Enhancement of subsurface geologic structure model based on gravity, magnetotelluric, and well log data in Kamojang geothermal field

Muhammad Yustin Kamah¹, Adilla Armando¹, Dinda Larasati Rahmani¹, Shabrina Paramitha¹

¹Upstream Technology Center, PT Pertamina (Persero), Jakarta

Email: yustinkamah@pertamina.com

Abstract. Geophysical methods such as gravity and magnetotelluric methods commonly used in conventional and unconventional energy exploration, notably for exploring geothermal prospect. They used to identify the subsurface geology structures which is estimated as a path of fluid flow. This study was conducted in Kamojang Geothermal Field with the aim of highlighting the volcanic lineament in West Java, precisely in Guntur-Papandayan chain where there are three geothermal systems. Kendang Fault has predominant direction NE-SW, identified by magnetotelluric techniques and gravity data processing techniques. Gravity techniques such as spectral analysis, derivative solutions, and Euler deconvolution indicate the type and geometry of anomaly. Magnetotelluric techniques such as inverse modeling and polar diagram are required to know subsurface resistivity characteristics and major orientation. Furthermore, the result from those methods will be compared to geology information and some section of well data, which is sufficiently suitable. This research is very useful to trace out another potential development area.

1. Introduction
Kamojang Geothermal Field is located in Garut, West Java, Indonesia. The volcanism in Kamojang region consists of a quartenary volcanic succession that produces lavas with andesitic and basaltic composition. Geologic structure plays important role in controlling the path of fluid flow and circulation of geothermal system. There are numbers of uncertainty in predicting the subsurface condition, especially in identifying the geologic structures which related to the geothermal reservoir and the path of fluid flow for tracing out another potential development area. Therefore, this study provides combination of geophysical methods which consist of gravity and magnetotelluric for identifying the subsurface geologic structure. Moreover, the result from those methods will be compared with geology information and some section of well data, thus the uncertainty interpretation of subsurface geologic structures will be reduce and another potential development area can be delineated.

2. Geologic Settings
The Kamojang Geothermal Field is located in West Java, around 40 km southeast of Bandung (figure 1). The field has 15 km long and 4.5 km wide. It lies in a big volcanic chain between Rakutak Mountain and Guntur Mountain. The development of this volcanic chain can be observed from the
alignment of magmatic center of the volcanoes which began to develop from west to east. The order from oldest to youngest: Rakutak Mountain, Ciharus Lake, Pangkalan Lake, Gandapura Mountain, Masigit Mountain, and Guntur Mountain.

Kamojang Area can be divided into two formations (from older to younger): Pangkalan Formation and Gandapura Formation. Pangkalan Formation (1.2 Ma), which consists of weathered andesite, lies to the west of Pangkalan Lake, while Gandapura Formation (0.4 Ma) is formed by pyroxen andesite rocks and situated on the east of Kamojang.

Two important faults in these volcanic series are Kendang Fault and Citepus Fault. Both of them are NE-SW orientation faults. The orientation is in conformity with the tectonic regime in the region where the direction of subduction of Australian Plate under the island in north-south. This opening creates a passage for volcanism. Two known vapor system are found in the vicinity of the fault, Kamojang in the north and Darajat in the south.

These series are also affected by a 6 km wide graben, which is extending from Ciharus Lake to the Kamojang crater. Kamojang Area is located in the Pangkalan Depression Fault that forms a sort of cover which is ideal for the formation of dry steam geothermal systems. The depression which is be able to be observed in the field, can be divided into several sub-structures corresponding to small grabens and horsts. Tectonic activities of this area which have created current Kamojang structures:
Figure 2. Regional Geological Map of Kamojang [2].
a. The collapse pit of Pangkalan:
This circular structure is located in the western part of Kamojang field. It is limited by a rim which outcrops clearly in the western and southern part. In the northern and eastern part, regional fractures collapse it and young lava flows conceal it. This rim delineates a 2 km long and 1.5 km wide circular area.

b. NE – SW system:
Dominant regional geologic structures in Kamojang have a NE-SW trend, including Kendang Fault and Citepus Fault. This system consists of tensional (lateral origin) faults set, which have been identified as a very important structures, related to the main target of reservoir Kamojang field. Even if the faults and fractures have been altered in the upper part of the surface and form non-permeable seals, the bottom sections may still be highly permeable. This system is parallel to the magmatic axis. After Pangkalan Structure had formed, small volcanic complexes or cones came up alongside the system, which is estimated to present a possible heat source for the geothermal field of Kamojang.

c. NW – SE system:
6 km wide graben is a major expression of NW-SE tensional faults. On the southern part of the field, these normal faults delineate two narrow downthrown structures which clearly affect the rim of Pangkalan Structure. On the northern part, these grabens can be observed too; but on the central part where the NE – SW shear system extends, they cannot be seen at the surface. These tectonic features seem to be slightly younger than the NE – SW system. There is good correspondence between these surface observation and interpretation of electrical surveys carried out by Pertamina (1981).

