

The First Magnetotelluric Investigation of the Tawau Geothermal Prospect, Sabah, Malaysia

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ABSTRACT

The Tawau geothermal prospect is situated about 20 km northeast of the Tawau Town, Sabah, Malaysia. The geological condition of the area with active geothermal indications consists of Quaternary volcanic rocks (i.e. dacitic, andesitic to basaltic lava and tuff) of the Mt Maria and Mt Andrassy covering Tertiary sedimentary formations. The volcanic activity is caused by the extension of the Sulu Archipelago Arc-Trench System into the Semporna Peninsula, which was most active during the Pleistocene. The surface manifestations are steam-heated hot springs and young volcanic craters found in the vicinity of Mt Maria summit as an indication of up-flow zone and chloride hot springs in the lower level indicating direct connection to the reservoir. Subsurface temperature assessed from fluid geothermometry indicates the geothermal reservoir temperature beneath Mt Maria – Mt Andrassy region of about 190°C to 236°C.

The boundary of the prospect area, geometry of the reservoir and geothermal conceptual model was investigated using modern geophysical technique – i.e. Magnetotelluric (MT) and Time Domain Electromagnetic (TDEM) method. The MT and TDEM survey was focused in the central area of thermal manifestations. The total MT and TDEM soundings were 42 measurement points respectively, distributed on the gridding survey design with interval distance of 1200 meter. Remote reference MT sounding was also conducted to overcome the possible noise recorded in the MT data. Most of the MT data quality is excellent while the others are good. MT processing data was conducted following the standard procedure with emphasis on the noise removal and static shift correction using TDEM data.

Two-dimensional resistivity inversion was carried out along 15 lines crossing the survey area using the WinGLink Software. We developed interactive 3-D viewing software for further interpretation of the MT data. Results of this study show a conductive layer (< 15 ohm-m) down to about 1,000 meters distributed in the survey area. The conductive layer is interpreted as the clay cap of the geothermal system. The slightly resistive substratum (20 - 200 ohm-m) was also found underlining the clay cap which is interpreted as the reservoir zone. A more resistive dome shaped basement, distributed in the central area with continuation to the northern part of the survey area, is interpreted as hot rock. Based on this study, a conceptual geothermal model has also been developed for guiding the exploration drilling activities.

1. INTRODUCTION

The magnetotelluric (MT) method is a frequency domain electromagnetic tool that utilizes natural variation in the earth's magnetic field as a source. Variations in the Earth's natural magnetic field supply frequencies ranging from nearly DC (0.001 Hz) to ten Hertz. The wide frequency range MT gives us the ability to study the electric substructure of the Earth from near surface to greater depth. The large frequency range also means that the method can handle conductive overburden and has large penetration depth. The MT method measures simultaneously the electric and magnetic fields in two perpendicular directions. This provides useful information about electrical anisotropy (mostly structural) in an area.

MT has been a worldwide geophysical method applied in geothermal exploration. MT is also a powerful geophysical method to delineate conductive clay zone overlying a geothermal reservoir. Accordingly, MT has been utilized to guide drilling sites in many geothermal explorations (Daud et al., (2003)).

Tawau geothermal prospect is located in the Sabah State of the Malaysian Kingdom. It is situated in the northern part of the Kalimantan Island (Figure 1). The geothermal system is possibly associated with young dacitic-andesitic-basaltic volcanic complex centered in the Mt Maria. Surface manifestations found in the area are chloride hot springs and steam heated acid sulfate springs indicating that a low to moderate temperature geothermal system exists in the subsurface. However, no geophysical data is available to characterize the subsurface geothermal reservoir, except the Schlumberger traversing with maximum AB/2 = 1000 m.



Figure 1: Location of Tawau Geothermal Prospect Area, Sabah, Malaysia.

Based on the above conditions, an MT survey was then carried out in the Tawau geothermal prospect. This was the first MT survey not only in the Sabah State but also in the Malaysian Kingdom. The objectives of the survey were to delineate the boundary of the geothermal prospect, the subsurface resistivity structure associated with the clay cap and underlain reservoir, and to develop a geothermal conceptual model. This paper describes MT investigation in the Tawau area from data acquisition to data interpretation for delineating the subsurface resistivity structure associated with the promising geothermal prospect.

