Structure identification of geothermal field “X” using ML-SVD method of gravity data

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Abstract. Understanding the main geothermal components such as clay cap, reservoir, heat source and faults structure can reduce the risk at the drilling stage. The role of the faults is very important since it can be a recharge/discharge medium of geothermal fluid. One method that can be used to identify the faults is the gravity method. The combination of the upward continuation and second vertical derivative (ML-SVD) methods is carried out to characterize the geological structure both the slope direction, depth estimation, dip estimation and type of structure. Upward continuation is carried out from a height of 0 - 2000 meters with an interval of 250 meters. SVD filter is applied at each height level. ML-SVD result shows that the fault structures at the study area have a value of dip > 70º with various fault configurations. Some faults are estimated at a certain depth under a layer of rock. ML-SVD shows a circular pattern that indicated as a caldera structure. The fault orientation of the study area tends SW-NE and NW-SE with dip perpendicular to the strike.

1. Introduction
A fault is one aspect that is sought when conducting geophysical investigations. The faults in the case of geothermal acts as a discharge/recharge medium of geothermal fluid [1]. Aside from being a medium, faults sometimes act as barriers to the geothermal system. The barrier formed by the deposition of geothermal minerals that fills the fracture gap so that becomes an impermeable zone. Understanding fault structure in the geothermal field can improve the information of geothermal fluid flow, the structureted to the geothermal reservoir and another potential development area. Faults identification needs to be done to reduce the potential risk in geothermal well drilling. The aim of this study is to understand the characteristic of fault at X area that associated with geothermal. One geophysical method that can identify the fault existence is the the gravity method.

Gravity data processing methods have been developed by many researchers for subsurface analysis. Gravitational data analysis methods are derivative analysis [2,3], Euler deconvolution analysis [4], and anomaly separation analysis [5]. Euler deconvolution method aims to determine the type of subsurface objects and its depth but we must choose the type of structure input. The anomalous separation method aims to separate regional anomalies and residual anomalies. The processing method that can identify the presence of fault is horizontal derivative analysis. A horizontal derivative can detect any kind and shape of structure because of it was sensitive to lateral density contrast. The purpose of this study is to understand the characteristic of faults in the study area associated with the geothermal system using the ML-SVD method.

The study area consists of several structure that is A Caldera that has an important role in the study area. Inside the caldera structure, there is a permeability zone which can be a geothermal upflow zone.
Usually, hydrothermal or geothermal that associated with caldera limited to the ring structure [6]. Another structure that has an important role in this study area is a 6 km wide graben that possibly associated with WAL fault at the east part of graben. East structure of graben has a roll as a tunnel so that geothermal fluid can ascend to the surface. Based on geological information, KG fault is shown on the west part of the study area and bordering the northern part of the caldera.

2. ML-SVD Methods

The ML-SVD method is a combination of upward continuation filter and SVD (Second Vertical Derivative) filter. This method developed by Rosid & Naufal [7]. ML-SVD is a band-pass filter because the upward continuation passes the gravity anomaly associated with the low frequency while the SVD passes the high-frequency anomaly. Low-frequency anomalies are associated with the deep source while high-frequency anomalies associated with shallow or faults objects. SVD can detect the fault because SVD is sensitive to the lateral density contrast. Also based on SVD we can calculate the depth of fault from the surface. This is because fault at certain depth gives some unique respond so that the depth of fault below the surface can be calculated [7]. The principle of this method is performing SVD operation on the results of upwards continuation. This is like looking for a fault at a certain depth.

In practice, ML-SVD is carried out by applying SVD operations at each level of height. Illustration of ML-SVD is shown in Figure 1.a. Figure 1.a seen that with increasing the height of the continuation the location of fault based on SVD will be shifted according to the dip direction. Upward continuation is carried out on gravity data that has been transformed into the frequency domain by applying equation (1). Where \( F[U] \) is gravity data in the frequency domain, \( e^{-\Delta z k} \) is the filter function where \( z \) and \( k \) is the height of continuation in meter and wave number respectively, \( F[U_c] \) is the result of upward continuation in the frequency domain. SVD operations are performed on gravity data in the spatial domain because gravity satisfies Laplace’s equation [9]. Equation (1) shows that the higher the continuity, the frequency passed is dominated by low frequencies. The dominance of low frequencies passed reflects deeper subsurface conditions. The combination of SVD and upward continuation shows that there is a relationship between the height of upward continuation and depth [7]. The relationship is shown in Figure 1.b which means that the higher the height of continuation, the deeper the detected faults.

\[
F[U_c] = F[U] e^{-\Delta z k}
\]  

(1)

![Figure 1. a) Illustration of ML-SVD concept. b) Relationship between the height of upward continuation and depth [7].](image-url)
The study site is located in an area that has a geothermal system associated with volcanos. There are 200 gravity measurement stations with a distance of 250 meters covering an area of 31 km$^2$. A series of corrections to gravity data is performed to obtain the gravity caused by density variations in the subsurface. The ML-SVD concept that has been carried out by Rosid & Naufal [7] is used to determine the fault characteristics of the study area. ML-SVD analysis is performed by filtering SVD at each continuity level with a height interval of 250 meters.

