Delineation of Sedimentary Subbasin and Subsurface Interpretation East Java Basin in the Madura Strait and Surrounding Area Based on Gravity Data Analysis

Delineasi Subcekungan Sedimen dan Interpretasi Bawah Permukaan Cekungan Jawa Timur Wilayah Selat Madura dan Sekitarnya Berdasarkan Analisis Data Gayaberat

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ABSTRACT: East Java basin is a very large sedimentary basin and has been proven produce hydrocarbons, this basin consists of several different sub-basins, one of the sub-basin is in the Madura Strait and surrounding areas. Gravity is one of the geophysical methods that can be used to determine geological subsurface configurations and delineate sedimentary sub-basin based on density parameter. The purposes of this study are to delineate sedimentary sub-basins, estimate the thickness of sedimentary rock, interpret subsurface geological model and identify geological structures in the Madura Strait and surrounding areas. Data analysis which used in this paper are spectral analysis, spectral decomposition filter and 2D forward modeling. The results of the spectral analysis show that the thickness of sedimentary rock is about 3.15 Km. Spectral decomposition is performed at four different wave numbers cut off, namely (0.36, 0.18, 0.07 and 0.04), each showing anomaly patterns at depth (1 Km, 2 Km, 3 Km and 4 Km). The sub-basins that can be delineated from the gravity data analysis are 10 sedimentary sub-basins, while the structural patterns identified are basement high, graben and fault. 2D modeling results indicate that the basement is a continental crust with a mass density value of 2.7 gr/cc. Sedimentary rock from modeling result consecutively from the bottom to up, the first is Paleogene sedimentary rock with mass density value of 2.4 gr/cc and above this layer is Neogene sedimentary rocks with mass density values of 2.25 gr/cc. The results of the subsurface geological modeling analysis show that based on the graben pattern and the basement high of the East Java basin in the Madura Strait and surrounding areas there are many structural patterns that support the development of petroleum systems like at the western part of the East Java basin that have already produced hydrocarbon.

Keywords : Gravity, spectral analysis, spectral decomposition filter, 2D Modeling, East java basin

ABSTRAK: *Cekungan Jawa Timur merupakan cekungan sedimen yang sangat besar dan telah terbukti memiliki kandungan minyak dan gas bumi. Cekungan ini terdiri atas beberapa sub-cekungan yang berbeda-beda, salah satunya adalah sub-cekungan yang ada pada wilayah selat Madura dan sekitarnya. Gayaberat merupakan salah satu metoda geofisika yang dapat digunakan untuk mengetahui konfigurasi bawah permukaan serta mendelineasi sub-cekungan sedimen berdasarkan parameter rapat massa (densitas). Tujuan dari penelitian ini adalah untuk mendelineasi sub-cekungan sedimen, memperkirakan ketebalan sedimen, menginterpretasi geologi bawah permukaan serta mengidentifikasi struktur yang ada pada wilayah selat madura dan sekitarnya. Analisis data yang digunakan yaitu analisis spektral, filter spektral dekomposisi serta pemodelan maju (forward modeling) 2D. Hasil analisis spektral menunjukaan bahwa tebal batuan sedimen rata-rata adalah sekitar 3.15 Km. Spektral dekomposisi dilakukan pada empat bilangan gelombang cuttoff yang berbeda beda yaitu (0.36, 0.18, 0.07 dan 0.04) yang masing-masing menunjukkan pola anomali pada kedalaman (1 Km, 2 Km, 3 Km dan 4 Km). Sub-cekungan yang dapat didelineasi dari analisis data gayaberat ini adalah sebanyak 10 sub-cekungan sedimen, sedangkan pola struktur yang teridentifikasi yaitu berupa tinggian, graben dan patahan. Hasil pemodelan 2D menunjukkan bahwa batuan dasar adalah berupa kerak kontinen dengan nilai rapat massa 2.7 gr/cc. Batuan sedimen hasil pemodelan secara berturut turut dari bawah ke atas yang pertama yaitu batuan sedimen yang berumur Paleogen dengan nilai rapat massa 2.4 gr/cc dan di atasnya adalah batuan sedimen berumur Neogen yang mempunyai nilai rapat massa*

2.25 gr/cc. Hasil analisis model bawah permukaan menunjukkan bahwa berdasarkan pola graben dan tinggian cekungan Jawa Timur segmen selat Madura dan sekitarnya cukup banyak terdapat pola struktur yang mendukung berkembangnya petroleum system seperti pada wilayah sebelah barat cekungan Jawa Timur yang sudah berproduksi hidrokarbon.

Kata Kunci *: Gayaberat, spektral analisis, filter spektral dekomposisi, pemodelan 2D, Cekungan Jawa Timur*

