Subsurface structure identification of ‘X’ geothermal prospect area based on gravity and magnetotelluric data

E W Sugiyo and Y Daud
Department of Physics, Faculty of Mathematics and natural Sciences (FMIPA), Universitas Indonesia, Depok 16424, Indonesia

Corresponding author’s email: ydaud@sci.ui.ac.id

Abstract. Exploration stage has the highest risk, due to discover the interest reservoir zone include high temperature and pressure, middle to high permeability, and non-acidic fluid. Permeability is one of the most difficult parameters to be determined in this stage. Fault zone could be able to control and provide fluid flow within reservoir. It is usually related to high permeability zone. Fault identification become an important and interesting parameter in to be explore. The aim of this research is identified subsurface structure to build up a conceptual model of geothermal system. The methods include magnetotelluric data analysis and 3D MT structure interpretation together with first horizontal derivative and second vertical derivative analysis of gravity data. Geochemistry and geology data are used as supporting data. There are structure types of normal and reverse fault identified in the research area. MT and gravity interpretation show that structures are direct to northeast-southwest and northwest-southeast. Up-flow zone is predicted between TPP-TPB manifestations. Structures supposed to highly contribute in providing permeability zone in the research area. Manifestations fluid have the characteristics of meteoric and magmatic fluid (volcano-hydrothermal system). The clay cap thickness average is predicted between 500–700 m. The reservoir thickness average is predicted between 1500–2000 m. Temperature estimation of the reservoir is 240–280 ºC. Heat source might be located between TPB and TPP manifestations. Subsurface structure analysis might be useful to increase success ratio in drilling.

Keywords: Structure, gravity, magnetotelluric, geothermal

1. Introduction
Geothermal system should be consisted of some most important component such as heat source (hot rocks), reservoir zone, clay cap and subsurface geological structures. The natural output of geothermal system is appeared as surface manifestations such as fumarole, warm or hot springs, warm ground, steaming ground etc. This indicates geothermal resources that could be explore. Geothermal exploration stage has the highest risk because there are uncertainty resources, due to discover high temperature (> 200 ºC) and high pressure of reservoir, middle to high permeability zone at shallow depth (< 2 km), and non-acidic fluid [1, 2].
Permeability is one of the most difficult parameters to be determined, specify in geothermal. Although there is a large heat storage of rock bodies in late Tertiary and Quaternary volcanic fields, it’s might be useless for geothermal fluid production if it just has low permeability [2]. Fault zone could be
able to control and increase fluid flow within reservoir. It is usually correlated to middle or high permeability zone [3]. Fault identification become an important and interesting parameter to be explore.

Contrast in rocks properties as density and resistivity may become an indication existence of geological subsurface structure. Resistivity is a sensitive parameter to temperature, porosity (connected and filled with fluid), salinity, and clay mineral. This parameter is very useful in geothermal exploration [4]. Density contrast appeared as an effect of medium discontinuity, which may identify in fault zone. The aim of this research is identified subsurface structure to build up a conceptual model of geothermal system.

2. Literature review

There are around 117 active volcanoes spreading along Indonesia islands that predicted have concealed high temperature of geothermal system [5]. Volcanic geothermal system might have neutral-chloride hot springs in outflow, acid-sulphate hot springs and fumarole in up-flow. Hydrothermal system is one of geothermal system types that have free convection heat transfer from the heat source with or without trace of magmatic fluid.

Geological structure analysis in gravity data can be interpreted from FHD maximum value, that mean horizontal maximum contrast density and it’s must be exactly correlated with zero value of SVD profile. FHD technique (in x axis and y axis) for gravity data analysis is based on equation 1 as follow:

\[ |H(x, y)| = \sqrt{\left(\frac{\partial G}{\partial x}\right)^2 + \left(\frac{\partial G}{\partial y}\right)^2} \]  

(1)

Potential gravity field (U) in free space fulfilled Laplace equations. These equations can be written as Equation (2) and SVD equations can be written as Equation 3. SVD profile is used to identify the Geological structure types, normal or reverse fault.

\[ \nabla^2 U = 0 \]

\[ \nabla^2 U = \frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2} + \frac{\partial^2 g}{\partial z^2} \]  

(2)

\[ \frac{\partial^2 g}{\partial z^2} = -\left(\frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2}\right) \]  

(3)

Normal fault is interpreted when there are maximum SVD value that is greater than absolute minimum SVD value Equation 4a in a same location that has high FHD value. It’s become the strong interpretation that the fault is identify in this location. Meanwhile, reverse fault is interpreted when maximum SVD value is less than absolute minimum SVD value Equation 4b in a same location that has high FHD value.

\[ \left(\frac{\partial^2 g}{\partial z^2}\right)_{max} > \left(\frac{\partial^2 g}{\partial z^2}\right)_{min} \]  

Normal Fault  

(4a)

\[ \left(\frac{\partial^2 g}{\partial z^2}\right)_{max} < \left(\frac{\partial^2 g}{\partial z^2}\right)_{min} \]  

Reverse Fault  

(4b)
Splitting curve is a separation of TE and TM mode pattern in MT curve, that mean there are inhomogeneity subsurface structures [6]. Induction arrow is real vector of geomagnetic transfer functions, that used to know if there are lateral conductivity variations. Polar diagram is used to know subsurface structure directions and rocks dimensionality.