3. Gravity Techniques
This study was conducted in Kamojang Geothermal Field, around (5233 x 7183) m². It used 188 observation stations on gravity survey. The obtained value of Complete Bouguer Anomaly (CBA) based on processing gravity is (9.3 – 21.6) mGal, figure 5(b), and background density 2.61 mGal. Furthermore, it applied spectral analysis, and advance gravity data processing such as First Horizontal Derivative (FHD), Second Vertical Derivative (SVD), and Euler deconvolution to identify boundary contact of body anomalies, type of faults, and depth of body anomalies contact in order to enhance the interpretation of geological structure.

3.1. Spectral Analysis
This method is used to produce a variety of filtered anomaly maps. There are several types of filters in spectral analysis. Low-pass filter is used to remove undesirable high-wave number which associated with small and shallow sources, and to reduce errors in observations and reduction of the gravity anomalies. On the other hand, high-pass filter remove the longer-wavelength components associated with large and deep sources that are usually regarded as the regional anomaly [3]. The objective of wavelength filtering is to focus attention on anomalies derived from specified depth range and to determine the depth slice of residual and regional anomaly.
Based on figure above, there are 2 intersection points hereinafter correlated with depth estimate curve. The A point is located at about 0.45 km depth from surface which is identified as depth of regional body anomalies. While B is located at about 0.2 km depth which is identified as depth of residual body anomalies.

3.2. First Horizontal Derivative (FHD)
This method is used to interpret boundary contact of body anomalies. The accuracy of FHD map is affected by data control and errors, as well as dip variations and depth of body anomalies.

3.3. Second Vertical Derivative (SVD)
SVD can also be used to interpret the boundary contact of body anomalies. Moreover, it could help decide the type of faults, whether it is normal fault or thrust fault based on comparison of maximum absolute SVD value with minimum absolute SVD value.

3.4. Euler Deconvolution
Euler deconvolution method can be used to enhance potential field data interpretation, such as gravity and magnetic, in terms of depth and geological structure trends. By using the Euler deconvolution, the geological features such as faults, contacts, sill, and dykes would be estimated, depends on the structural index used. In this study, the structural index used is 0 (zero) which indicates contact or step of body anomalies at certain depth. The equation of Euler’s homogeneity can be shown by equation 1.

\[
(x - x_o) \frac{\partial g(x,y,z)}{\partial x} + (y - y_o) \frac{\partial g(x,y,z)}{\partial y} + (z - z_o) \frac{\partial g(x,y,z)}{\partial z} = -N x g(x,y,z)
\]

where:
\(x,y,z\) : coordinates of observation station
\( x_0, y_0, z_0 \): coordinates of source

\( g \): total gravity values at coordinates \((x, y, z)\)

\( \frac{\partial g}{\partial x}, \frac{\partial g}{\partial y}, \frac{\partial g}{\partial z} \): derivatives of \( g \) on direction \( x, y, \) and \( z \)

\( N \): degree of homogeneity, also known as structure index which is correlated with the geometric structure of the field source

**Table 1.** Structural Index \( N \) for Magnetic Field and Gravity Field.

| SI | Magnetic Field | Gravity Field |
|----|----------------|---------------|
| 0  | Contact / Step | Sill / Dyke / Ribbon / Step |
| 1  | Sill / Dyke    | Cylinder / Pipe |
| 2  | Cylinder / Pipe | Sphere |
| 3  | Sphere / Barrel / Ordnance | N / A |

**4. Magnetotelluric Techniques**

Potential geothermal areas require the presence of water, heat, and high permeability of reservoir. Since the physical parameter of subsurface such as resistivity can changes due to fluid and rock permeability, magnetotelluric (MT) method can be useful and suitable for geothermal exploration. It provides information about lateral and vertical resistivity variation in the subsurface by measuring the magnitude response of electric fields (\( E \)) and magnetic fields (\( H \)) of the electromagnetic nature.

To provide the MT data, MT-TDEM survey has been done in Kamojang Geothermal area. Instrument used in this survey is MTU-5 Phoenix 24bit satellite synchronized system which has frequency 384 down to 0.001 Hz. It has been applied the robust processing for noise elimination and static shift correction based on TDEM data. There are 3 lines used in MT-TDEM survey which is shown by figure 4.

Moreover, magnetotelluric method can detects the geoelectric strike which is one of the parameter measured by tensor impedance. Principally, when diagonal segment is minimum (segment \( Z_{xx} \) and \( Z_{yy} \)), it can be represented as geological feature (geological structure).

\[
Z = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix}
\]

(2)

It’s very difficult to set up the MT field layout parallel to the strike trend. So that, for 2D analysing, it takes a proper rotation on the impedance curve tensor by swift angle \( \alpha \), which refer to the strike way in the field. The angle of the swift is:

\[
\alpha = \frac{1}{4} \tan^{-1} \left( \frac{(Z_{xx} - Z_{yy})(Z_{xy} + Z_{yx}) + (Z_{xx} + Z_{yy})(Z_{xy} - Z_{yx})}{|Z_{xx} - Z_{xx}|^2 - |Z_{xx} + Z_{xx}|^2} \right)
\]

(3)
Identical swift angle obtained by inputting the appropriate impedance values strike direction (by strike angle selection mode when the robust processing) and plotting the impedance curve into the polar diagram. All polar diagram obtained, we can determine the dominant direction trend [2].