INTRODUCTION

Indonesia region located at the zone of three tectonic plate which still actively move namely the Eurasian plate, the Indo-Australian Plate and the Pacific plate. Interaction of the three plates resulting the emergence of volcanoes, faults and sedimentary basins in the Indonesian area. One of oil and gas basin which has produced in Indonesia is East Java Basin, East Java basin located in the southeast part of Sunda shelf which bounded by Karimunjawa arc at the western part, Meratus high at the northern part, and Masalembo high at the eastern part, and volcanic series at Southern part of East Java (Sribudiyani, 2003). The purposes of this research are to delineate Madura Strait subbasin and the surrounding area, to know structural patterns and subsurface geological configurations by using the gravity method. Gravity is one of the geophysical methods that can be used to determine the geological subsurface condition based on the physical parameters of density. There are several filter methods that can be used to analyze gravity data including a Gaussian filter to separate regional and residual anomalies from gravity data (Karunianto *et al.,* 2017), (Obasi *et al.*, 2016) use the trend surface analysis method to separate residual and regional anomalies from gravity data. Zahra and Oweis, (2016) use high pass filter on gravity and geomagnetic data to obtain short wavelength anomalies associated with shallow anomaly sources. In the processing of gravity data, anomaly will appear as the target of a study that makes it easy to interpret the geological subsurface conditions, the anomaly in the gravity method is known as the Bouguer anomaly. Bouguer anomaly is a superposition of anomalies component from various depths, information about depth and position of the object anomaly source becomes very important at the interpretation stage. Spectral analysis is a method that can be used to estimate the depth of anomalies in the frequency domain of gravity data. In this study, spectral analysis, spectral decomposition filter and 2D modeling of gravity data will be carried out. The purposes of spectral analysis are to estimate basement depth and to obtain optimum window width to determine regional and residual anomalies in the study area, while spectral decomposition is carried out to determine structure anomalies pattern based on spectral analysis at several different depths. 2D modeling is carried out to find a quantitative interpretation of subsurface geological model so it is easier to be interpreted. The interpretation results of both qualitative and quantitative gravity data will be expected to add subsurface and geological structure information which can be used to enrich exploration activities references in the East Java basin, especially in the Madura Strait and surrounding areas. Geographically, the location of the study area is in the Madura Strait and surrounding areas of East Java Province at coordinates (112 - 113.5) East and (7-8) South as shown in Figure 1.

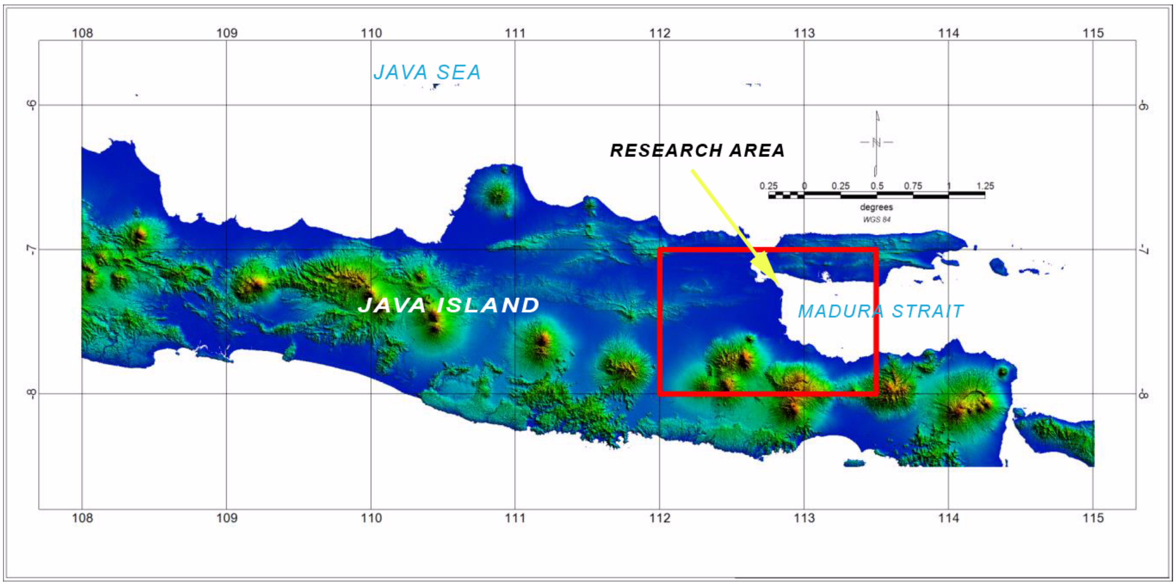


Figure 1. Research area in the Madura Strait and surrounding areas, East Java Province

GEOLOGY OF RESEARCH AREA

The East Java Basin geologically was formed as the result of uplift and unconformity process as well as other processes, such as sea level subsidence and tectonic plate movement. The initial step of forming the basin is characterized by the presence of half graben which is influenced by the geological structure formed previously. The geological structure of the East Java Basin generally are reverse fault, normal fault, strike slip and folding with relative East-West trend due to the influence of the compression force from the South to North direction. The development of tectonics in the East Java Basin is inseparable from the tectonic activity of the Southeast Asian region to wit the movement of the Indo-Australian Ocean Plate northward, the Philippine and Pacific Oceanic Plate moving westward, and the relatively stable Eurasian Plate. The East Java Basin is classified as a back arc basin and located at the

