Identification of geological structures by using ESA-MWT and MS-HDVD gravity data at Slawi, Central Java

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Abstract. It has been done of a geophysical measurement by Pertamina in the Slawi area of Central Java. The results of the seismic section show that there is an up dome in the field “M”. The location of this area is in the mt. Slamet zone. So that the existence of an up-dome structure does not automatically provide the possibility of a hydrocarbon trap in the area. This study was conducted to characterize the existence of these structures using gravity data. The ESA-MWT (energy spectral analysis multi window test) and MS-HDVD (multi scale-horizontal derivative vertical derivative) methods of gravity data are applied in this study. The ESA-MWT method is able to map lateral rock variations very well, whereas MS-HDVD is more sensitive to vertical variations even though it is also good for identifying rock variations in both vertically and laterally. There are five horizons detected in the field. These five interfaces with density contrast extend over a depth range between 416 to 2112 meters. The horizons are identified as being associated with sediment rocks namely Formations of Tapak, Penosogan, Kumbang, Halang and Rambatan. The sediments are likely to be intruded by diorite stones (in up-dome form) which happened during the Late Miocene. The peak, or top, of the intrusion body is estimated at around 620 to 755 m depth on the Penosogan Formation.

Keywords: ESA-MWT, MS-HDVD, diorite intrusion, Slawi

1. Introduction
In a geophysics exploration, the one of designated targets is reservoir [1]. A reservoir is a place where fluids - such as oil, gas, or water, which have emigrated from source rocks-accumulates. It can be categorized as a good one if it has a high level of porosity and permeability [1]. The migration process of a fluid in a hydrocarbon system needs a medium, which is a fracture structure. The structure is an important factor in an exploration because it serves as a medium for fluid migration from source rocks [2], or as a fluid’s way to the surface. Besides all those things, a fracture structure is also an important component in the petroleum system.

One of the main causes of a fracture is a tectonic force that comes from within the earth, resulting from the continuous movement of the earth’s crust. A fracture structure is characterized with a high level of permeability and density contrast. Based on the permeability and density contrast parameters, we should determine a method which could identify the fracture structure. One such method which suits the research is gravity method, which is a geophysics exploration method commonly used to map out and identify geological structures based on the variety of gravitational value caused by different density values on each rock. A significant level of density contrast indicates that the zone is a fracture zone.
Besides determining a fracture system, this research will also use the gravity method to estimate the basement’s depth. A basement is the deepest layer of rock, which serves as a sedimentation container in the hydrocarbon system, and commonly have high rock mass density levels. For the purpose of this research, the basement is defined as a sediment layer which has a high density contrast level compared to layers above it. Its determination is essential to further determine the location and the depth boundaries of a rock formation or structure.

This study is conducted in Slawi, West Java. The gravitational data in that area is then used in the Energy Spectrum Analysis-Multi Window Test (ESA-MWT) and the Multi Scale – Horizontal Derivative Vertical Derivative (MS-HDVD) methods.

2. Methodology

2.1. MS-HDVD method
The MS-HDVD method is commonly used to determine the location of a fracture structure. It begins with an upward continuation process, which involves moving the measurement plate upwards to see the gravitational value from a deeper source. Data obtained from this process is then used in the first-order vertical derivative calculation. The resulting calculation is called the multi-scale first vertical derivative. The next step is to find the horizontal gradient from the MSFVD result, which involves converting a vertical plate into a horizontal one. After doing so, the next step is to map out and re-calculate the steps from a different height parameter [3]. The first-order vertical derivative calculation is done with the following equation:

\[ g_{vd} = \left(\frac{\partial g}{\partial z}\right)_h = \frac{g_{up}^{\Delta h} - g_{up}^{h}}{\Delta h} \]  

(1)

where:
- \( g_{up}^{h} \) is the gravitational value of an upward plate of a \( h \) height
- \( g_{up}^{h+\Delta h} \) is the gravitational value of an upward plate with a \( h + \Delta h \) height value
- \( \Delta h \) is the height boundary of two different spots

The calculation to determine the horizontal gradient from the MSFVD process is done with the following equation:

\[ g_{hvd} = \sqrt{\left(\frac{\partial g_{vd}}{\partial x}\right)^2 + \left(\frac{\partial g_{vd}}{\partial y}\right)^2} \]  

(2)

where:
- \( \frac{\partial g_{vd}}{\partial x} \) is the gradient resultant towards the gravity (at x axis)
- \( \frac{\partial g_{vd}}{\partial y} \) is the gradient resultant towards the gravity (at y axis)

If the result of the \( g_{hvd} \) shows a large number, then it indicates the existence of a fracture structure under the earth’s surface in an area. The integration of both calculations will provide the location of a fracture structure based on its depth, which would map out the dip of the fracture.

