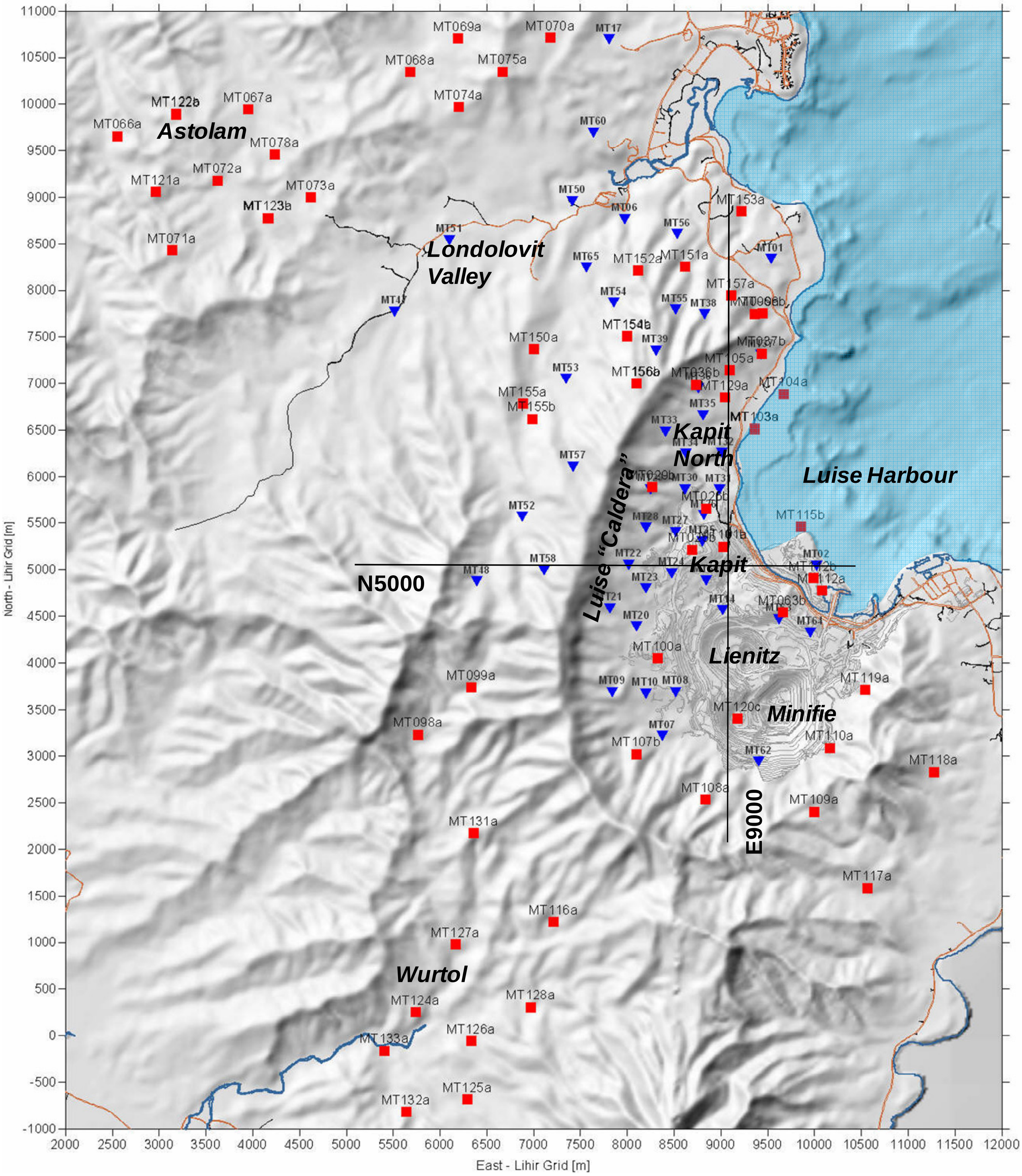

Figure 2:. Extent of the MT surveys at Lihir. 2004 Survey (blue triangles), 2007 Survey (red squares). Axis ticks are 500m spacing. Resistivity section lines E9000 and N5000 are shown.