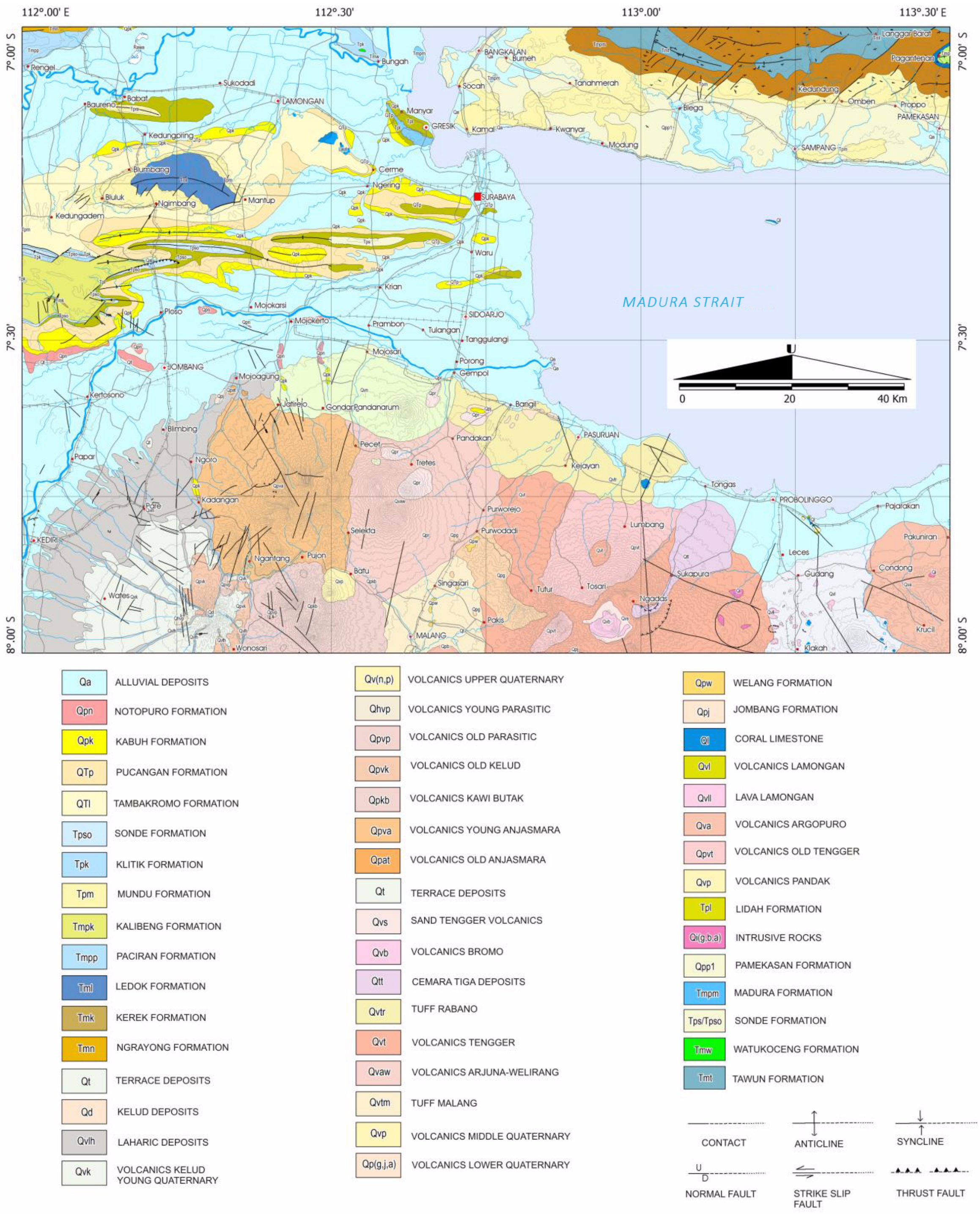


Figure 2. Geological map of study area, adopted from geological map scale 1 : 100.000 Published by Geological Research and Development Centre (GRDC).

southeast boundary of the Eurasian Plate (Mudjiono and Pireno, 2001) and situated on the edge of a stable Sunda continent. Geological map of study area can be seen at Figure 2, this map adopted from geological maps scale 1 : 100.000 namely geological map of Mojokerto quadrangle (Noya *et al.*, 1992), geological map of Kediri quadrangle (Santosa and Atmawinata, 1992), geological map of Malang quadrangle (Santosa and Suwarti, 1992), geological map of Probolinggo quadrangle (Suharsono and Suwarti, 1992), geological map of Tanjungbumi and Pamekasan quadrangle (Aziz *et al.*, 1992), and geological map of Surabaya and Sapulu quadrangle (Supandjono *et al.*, 1992) which have been published by Geological Research and Development Centre (GRDC).

Generally, volcanics rock are situated in the Southern part of the study area and characterized by high topography contour. Alluvial deposits can be found at north, central and eastern part east java along the beach and characterized by flat topography. Sedimentary rocks are distributed at many areas such as in the Northeast part of study area especially at Madura Island namely Ngrayong Fromation, Tawun Formation, Madura Formation and Pamekasan Formation. Many sedimentary rocks also found at Northwest part of study area such as Kalibeng Fromation, Ledok Formation, Mundu Formation, Paciran Formation, Lidah Formation, Kabuh Formation, Pucangan Formation, Kerek Formation, Sonde Formation, Notopuro Formation, Tambakromo Formation and Klitik Formation.

Stratigraphy of East Java Basin

The basement of the East Java basin generally is continental (granitic), melange and metamorphic rock. The stratigraphic sequence of the East Java basin (Sribudiyani *et al.*, 2003) is described seen in Figure 3.

Figure 3 shows the oldest sedimentary rock at the age of Early Eocene which deposited above the basement is the Pre Ngimbang Formation, this formation consist of sandstone, shale, siltstone and coal and found in the Kangean area in the eastern part of the East Java Basin. Above the Pre Ngimbang Formation is the Ngimbang Formation which is Middle Miocene age characterized by clastic sediments and consist of interspersing sandstone, shale, limestone and coal. Above the Ngimbang Formation was deposited the Kujung Formation consist of shale with limestone and sandstone insertions, the upper part of the shale insertion and clastic limestone is also known as Prupuh limestone. Above the Kujung Formation was deposited the Tuban Formation composed of clay layer, some