3. Results and Discussion
Before implementing ML-SVD to the data, a series of corrections is applied to gravity data to obtain CBA (Complete Bouguer Anomaly) value. To obtain Bouguer correction, the average density of the study area is calculated. The calculation of the average density is done using the Parasnis and Nettleton methods, which is an average of 2.687 g/cc. The density calculation is coincident with the geological conditions of the study area which is a volcanic area with the dominance of igneous rocks like andesite and basaltic lava.

CBA values in the study area varied from 60.5 mGal to 70.5 mGal. High CBA anomaly (> 67.5 mGal) is found in the southwest of the study to the middle area. The high CBA anomaly is thought to be associated with relatively higher density rocks. There is a circular pattern showing a low CBA anomaly (< 63.5 mGal) in the northern part of the caldera and the eastern part of the C fault. A low anomaly is thought to be associated with a mountain conduit structure around the anomaly. The CBA distribution map is shown in Figure 2.

![Figure 2. CBA map at the area of study.](image)

3.1. The fault of the Research Area based on ML-SVD
Fault's characterization at X geothermal field was performed using the ML-SVD gravity data method. ML-SVD did by the continuation of upwards to a height variation of 0-2,000 meters with an interval 250 meters. The plot of the location of SVD0 (SVD = 0 mGal/m$^2$) values for each continuity height is shown in Figure 3. The value of SVD = 0 mGal/m$^2$ is indicating the location of the fault.
Figure 3 shows the digitization of SVD0 which is indicated by the colored round symbol and the simplification of the ML-SVD results shown in Figure 4. The difference in color reflects the level of upward continuation that has been done. Round symbols of the same color appear to form a fault pattern. The red color represents the lowest level of continuity, the green color represents the medium level of continuity while the blue color represents the highest level of continuity. The picture shows that there is a shift of location as the height of the upward continuation increases. The higher the height of continuity reflects the deeper subsurface conditions [7]. The fault location shifting as the height of continuity increase that indicated the direction of faults slope (dip). Simplification of the display is done by drawing a fault pattern line based on the ML-SVD for easy interpretation of the fault structure (see Figure 4).

The ML-SVD pattern on the west of A caldera structure is thought to be an ML-SVD response due to RUS fault (number 1 in Figure 4). The ML-SVD pattern coincides with the RUS fault’s pattern and has the same strike direction based on geological information (northwest-southeast). The ML-SVD RUS fault pattern appears to the level of continuity 750 meters. The dip direction of the RUS fault based on ML-SVD is northeast with a dip of 75.84º. The calculation of rock layer thickness covering the RUS fault based on the SVD pattern is 280 meters. The density of footwall at RUS fault greater than the density of hanging wall. The vertical location of the RUS fault estimated at 1,300 – 900 meters above sea level (masl).
The fault information based on geology in the north is not much but the ML-SVD shows a fault pattern in the north. Fault in the north is dominated by the strike direction northwest-southeast with the direction of dip southwest and northeast. The ML-SVD fault pattern is suspected to have an association with WAL fault (pattern number 2). Pattern number 2 cannot provide the exact fault location because the ML-SVD fault pattern is not clear. The obscurity of ML-SVD fault pattern allegedly due to the dominance of noise associated with high frequency. The ML-SVD pattern at a continuation level > 500 meter appears more clear. The ML-SVD pattern at continuation level > 500 m indicates the alleged ML-SVD pattern correlates with the WAL fault. The ML-SVD which correlates with the WAL fault appears to 1,000 m continuation level. We tried to calculate the fault dip obtained at an angle of 71.22°.

The ML-SVD pattern number 3 is to the west of the ML-SVD pattern number 2 (or WAL fault). Geological data show the existence of a fault structure that correlates with pattern number 3. Based on the ML-SVD, it shows that the fault is under the rock layer with a thickness of 150 meters. Calculation of dip obtains estimated value 83.86°. The fault pattern numbers 2 and 3 are forming a graben structure with a width of about 500 meters. The fracture pattern number 2 and 3 is limited by a circular structure marked by pattern number 4. It is suspected that the structure of numbers 2 and 3 is the continuation of the ML-SVD pattern number 5 in the southeast. Fault number 2 & 3 estimated at 1300 – 900 masl.

The ML-SVD fracture pattern number 4 is an interesting one. The ML-SVD pattern number 4 forms a circular pattern at the center area with the eastern part open. The south and west sections of pattern number 4 coincides with the rim structure. The northern part of the number 4 pattern is thought to be
strongly related to the shifting of the rim structure north section. Shifting rim structure in the past is thought to have been caused by KG fault activity. KG fault in the past is a fault that has a lateral direction shift [7].

ML-SVD number 4 shows that the dip structure tends to point towards the inside of the circle. The rim structure appears to the level of continuity ML-SVD 2000 meters. The SVD curve in pattern number 4 shows the pattern $|{-}\text{SVD}| > |{+}\text{SVD}|$ which indicates that the density outside the circular structure is lower than the density inside the circular structure. Characteristics of pattern $|{-}\text{SVD}| > |{+}\text{SVD}|$ along the pattern number 4 indicate that the northern circular structure is part of the rim (A caldera) structure. Obscurity in pattern number 4 is seen in several parts. The obscurity is thought to be the complexity of the rim’s structure. The complexity of the rim structure is caused by volcanic events that occur in the study area, namely the emergence of younger volcanoes along with the rim structure.