2. GEOLOGICAL SETTING AND GEOCHEMICAL CONDITIONS

The regional geology of the Tawau geothermal area is associated with the volcanic activity triggered by the extension of the Sulu Archipelago Arc-Trench System into Semporna Peninsula, which was most active during the Pleistocene (Figure 2).

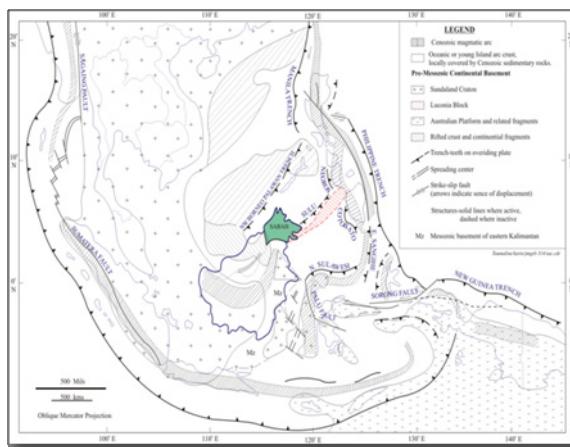


Figure 2: Tectonic Framework of Sabah, Malaysia.

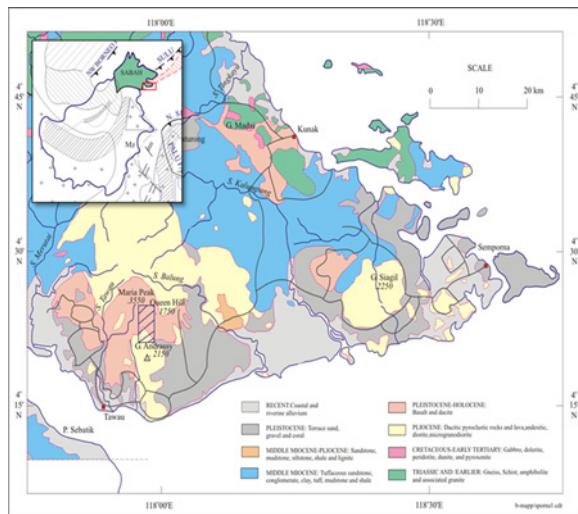


Figure 3: Geological Map of Tawau Geothermal Prospect.

The geological condition of the area consists of Quaternary volcanic rocks of Mt Maria and Mt Andrassy (dacitic to basaltic lava and tuff) covering Tertiary sedimentary formations (Figure 3). Takashima et al. (2005) reported the thermoluminescence dating of the Tawau volcanic rocks. The youngest age obtained is 0.009 Ma for monogenetic basaltic cinder cone. Ages of such young basaltic volcanoes are 0.10 Ma and 0.14 Ma. Ages of dacitic volcanic rocks

are widely distributed at the southern foot of the Maria volcano ranging from 0.34 Ma to 0.45 Ma. The ages of the underlying andesitic lava range from 0.27 Ma to 0.52 Ma. The geothermal indicators in the Tawau area are a young volcanic crater on the Mt Maria peak, steam-heated acid sulfate hot springs in the vicinity of Mt Maria summit and neutral chloride springs in the southern slope of Mt Maria. Altered rocks are also widely distributed in the vicinity of Mt Maria and Mt Andrassy.

Subsurface temperature assessed using SiO_2 and Na/K geothermometer showed temperature range between 190°C – 236°C, indicating moderate to high temperature geothermal reservoir (Figure 4). Isotopic study conducted by Javino et al. (2010) suggested that the origin of thermal water is meteoric water and modern oceanic origin without mixing with shallow young groundwater.

