Geothermal reservoir boundary delineation using 3D magnetotelluric inversion. case study: the “delta” geothermal field of Indonesia

Riki Irfan¹, Yunus Daud¹,²

¹Physics Department, University of Indonesia
²PT NewQuest Geotechnology (PT NQG)
Physics Department of University of Indonesia. Depok, 16424, Indonesia

Email: Riki.irfan@yahoo.com

Abstract. The “DELTA” geothermal field is a brown geothermal field in Indonesia. The field has been produced for many years. Most of productions wells are in the center of the reservoir, need to have step-out wells to reduce the well intervention risk. The first step-out well was drilled near reservoir boundary of conceptual model which is refer to “old” 3D Magnetotelluric (MT) inversion. The step-out well failed to produce steam and well data indicated outside the reservoir. After careful analysis, it found that the 3D MT model does not match with the well data. On this study, the author conducts 3D MT inversion re-modeling to re-delineate the reservoir boundary. To have comprehensive interpretation, the result of new 3D model which generate independently then compared with available data sets such as MEQ, gravity, geology map, geochemistry data and well data. The new 3D MT model shows better match to well data, re-delineate the reservoir boundary and give recommendation for well targeting areas.

1. Introduction
The "DELTA" geothermal field is located about 50 kilometers southeast of Bandung. It is a steam dominated system and currently as on the development stage. The last drilling campaign was 2009-2011 and the first drill step-out well in 2011 failed to produce steam. The 3-dimensional Magnetotelluric model being used as a reference was probably not accurate. Then this research is driven by the fact that the model refers on the last drilling campaign considered having issues and need to be revisited.

In this research, the authors performed data re-processing from raw data to EDI file, reproduced EDI file and conducted the 1D, 2D and 3D MT modeling. The final stage is to interpret the MT data that will be integrated with another supporting data such as MEQ data, well data and geochemical data. Thus, allow to image the resistivity structure of the subsurface of the study area. The objective of the study is to re-model the cap rock layer distribution covered the geothermal reservoir and to redraw the reservoir boundaries to increasing the drilling success ratio.

The purpose of this research is to redefine the reservoir boundary refer to 3D resistivity distribution based on the new 3D inversion model. The 1D and 2D inversion MT modeling were conducted using WinGlink software of PT Star Energy while the 3D MT inversion was conducted using MT3Dinv-X software of PT NewQuest Geotechnology (NQG).
2. Theoretical Background
Geothermal system consists of heat source, reservoir rock, cap rock and fluid [7]. The cartoon of geothermal system component is shown in Figure 1.

![Figure 1. The component on geothermal system [4].](image)

The heat source is usually a remnant of magma chamber or residual activity of ancient volcanoes in the form of igneous rock (batholith). The remaining energy in this rock warmth reservoir rock above which contains fluid. The reservoir rock is a porous and permeable which allow fluid to flow. The cap rock is impermeable that hold the fluid escape from the underlying layer, this layer is usually clay that formed naturally due to hydrothermal alterations.

Magnetotelluric (MT) method is a passive electromagnetic (EM) exploration method that utilizes EM field fluctuations which generate the sub-surface electric currents, the variations of electric and magnetic fields were measured on the surface [8].

Maxwell equations are the basis of MT method. In practical, the apparent resistivity ($\rho_{xy}$ and $\rho_{yx}$) of the earth as a function of frequency can be found from the relationship:

$$\rho_{xy} = \frac{0.2}{T} |\frac{E_x}{H_y}|^2$$
$$\rho_{yx} = \frac{0.2}{T} |\frac{E_y}{H_x}|^2$$

where:
- $T$ is the Period of the wave
- $E_x$ and $E_y$ are electric fields in mV/km
- $H_x$ and $H_y$ are magnetic fields in nanoTesla

The MT method has been known as geophysical method applied in geothermal exploration and powerful to delineate conductive clay zone overlying a geothermal reservoir. Accordingly, MT has been utilized to guide drilling sites in many geothermal explorations [1].

The MT inversion is a mathematical approach to produce the true resistivity subsurface model from the apparent resistivity and phase data that observed at the surface [2]. Thus, the 3D inversion is expected to be able to give the best approach on collecting the true subsurface resistivity distribution.

