Gravity Data Analysis Based on Optimum Upward Continuation Filter and 3D Inverse Modelling (Case Study at Sedimentary Basin in Volcanic Region Malang and Its Surrounding Area, East Java)

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Abstract. The study on the fore-arc sedimentary basin for hydrocarbon exploration is rare because of the more complicated geological structures, and conventional seismic methods cannot optimally penetrate the rock layers as there are many volcanic and limestone rocks. One of the natural resources potential in the Southern part of the East Java region, especially in Malang and its surrounding areas is the possibility of hydrocarbons in the fore-arc basin, so research is needed to know the existence of these sedimentary basins. The gravity method is one of the geophysical methods used to assess sedimentary basins based on physical parameters of mass density. The aims of this research are to delineate the sedimentary sub-basin, to find out its structure pattern, interpret subsurface geological and basement configuration. The data analysis approach used in this study involves spectral analysis, upward continuation filter, and 3D inverse modeling. The maximum height for the optimum upward continuation filter is 3000 m, which results in regional and residual anomalies. There were five sedimentary sub-basins identified based on residual gravity anomaly, and the gravity anomalies can also detect structure patterns such as basement high, lineament, and fault pattern. The bedrock is supposed as an intermediate igneous rock with a mass density of around 2.7 gr/cc according to the results of 3D inverse modeling. Deposition from bottom to upward is Mandalika, Nampol, and Wonosari Formations and completed by the uppermost are quaternary volcanic rocks. The inversion modeling results show that the Malang and surrounding areas have thick sedimentary rocks covered by volcanic deposits, which is impressive for further investigation to explore the possibility of the hydrocarbon existence in these areas.

1. Introduction
The Indo-Australian plate's subduction activities influenced the Geological setting of the southern part of East Java. The subduction activities resulted in geological structures that have implications for the potential of natural resources and disasters in this area. One of the Southern parts of East Java's potentials resources is the possibility of hydrocarbons occurrence in the fore-arc basin. The presence of oil and gas seepage on the surface at the volcanic area in the southern part of Java indicates an active petroleum system where volcanic rocks covered the sedimentary basin [1]. The Conventional seismic method cannot optimally penetrate the rock layers as there are many volcanic rocks and limestone. Information about basin boundaries, geological structure trends, and bedrock configuration in the fore-arc basin are essential to be known as initial information for hydrocarbon exploration. One of the geophysical methods that can be used to delineate and interpret sedimentary basins based on physical parameters of mass density is the gravity method. However, some techniques that can be used to separate regional and residual anomalies have been carried out by previous researchers include the use of upward continuation filter and trend surface analysis [2], application of polynomial filters on...
2. Data and Method

This research used gravity data from field measurement carried out by the sedimentary basin research team at the Center for Geological Survey (CGS) in 2017 and geological information as a constraint for analyzing and interpreting of the gravity model. This study used the optimum upward continuation filter and the subsurface geological model using 3D inversion modeling. The step of translating potential field data calculated at a surface level into data at a higher surface level is known as the upward continuation. The basic principle of this method is formulated by [5] as in the equation below:

\[
U(x, y, z0 - \Delta z) = \frac{\Delta z}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{u(x', y', z0)}{[(x-x')^2 + (y-y')^2 + (\Delta z)^2]^{3/2}} \, dx' \, dy' \quad \text{......... (1)}
\]

\(\Delta z > 0\), with \(U(x, y, z0 - \Delta z)\) is the total potential field in the upward continuation plane at the height \(h\) to the surface area (measurement plane), while the magnitude field \(u(x', y', z0)\) was known.

The main problem with this method is to determine the height level of the continuation. When using the upward continuation method, the continuation height is determined subjectively by comparing the level of continuation heights, while the continuation height affects the result of the regional anomaly. It is necessary to find out the optimum upward continuation height value so that the result of the regional anomaly is optimum. One of the possible methods to estimate the optimum upward continuation height is written by Zeng et al. (2007) namely by using cross-correlation to two successive continuation heights. The result of cross-correlation at successive heights will pass the maximum deflection at a certain height which is used to estimate the optimum upward continuation height. The cross-correlation \(r\) between the upward continuation anomaly \(g1\) and \(g2\) can be calculated using the following equation (Zeng, et al., 2007).

\[
r_{g1g2} = \frac{\sum_{i=1}^{M} \sum_{j=1}^{N} g1(xi, yj)g2(xi, yj)}{\left(\sum_{i=1}^{M} \sum_{j=1}^{N} g1^2(xi, yj)\right)^{1/2} \left(\sum_{i=1}^{M} \sum_{j=1}^{N} g2^2(xi, yj)\right)^{1/2}} \quad \text{......... (2)}
\]