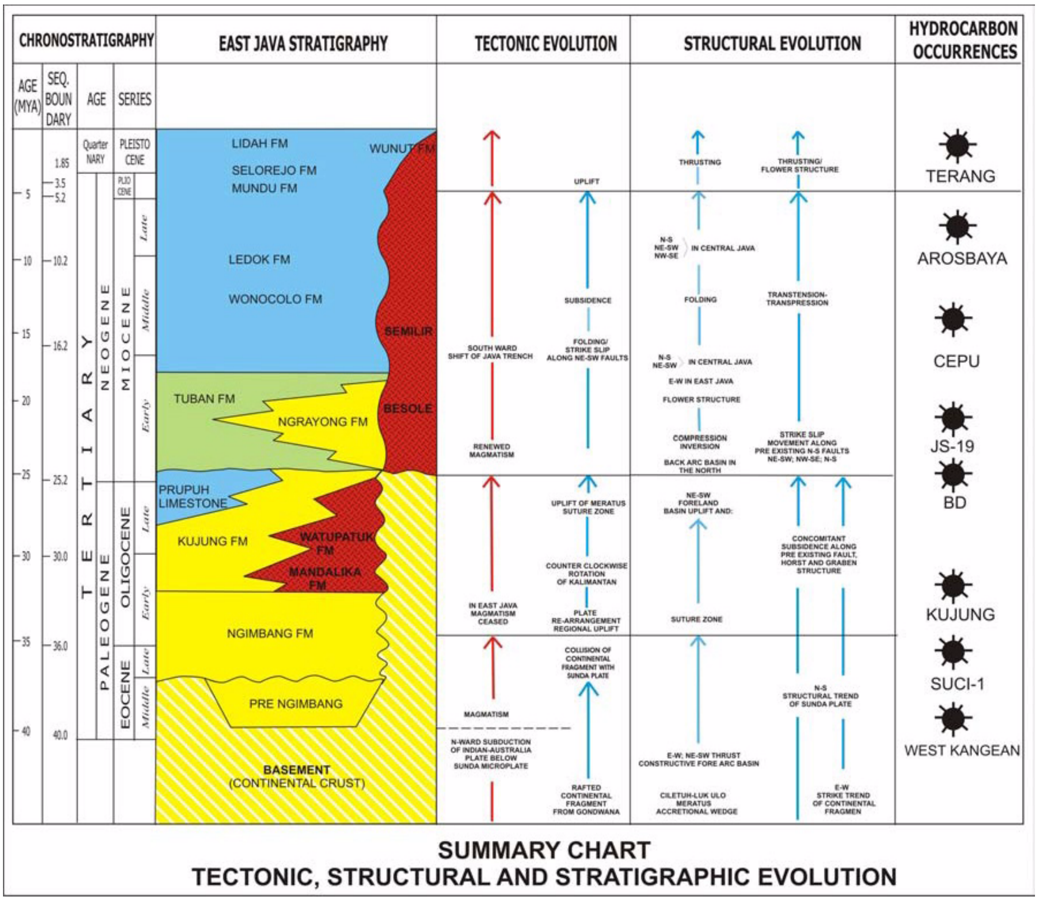


Figure 3. Regional stratigraphy of the East Java Basin (Sribudiyani *et al.,* 2003)

insertion of limestone and shale was formed at the beginning of the Miocene and deposited in the deep sea environment. Inter fingering with the Tuban Formation namely the Ngrayong Formation consist of sandstone, shale, clay, siltstone and limestone insertions. At the age of the early Miocene to Middle Miocene the Tawun Formation was deposited consisting intermittent of shales carbonat with sandstone and limestone. Above the Tuban Formation at the age of Middle Miocene to Late Miocene deposited the Wonocolo Formation was composed of marl and clay, at the bottom composed of sandy limestone. Above the Wonocolo Formation was deposited Ledok Formation consist of interspersing between sandstone and marl insertions. Above Ledok Formation was deposited the Mundu Formation consist of marl and sandy limestone. Above the Mundu Formation, the Selorejo Formation was deposited composed of interspersing between the marly limestone and sandy limestone. The uppermost formation at the age of the Plistocene was deposited by the Lidah Formation consist of black clay and marl.

Petroleum System

Most of the source rocks in the East Java Basin is shale which is rich of organic material and coal that came from the Pre Ngimbang, Ngimbang, Kujung and Tawun Formations. The results of the geochemical analysis of several wells indicate that the source rock in the East Java Basin is quite mature and has two possibilities as a source of oil or gas production. The main reservoir tagets in the East Java Basin are the sandstone Ngimbang Formation, Poleng limestone the Kujung Formation, Rancak limestone the Tawun Formation, sandstone the Ngrayong Formation, Bulu limestone the Tawun Formation, and Paciran limestone the Mundu Formation. Hydrocarbon migration occurs at close distance through fault and fracture structures such as migration into younger formations filled by gas and oil. The structural framework of the East Java Basin is very complex, formed by two main basins with the main orientation northeast-southwest and east-west, and some sub-basin whose initial establishment is characterized by rifting filled by clastic sediment Paleogen then followed by the main inversion structure, this major structural inversion (compression) event involves all components of the sequence stratigraphy (Sribudiyani, et.al., 2003). In general, almost all basins in East Java are classified into basins formed by complex structures, characterized by folds and reverse fault. The two main types of traps that can be identified in the East Java Basin are structural and stratigraphic traps. The sealing rock consists of clay, shale and marl, which is a good capacity sealer to hold a gas or oil column, the rock is believed as a seal for sandstone as hydrocarbon reservoir that is lies under the sealing rock (Mudjiono and Pireno, 2001).