2.2. The energy spectral analysis – multi window test (ESA-MWT) method
In estimating the location and depth of a basement in this area, the Energy Spectral Analysis is applied by giving a window. The Multi Window Test is used as a divider or a separator in conducting a calculation on a test spot. In this method, it is essential to determine the correct window size. If a
window is too small, the amount of data collected will be much smaller, which could not create a clear image of a horizon. On the contrary, if a window is too large, the horizon image will be dominated by regional data [4].

Based on the figure 1, it can be concluded that each spectrum analysis on each window results in a dipping curve of wave values [4]. The larger the window, the dipper the curve and the deeper the basement will be. The curve will result in an equation, $y = mx + a$, with $m$ being the gradient or slope. In estimating the position or the depth of the basement (in distance), the following equation can be used

$$\text{depth} = -\frac{slope}{4\pi}$$

3. Results and discussion

There is gravity anomaly value in this study area which is varied between 15.9 mgal to 49.2 mgal as shown in figure 2 of Complete Bouger Anomaly (CBA) map. The lowest value of gravitational anomaly is occurred at the North, whereas its highest value is at the South. The anomaly values are strongly associated with variation of rocks density. The range of 15.9–49.2 mgal most likely influenced by the laterally rocks variation ($\Delta\rho$) rather than the locations of rocks ($r$). However, in the middle of map there is an interesting close contour of high gravity. The ESA-MWT result also shows an up-dome structure generated at every layer in the middle area.

The cause of the anomaly may indicate either to be an intrusion of rocks, carbonate reefs, anticline, salt dome, or diapiric muds which generated below the surface of the study area. The parameters that strongly related to high gravity value are either intrusions rock or carbonate reef. The remains parameters tend to sediments which are mostly have lower density and so lower gravity values. The parameter which is considered as the defining factor is the susceptibility of magnetic data. As the carbonate reefs are the organic rock and poor content of ferro magnetic elements, the rocks have much lower levels of susceptibility compared to the igneous rocks. According to the results of magnetic data, it could be shown that the body anomaly in the middle area has really high magnetic susceptibility values [5]. Therefore, it most likely an intrusion rock that intruded the area and made an up-dome. This is identified as well by the high density level in the deepest layer compared to density level of shallower layers. The intrusion rocks are the igneous rocks. Therefore, the deepest layers are igneous rocks, and it geologically happens during the Late Miocene Period, which paves the way for the appearance of diorite rocks [6].
Intrusions means that the magma flow does not reach the earth surface. It was caused by volcanic activity with lesser power rather than overburden pressure. The intrusions happen after the formation of different structures beneath the earth’s surface in the study area [6]. The analysis is made based on the age sequence data of rocks from the surface exposed (table 1) [6].

Stratigraphically, the composition of sedimentary rocks in the study area consists of (from the youngest to the oldest) Tapak Formation, Penosogan, Kumbang, Halang, and Rambatan Formations. The oldest four formations of Penosogan, Kumbang, Halang, and Rambatan are intruded in the Late Miocene and therefore form an up-dome. The Tapak Formation as the youngest sediments, however, does not intruded. The intrusion did not breach the formation. Therefore, the formation is the youngest rocks in the study area that deposited after the intrusion happened.

| No | Name                | Age            | Lateral appearance |
|----|---------------------|----------------|--------------------|
| *  | Intrusion           | Late Miocene   | x                  |
| 1  | Tapak Formation     | Pliocene       | √                  |
| 2  | Penosogan Formation | Middle Miocene | x                  |
| 3  | Kumbang Formation   | Middle Miocene | x                  |
| 4  | Halang Formation    | Middle Miocene | √                  |
| 5  | Rambatan Formation  | Middle Miocene | √                  |

Figure 2. A Complete Bouguer Anomaly map with line L2 and L4.
All the five rock formations might be represented in the interpreted seismic section of figure 3. The Pertamina’s report (unpublished) draws the five-layer lines that are allegedly associated with the five existing sediment formations in the area. The top of the plateau layer is interpreted as a formation of rocks which are younger than the intrusion. However, even though the Tapak Formation is alleged to be the youngest layer, the exact layer above the alleged intrusion rocks appears to be more tightly and denser than the further of this intrusion zone. This could be due to the intrusion effect (with high enough temperature and pressure) that continues to work so that the upper layer will be more compressed than others.

The ESA-MWT method is based on the results of the Fourier Transformation (FFT). The transformed gravity data, then plotted in x-axis as a spectrum number (in cyc/km) and y-axis as ln Power. The curve call as a RAPS curve (radially averaged power spectrum). The RAPS curves are generated for many different windows sizes on each test point. The horizon is determined to correlate a number of points based on the same of frequency window. The difference depths resulted at the same window size, giving figure out of a subsurface structure.