The fault dip calculation in pattern number 4 obtained with value 71.22°. Another calculation based on the MEQ method shows that A caldera having an estimated angle of 76.65° [8]. The calculation results obtained have a difference of 6% from ML-SVD calculation. The SVD signal provides information that the A caldera is under a layer of rock with a thickness of 1,000 meters at the western part and 200 meters at the northern part. This is assumed at a depth of 1,000 meters to the surface, contrast density in the fault area is very low. The alleged low-density contrast is proven by geological information showing the presence of a caldera structure on the surface and SRTM imagery showing a circular pattern. A caldera is located from -110 – 800 masl at the western part and 300 – 1400 masl at the northern part.

ML-SVD cannot provide KG fault information to the west of the rim structure. This is thought to be related to the initial history of the formation of the KG fault (the KG fault is shifted laterally). The density contrast of lateral fault is generally so low (in fact there is almost no density contrast) that the ML-SVD cannot detect lateral faults. This also applies to the two lateral faults that are in the southwest part of the A caldera. The southwest part of the A caldera has two faults in the northeast-southwest strike direction which shifts the caldera laterally. The two faults in the southwest are not identified by the ML-SVD method. Very low-density contrast produces relatively homogeneous gravitational anomalies so that indications of a fault are not visible when an SVD filter is performed.

There is an ML-SVD pattern that forms a fault pattern inside the caldera structure (fault pattern number 5). The two faults form a pattern in the northwest-southeast direction with the NE and SW dip. The western fault has a dip to the northeast while the east fault is directed southwest to form a graben structure. Both faults are thought to be associated with a fault in the east N 140° E strike direction found on the past study [8]. The fault in the western graben structure is thought to have a connection with the alleged fault that is located west of the WAL fault. If a line is drawn between pattern numbers 2 and 3 with pattern number 5 the two faults will form a continuity. This fault pattern confirms the faults in the direction of the N140°E strike in the study area forming a graben structure with a width of ± 6 km. The western part of the graben structure ± 6 km in this study was not found because the area of gravity data did not cover the western structure. The eastern graben structure is thought to act as a geothermal fluid discharge as indicated by the presence of geothermal manifestations on the surface.

Based on ML-SVD calculation, the subsurface fault model can be done. The subsurface fault model is shown in Figure 5. Figure 5.a shows the cross-section of the fault model in SW-NE direction while Figure 5.b shows the cross-section of the fault model in NW-SE direction. The depth of the fault location is obtained by converting the height of the continuity value into a depth value. Rosid & Naufal argues that there is a relationship between continuity height and depth so that the conversion can be done by considering the dip of the fault [7]. The top of the reservoir line provided from resistivity modeling result of the magnetotelluric method [8]. From ML-SVD calculation A Caldera is located about 1,000 m below surface and by combining magnetotelluric data A Caldera is shown at reservoir zone. ML-SVD cant sho the shallow part of the caldera is possible because of low-density contrast at shallow part. The resume of ML-SVD calculation shown in Table 1.
Table 1. ML-SVD calculation result

| Fault no | Dip (°) | Depth from Surface (mbs) | Vertical Location | Association       |
|----------|---------|--------------------------|-------------------|-------------------|
| 1        | 75.84   | 280                      | 1,300 – 900 masl  | RUS Fault         |
| 2        | 71.22   | 100                      | 1,400 – 900 masl  | WAL Fault         |
| 3        | 83.86   | 150                      | 1,250 – 900 masl  | un                |
| 4        | 71.22   | 1000                     | 800 masl – 100 mbsl | A Caldera        |
| 5        | 70.02   | 300                      | 1,200 – 900 masl  | East graben?      |

un = unidentified  mbs = meter below surface  masl / mbsl = meter above/below sea-level

ML-SVD method still needs further development. This method requires more simulation by considering the faults in the real case. The equation to estimate dip of fault, depth of fault beneath rock layer and upward height-depth conversion can be complete if more simulation and more real cases have been done. At this point, this method can tell the direction of fault dip well enough. However, the method is difficult to identify the shear fault due to the small density contrast.

Figure 5. Cross-Section of ML-SVD Fault Model, a) Southwest-Northeast direction, b) Northwest-Southeast direction.
4. Conclusion
ML-SVD method can be implemented to figure out some fault structures in geothermal fields. The faults identified by ML-SVD are RUS faults, A Caldera, WAL faults that are associated with graben structure. The fault that can be identified with the ML-SVD method mostly has dip > 70°. The A caldera is a rim that has open structure at the east section with dip direction to the inside of the circle. The northern part of the caldera is thought to be buried 1000 meters below the surface. Faults in the study area are under a rock layer with a certain depth indicating low-density contrast on the surface. Some faults which cannot be detected by the ML-SVD method are caused by low-density contrast in the fault.

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