RESEARCH METHODOLOGY

The data used in this study has been published by Geological Research and Development Center (GRDC), while the data for the sea area is taken from satellites (Topex, 2019). Bouguer anomaly data used in this study covering some quadrangle map namely Bouguer Anomaly Blitar quadrangle map (Nainggolan *et al.*, 1995), Mojokerto quadrangle (Nainggolan *et al.*, 1994a), Tuban quadrangle (Nainggolan *et al.*, 1994b), Turen quadrangle (Tasno *et al.*, 1995), Malang quadrangle (Buyung *et al.*, 1994), Surabaya and Sepulu quadrangle (Syarif *et al.*, 1994), Bawean and Masalembo quadrangle (Tasno and Ermawan, 1997), Lumajang quadrangle (Suharyono and Sucihati, 1994), Probolinggo quadrangle (Nainggolan and Iryanto, 1995), Tanjungbumi-Pamekasan quadrangle (Ermawan and Tasno, 1994). The bouguer anomaly data processing comprise of griding and contouring, continued by spectral analysis to estimate the basement depth and find out the optimum window width, and then spectral decomposition to determine the patterns of structure anomaly at a certain depth. 2D modeling was also carried out to determine subsurface geological models in the study area. The combined results of gravity data analysis and geological information are then used to interpret the geological conditions of the study area. The complete research flow diagram can be seen in Figure 4. Spectral analysis can be used to estimate the optimum window width and depth of the gravity anomaly source, spectral analysis was done by fourier transforming of the Bouguer anomaly path that has been determined previously in the Bouguer anomaly map. In general, fourier transform is rearranging or decomposing arbitrary waves into sine waves with varied frequencies where the sum of the sine waves is the original waveform. The spectrum is derived from gravity potential and observed in a horizontal plane (Blakely, 1996), where the Fourier transform is as follows:

$$F(g_z) = 2\pi G m e^{|k|(z_0 - z_1)}, \; z_1 > z_0 \quad (1)$$

$$A = C\, e^{|k|(z_0 - z_1)} \quad (2)$$

$$\ln A = (z_0 - z_1)|k| + \ln C \quad (3)$$

Where A is Amplitude, C is Constant, z is depth, and k is wave number.

The resulted equation can be analogized to a straight line equation :

$$y = mx + c \quad (4)$$

While *ln A* act as the y axis, $|k|$ as the x-axis, and $(z_0 - z_1)$ as the slope (gradien). Therefore, slope of the lines indicate the depth of shallow and deep planes. $|k|$ as the x-axis as defined as the magnitude of the wave number $\frac{2\pi}{\lambda}$ in *cycle/meter* unit, while λ is the wavelength. Window width can be formulated as follows:

$$N = \frac{2\pi}{k_c.\Delta x} \quad (5)$$

where x is the space domain to be used in Fast Fourier Transform (FFT), and k_c is the wave number cut-off.

The value of wavenumber (k) is linear with frequency (f), relation between wavenumber (k) and frequency expressed as equation $k = \omega/v$ or $k \propto 2\pi f$, it means the low frequency comes from regional anomaly sources and high frequency comes from residual anomaly sources.

Fast Fourier Transform (FFT) results can be plotted as graphical correlation between Amplitude and Wave Number as shown in figure 5. The graph consisted of three zone namely noise zone usually located in the high frequency/wavenumber, residual anomaly zone in the middle wavenumber, and the regional anomaly zone located in the low wave number.

The signals results of the Fourier transform (FFT) which consist of wavenumber and amplitude spectrum reflecting a combination of subsurface anomalies from long wavelength (deep anomalies) to short wavelength (shallow anomalies). This signal anomaly can be decomposed to find out the anomaly pattern at a certain depth by determining the wavenumber cutoff, the technique to decompose spectrum of the FFT signal results is known as the spectral decomposition. Spectral decomposition analysis on gravity data can be done by parsing or making several wave number cut off and

