INTEGRATED GEOPHYSICAL EXPLORATION IN MATALOKO GEOTHERMAL AREA, CENTRAL FLORES - EAST NUSATENGGARA

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ABSTRACT

Integrated geophysical explorations including DC-resistivity, Magnetotelluric, gravity, magnetic and self-potential methods have been conducted to provide an integrated information on electrical resistivity distribution, to assess a likely structure and hydrology of geothermal reservoir in conjunction with the existing geological and geochemical data of the Mataloko geothermal prospect. The resistivity models of the MT in Mataloko area is very consistent with the 2-D resistivity models of the Schlumberger data. There is generally a thin high-resistive surface layer except the manifestation zones. Below it, the Mataloko area is entirely underlain by a low resistive layer in the shallow zones. Resistivity of this layer is very low (1Ωm), near the manifestation zone. This is interpreted as a clay-rich zone which corresponds to a cap layer of the geothermal reservoir system. A large high-resistive body is interpreted below this cap layer in the Mataloko surface manifestation zone. Residual gravity anomalies show a broad negative anomaly of -10 mgals which extends from Mataloko to the eastern part of the manifestation area. This anomaly may indicate a concealed graben structure. The negative anomaly could be caused by negative density contrast between the graben structure infill and the more dense surrounding rocks. Residual magnetic anomaly occurs over the central part of the geothermal prospect, which is slightly narrow negative anomaly almost superimposes the low resistivity anomaly. It is considered that a hydrothermal activity in this area demagnetized the volcanic rocks. Self-potential data shows the highest positive anomaly in the main geothermal manifestation area along the stream Wae-Luja. A 2-D hydrological and electrical structure model was numerically constructed and the result suggests the existence of high permeability zone around the main manifestation area. A local dipolar SP anomaly found in the southern area is corresponding to a fault zone suggested by gravity survey. This fault probably act as a conduit for ascending geothermal fluid in this study area.

1. INTRODUCTION

In the early 1997 a reconnaissance study conducted by Volcanological Survey of Indonesia identified Mataloko, Central Flores-East Nusa Tenggara **(Fig.-1)** as a promising geothermal prospect. Subsequent studies including geologic mapping, geochemical prospecting and geophysical survey were then conducted. The prospect area ranging from 4.5-5 km^2 was estimated from geophysical data. Dwipa and Andan (1998) concluded, however, that further detailed investigations were needed to accurately establish the resource characteristic of the system.

From 1997 to 1999 intensive explorations at Mataloko were carried out by Volcanological Survey of Indonesia (VSI), Geological Survey of Japan (GSJ) and New Energy and Technological Development Organization (NEDO). These activities are a part of the Indonesia-Japan cooperative research project "the exploration of small-scale geothermal resources in the eastern part of Indonesia".

The purpose of the survey is to provide an integrated information on electrical resistivity distribution, to assess a likely structure and hydrology of geothermal reservoir in the study area. We have applied two-dimensional (2-D) inversion to the MT data and have made preliminary interpretation on geothermal reservoir of the area together with other geological and geochemical data.

In this paper, authors focus on the geophysical data and summarize the significant results of our studies.

2. FILED MEASUREMENT AND DATA PROCESSING

2.1. DC-resistivity.

Locations of the Schlumberger soundings and mappings are shown **in Figure 2**. There are eleven survey lines in Mataloko area. The number of Schlumberger sounding stations is 19. The current electrode spacing, *AB/2,* for the sounding varies from 1.6 m to 2,000 m. The number of mapping sites is 87 including the sounding stations. The interval of the mapping sites is 500 m along the survey lines. The electrode spacing, *AB/2*, for mapping are 250, 500, 750 and 1,000 meters. The expansion of the electrode array is along the survey lines for both sounding and mapping.