2. GEOLOGICAL SETTING AND FLUID CHEMISTRY

Lihir island is situated within the Tabar-Lihir-Tanga-Feni volcanic island chain which is a group of Plio-Pleistocene (<3.5 Ma) alkaline silica-undersaturated volcanic rocks in the New Ireland province of Papua New Guinea (Carman, 2003). The island is dissected by mafic to intermediate stratovolcanoes (Huniho, Kinami and Luise) underlain by Pliocene basement of basalt and ankamerite. The Luise caldera, interpreted to be a collapse structure rather than an actual eruptive feature, hosts the Ladolam gold deposit.

The Lihir gold mine is separated into 4 open pit mining sectors, viz: Minifie, Lienitz, Kapit and North Kapit (Figure 2). Quaternary coral limestone fringes the island up to maximum elevation of 100 m above sea level. Two main phases of alteration have produced five different assemblages from early porphyry-style potassic and propylitic alteration to a later phyllic, argillic, and advanced argillic assemblages (White et al. in WGC 2010 proceedings). Surface alteration is dominated by argillic mineral assemblages of smectite, kaolinite and interlayered illite-smectite clays. Argillic alteration extends to a depth of 200 m and has the lowest resistivity. The shallower part of the argillic zone is the most conductive as the proportion of illite decreases with depth.

The Lihir reservoir water is highly saline, sodium-chloride-sulphate fluid with TDS of around 80,000 ppm (i.e. twice that of seawater). The chloride concentration of Lihir water ranges from 15,000 to 23,000 ppm and the main charged species consist of Na^+, K^+, Cl^- and $SO_4^=$ To define the salinity of the deep reservoir water for the purpose of understanding pore water conductivity within the MT resisitivity modelling, the conductivity of two chloride ions is set equal to one sulphate ion assuming the relative conductivities are equal. Sodium chloride water would need around 33,000 ppm chloride equivalent to 1.5 times the Lihir reservoir chloride concentration to give the same total charge. This means that the Lihir reservoir fluid has conductivity similar to that of sea water.

3. MT SURVEYS

The 2004 MT survey consisted of 65 stations (Figure 2) and was planned to expand the geothermal investigation wider within the Luise caldera, and even beyond the caldera. This survey showed that the geothermal system was characterized by a classic conductive cap overlying a resistive deeper body that coincided with the high temperature reservoir. The results indicated that the geothermal system may extend well beyond the area of resource that was drilled at that time, particularly to the north and west.

Lihir Gold embarked on an exploration drilling program to test these extensions to the system using a slimhole drilling rig capable of drilling to about 1300 m depth. This drilling was successful in proving the coincidence of the extent of the conductive cap with the extent of the geothermal system and showed that isotherms typically representing top of reservoir (about 200°C) followed the base of the conductive cap as may be expected in many other geothermal systems (Ussher et al., 2000).

The 2007 survey was planned to expand upon the MT survey undertaken in 2004 to improve coverage of the western flanks of the Luise Caldera and Londolovit valley and also to investigate two warm spring areas at Astolam and Hurtol. A total of 57 new full tensor MT soundings were completed. Permitting difficulties restricted access into Londolovit valley and meant that only limited additional coverage could be achieved on the western flanks of the Caldera. Coverage was improved over the northern part of the Caldera and at North Kapit additional stations provided improved east-west coverage including some stations on the shore platform.

The two stations measured on the shore platform were installed in shallow water with electrodes embedded in clay to improve contact resistance onto the coral reef. (Figure 3) The magnetic field was measured onshore at about 100m distance from the electric field. Results from the stations on the coral reef were of variable quality but have helped resolve the conductive layer in this important direction.