3. Methodology
This study focusses on data processing and modeling of Magnetotelluric (MT). The interpretation of resistivity results will be combined with supporting data i.e. MEQ data, geological data, geochemical
data and well data. Those to obtain comprehensive conceptual model. The data processing activities are consisting of: 1) plotting and viewing data time series MT; 2) QC data and noise-elimination to increase signal to noise ratio) and 3) data processing. The sketch of the data processing stages is shown in Figure 2.

The MT time series data was recorded by Metronix type ADU-06. Then time series converted to ADU-07 format that can be read by the available software. The time series data example shown in Figure 3.
There is also an instrument calibration option to select robust processing at a certain frequency range. The next stage is to do the editing) and static shift correction as shown in Figure 4.

Figure 4. Example of a MT apparent resistivity and phase data before and after static shift correction.

In this study, 31 MT EDI files data were used on the 3D inversion. 12 selected frequencies (4 frequency per decade) and 8 tensor impedance elements were set for each station data and the inversion set to 50 iterations and applied the numerical shift correction. The parameter used are 50 grid from South to North (grid block size 200m), 54 grid from West to East (grid block size 200m), and 22 vertical grid (grid block size 10m). All block size out of the grid given the coefficient of 1,5 time from block size inside the grid. The total grid number $M = 50 \times 54 \times 22 = 59,400$. The initial half space model ste to fix resistivity value of with 100 Ohm-meter (figure 5).

Figure 5. Parameter setting of 3D MT inversion modeling with numerical static shift corrections.
The geophysical data sets using as data support for this research are Microearthquake (MEQ) and gravity data. The MEQ data used is the MEQ density contour data 2003 up to 2010 (shown in Figure 6), period prior to drilling well step out well in 2011 [5].

The gravity data that used as supporting data is the residual gravity anomaly map. This map indicates that high density anomaly was overlaid the current area defined as reservoir area as shown in Figure 7 [6].
The geology map of "DELTA" is shown in Figure 8. This map shows Kiamis obsidian and Kiamis tufa as the youngest rock in the field. The reservoir rock is associated with Kendang volcanic complex which the product of Quaternary andesitic stratovolcano that was eroded. The volcanic sediment contains intermediate to mafic rock compositions, except for Kiamis obsidian and pyroclastic deposits found where located on vent between the study area and Kamojang field.

![Geology Map of "DELTA" geothermal field](image)

**Figure 8.** Geology Map of "DELTA" geothermal field [3].

4. Result and Discussion
In this study, a map of cap rock distribution and some resistivity cross sections were produced. This is done to delineate the boundary area of the "cap rock layer" which limits the reservoir's commercial area in the "DELTA" field which is expected to be obtained by the size of the reservoir area to increase the understanding of the potential of the research area.

The remodeling was conducted on 31 MT data. The final results, give an RMS error ranging from 9.5 to 10.5 RMS. The model stopped at the 15th iteration run, with a relatively small RMS error value and stable. The inversion model using numerical static shift correction parameter is considered as the most appropriate model for further interpretation. This inversion scenario produces the most stable and representative model to be combined with supporting data and interpreted further.

Figure 9 shows the present of low resistivity anomaly, covered the study area indicates that cap rock that overlay above the geothermal reservoir. The model shows the dooming shape of low resistivity layer as typical shape of geothermal cap rock.
In this research, authors create 3D resistivity model based on 3D MT inversion result to map the cap rock distribution. This will help to delineate the geothermal reservoir boundary. The information is needed to redefine the boundary and potential size of the “DELTA” field. Some maps and cross sections of resistivity model were created to have a better understanding on the subsurface condition based on the resistivity data.

Figure 10 is resistivity map at some elevations. It shows agreement with current interpreted geology structures. Those maps are well aligned to the main geological structure trend, SW-NE and as well S-N trend.

Figure 11 shows some resistivity cross sections as 3D inversion result. In general, all section indicates a doming shape of low resistivity layer that possible cap rock zone overlay the reservoir below the low resistivity anomaly layer.

Figure 12 and 13 show the comparison result from 3D resistivity model inversion model 2004 compared with inversion remodeling 2017. Both figures indicates that new model (right figures) clearly have better agreement with the temperature contour from wells data dan the MEQ hypocenter plots.
Figure 10. Resistivity maps based on 3D MT Inversion at some elevation overlaid with geology structures. Blue dash line was the previous reservoir boundary.