3. Method
The methods include magnetotelluric data analysis and 3D MT structures interpretation together with first horizontal derivative and second vertical derivative analysis of gravity data. Geochemistry and geology data is used as supporting data. Magnetotelluric, gravity, geochemistry, and geology methods together are combined to build up a conceptual model of geothermal system. The methods in this research is resumed as a research flow chart in figure 1.
4. Results and discussion

Hadi et al. divided the stratigraphy of this research area into eight volcanic eruption products and one sedimentary rock [7]. The volcanic complex in this research area can be divided into four parts, those are old volcanic sediment, pre-caldera volcanic sediment, caldera formation volcanic sediment, and post-caldera volcanic sediment. Structure pattern in the research area are divided into volcanic faults, faults that directed to north-south, faults that directed to southwest-northeast, and faults that directed to northwest-southeast. Geothermal surface manifestations distribution in this research area can be seen in figure 2. They appeared as fumaroles (GS1 and GS2), hot springs (APS and APB), warm springs (APAM, APT1, and APT2), cold springs (ADS and ADM), and warming ground (TPA, TPK, TPP, and TPB).

The springs have temperature between 22.56 to 99.89 °C and pH between 0.01 to 7.17. The spring manifestations can be divided into chloride water, volcanic water, and bicarbonate water. APS manifestation has O18 and Deuterium higher than sea water and magma position in isotope plot. It means that there are volcanic fluid circulation system and evaporation process in this acid lake. Gas geothermometer from GS1 and GS2 show that average reservoir temperature estimation is between 240 to 280 °C (indicate high temperature of geothermal system). The appearance of hot (APB) and warm springs (APAM, APT1, and APT2) might be indicate of outflow zone. The warming ground manifestations have wide area coverage, that imply there are massive alterations from development of potential geothermal system.

Gravity data corrections result is complete bouger anomaly (CBA). It shows gravity value that affected by subsurface rocks density because of geological factors. There are closest high-low anomaly closure, which show contrast density indications or subsurface structure in this research area. Dense closures (high frequency) indicate a gravity anomaly near the earth surface, while wide apart closures (low frequency) indicate deeper gravity anomaly influence. The average subsurface rocks density in this research area is 2.6917 g/cm³ based on Parasnis methods. CBA map as a result of gravity data correction of research area is shown in figure 3.

![Geothermal Manifestations Map](image_url)

**Figure 2. Geothermal surface manifestations map**
There is high CBA gravity value (more than 131 mGal) around warming ground manifestations. It might be affected by high density of subsurface rocks and that could be a possible heat source location. Relative wide apart closures around warming ground manifestations indicate there are deeper gravity anomaly (possible heat source). Low CBA gravity value (less than 115 mGal) in southern part of area coverage might be caused by the limited datum point. Low CBA gravity value (less than 122 mGal) in northeast part of area coverage is interpreted due to response from sedimentary rocks (geology).

First Horizontal Derivative from CBA gravity value of research area are plotted in a FHD map and shown in figure 4a. FHD map show there are maximum amplitude (> 0.008 mGal/m) which associated with warming ground manifestations (TPB, TPP, TPA, and TPK), warm-hot springs (APB, APAM, APT1, and APT2), and cold springs (ADS and ADM). It means the appearance of geothermal surface manifestations are controlled by faults. Maximum FHD magnitude has slightly slope pattern (not spike), it means that the faults structure is not exactly vertical or there are nearby structures (minor faults).

Second Vertical Derivative from CBA gravity value of research area are plotted in a SVD map and shown in figure 4b. SVD analysis is used to define the type of fault, normal fault or reverse fault. The combination of FHD and SVD analysis show that possible point faults location. When FHD value has maximum value correlated to zero value of SVD in same location, it’s interpreted as geophysics fault location (blue dashed line). Normal faults (red) and reverse faults (blue) in the line profiles A-A’ to J-J’ have been plotted in FHD and SVD contour map in figure 4a and figure 4b.

