Mapping of basement layer in field “X” petroleum system using ESA – MWT technique gravity data

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Abstract. Land gravity data acquired over part of North Sumatera Basin, Indonesia, was used to estimate depth to multiple horizons of density interface. Recently, gravitational data has difficulty to map the depth of subsurface layer structure except by using modeling. Here, we apply the energy spectral analysis–multi window test (ESA–MWT) technique to map the subsurface horizons. The estimated depth was computed from energy spectral analysis as the transformation of the gridded gravity data to 2D Fourier transform (Fast Fourier Transform). The energy spectrum analysis is performed at a test point by windowing the gridded complete Bouguer anomaly (CBA) at that test point with the square window size constantly increasing 1 km width from the previous window size. The distance between the test points is about 2 km on each of the gravity measurement lines. Plateau depths are then obtained which represents the density interfaces of the plot result between the depths of the anomaly to the window size. The results of the mapping of density interfaces correspond to sedimentary interfaces, those are the economic basement as Top Tampur Formation (Horizon 1), the top of several other sedimentary interfaces (Horizon 2-6), one of them is Top Belumai Formation (Horizon 2).

1. Introduction
Petroleum system of field “X” is the part of one of the back-arc basin in Northern Sumatera, Indonesia, formed by the convergence subduction activity of Indo-Australian oceanic and Eurasian continental plates.

Gravity data integrated with the seismic section can be used in petroleum exploration. The horizon of the sedimentary interfaces as contrast density can be mapped by applying energy spectral analysis – multi window test (ESA-MWT) technique gravity data. The technique will be useful especially in an area where seismic has difficulties, such as the onshore petroleum system “X”. The ESA–MWT technique has been successfully applied in some fields. Offshore Andaman Sea basement has been mapped clearly and was confirmed by regional geology and geophysical data from the nearest field (Kivior et al. 2012). Markham et al. (2011) also mapped onshore field of Delta Baram, Sarawak that has a good correlation with seismic data, and onshore field of Canning Basin (Kivior et al., 2018) that has good correlation with seismic and well data. The objective of the study is to map the basement layer as well as other horizontal layers in the field “X” petroleum system by using ESA-MWT technique gravity data.
The location of the study in the field “X” has the fault structures that overlap (complex). This makes the depth of the sedimentary layer varied, which becomes a challenge in the process of structure mapping. Contrast density between the basement and the above sediments is the main reason for the success of mapping the top basement horizon. Gravity data were acquired over a 50x70 km² area with 11 measurement lines and the tie lines. The distance between the gravity measurement points is about 1 km on each of the gravity measurement lines.

2. Regional Geological Setting
The petroleum system “X” is part of a NW-SE oriented back-arc basin formed by convergence tectonic activity in the perpendicular direction (figure 1). This back-arc basin is a sedimentation depocenter as the Pre-Tertiary granitic and metamorphic basement. The basin platform is a boundary that borders the shallow basement area exposed as a Pre-Tertiary outcropped basement as a mountain in the Southwest and basin slope complex and basin deep in the Northeast. Tertiary sediments begin to be deposited as carbonate platforms (until Late Eocene) as the economic basement that makes up Tampur Formation. Then above the Tampur Formation, is overlaid by clastic that dominated by sandstones in the formation above it (Oligocene to recent) (Doust and Noble, 2008).

![Figure 1. Basin configuration with a prospect area which bounded by blue lines (modified from Doust and Noble, 2008).](image)

3. Gravity Data Reduction
The reduction process of gravity data is done to obtain a complete Bouguer anomaly (CBA) using equation (1). Some corrections are applied to the observed gravity data ($G_{obs}$). The corrections are normal gravity correction ($G_N$), free-air correction ($FAC = 0.3086 \cdot h$), Bouguer correction ($BC = 0.04192 \cdot \rho h$), and terrain correction ($TC = \rho T$). The parameter of $h$ is an elevation of gravity station in meters, $\rho$ is the average density of the area in gr/cc, and $T$ is the geometrical factor of terrain correction in mgal.cc/gr.
Estimation of the average density of the area can be calculated using Parasnis method by modifying CBA’s equation to be a linear equation $y = mx + c$, where an independent variable $x$ as $(0.04192 h + T)$, a dependent variable $y$ as $(G_{obs} – G_N + FAC)$, and the slope of the linear equation $m$ as the density $\rho$ in gr/cc. The separation of the density counting area was done as shown in figure 2 because the density calculation was not successful in total area. The density value of the total area of 3.66 gr/cc is not scientifically acceptable. The results of the calculation of the average density show a good correlation with the geological information in figure 1. The higher gravity anomaly area in the Southwest direction relates to a higher density area of 2.53 gr/cc compared to the lower gravity anomaly in the Northeast direction of 2.27 gr/cc. Shallow basement in the high gravity area resulting in a density of the area is dominated by basement rocks that have a higher density. In the final calculation, we obtain a value of the average density estimation of 2.37 gr/cc as shown in equation (2) which is then used for gravity data reduction.

$$\rho = \frac{\sum \rho_i A_i}{\sum A_i} = \frac{(2.5274 \times 925715549) + (2.27 \times 1572297619)}{(925715549 + 1572297619)} = 2.365 \text{ gr/cc}$$

where $\rho_i$ are the densities of each area in gr/cc, and $A_i$ is the areas in m². The gridded CBA contour is processed with 100 m grid cell size, resulting in a CBA map.

![Figure 2.](image_url)  
(a) Parasnis method for calculating the average density area, and (b) distribution of measurement points (separation points) to calculate the estimation of the average density of the area, L1-L11 is the measurement lines.