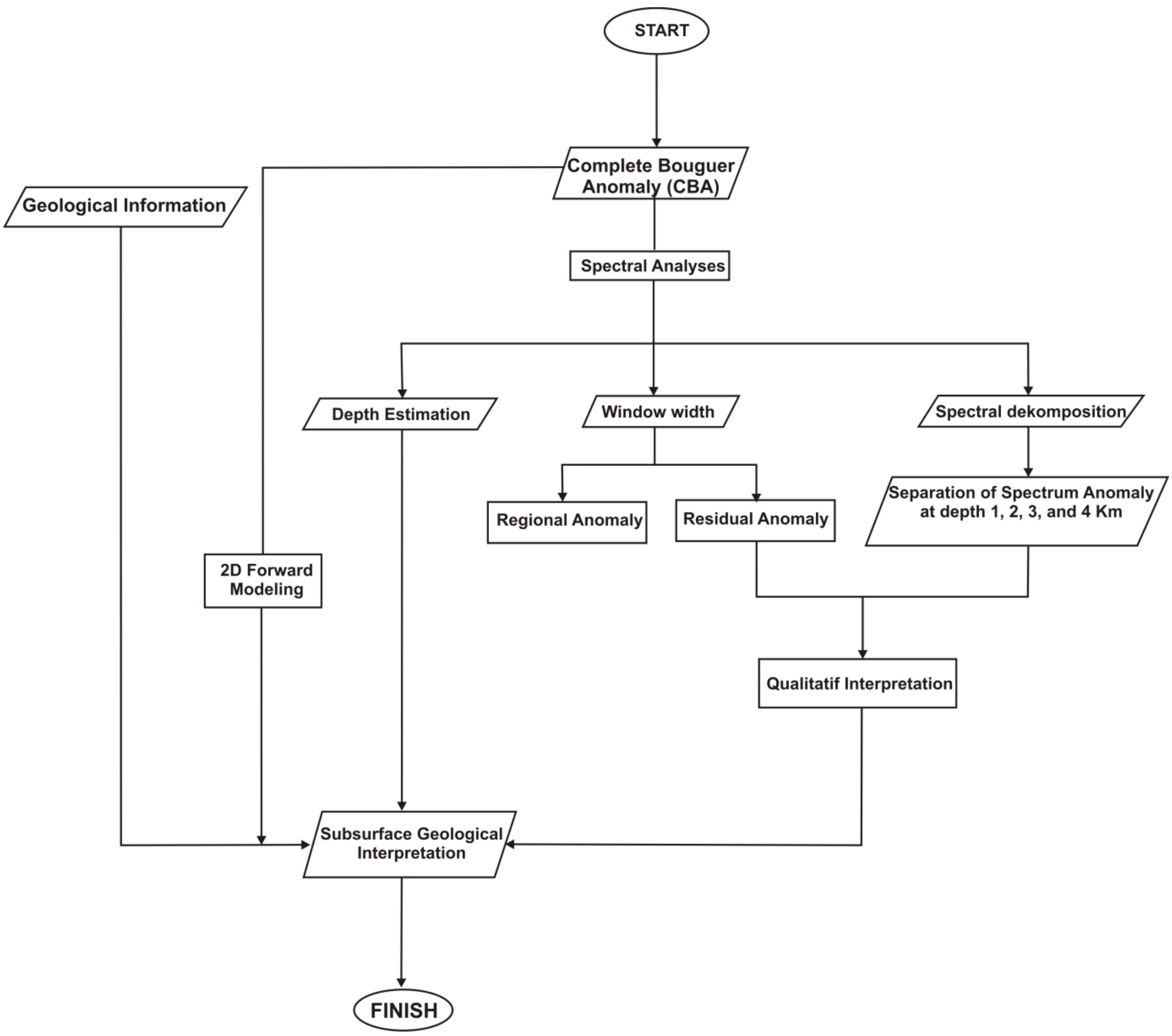


Figure 4. Flow Chart of gravity data analysis at the East Java Basin in the Madura strait and surrounding area

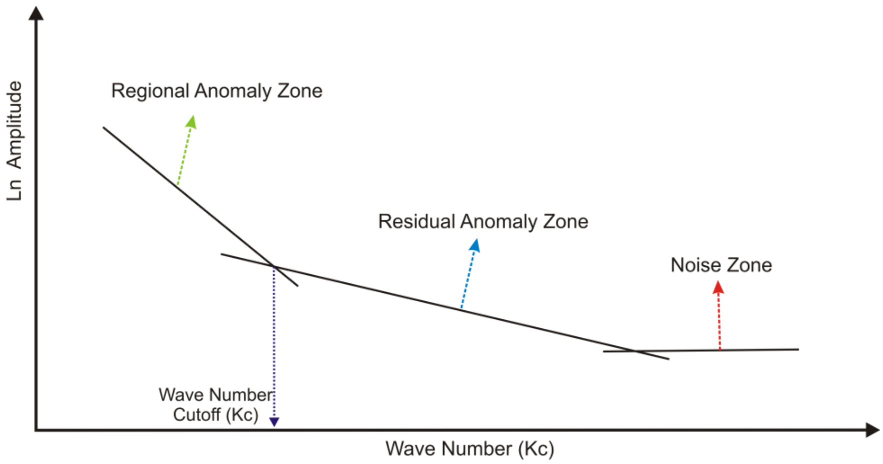


Figure 5. Graphical correlation between Amplitude and Wave Number in Spectral Analysis

window width by dividing in different depths which will be analyzed one by one (Dicky *et al.*, 2017). This spectral decomposition analysis intended to obtain information about the geological structures at any determined depth.

RESULT AND DISCUSSION

Bouguer Anomaly

Bouguer anomaly map which generated from combined terrestrial data mapped by the Geological Research and Development Center and the sea data originating from satellites (Topex, 2019) can be seen in Figure 6, from these images, it can be seen that the anomaly values range between (-38 to 43) mGal. High gravity anomalies are shown in red colour occupies in the south and north part, with the anomaly value between (10 to 43) mGal. In the southern part, the high anomaly may be due to the influence of the southern mountain volcanic rocks, while the high anomaly in the northern part may be caused by the influence of the basement which is lifted more upward. Low gravity anomaly which is showed by blue and green colour occupies in the middle part that is extends from east to west, this anomaly range between (-38 to 9) mGal. Low anomaly in the middle part is probably caused by sedimentary rocks with lower mass density values, areas with low gravity anomalies in the middle area known as Kendeng zones which have thick sedimentary rock. Bouguer anomaly is a combination (superposition) from short wavelengths which is represent near surface anomalies and the long wavelengths which comes from the rocks in the deep locations. To see the more detail geological structures pattern, the Bouguer anomaly needs to be filtered to separate the influence of residual anomalies that is come from the rocks in the shallower position with regional anomalies which is originated from the rocks at the deeper position. Rocks with a deeper position are usually as a bedrock (crust to moho), usually have a greater density it will influence the Bouguer anomalies value that measured on the surface, therefore it is necessary to be separated regional and residual anomalies from Bouguer anomaly, and to see the shallow geological structures can be used from the result of residual anomaly.