The anomaly still consists of a mixture of regional and residual anomalies when the level height of upward continuation is less than the optimal value. The residual anomaly will decrease and almost disappear if the height of the upward continuation is greater than the optimal value; this condition will create a regional anomaly pattern [4]. Inversion modeling was done by optimizing the Singular Value Decomposition approach to gravity anomalies. The method is based on the linear inversion technique. Singular Value Decomposition (SVD) is a matrix factoring method that is closely related to the singular value of the matrix, which is a well-known numerical analysis technique for diagonalizing the matrix. Other than SVD, the Occam inversion method which consists of Occam density and Occam height is also carried out at this inversion. Occam density is used to optimize or maximize the block density value, resulting in a smoother model, while Occam h (Occam heights) is used to optimize block height or layer depth. The result of this inversion modeling is the mass density distribution of gravity data [3]. The purposes of this study are to delineate sedimentary sub-basins, interpret geological structure trends, basement configuration, and subsurface geological model due to gravity data analysis using the best upward continuation filter and 3D inverse modeling. This paper will do separation regional and residual anomalies from Bouguer gravity anomalies using the optimum upward continuation technique as proposed by [4]. The Optimum upward continuation filter is carried out by correlation between upward continuation at two successive heights. The maximum deflection results from the cross-correlation of two successive heights will be used to determine the optimum upward continuation filter then applied to calculate regional and residual anomalies. Modeling was done by 3D inversion using grablox software, and geological information is used as a constraint to interpret the subsurface geological model. The study's benefits include designing a 3D model to know subsurface geological conditions based on the physical parameter of density and offering an alternative approach to obtaining the best continuation elevation value in obtaining regional anomalies.
the rock in three dimensions. Inversion modeling is carried out with Grablox software [6], then plotted using Matlab.

3. Result and Discussion
Gravity data that has been processed entirely as well as gridding and contouring produce a gravity anomaly pattern and measurement point distribution as shown in Figure 1. From the figure, it can be seen that the distribution of measurement points is relatively even with a spacing of about 2 Km. The gravity anomaly value between (35 to 121) mGal, the anomaly pattern is divided into three different anomalies patterns, the first is a high anomaly with anomaly range between (100 to 121) mGal, moderate anomaly ranges from (60 to 99) mGal, and Low anomaly has values between (35 to 59) mGal.

![Figure 1. Gravity anomaly map at Malang and its surrounding area.](image)

High gravity anomaly characterized by red color occupies in the southern part and covering area around Sidomulyo, Sitiarjo, Tambakasri, Purwodadi, and Pujiharjo, possibly related to the andesitic basement a mixture of oceanic and continental crust which is in some places appears as an intrusion on the surface. The moderate anomaly is characterized in green color and probably related to the basin’s boundaries of the Malang area. Meanwhile, the low anomaly marked in blue color is probably the deepest basin of the Malang area Southern part of East Java. The obtained gravity anomaly pattern was then subjected to an Upward Continuation filter at different heights to determine the best regional anomaly.
The upward continuation heights were used starting from 500 m to 9000 m with an interval height of 500 m. The upward continuation was calculated on each height map using a grid size (2 x 2) Km using Geosoft Oasis Montaj software. Cross-correlation was carried out at successive height with an interval of 500 m using Matlab. Figure 2 shows the cross-correlation effects of continuation to two successive heights, as well as the deflection curve resulting from the correlation between two successive heights. The cross-correlation results between two successive heights are then calculated to determine the maximum deflection so that the optimum height of upward continuation can be found and will be used to calculate the residual anomaly. The height associated with the maximum deflection is used to estimate the optimum upward continuation height. The maximum deflection at 3000 m upward continuation height is shown in Figure 2b. When the upward continuation height is less than the optimum height, the upward continuation anomaly has two elements: regional and residual anomalies. As the upward continuation height reaches the optimum value, the residual anomaly will lower and almost vanish. Meanwhile, the residual anomaly will attenuate and reach zero when the upward continuation height is greater than the optimum height. The maximum deflection value indicates the optimum residual variable and has not been attenuated when the upward continuation height is at its optimal value [7]. The regional anomaly is obtained from the Bouguer Anomaly from the result of the optimum upward continuation filter at 3000 m height. At the same time the residual anomaly is obtained by subtracting Bouguer anomaly and Regional anomaly. The interpretation of gravity anomaly will be made by qualitative and quantitative. The qualitative interpretation was done to interpret the lateral anomaly changes based on the residual anomaly that has been obtained from the optimum upward continuation filter results.