Figure 3: MT sounding on coral shore platform.

4. MODELLING AND INTERPRETATION METHODOLOGY

The conductor has been modelled using the 1D, 2D and 3D methodologies. The one-dimensional (1D) modelling was done using the Occam's models which are useful in rapidly generating resistivity cross-sections to see broad trends. It consists of approximately twenty layers that increase logarithmically as overall depth increases. The Occam's inversion techniques often generate quite sharp transitions between layers.

The two-dimensional (2D) modelling was done using the WinGLink system that incorporates the Mackie 2D inversion code (Rodi and Mackie, 2001). The data were rotated appropriately for each modelling direction to ensure consistency of selecting "TE" and "TM" mode data with the 2D models. The 2D models were run on W-E lines to suit the main NNW-SSE electrical structure direction and to enable the modelling of the sea to the east of the caldera.

A three-dimensional (3D) inversion model was constructed to improve the modelling of deeper structures and to model the effects of the sea surrounding the Lihir Island. The 3D model covered the terrain and the sea which was represented by a fixed low resistivity body between the bathymetry model and 0 masl. The grid was rotated to suit the main NNW-SSE electrical structure direction.

A multi-disciplinary interpretation is necessary to assist in the interpretation of the resistivity patterns in Lihir. The resistivity data were correlated with measured temperatures, fluid chemistry and clay mineralisation data from existing wells. Low resistivity in geothermal systems is normally controlled by temperature, fluid salinity, porosity and the presence of clay minerals resulting from hydrothermal alteration.

The smectite clays produced by alteration between 50°C to 200°C are more conductive than illite clays that dominate above 200°C. In andesitic volcanic systems, the high temperature reservoir tends to have higher resistivity than the clay cap that normally overlies the reservoir. However, in basaltic volcanic piles, the depth of the conductive cap is deeper as interlayered chlorite-smectite clays become substantially abundant and are stable up to 255°C.

5. RESULTS

The 2004 MT survey mapped a conductive layer extending from Minifie in the south, through Kapit and under the northern caldera rim in the north (Figure 4). The conductor is domed in the Minifie-Lienitz area where it is exposed at the surface and extends to 250 m below sea level While modelling of the 2004 survey indicated a thickening conductive layer in the east towards the Luise Harbour which suggests an eastern boundary to the system, the expanded MT coverage from 2007 survey shows that the conductor does not deepen as rapidly to the east (Figure 5) and may extend further east into the harbour. This is consistent with the measured well temperatures and the sea floor temperature survey (Figure 6) in the area. Slimhole drilling (i.e. 1300 m vertical depth) has confirmed the extension of high temperature (>220°C) geothermal reservoir in this sector.

To the west, the conductive layer thickens and rises to higher elevation towards the northwest and extends around 1.5 km west and north of the Caldera rim. The resistivity of the conductive layer ranges from 1 Ωm in the east to 3 Ωm across a broad area reducing to 5 to 7 Ωm to the west, before grading quite rapidly into higher resistivity further west.

The results of the 1D and 2D modelling are generally similar in delineating the conductive layer since the data appears to be mainly 1-dimensional through much of the frequency range detecting this layer. The 3D modelling has effectively resolved the conductive layer, provides some indications of trends in the deeper structures and has fully included the effects of the surrounding deep seawater. The 3D model shows that, despite the high salinity of the deep reservoir, quite high resistivity of greater than 30 Ωm occurs beneath a conductive layer which is 200 to 400m thick. This high resistivity in the reservoir indicates low porosity. A zone of moderate resistivity (20 Ωm) at depth of 300 m in North Kapit underlying a shallower conductor in this location (Figure 7) indicates a SW-NE oriented zone of greater porosity.