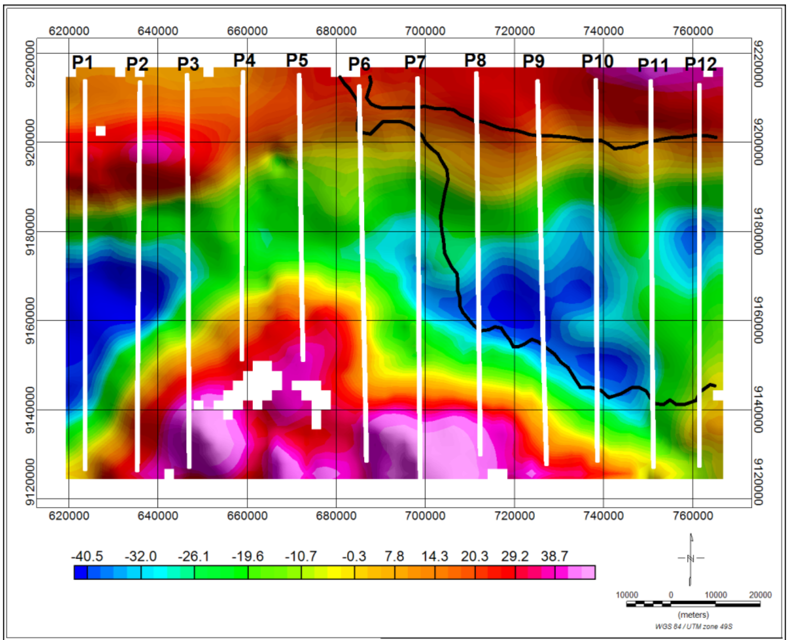
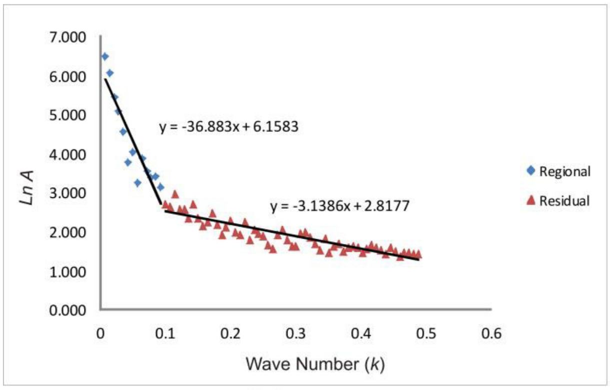


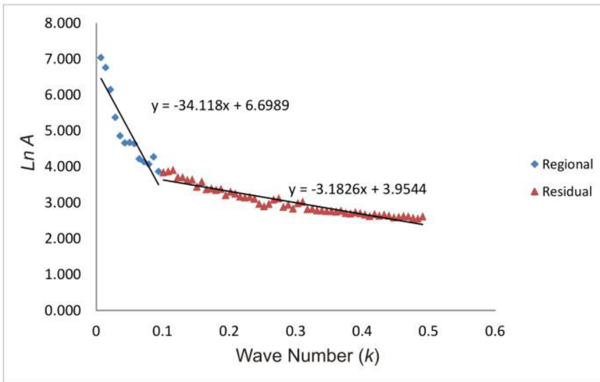
Figure 6. Bouguer anomaly patterns and spectral analysis line sections of the East Java Basin

Spectral Analysis

Spectral analysis was done by making some line section of the Bouguer anomaly map, then from the line section the Fast Fourier Transform (FFT) were done to determine the signal content along the trajectory to know the Amplitude spectrum and wave number. In this analysis, a Fourier Transform (FFT) will be done on 12 line as shown in Figure 6, Spectral analysis was carried out at the selected line (P1-P12) to determine the signal content at each line of the Bouguer anomaly. The signal content in the



7a. Graph *k* vs *Ln A* Line P1



7a. Graph *k* vs *Ln A* Line P2

Figure 7. Graph example of wave number (k) vs Amplitude (Ln A) Line P1 and P2

Bouguer anomaly line section is a combination of high frequency and low frequency signals.

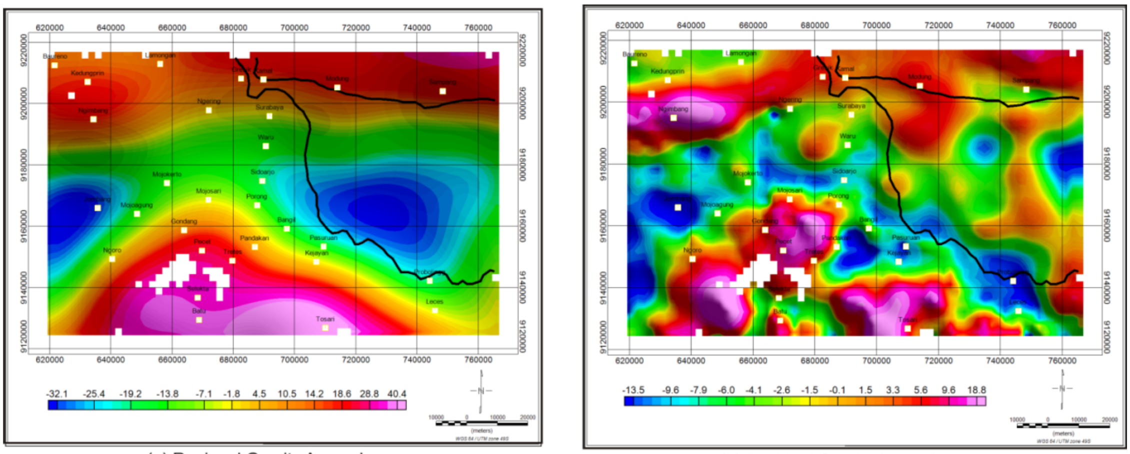
Graph example of wave numbers (*k*) versus amplitude (*LN A*) can be seen in Figure 7. Figur 7.a that the depth of residual discontinuity plane in the line P1 is 3.14 Km while the depth of regional discontinuity plane is 38.88 Km. While on Figure 7.b shallow depth of discontinuity plane is at 3.18 Km and depth of discontinuity plane is 34.11 Km. The results of spectral analysis can be used to determine the wave number cutoff (k_c), window width (*N*) and to estimate the depth of the shallow and deep discontinuities plane, the results of the spectral analysis can be seen in Table 1.

From the table it can be seen that the average of wave number cutoff (k_c) is 0.099, this wave number cutoff (k_c) will be used to calculate the optimal window width (*N*). The average of regional discontinuity depth is 36.3 Km, the depth reflect the regional anomaly which is probably caused by undulation of the lower crust or Moho plane.The average depth of the local discontinuity plane is about 3.2 Km, this depth indicates the shallow discontinuity plane which probably due to the basement undulation pattern in this area. Beside to know regional and local discontinuity plane, spectral analysis can also be used to determine the optimal window width that used for the Bouguer anomaly data filtering to produce residual and regional anomaly, from the table appears that the optimal window width is 12.7 or rounded to N = 13 so that the optimum wavelength filter grid used is (60 x 60) Km. By using Geosoft Oasismontaj software, a regional and residual anomaly is separated by entering the cutoff wavelength (optimum window width obtained from spectral analysis results). Regional and residual anomaly patterns can be seen in Figure 8.