We have applied two-dimensional (2-D) inversion to ten survey lines. The 2-D inversion method utilizes the conventional linearized least-squares scheme and applies a smoothness regularization for stabilizing the illposedness of the problem. The minimization of data misfit and model roughness are simultaneously achieved by introducing the Bayesian likelihood. The forward modeling utilizes the finite-element method. Therefore, topography can be easily incorporated in the modeling. Starting with a homogeneous earth of 10,000 Ω-m with topography as an initial model, the iterative inversion procedures almost converge after several (say, 5-7) iterations.

2.2. Magnetotelluric.

Locations of the MT sounding stations are shown in **Figure-2**. Five NE-SW survey lines, lines B-F, were arranged around the Mataloko manifestation area. Four MT field instruments, Phoenix MTU systems, were used for the data acquisition. Three of them were five components (MTU-5, three magnetic fields and two electric fields) and one is two components (MTU-2, only electric fields). One MTU-5 was permanently installed in the Mengeruda manifestation area, which is approximately 15 km away to the north from the Mataloko area. It was for the acquisition of the remote reference data. The rest three instruments were used in the survey area. We have to record the times series data of natural electromagnetic signals simultaneously, with the exactly same clock timing, at the survey stations and the remote station. The instruments utilizes the clock signal from GPS satellites for such synchronization. The measurement was done for 15 hours from evening to the next morning. The actual field measurement started on August 31 and ended on September 25, 1999. The total number of stations is 41 on the Mataloko lines. Station interval is approximately 600 m in the line direction. Line spacing in the Mataloko area is 500 m.

The time series data of both the survey station and the remote station were first processed together for in the remote–reference analysis. It is to remove local noises at the survey station, which are not correlated with other noises at the remote station. Fortunately, the surveyed area is relatively quiet from the point of cultural noises. Also, when we select a site for the measurement, we tried to choose an open space as much as possible, rather than near big trees, in order to avoid wind noises. Therefore, wind noise was not large except the stations on line H, Which are located near a peak or aslope of volcanic cones.

The remote reference processing was done by using the Phoenix software, and power spectrum of magnetic and electric fields were obtained. The number of processed frequencies is 40; approximately from 0.0005 Hz to 300 Hz. Quality of the low frequency data at 0.0005 Hz was usually low, because the recording time, 15 hours, is not enough to obtain enough number of averaging for such low frequency data. But, data quality in the frequency range that is needed for the interpretation of geothermal reservoirs (usually from 0.01 Hz to some 100 Hz) was generally very good, when we compared them with noisy MT data in Japan. The impedances data were converted to the EDI MT standard format, then transferred to data processing software called Geo-tools. Using the software, we first checked the quality of the data and examined general characteristics of the resistivity structure. Then, we converted the data to the format which we use for the 2-D inversion of each survey line.

In the 2-D interpretation, we assumed that the strike direction is perpendicular to the line. Then, we used so-called TM mode data, which is an electrical field in the line direction and a magnetic field in perpendicular, for the inversion. The number of frequency used was 12, ranging from 0.07 Hz to 120 Hz. Both apparent resistivity and phase are used as the observed data. Minimum noise assumed was 1% in apparent resistivity and equivalent amount in phase. The inversion method used here is the linearized least-squares scheme with a smoothness regularization for stabilizing the ill-posedness of the problem. The minimization of data misfit and model roughness are simultaneously achieved by introducing the Bayesian likelihood (Uchida,1993).

2.3. Magnetic.

We conducted ground magnetic surveys using two Scintrex MP-3 magnetometers with the precision of 0.1 gamma (nTesla). While one magnetometer was collecting data in the field, the other one was used to record magnetic variations in the study area at the base station. The base station was established almost in the central area of magnetic survey. Magnetic measurement stations were taken along the main road except for Mataloko geothermal are covered all DC-resistivity and gravity stations. Most of the stations were located at altitude control points in 1:50,000 scale topographical maps, and the locations of stations were determined by means of T0-type theodolit geodetic instruments. Some triangulation points in this area were used as reference point of measurements. As we used the closing loop method for magnetic surveys, some magnetic stations which are selected from benchmarks were used as the magnetic control points to check the drift of the magnetometer. For the data reduction we adopted the method written by Nettleton (1971).