The conductive layer, which corresponds with temperatures between 50 °C and around 200 °C, correlates very well with the argillic alteration zone that has been mapped by numerous mineral coreholes across the area. The up-domed base of the conductive layer centred on the Minifie-Lienitz sector coincides with areas of surface hydrothermal alteration, hot ground and thermal water outflows. The highest temperatures have also been observed at depth in this area (GW05 and GW18). In North Kapit, the conductive layer deepens under the Caldera rim although no surface discharges are found in this area. However, exploration drilling since 2004 has shown that there is good correlation of the resistivity with temperature as the top of reservoir deepens northwards and the base of the conductor marks approximately the 200 °C temperature level above the reservoir (Figure 4).

The conductive layer is exposed at the surface in the southern half of the Caldera and in the most southern parts has higher resistivity or is non-existent. The exposure of the "clay cap" at the surface is considered to be due to the sector collapse which removed much of the volcanic overburden when the Luise caldera formed. It is inferred that the hydrothermal alteration within this cap actually provided the weak zone along which the collapse occurred. It is possible that the collapse removed more of the original clay cap in the south which explains the present absence or weakened conductor in the south. The removal of the cap appears to have allowed the hydrothermal system to decline in the southern sector of the field.

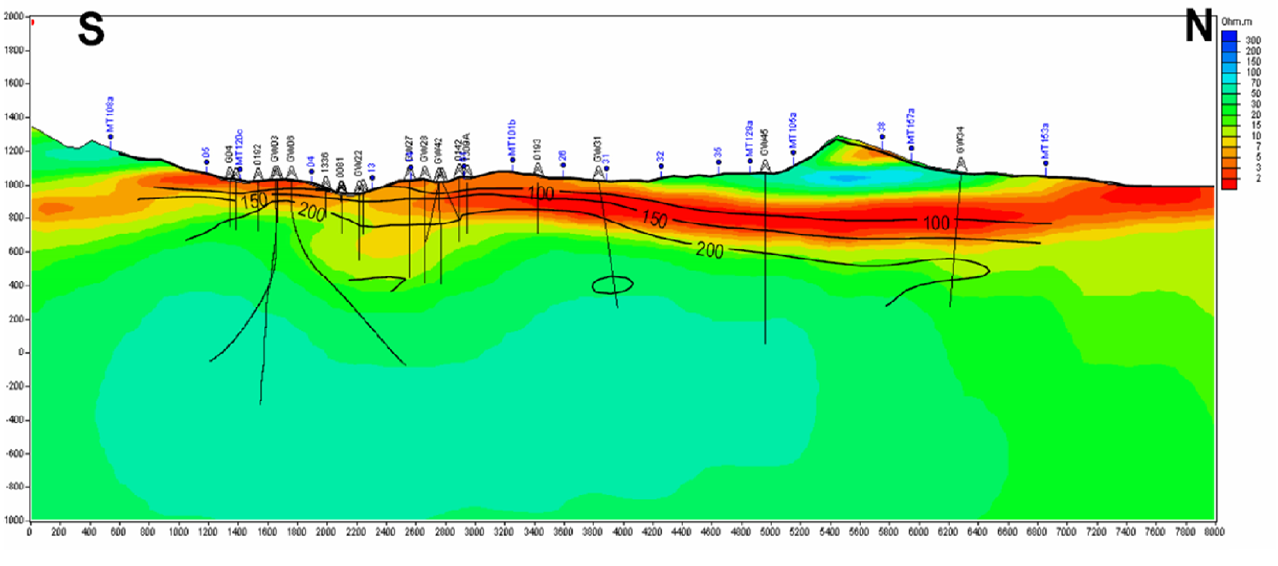

Figure 4: 3D MT resistivity model and well temperatures in S-N section line E9000. Please refer to Figure 2 for the location of the section line.