Figure 2. (a) Cross-correlation upward continuation to two successive height and (b) maximum deflection curve
Qualitative interpretation is used to determine the geological structure patterns, alignment, and delineation of the sub-basin. In general, the alignment of the structural geological patterns has a relative southwest-northeast direction as shown in Figure 3a, this is following the regional pattern, namely a Meratus trend which is probably due to the influence of subduction activity in this area. The sub-basin patterns that can be delineated from the residual anomaly consist of 5 sub-basins as shown in Figure 3b. The residual gravity anomaly indicates that the low anomaly (blue color) is supposed as a graben filled by sedimentary rock with low-density values. The presence of the thick sedimentary rocks makes this area interesting for further research, especially regarding the petroleum system of geology, such as to determine the source rock of hydrocarbons, reservoir rock, and structures where hydrocarbons are trapped. The purposes of quantitative interpretation are to interpret the subsurface geological model such as the dimensions, the type of rock based on the physical parameters (density), shape and size of the model. The quantitative interpretation results are expected to know the depth of the bedrock and the composition of the sedimentary rock above it. The quantitative interpretation was carried out by doing 3D inversion modeling using the grablox program [6] which is then plotting using the Matlab program. The results of the 3D inversion and the cross-section direction of the 2D model, the spread of the sedimentary rock based on the 3D inversion model, and the subsurface cross-sections models of the AA’ and BB’ can be seen in Figure 4. The inversion results show that the rocks density variation ranges between (2.4 to 3.1) gr/cc represent sub-surface density values of the Malang and its surrounding area (Figure 4a). The distribution of sedimentary rocks based on 3D inversion results has density values between (2.4 to 2.55) gr/cc and can be seen in (Figure 4b). The spreading of sedimentary rocks is in the center, northeast, and southwest part of the research areas. The AA’ section (Figure 4c) has a relative North-South direction, the model on the AA’ section shows that the basement may have a density value of about 2.7 gr/cc which is interpreted as an intermediate igneous rock of the Mandalika Formation (Old Andesite Formation), then above it is Nampol Formation consists of sandstones, marl, clay, and tuff. Above the Nampol Formation is the Wonosari Formation, which is consists of limestone, and the uppermost layer is quaternary volcanic deposits.
Figure 4. Subsurface geological interpretation based on 3D gravity inversion, (a) 3D inverse modeling result, (b) spreading of sedimentary rocks based on 3D inverse modeling, (c) 2D cross-section AA’ and (c) 2D cross-section BB’

Figure 4d shows the cross-section of BB’ under the surface of the 3D inversion result. BB’s cross-section has a West-East relative direction through the Wonosari Formation and volcanic rocks on the surface. The model results in this section show that the basement undulation which consists of andesite rock is located at a depth between (2-7) km with a density value of about 2.7 gr/cc. Above the basement is the Nampol Formation consists of sandstones, marl, clay, and tuff; above Nampol Formation is the Wonosari Formation which consists of limestone, uppermost layer is the quaternary rock. Based on geological information, the outcrop in the study area is quaternary volcanic rocks, only a small part of the outcrops occupied by sedimentary rocks, namely in the central and southern regions. The gravity analysis results show that in several places where volcanic rocks are exposed on the surface, gravity anomalies and the inversion model show some low anomalies and deep basins. This shows that there are some thick sedimentary rocks which are covered by quaternary volcanic rocks in this location. The presence of thick sedimentary rocks below the volcanic layer is interest for further research, especially the petroleum system that develops in this area.

4. Conclusion
The structure pattern in the study area due to the residual anomalies analysis results has trend in a southwest-northeast direction, this follows the regional pattern namely a Meratus trend, which is probably caused by the influence of subduction activity from the south movement. The optimum upward continuation filter results show that the optimum height is at 3000 m height; this result was used to determine regional and residual anomalies. Regional anomaly shows anomaly with long wavelengths, which is interpreted as regional structures while residual anomaly reflecting anomaly with shorter wavelengths and be interpreted as localized (shallow) structures. The number of
sedimentary sub-basins that can be delineated based on the gravity data analysis is five sedimentary sub-basins. The basement in the study area is interpreted to be andesite rocks with a mass density of about 2.7 gr/cc. The gravity analysis results are useful for knowing geological structure, fault, graben patterns, and basement high which are interesting for further research to find more detail of the petroleum system in this area.

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