There are five horizons resulted from the ESA-MWT. Horizon 1 stretches at depths between 400–650 m below the surface. According to the table 1, the horizon could be categorized as the Tapak Formation. Horizon 2 is at a depth between 650–1000m below the surface, which may be correlated with the Penosogan Formation. Horizon 3 is expected to be at depths between 1000–1440 m below the surface, which may be correlated with Kumbang Formation. Horizon 4 is in the depths between 1380-1800m below the surface, which is correlated with the Halang Formation. The deepest horizon detected in this study area, horizon 5, is thought to be at a depth between 1600–2200 m below the surface, which may be correlated with the Rambatan Formation. The shape of each horizon depicts a plateau or a layer beneath the surface. In the middle of the plateau, both from South to North (L2 line) and West to East (L4 line), have indicated an up-domes. The structure is believed caused by an intrusions rock occurring in the study area. The depth of top intrusion body is at about 750–850m below the surface [5].

Figure 3. The seismic plateau in line 2, as interpreted by Pertamina [7].
To ensure the presence of rock intrusion structures in this area, MS-HDVD method has been applied. The intrusion body is analog with reverse faulting. The horizontally contrast density or horizontal border layer is identified as a peak of HDVD curve. In line L2, there are 3 border density identified. Whereas along line L4, four suspected faults are identified. The maps can be seen in figure 4.

The faults characteristics can be shown from the curves of MS-HDVD. The peak of HDVD curves indicates the location of faults. Peak shifting of the multi scale curves may determines the dip of fault. In this study, the faults here are the borders of an intrusion body. There are 3 and 4 peaks of curves shown in figure 4a and figure 4b, respectively, which have associated with the intrusion borders. Determination of 2 peak HDVD curves associated with body intrusion is also controlled by the results of ESA-MWT. The border 1 and border 2, which generated from the upward continuation of MS-HDVD has the same width as the estimated borders of ESA-MWT. The intrusion borders are marked by B and C in both figure 4a and figure 4b. Integrated results of ESA-MWT and MS-HDVD along both lines of L2 and L4 (as seen in figure 5) show primary structure of 5 layers of sediment with suspected the secondary structures of faults and intrusion body.

![Figure 4](image1.png)

**Figure 4.** MS-HDVD curve along (a) Line 2 and (b) Line 4. There are some faults identified along the lines.

![Figure 5](image2.png)

**Figure 5.** Integration results of ESA-MWT and MS-HDVD in (a) Line 2, and (b) Line 4. The two red vertical lines most likely represent existing the alleged an intrusion body.
Comprehensively overview of model of subsurface structure resulting from the combined seismic section data and gravity data of ESA-MWT and MS-HDVD can be seen in figure 6 (for L2) and figure 7 (for L4). The sedimentary layers produced by ESA-MWT gravitational data are generally confirmed by predicted rock-layer results on the seismic section, as well as the existence of secondary structures of faulting and its intrusion body. The width of the intrusion body is predicted to be around 6000–11500 m. The top of the intrusion body here is estimated to be at a depth range of about 620–755 m and 530–540 m below the surface at the line L2 and L4, respectively. The top intrusion most likely at the Penosogan Formation. It is obvious that the effect of the ascending magmas as an intrusion body is the formation of up-dome structures in the area. However, the two fault structures depicted on the results of MS-HDVD of the line 4 were apparently poorly justified by the interpretation of the interpreted seismic section.

Figure 6. Integrated models of subsurface structures resulting from seismic interpretation data and ESA-MWT and MS-HDVD gravity data in line L2.

Figure 7. Integration model of subsurface structures generated from the seismic data and gravity data in line L4.
4. Conclusion
Based on the data calculation of the ESA-MWT and MS-HDVD gravity data, and supported by seismic and geological data, it can be concluded that:

The ESA-MWT method can be used to map out the depth of each horizon. There are 5 horizons that possibly correlated to the geology condition of the study area, further indicated by the age of rocks and formations. Horizon 1 correlates with the Tapak Formation; Horizon 2 with the Penosogan Formation; Horizon 3 with the Kumbang Formation; Horizon 4 with the Halang Formation; and the Horizon 5 with the Rambatan Formation.

The top of the intrusion occurring in the study area exists between 620–755m below the surface in depth in Line 2 of South to North. Meanwhile in Line 4, it also exists between 530–540m below the surface in depth. The width of the intrusion body is indicated to be around 6000–11500m laterally.

The dip of the intrusion border is almost vertical in form of N208.51°E for border 1 and N36.11°E for border 2 in line L2 and N19.04°E for border 1 and N31.59°E for border 2 in line L4.

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