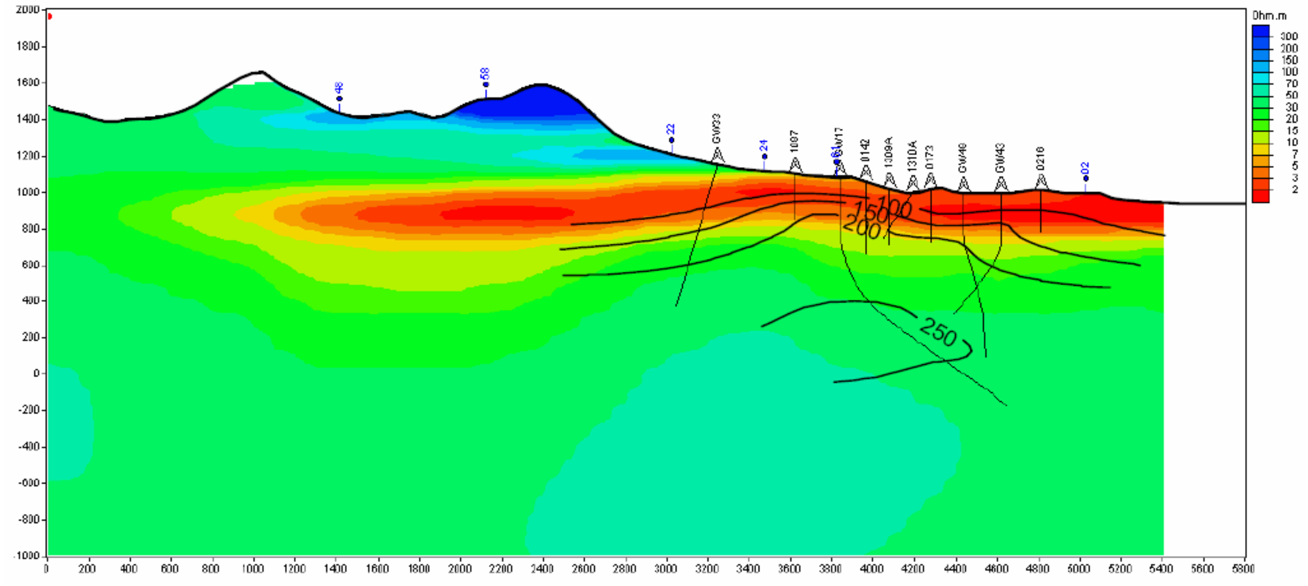

Figure 5: 3D MT resistivity model in W-E section line N5000.