2.4. Gravity.

The Mataloko area is characterized by a relatively low residual gravity anomaly associated with a graben structure. The detailed gravity structure of the study area had not been revealed until the gravity measurements were carried out in 1997 and 1998. Gravity measurements can be carried out using a Scintrex CG3-M meter (Dwipa, 1994) and a Superconducting gravity meter (Dwipa et al., 1998), however, for this study we use a G-type LaCoste & Romberg gravity meter. This survey covered the Mataloko geothermal prospect. The standard reduction procedure, namely, reduction of normal gravity using the gravity formula 1967, free air reduction, terrain and Bouguer corrections were applied to gravity data. In the procedure the density of basement was assumed to be 2.67 gr/cm^3.

Trend surface analysis was also used to abstract an overall trend from the gravity distributions. The result has revealed that the second order residual gravity correlates relatively better with the distribution of the Tertiary. This means that the third order trend surface has included some information about the Tertiary. Correspondingly, some amount of information of Tertiary has been lost in the third order residual gravity. Thus the second order residual gravity map can be adopted on the basis of the above mentioned trend surface analysis.

2.5. Self-potential.

Self-potential survey in Mataloko was conducted around the Wae-Luja river, across the alteration zones identified by geological surveys. The total number of the SP measurement points is 430 with a spacing of 100 m along survey lines. The covered area is about 5 km in the E-W and 6.5 km in the N-S directions. **Figure-3** shows the location of the SP survey points in Mataloko area. The electric potential at a survey point P1 is assumed to be zero. Loop corrections were applied to measured SP data.

A two-dimensional SP model was completed along an E-W survey line with a coupled fluid flow and SP simulator *PTSP* (Yasukawa et al,1993). Line-C' is located approximately 500 m north of a resistivity survey line-C conducted by Dwipa and Andan (1998) which crosses the main manifestation area. The solid line in **Figure-4** shows the observed SP profile along line-C'. This SP profile is totally different from the pattern expected from its topography; the higher the elevation, the lower the SP. Therefore several effects of inhomogenety of physical properties must be present. In *PTSP*, temperature and pressure distributions in a system are calculated based on the energy and mass conservation equations for the proper boundary conditions. The distribution of fluid velocity is thus obtained and the current source distribution caused by fluid flow is calculated for a given electro-kinetic cross-coupling conductivity. The methods developed by Ishido and Mizutani (1981) and Morisson et al.(1978) were used for data reduction.

3. RESULTS AND DISCUSSIONS.

3.1. DC-resistivity.

Here we discuss only lines B, C and D for Schlumberger-resistivity and magnetotelluric, Figure 5 shows 2-D model of lines B,C and D. Generally, almost all the sites are underlain by a surficial resistive layer of an order of 100 Ω-m. Thickness of this resistive layer varies site by site gradually, from less than 100 m to grater than 500 m. Below this resistive layer, a conductive layer (<10Ω-m) is widely distributed and only a few sites are lacking the conductive second layer. This conductive layer may be related to clay alteration in low temperature zone. At many geothermal areas, high-temperature reservoirs are often located within a relatively resistive layer beneath the conductive shallow layer. The site we can recognize such resistive layer are around site C-51. Further measurement by CSAMT/MT are necessary to obtain more reliable resistivity information on deep structure.

3.2. Magnetotelluric.

Figure-6 shows 2-D model of lines B, C and D. The convergence of the inversion was not good for line B. This means that the assumption as a 2-D trend in NW-SE direction is not valid for line B. It seems to be because Line B is close to a large low-resistivity body located to the west of the survey area, which was identified by induction vectors. The low-resistivity body probably created a three-dimensional effect to the 2-D inversion. The inversion is stable for all NW-SE lines and good for lines D, E, and F. Therefore, most of the models seem to be all right for the further interpretation.