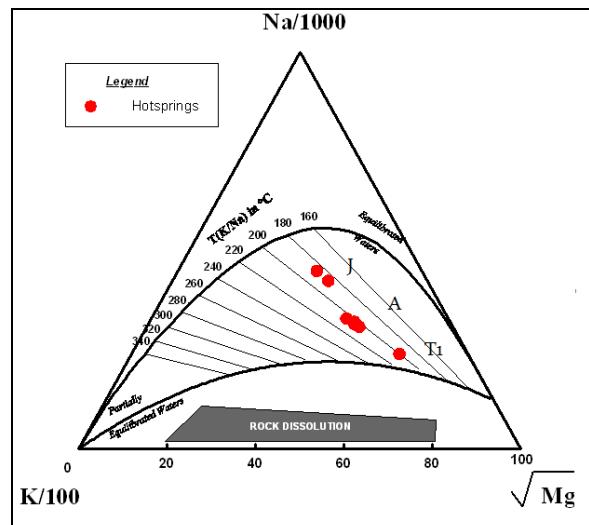


Figure 4: Ternary diagram of Na/K geothermometry

3. MAGNETOTELLURIC SURVEY

The MT survey in the Tawau geothermal prospect was aimed at delineating the boundary of the promising zone, figuring out the subsurface resistivity structure associated with the clay alteration zone and the underlying reservoir. The MT survey was carried out at 42 stations covering the southern slope of Mt Maria and northern Mt Andrassy. The survey was designed using a grid system with interval stations of 1200 meter (Figure 5). The condition of the survey area is dominated by forest covering two thirds of the area where the topographic condition is high, while the rest third is oil palm in the more gentle elevation. The possible noise is originated from human activities in the eastern and southern part of the survey area. In order to remove noise, a Remote Reference MT measurement was conducted about 56 km west of the MT sites with time synchronization using GPS.

To overcome possible static shift of the MT curves, Time Domain Electromagnetic (TDEM) was also measured at the same location as the MT stations using Phoenix equipment. The justification is on the theoretical basis that they do not measure electric fields, and so are largely immune to static shift (Sternberg et al., 1988).

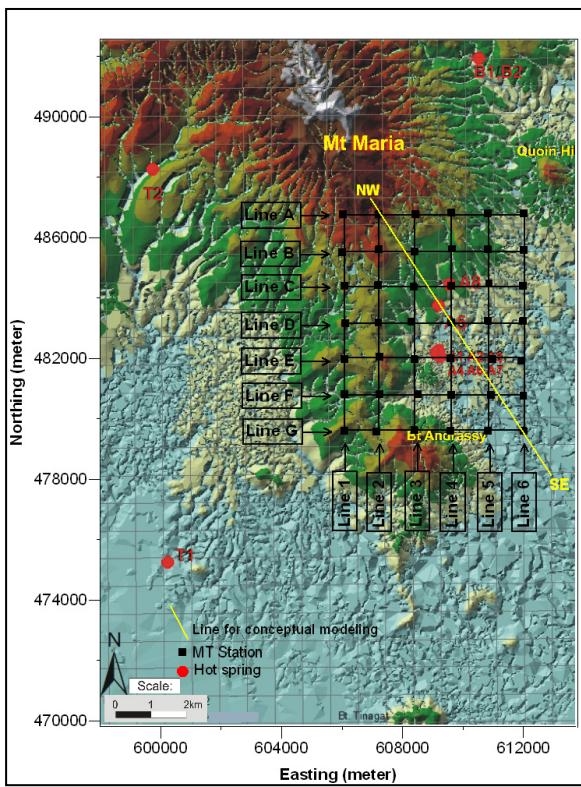


Figure 5: MT Survey Design of the Tawau Geothermal Prospect.

TDEM data provide the estimation of the true resistivity, which is used to shift the observed MT apparent resistivity along the resistivity axis. In practice, the TDEM data were inverted to fit a layered model using the minimum number of layers possible. The pseudo-MT response of this TDEM layered model was then calculated using WinGLink Software to which the actual MT apparent resistivity curves were shifted.

MT measurements were conducted using MTU-5 Units product of Phoenix Geophysics Inc., Canada using a frequency range of 0.001 to 385 Hz. The electric field was measured with dipole length of 100 m oriented to North-South (Ex) and East-West (Ey), while magnetic field was measured using induction coils oriented to North-South (Hx), East-West (Hy), and vertical (Hz). Data was then processed using standard procedures by utilizing SSMT-2000 and MT Editor Software. Most of the MT data were of good to excellent quality (Figure 6). To correct the static shift of the MT sounding curves, TDEM data was then utilized.