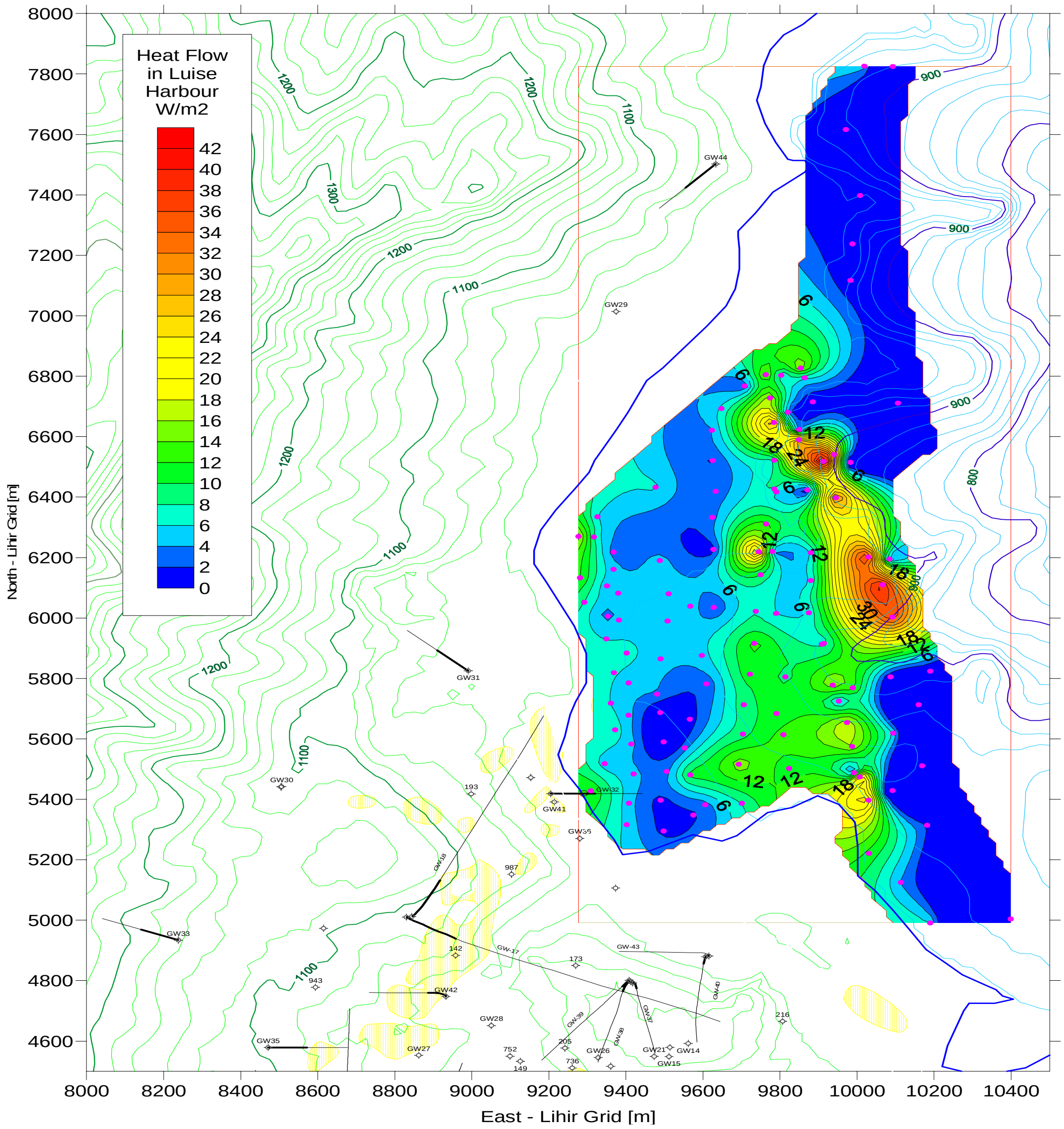

Figure 6: Heat Flow map computed from the seafloor temperature survey under Luise Harbour