The typical features of the 2-D models are as follows:

1. There is a thin surface layer of high resistivity, It corresponds to volcanic rocks and tuffs with less alteration.
2. Below is a very low-resistivity layer. It distributes in the entire survey area. An average thickness in the center of the area is small (several hundreds meters), but resistivity is very low (approximately 1Ωm). Thickness becomes larger in the western part of area, but resistivity becomes bigger there, too.
3. There is a high resistivity zone beneath the very low resistivity shallow layer. Resistivity of the body is higher in eastern side of the area.

These figure is consistent with 2-D models obtained by an inversion of schlumberger data. The very low-resistivity layer is interpreted as a cap layer that contains a large amount of clay alteration minerals. The high-resistivity deep zone may be interpreted as a high-temperature reservoir zone. Depth of this resistive layer is the shallowest near the manifestation zone, e.g., Stations 120 and 128. resistivity of the low-resistivity cap layer is the smallest in this zone. It indicates that an extensive hydrothermal activity took place near this zone.

3.3. Magnetic.

A preliminary residual magnetic map of the study area is presented in **Figure-7**. Surprisingly, **Figure-7** is in good agreement with resistivity data (see **Figure-8**) and gravity data (see **Figure-9**) suggesting that the magnetic anomalies reflect deep structures. Then qualitative interpretation can be done. The most obvious feature of the residual magnetic anomaly occurs over the central part of the Mataloko geothermal prospect, which is a slightly narrow negative anomaly (<200 gamma). This anomaly almost superimposes the low resistivity anomaly of **Figure-8**. It is considered that a hydrothermal activity in this area demagnetized the volcanic rocks. Other features are two groups of low magnetic anomalies; one is located in the western part and another one is in the eastern part of the study area. The eastern anomaly coincides with a low resistivity anomaly. The source of this anomaly is yet unknown since there is no surface manifestation in this area. Speculatively, one can say that this anomaly reflects an extinct geothermal system of the area. The western anomaly is possibly an affect from a hydrothermal activity in this area where the surface manifestation can be found in the west outside of the survey area. In terms of subsurface structure, the lineaments that are mapped by gravity are also shown in **Figure-7**. The fault structure is clearly shown by the straightness of the magnetic lines.

3.4. Gravity.

Residual gravity anomalies of the Mataloko geothermal prospect are shown in **Figure-9.** One of the most outstanding features of **Figure-9** is a broad negative anomaly (-10 mgals) of wavelength more than 3 km wide and 6 km long which occurs over the eastern part of the Mataloko geothermal prospect. The area of this negative anomaly extends from Mataloko to the eastern part of this village. This anomaly may indicate a concealed graben structure. The negative anomaly could be caused mainly by negative density contrast between the graben structure infill (pyroclastic of Inerie Volcano) and the more dense surrounding rock (i.e. andesitic lavas of Inerie in the west and andesitic lavas of the Tertiary volcanics in the east).

Another feature is a NW – SE trending elongate positive anomaly (20 mgals) which covers the study area of about 3 km wide by 7 km long. This anomaly is observed almost parallel to the negative anomaly previously mentioned. The gravity gradient of this positive anomaly of the western side seems steeper than that on the eastern side. These large gradients probably reflect the effects of the boundary between the more dense Inerie lava and Inerie pyroclastic rocks that are deposited in the graben like structure.

3.5. Self-potential.

About the Mataloko numerical modeling, the uniqueness of the resistivity and permeability distributions shown in this study is not clarified yet. Especially the sensitivity of the vertical extent of the high permeability zone should be investigated in the next stage. However, the SP numerical modeling proves the existence of high permeability zone suggests the surface extent of this zone. Therefore the combination of a resistivity survey and SP survey is quite convenient to investigate the permeability structure.