The magnetotelluric data were further inverted using the 2D finite-difference based on the non-linear conjugate gradient algorithm following Rodi and Mackie (2001). Conjugate gradient relaxation is also used as the forward operator. The program is able to invert both TM and TE mode data and perform TM-TE joint inversion, and solves for both resistivity and phase. Arbitrary data frequencies are allowed, although it is always assumed that at any particular frequency, there are both the amplitude and phase values. The program also allows for surface topography.

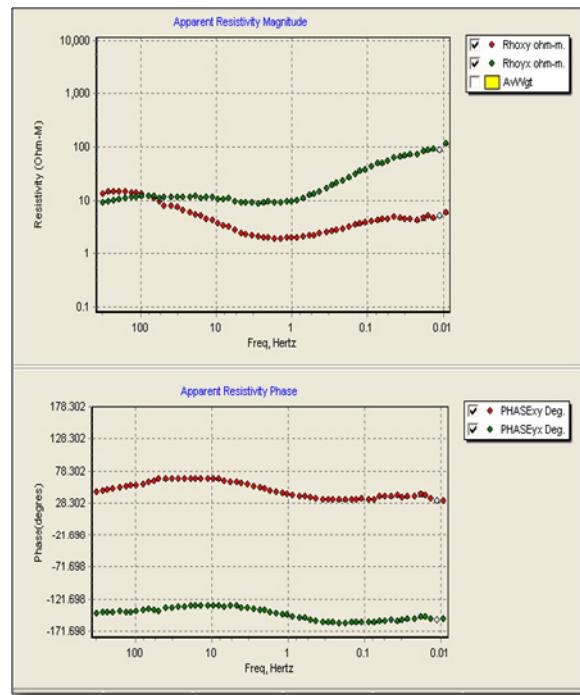


Figure 6: Example of MT Data Quality (Excellent).

The MT survey at the Tawau geothermal prospect was designed to provide information along the profiles parallel and perpendicular to the known structural system. Thirteen 2-D inversion models were run along profiles Line A to Line G (Figure 7) oriented east-west and Line 1 to Line 6 (Figure 8) oriented north-south (the locations of the profile lines can be seen in Figure 5).

The inversion results for the all profiles show a low resistivity layer (<20 ohm-m) from the surface down to various depths from 500 meters to about 1500 meters, except in the point G1 where the low resistivity extends down to about 3000 meters. This is interpreted as the alteration clay zone. The basement resistive layer (>300 ohm-m) is also found in all the section lines starting from about 2000 meter depth.

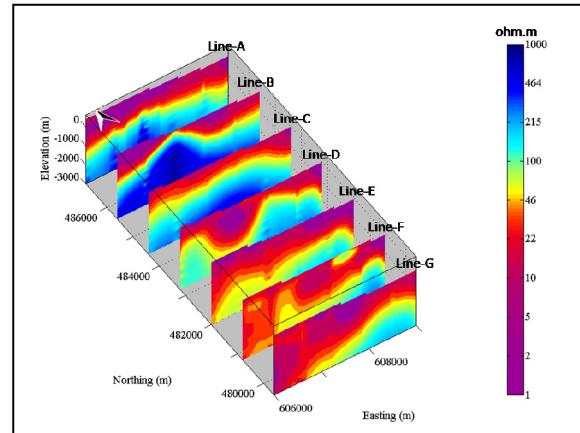


Figure 7: Two-dimensional inversion models of Line A to Line G.

The transition zone is characterized by slightly higher resistivity than the resistivity of the clay zone (between 20–300 ohm-m).