5. Result and Discussion

5.1. Gravity
In this study, CBA data is applied spectral analysis in order to dissociate regional and residual anomaly. CBA represents the combination of regional and residual sources. Therefore, it can be used to interpret the existence of regional structure which continuous to the surface. On CBA map, Figure 5(b), there are dominated by high gravity anomaly on southeastern area and rounded low gravity
anomaly on western area. Low gravity anomaly on CBA and residual map in Figure 5(b) and (d) correlates with Ciharus Lake and fault which has a role as boundary to other rocks adjacent. While regional map, Figure 5(c), tends to represent deeper source of body anomalies (based on regional depth on spectral analysis). There are also high gravity anomaly on southeastern area and low gravity anomaly on western area, the contact between low and high gravity anomalies is identified as regional geological structure which has major trend NE-SW.

Based on FHD map, Figure 5(e), it can be estimated that there are boundary contacts of body anomalies which have trend direction NE – SW as well as NW-SE. Those boundary contacts is identified as geologic structure. SVD map, Figure 5(f), shows geological structure trends which correlate to FHD map. Moreover, it can be seen another gravity anomaly on FHD and SVD maps in northwestern and northeastern survey area which can be estimated as faults or geological structures. This gravity result shows potential existence of geological structures which could be used as additional information to the geological data.

Figure 5(h) and (i) show the FHD and SVD curve toward axis coordinates which can be used for identifying the type of fault in slice area. The normal faults can be identified by the amplitude of absolute maximum SVD value which higher than absolute minimum SVD value, otherwise represented as thrust fault. Based on the curve, it can be determined that the survey area is dominated by normal fault. Based on Euler deconvolution map, Figure 5(g), it can be identified the contact of body anomalies at the certain depth which have NE-SW and NW-SE trends.

5.2. Magnetotelluric

The aim of MT-TDEM inverse modeling is to show the resistivity characteristics of subsurface. It found spot of low resistivity at shallow depth which is associated with surface thermal manifestation (fumarolic) as upflow zone and some alteration area (in middle area). At a shallow-intermediate depth, the conductors merge and become penetrated that has a thickness approximately 1000 m (situated from 1000 to 0 masl). Beyond this level, we find the propylitic zone contains wairakite and epidote and interpreted from resistivity structure. This zone currently provides the steam zone for the 235 MW power electric generation, especially from the north and west arms [4]. For more enhancing the interpretation of subsurface, MT-TDEM inverse modeling is applied in this study.
Figure 5. Processed gravity map and curve result in Kamojang survey area.
(a) Topography map. (b) Complete Bouguer Anomaly map. (c) Gravity regional map. (d) Residual anomaly map. (e) First Horizontal Derivative (FHD). (f) Second Vertical Derivative (SVD). (g) Euler deconvolution map. (h) FHD and SVD curve toward axis coordinate on slice 1. (i) FHD and SVD curve toward axis coordinate on slice 2.

Figure 6. 2D Inversion model in line 1 Kamojang area (SDT Geothermal, 2006)
Figure 7. 2D inversion model in line 2 Kamojang area (SDT Geothermal, 2006)

Figure 8. 2D inversion model in line 3 Kamojang area (SDT Geothermal, 2006)
It has been analyzed 3 panels of Polar Diagram. First Panel 0.98 seconds, shows no obvious alignment except a weak north-south and east west signatures. The second panel shows a transition between the first and third panel where the NW-SE trend becomes apparent. The third panel, at 90.91 seconds, displays an alignment pointing to the NW-SE, where its directions are perpendicular to the Kendang fault [4].

5.3. Well Correlation Data
According to Raharjo[4], FMS (Formation Micro Scanner) logs recorded from Kamojang reservoir are used to confirm the structural alignment. Figure 5 shows two rosette diagrams which reveal the strike of conductive fractures from well KMJ-50 and KMJ-52 (only fractures having a dip greater than 60° are plotted).
It can be seen clearly from the rosette diagram of well KMJ-50, within the depth of 890–1490 m, fractures dominantly striking N 235° E. This direction is in agreement with the Kendang Fault. In contrast, KMJ-52 encounters major fractures oriented to N 295° E – N 315° E and N 105° E.

Generally, orientation of fractures plotted in the rosette diagrams are suitable to the identification of geologic structures from gravity data, which is interpreted that have trend direction NE–SW and NW–SE.

6. Conclusion
It can be concluded that based on regional geology, gravity, magnetotelluric, and FMS log data, the major structures in Kamojang Geothermal Field have trends NE–SW and NW–SE. From gravity data, we interpret other new potential existence of faults which have trend NW–SE in northwestern part of survey area and trend NE–SW in northeastern part of survey area. Those areas are potentially developed for geothermal field area. There is a good correlation between analysis of regional geology, gravity, magnetotelluric, and FMS log data to the structure interpretation. The result can be used for delineating new potential development areas.

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