For this numerical model, no hot fluid source was assumed because there is no clear surface manifestation along C'-line. This SP modeling was performed assuming the SP anomaly is caused only by topographic effects and resistivity and permeability structure. Since the SP profile along C'-line was thus constructed by a model without an up-flow from a depth, this modeling improves that the surface discharge is merely a local phenomenon.

A large negative anomaly, not corresponding to the topography, was observed around Y8 east of the main manifestation area (see **Figure-3**). An SP profile across this zone is numerically analyzed in the next section. Another negative anomaly around S1 in the south corresponds with the location of a fault suggested from a gravity survey (Dwipa and Andan, 1998). The other SP profiles are rather flat and the main causes of the anomalies are topographic effects or artificial noise around residential areas. For SP profile for each line, see Yasukawa wt al.(1999).

Figure-10 shows the resistivity and permeability grids of the numerical model. The resistivity grid is based on the result of resistivity surveys conducted by VSI (Dwipa and Andan, 1998). A low resistivity layer (5 ohm-m) reaches to a shallower depth at the vicinity of Wae-Luja. Since a negative SP anomaly an a topographic slope can not result from a resistivity structure alone (Yasukawa and Mogi, 1998), a permeability model was also introduced. At first a permeability model with the same geometry as the resistivity was applied; for the lower resistivity layer a higher/lower permeability was given. However, no high SP anomaly was resulted for this layered permeability model. Therefore a vertical contact model was considered; a higher permeability column was assumed near the negative anomaly zone.

4. CONCLUDING REMARKS.

MT survey in the Mataloko geothermal field shows the data quality is very fine except some station in the mountains. 2-D inversion was successfully applied to all the data. The resultant 2-D resistivity models are consistent with the existing DC resistivity models and geothermal features in the areas. A typical resistivity distribution recognized is a very low-resistivity layer distributed around the Mataloko manifestation area. Thickness the this layer is several hundred meters, and below is a large high-resistivity body. We interpret that the low-resistivity layer is a clay rich cap layer of a reservoir system and the high resistivity body is a high temperature water circulation zone.

SP data shows the highest positive anomaly in the main geothermal manifestation area along the stream " Wae-Luja" running eastward. SP value drastically drops toward north, south, and west while the value gradually decreases toward east. It is consistent with the fact there exist some more hot springs only in the east of the main manifestation area.

A two-dimensional hydrological and electrical structure model indicates the existence of high permeability zone around the main manifestation area. A local dipolar SP anomaly found in the southern area is corresponding to a fault zone suggested by gravity survey. This geological structure which clearly shown by the straightness of the magnetic lines probably act as a conduit for ascending geothermal fluid in the Mataloko geothermal prospect.

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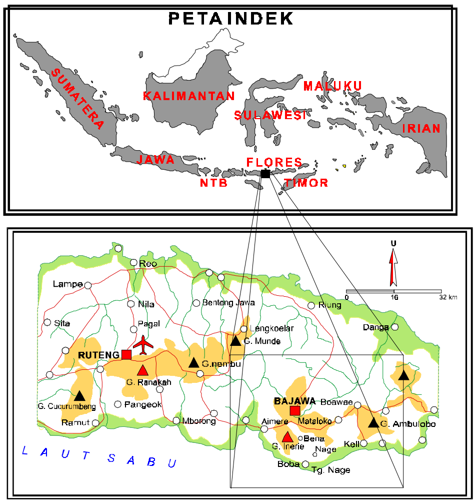