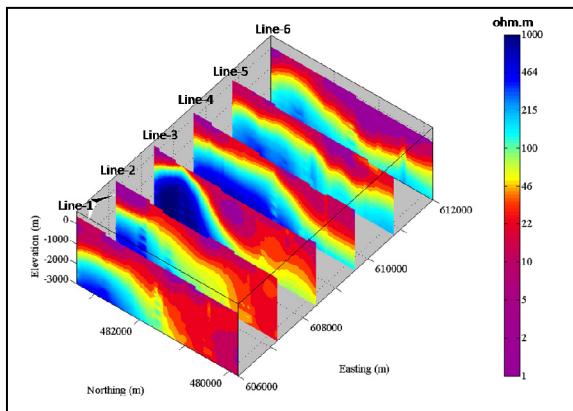


Figure 8: Two-dimensional inversion models of Line 1 to Line 6.

In order to understand the subsurface resistivity structure of the Tawau Geothermal Prospect, the true resistivity data calculated using 2-dimensional inversion can be presented in the 3-D visualization software GeoSlicer-X (Daud and Saputra, 2010). This software was developed by the Exploration Geophysics Laboratory of the University of Indonesia which can be utilized for displaying the resistivity data in the 3-dimensional “cake” model as well as horizontal and vertical slicer model. By using this 3-D view it is easy to analyze the subsurface resistivity structure from different view sides by rotating the 3-D model, slicing the model for certain depths, as well as slicing the model for certain sections.

Figures 9 shows the 3-D view of the resistivity structure of the Tawau Geothermal Prospect in the “cake” model with a maximum depth of 3000 m. It is shown in the Figure that low resistivity dominates the near surface layer down to various depths. It is also shown in the Figure that the low resistivity zone continues down to the 3000 m depth in the south western part of the survey area (the front corner of the “cake” model). The shallowest depth of the conductive layer is situated in the northern part of the survey area. The low resistivity layer is interpreted as the conductive clay alteration as a result of hydrothermal activity.

The slightly higher resistivity (more than 50 ohm-m) is found in Figure 10 underlying the conductive layer with up-dome shape centered in the northern half of the survey area. This zone is interpreted as a promising reservoir zone and can be found from the depth of about 1500 m.

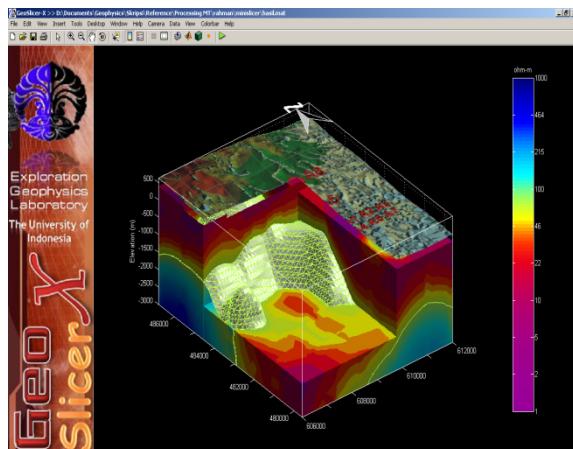


Figure 9: 3-D visualization of Tawau Geothermal Prospect.

4. DISCUSSIONS

A geothermal conceptual model is a comprehensive geothermal model developed by incorporating geophysical data with geological and geochemical data. The geophysical data of the Tawau geothermal prospect is focused on subsurface resistivity derived from Magnetotelluric measurements. Geologically, the geothermal prospect in the Tawau area is associated with the occurrence of Quaternary dacitic to basaltic rocks product of Mt Maria as heat source. This is supported by the occurrence of a young volcanic crater, steam heated hot springs and neutral chloride springs in the vicinity of Mt Maria peak. Subsurface temperature assessed from fluid geothermometry indicates that the geothermal reservoir temperature beneath Mt Maria – Mt Andrassy region is of about 190°C to 236°C. The geological and geochemical data suggest that the main reservoir is probably located in the northern part of the survey area close to the Mt Maria summit.

The magnetotelluric data as described in the previous paragraphs shows a dome shaped reservoir structure centered in the northern half part of the survey area supporting the hypothesis.

From the geo-scientific data the conceptual model of the Tawau geothermal prospect can be presented as in Figure 10. The meteoric water mainly precipitates in the Mt Maria summit as indicated by isotope data and downflow to the subsurface and it is then heated by the hot rock at a depth of more than 2000 m and circulated in the permeable reservoir zone. The promising geothermal reservoir zone is located in the northern part of the survey area with the depth of the reservoir top is variously distributed with the shallowest position is about 1500 m. The location of the promising zone is supported by the indication of an up-flow zone where the temperature is expected high in this region. The area of the promising zone is about 12 km² (Figure 11). The A5 and A8 hot springs are located near the promising zone, while the A1, A2, A3 and A4 hot springs complex is typical outflow of this system.