Splitting MT curve analysis show that there are strong and weak splitting between TE and TM curve mode. Splitting in high frequency indicate MT measurement point is located near subsurface structure. Otherwise splitting in low frequency indicate a distant subsurface structure from MT measurement point. Polar diagram, tipper, and induction arrow analysis indicate the directional of the fault dominated in northeast-southwest, northwest-southeast, and north-south. Conductive structure area from result of induction arrow analysis interpreted as an area that contain geothermal fluid. 3D MT inversion result in line F (shown in figure 5) is used to drag a line of conceptual model in research area. Updome pattern bellow TPP manifestation could become an up-flow zone. Conductive layer which has resistivity value less than 10 Ωm is interpreted as clay cap.

Resistive layer in depth about -2000 m and has high resistivity more than 200 Ωm is interpreted as possible heat source. Some contour pattern and MT analysis show that might be located supposed structure (blue dashed line) that control some manifestations.
Surface manifestations as hot springs, warming ground, fumarole, and altered rocks in the research area become a clue of geothermal system beneath subsurface. It pushes high motivation to explore better understanding of the geothermal system. That supposed to be volcanic-hydrothermal geothermal system located in the research area. The massive combination of volcanic characteristics (magmatic) and its highly involved of meteoric water become the reason of this volcanic-hydrothermal type. Active volcanic activity in the research area support the presence of possible heat source for geothermal system. Fluid flow (black and red arrow) that support the geothermal system is predicted in the conceptual model of this geothermal system. All results from the method is resume in a shape conceptual model of ’X’ geothermal prospect area as shown in figure 6.

Figure 4. (a) Anomaly FHD, (b) Anomaly SVD.
Figure 5. 3D MT inversion result of line F.

Figure 6. Conceptual model of ‘X’ geothermal prospect area.

APB manifestations is a mature water that might be directed from deep reservoir fluid and become outflow. There is an indication of seawater mixing and meteoric water dilution in APB. APS is a volcanic water with high concentrations of Cl, SO_4, and F, that might be came from magmatic gas condensations near surface meteoric water. The other springs are bicarbonate water and supposed to be located as outflow zone. Gas sample has the characteristic of magmatic fluid. The average of reservoir temperature estimation is between 240 to 280 °C (moderate to high temperature of geothermal system). The resume of structures identified in the research area are plotted in a map (figure 7). There are structures identified from geology (black), gravity (blue), and MT (orange). Delineation of up-flow zone and possible reservoir also figure out in this map.

Structures in this research area are dominated by northeast-southwest faults and northwest-southeast. Minor faults are identified in this area and supposed to be the cause of spreading maximum FHD value. The structures in this research area highly contribute to provide permeable zone for fluid entrance as recharge of geothermal system. Structures near the surface manifestations are supposed to control fluid discharge from reservoir.
5. Conclusion
There are structure types of normal and reverse fault identified in the research area. MT and gravity interpretation show that structures are direct to northeast-southwest and northwest-southeast. Up-flow zone is predicted between TPP-TPB manifestations. Structures supposed to highly contribute in providing permeability zone in the research area. Manifestations fluid have the characteristics of meteoric and magmatic fluid (volcano-hydrothermal system). The clay cap thickness average is predicted between 500-700 m. The reservoir thickness average is predicted between 1500-2000 m. Temperature estimation of the reservoir is 240-280°C. Heat source might be located between TPB and TPP manifestations. Subsurface structure analysis might be useful to increase drilling success ratio.

Acknowledgments
I would like to extend my gratitude to PT. NewQuest Geotechnology and LPDP for their support.

References
[1] Daud Y, Aswo W, Mulki D, Fahmi F, Pratama and Hadi J 2015 Proc. World Geothermal Congress (Melbourne: Australia)
[2] Grindley G W and Browne P R L 1975 Proc.: Second United Nations Symp. on the Development and Use of Geothermal Resources (San Francisco) vol 1 (Barkeley: Lawrence Berkeley Laboratory) pp 377-86
[3] Hadi M N and Kusnadi D 2015 Survei Geologi dan Geokimia Daerah Panas Bumi Pulau Pantar Kabupaten Alor, Provinsi Nusa Tenggara Timur available at http://psdg.geologi.esdm.go.id
[4] Kamah M Y 2001 Proc. of the 5th INAGA Annual Scientific Conference and Exhibitions (Yogyakarta, Indonesia)
[5] Nasruddin, Alhamid M I, Daud Y, Surachman A, Sugiyono A, Aditya H B and Mahlia T M I 2016 Renew. Sust. Energ. Rev. 53 733-40
[6] Rosid M S and Siregar H 2017 AIP Conf. Proc. 1862 03071
[7] Ussher G, Harvey C, Johnstone R and Anderson E 2000 Proc. World Geothermal Congress (Kyushu-Tohoku, Japan)