Figure 1
Map showing the Mataloko geothermal prospect

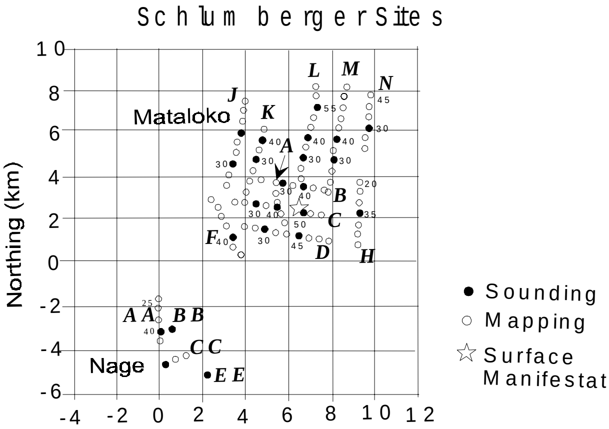

Figure 2.
Survey lines of Schlumberger sounding and mapping at the Mataloko and Nage geothermal areas central Flores. A solid indicates sounding sites and open circle means a mapping sites The surface manifestation in Mataloko area is located near site C-50 on Line C.

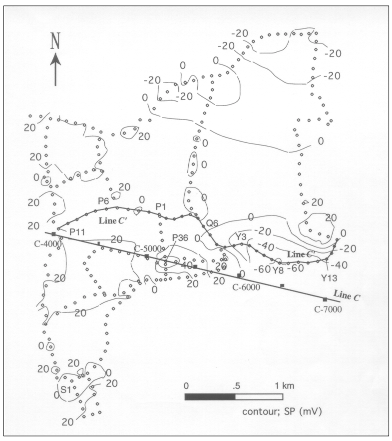

Figure 3
SP distribution in the Mataloko area

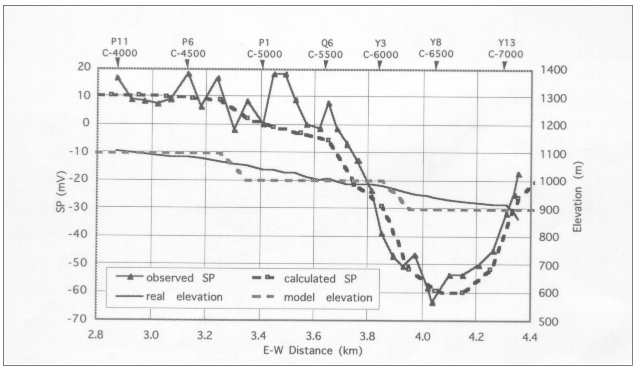

Figure 4.
Comparison of observed and calculated SP profile along *line* C

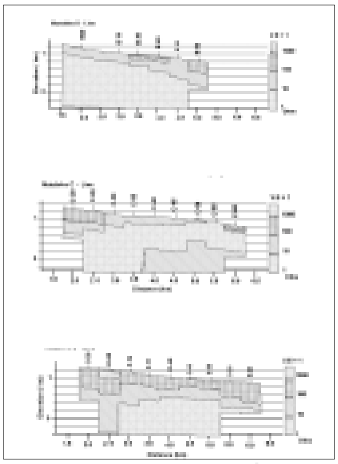

Figure 5
2-D models obtained from Schlumberger data on lines B, C, and D in Mataloko