Exploration drilling should, therefore, be located in the promising zone. However, further investigation is necessary before drilling to confirm the subsurface structure of the associated geothermal system using the gravity method.

5. CONCLUSIONS

An MT/TDEM survey using gridding survey design with 42 measurement stations has given a conclusive result. The overall quality of MT/TDEM data is good to excellent. The subsurface resistivity structure of the survey area is dominated by a low resistivity layer (< 20 ohm-m) in the near surface down to a depth of about 1500 m. A low resistivity zone in the southwestern part of the study area continues down to the depth of about 3000 m. This low resistivity zone is interpreted as hydrothermally altered rocks. The reservoir zone is found in the northern half of the survey area characterized by a slightly higher resistivity (more than 50 ohm-m) zone with a dome shaped structure where the depth of the reservoir top is located from the depth of about 2000 m. The reservoir zone tends to extend to the north. More resistive (> 300 ohm-m) dome shaped basement distributed in the central area with continuation to the northern part of the survey area interpreted as hot rock. The promising reservoir zone as revealed by the MT/TDEM survey covers about 12 km².

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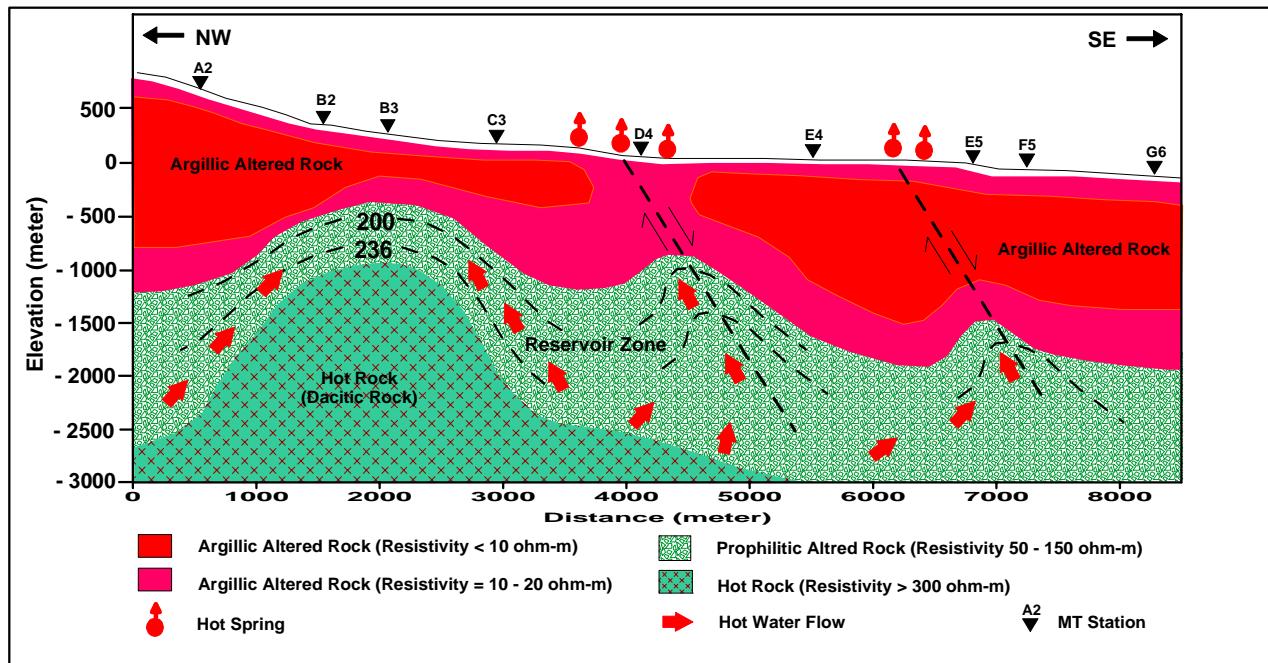


Figure 10: Conceptual Model of Tawau Geothermal Prospect.