4. Methodology

ESA – MWT technique is applied to the mapping horizon in the area of study. The technique is based on spectral energy analysis (ESA) that utilizes 2D Fourier transforms based on the original work of Bhattacharyya (1966). Fourier transforms work mathematically to transform the function of the anomaly amplitude in the spatial domain into the function in the frequency domain (wavenumber). Lower wavenumber related to deeper anomaly components, this is identical to the regional gravity component at conventional interpretation. And higher wavenumber related to shallower anomaly component. By following Spector and Grant (1970), a causative body is modeled by a statistical multi-prism with
uniform density or susceptibility. The curve of the log spectrum energy to the radial frequency (the radially averaged power spectrum/RAPS curve) can be interpreted to determine the depth of the causative body as,

$$\text{Depth} = -\frac{s}{4\pi}$$

where $s$ is the slope of RAPS curve.

**Figure 3.** The windowing CBA map at a test point (30412, 45141).

**Figure 4.** The multi-window test (MWT) graph at the same test point (30412, 45141) of figure 3.

Multi-window technique is applied to a test point as the centre of the window. Anomaly limiting values aim to localize anomalies where the size of the window corresponds to the depth of the anomalous body, the larger the window, the deeper the anomaly is contained in the window. By calculating the energy spectrum in that window series, where the window size varies constantly increases. Depth plateau is detected when the depth of the source ensemble does not change significantly between two or more window sizes (Kivior et al., 2012). The depth plateau is used to approximate density interfaces. The processing procedures are shown in figure 3 and figure 4.

ESA – MWT technique is performed at a test point by windowing the CBA map at that test point with the square window size constantly increasing 1 km width from the previous window size. The
window size starts from 4x4 km² to 20x20 km². The distance between the test points is about 2 km on each of the gravity measurement lines.

5. Results and Discussion
The ESA-MWT mapping results in 6 sedimentation horizons. Integration with estimated horizons from a seismic section on the L6 measurement line (figure 5), Horizon 1 is suspected to correlate with top economic basement as top Tampur Formation, Horizon 2 is suspected to correlate with top Belumai Formation which is containing limestone and shale, and dominated by sandstone. Horizon 3-6 are suspected as layers of clastic sediments above Belumai Formation (intra-sedimentary and shallower sediment), Horizon 4 is suspected to correlate with top MBS Formation as the top Intra-Sediment 2. In general, the pattern of the horizon mapping results from ESA - MWT correlates with the seismic section. However, there is some deviation on Horizon 1 and 2 which is a deeper depth there is a shift to the estimated seismic horizon. In the middle (anticlines) shifts upward about 1 km and to the right, and deviation at some other location.

![Figure 5. Correlation between horizons from ESA–MWT with estimated horizons from the seismic section at measurement line L6.](image)

The existence of a highly complex fault structure associated with the sedimentation layer in this area, making the undulation of the depth in a formation very extreme. The fault is likely to be the main factor responsible for the deviation of the horizon depth. The tectonic activity causing the faults are likely to create a high degree of compression in the syncline area. Thus, the density of rocks above Tampur Formation may not be too contrasted with Tampur Formation causing the mapping to shift.

The economic basement mapped using the ESA–MWT technique has been justified by the pattern of the estimated horizon from the seismic data. The three deepest horizons (figures 6a, 6b, 6c) have extreme depth undulation which is typical of the formation in the field "X" petroleum system. This is due to the presence of many reverse faults (figure 5), the undulation of a formation varies at around 2-3 km.
Figure 6. Mapping horizon results: (a) Horizon 1 as the top Tampur Formation (economic basement); (b) Horizon 2 as the top Belumai Formation; (c) Horizon 3 as the top Intra-Sediment 1; (d) Horizon 4 as the top Intra-Sediment 2; (e) Horizon 5 as the top Intra-Sediment 3; (f) Horizon 6 as the top Intra-Sediment 4; cross represents the test points.
The undulation is also shown on the gravity profile as the high rate of gravity change in the SW-NE direction along the cross-section in figure 5, where there is a high anomaly in Southwest whose value drops significantly to the Northeast. Sedimentation depocenter as the low anomaly area separated by a reverse fault group as the group of faults on the left side in figure 5. These reverse faults are a major fault in this study area. Based on geological data (figure 1) these faults appears as a separator of the shallow basement area in the Southwest and the basin depocenter in the Northeast. This field has a high level of structural complexity, which is very potential for the petroleum system with the type of trap as a structural and stratigraphy trap.

The mapping results at 2 shallower horizons (figures 6e and 6f) have no extreme depth. The gravity anomaly data is dominated by the regional anomaly that results in a syncline structure on the shallower horizon that is not well mapped. So, the results of the horizon mapping are flatter than the deeper horizon (see figure 7).

**Figure 7.** 3D surface view from Tampur economic basement (above) and the whole of mapping horizon result (bottom).

6. Conclusions
We can conclude that in the field “X” petroleum system the mapping of density interfaces using ESA–MWT technique gravity data can provide good estimates of depths of economic basement and the deeper other sedimentary interfaces as the regional anomaly domination. However, there is some deviation in estimating depths of the seismic horizon caused by structures complexity. There are 6 horizons identified, the Horizon 1 as top Tampur Formation (as an economic basement), Horizon 2 as top Belumai Formation, Horizon 3 as top Intra-Sediment 1, Horizon 4 as top Intra-Sediment 2, Horizon 5 as top Intra-Sediment 3, Horizon 6 as top Intra-Sediment 4.
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