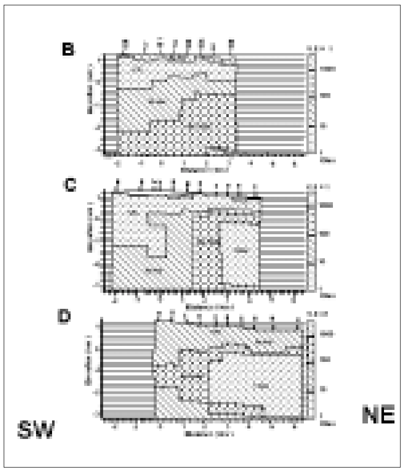

Figure 6
2-D resistivity models of SW-NE survey lines; B, C and D

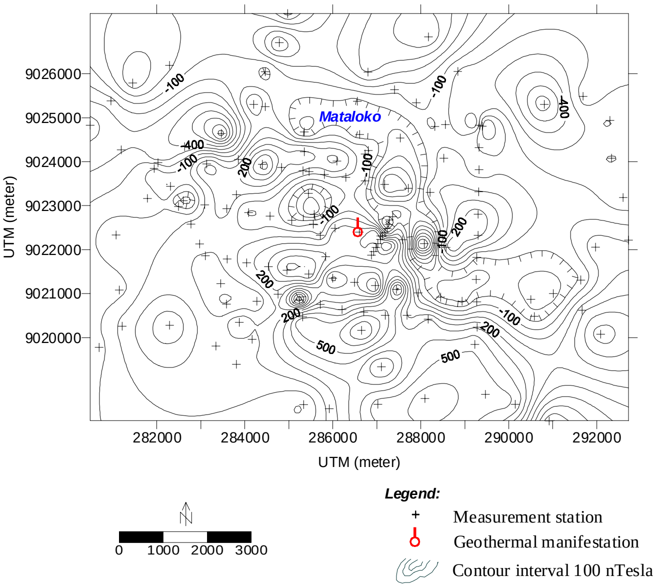

Figure 7
Residual magnetic anomaly of Mataloko geothermal prospect

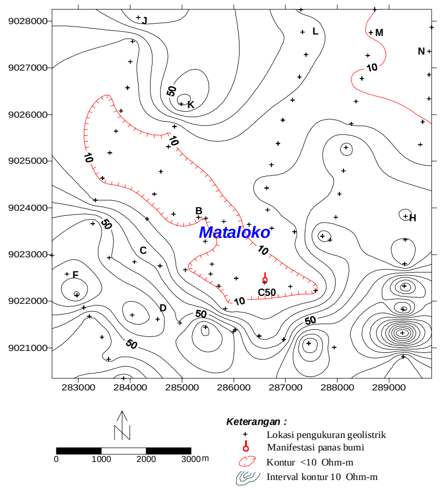

Figure 8
Iso apparent resistivity map at AB/2 = 1000 m of Mataloko Geothermal prospect

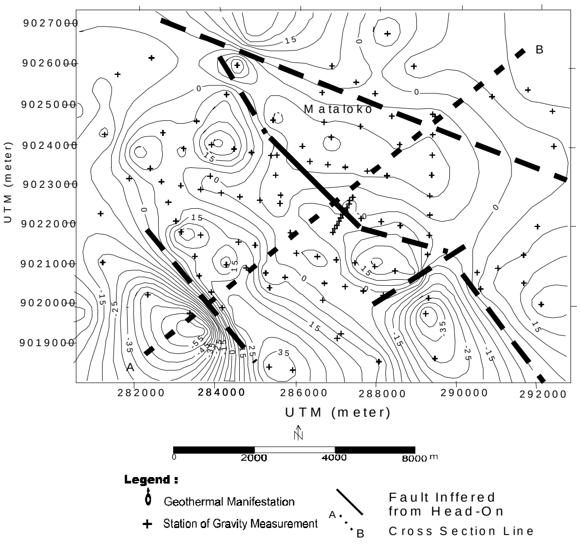

Figure 9

2nd order residual gravity anomaly of Mataloko geothermal prospect.

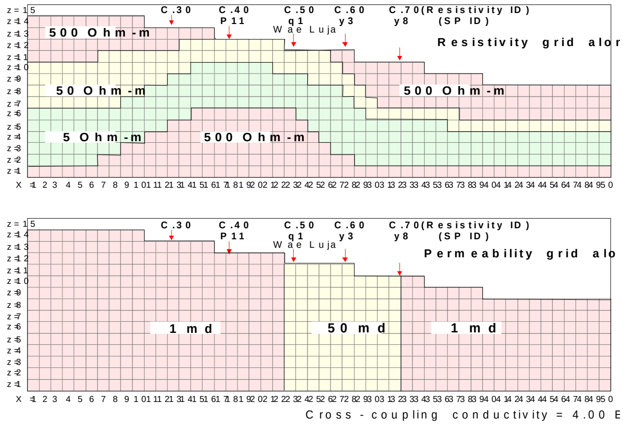

Figure 10.

Physical property grids of the model