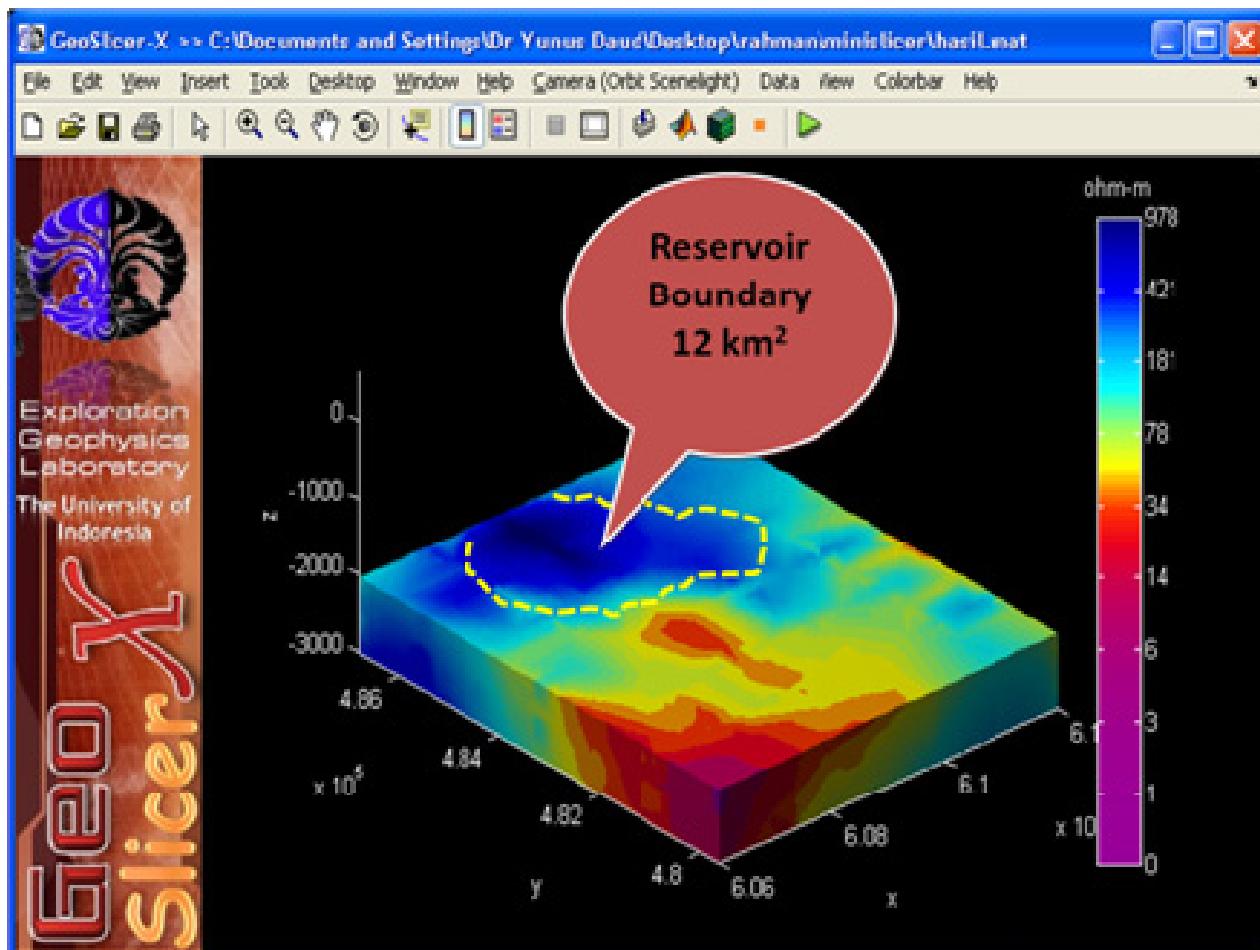


Figure 11: Reservoir Boundary of Tawau Geothermal Prospect.