Figure 11. Example of subsurface resistivity sections based on 3D MT Inversion at some directions.
Figure 12. SW-NE cross section of MT 3D resistivity 2004 (left) and remodeling 2017 (right) overlaid with well trajectory, temperature and MEQ data period 2003-2010.

Figure 13. N-S cross section of MT 3D resistivity 2004 (left) and remodeling 2017 (right) overlaid with well trajectory, temperature and MEQ data period 2003-2010.

The 3D MT model and other data which is available were combined to help the interpretation. In general, there is resistive (> 100 ohm-m) layer of about 300m up to 500m thickness at surface. The second layer is low resistive layer (< 10 ohm-m) with doming shape in the center part. This layer interpreted as cap rock layer. The third layer is 20 ohm-m up to 200 ohm-m at deeper part. Those layers were typical resistivity trend in the geothermal system.

A simple map as a conceptual map delineate the reservoir boundary of geothermal field is created as shown on Figure 14. The Figure shows reservoir boundary (red dash lines), some of wells, interpreted geological structures and two proposed drilling target areas for make-up wells shown by two black circles.
Figure 14. Well target area recommendation based on the study result on “DELTA”. W1 and W2 are the proposed drilling target area. Red dash line is the new Reservoir boundary with coverage area of about 15 km².

The conceptual model is shown in figure 15. This cross section was produced to get better understanding of the subsurface condition of study area. Green layer is interpreted as a clay cap layer. The cap rock deepening both to edge of the profile. The Western part is more thicker compare to east part. It is clear doming of cap rock in the center, which is coincide with area where high temperature and pressure is observed from well data. This area interpreted as the nearest area to possible up flow location.

Figure 15 illustrates an up flow of the Eastern part of the fumarole area. It is seen that the vertical tendering of MEQs in up flow areas where the fluid (steam) flows from the bottom upwards of the fumarole area. It is noticed that D43 wells are drilled in a cap rock area (green) outside the reservoir where the rock cap layer thickens and the profile contours 175° C deep, at the depth of the well depth target.
5. Conclusion
1. New 3D MT model results indicate a pattern that aligns with the profile temperature model, alteration and lithology obtained from well data.
2. The new 3D MT model could redefine the reservoir boundary and provide information of resistivity characteristics associated with cap rock and geothermal reservoir rock in the "DELTA" field. The cap rock having resistivity of less than 10 ohm-m. While the reservoir rock are ranges from 40-60 ohm-m.
3. Map of 3D remodeling at sea level elevation and the base elevation map of cap rock shows agreement with data from permeability map. Thus, provides more accurate reservoir geometry calibrated to well data as real reference. The new reservoir area is about 15 km square, not much changed from the previous model size (about 16 km²), but the boundary position changes.
4. Northwest region (W1 circle), and northern area (W2 circle), is expected as the next production well target for drilling.

Acknowledgements
The authors acknowledge Management of PT NewQuest Geotechnology for geophysical software used for processing and 3D inversion modeling.

References
[1] Daud Y 2010 Diktat Kuliah: Metode Magnetotellurik (MT) Laboratorium Geofisika FMIPA Universitas Indonesia.
[2] Daud Y 2015 MT and TDEM Technology for Geothermal Exploration FMIPA Universitas Indonesia.
[3] Intani R and Irfan R 2015 Darajat Edge Field Evaluation (Melbourne: Proceeding World Geothermal Congress 2015)
[4] Irfan R 2004 *Skripsi: Delineasi Prospek Panas Bumi area X dengan menggunakan metode Magnetotellurik* Teknik Geofisika FIKTM Institut Teknologi Bandung.

[5] Irfan R 2012 *Darajat MEQ monitoring during drilling Darajat campaign 2009-2011* (INAGA Lampung)

[6] Rejeki S Dave R Gregg N Fitriyanto A 2010 *Geologic Conceptual Model Update of the Darajat Geothermal Field* (Bali: Proceeding World Geothermal Congress 2010)

[7] Santoso D 2000 *Catatan Kuliah Vulkanologi dan Eksplorasi Geotermal* Penerbit ITB

[8] Vozoff K 1991 *The Magnetotelluric Method in Electromagnetic Methods in Applied Geophysics* Vol 2B (Tulsa: Nabighian, M.N., Soc Expl. Geophys) pp 641-711