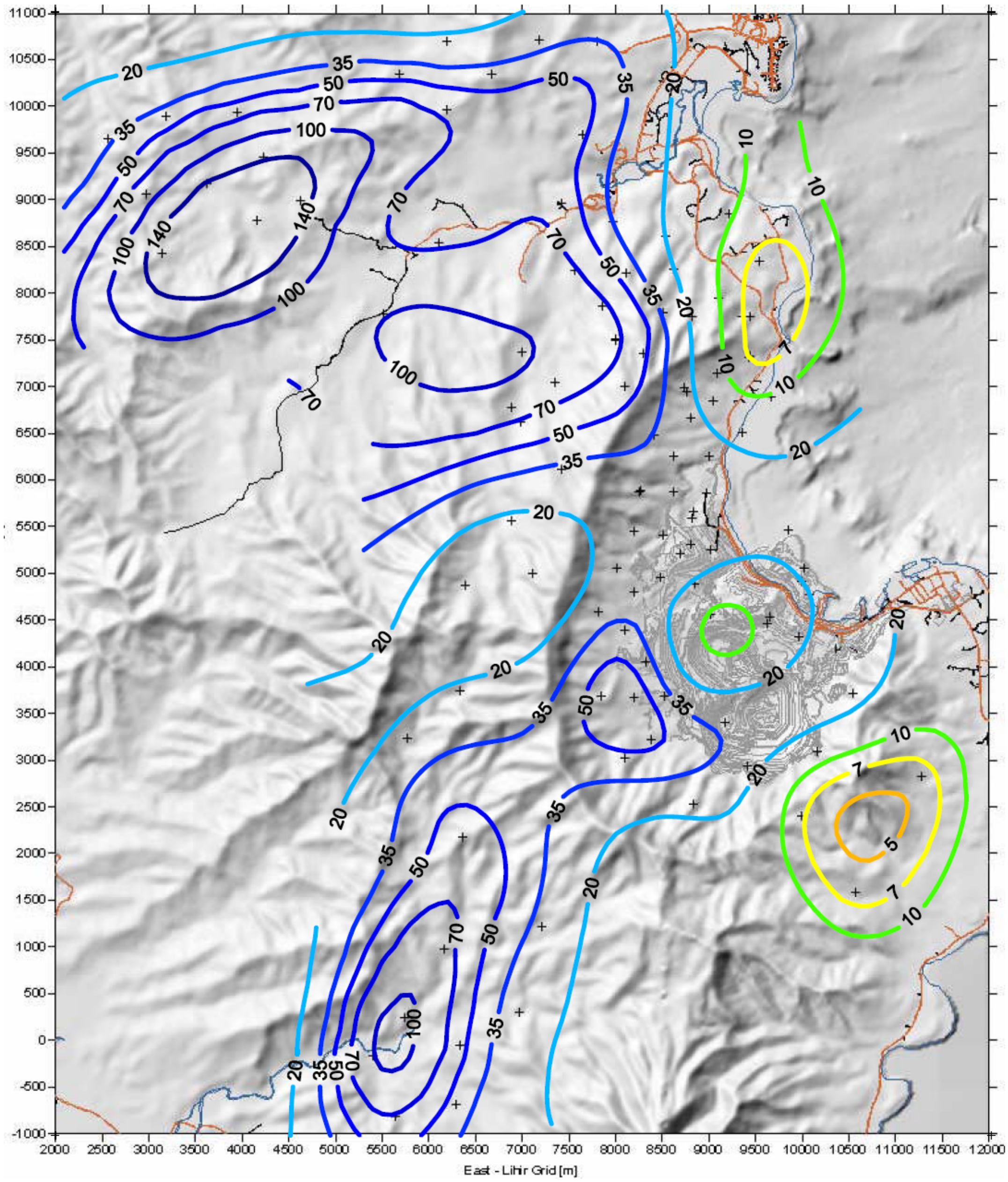

Figure 7: Resistivity at 600 m RL from 3D model

6. CONCLUSIONS

The MT method has proven successful for mapping the extent of the geothermal system at Lihir.

The electrically conductive clay cap is the main marker that is detected by the MT surveys and has provided a useful guide to present hydrothermal conditions in the deep reservoir. A sector collapse, possibly facilitated by hydrothermal alteration within the clay cap, has exposed the clay cap at the surface, and may have removed part of the cap completely, with consequent effects on the deeper system.

Although the geothermal reservoir has very high temperature and contains fluids with high mineralisation with electrical properties similar to that of sea water, the reservoir is observed to have high resistivity as seen in almost all other high temperature geothermal systems. The reservoir porosity is assumed to be low, and variations of resistivity in the reservoir may be reflecting variations of porosity.

The MT survey was completed successfully in a difficult environment. Although there were many noise sources from mining operations, power generation and power lines through the area explored, the low resistivity seen near the surface seems to have reduced the effects of that localised electrical noise. The survey outputs indicate that the Lihir reservoir probably extends under the sea. The use of MT stations on the coast has facilitated definition of that extension of the system. The location of stations on the coast adjacent to relatively deep sea water was made possible by using 3D inversion to explicitly model the effects of the nearby sea. Some MT stations were made on the coral shore platform in shallow sea water by recording only electric signal and recording the magnetic signal simultaneously nearby on dry land. Comparison of results obtained between the 2004 survey when we avoided the coast and the 2007 survey that included many more coastal sites showed that there was definite value in measuring near the sea if necessary.

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