Figure 8(a) is a regional anomaly pattern while Figure 8(b) is a residual anomaly pattern in the East Java basin of Madura strait and surrounding areas. Regional anomaly patterns in Figure 8(a) show anomalies with longer wavelengths, this anomaly is probably due to the influence of rocks with high density values, and based on the results of spectral analysis calculations is originated from a depth of about 36 Km, this anomaly may be caused by undulation of lower

Table 1. Depth of the deep discontinuity plane (regional depth), shallow discontinuity plane (local depth), wave number cut-off (kc), and window width (N)

No	Line Section	Wave Number (Kc)	Window Width (N)	Regional Depth (Km)	Local Depth (Km)
1	Line P1	0.100	**12.560**	36.88	3.14
2	Line P2	0.101	**12.436**	34.11	3.18
3	Line P3	0.099	**12.687**	39.62	3.37
4	Line P4	0.087	**14.437**	38.21	2.99
5	Line P5	0.102	**12.314**	40.13	2.97
6	Line P6	0.104	**12.077**	35.91	2.91
7	Line P7	0.091	**13.802**	33.81	3.28
8	Line P8	0.102	**12.314**	37.46	3.05
9	Line P9	0.102	**12.314**	34.23	3.72
10	Line P10	0.102	**12.314**	40.78	3.12
11	Line P11	0.101	**12.436**	32.28	2.98
12	Line P12	0.095	**13.221**	32.04	3.13
	Avarage	**0.099**	**12.743**	**36.288**	**3.153**



(a) Regional Gravity Anomaly (b) Residual Gravity Anomaly

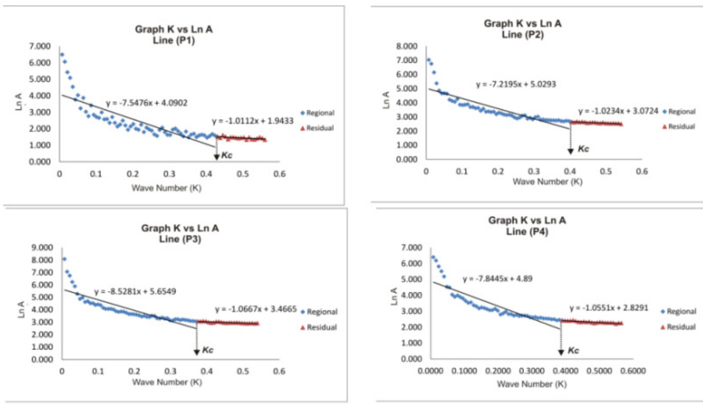
Figure 8. Regional and residual gravity anomaly map of the East Java Basin in the Madura strait and surrounding area

crust or Moho, where in the southern and northern part the discontinuity plane are relatively curve upward while in the middle part is relatively curve downward. This condition probably caused the formation of kendeng zone where position is in the middle, relatively concave to downward and filled by a layer of sediment that is quite thick, Kendeng zone extends with relative east-west direction. Figure 8(b) displays the residual anomaly pattern of the study area, this residual anomaly shows an anomaly pattern with a shorter wavelength and usually shows as a basement undulation pattern. Based on the calculation of the spectral analysis the depth of this anomaly is around 3.2 Km, so that the basement in this area probably 3.2 Km depth. Low anomalies are shown in blue colour, these anomalies indicate areas with lower density values and filled by thick sedimentary rocks. High anomalies are shown in red colour, these anomalies spread in the south and north area. High anomaly in the southern part may be caused by the presence of volcanic rock in the southern mountains, while in the northern part probably due to the presence of the basement high which is relatively rises to the top so that responds of the anomaly is higher.

Spectral Decomposition

Gravity anomaly that measured on the surface is combination of anomalies which originate from shallow sources (near surface position) and usually has short wavelength, and deep sources come from subsurface rocks that are deeper position and have longer wavelength. By using spectral analysis that is by doing the Fourier Transform (FFT) of the trajectory from selected gravity data, it will known the signal contained in each gravity trajectories data. Spectral decomposition is a technique to parse the spatial domain signal of the FFT so that anomalous sources can be found from short wavelengths (shallow sources) to long wavelengths (deep sources).

This technique is used to know the pattern of structure anomaly at a certain depth that we want to know the geological structure related to the sedimentary basins in the study area. In this study, spectral decomposition will be conducted at depths of 1 Km, 2 Km, 3 Km and 4 Km. The processing starts from FFT of the selected gravity data trajectory (P1-P12), then We determine the wave number cut-off from signal (graph



No	Line	Wave Number (Kc)	Window Width (N)
1	Line P1	0.43	2.921
2	Line P2	0.404	3.109
3	Line P3	0.377	3.332
4	Line P4	0.389	3.229
5	Line P5	0.353	3.558
6	Line P6	0.336	3.738
7	Line P7	0.378	3.323
8	Line P8	0.389	3.229
9	Line P9	0.401	3.132
10	Line P10	0.375	3.349
11	Line P11	0.37	3.395
12	Line P12	0.36	3.489
	Avarage		**3.317**
	Window Width at depth 1 Km		**(10 x 10) Km**

Figure 9. Graph and table of spectral decomposition analysis at depth of 1 Km

wave number (k) and amplitude (A)) until certain depth level that we want. Figure 9 shows an example graph and table of spectral decomposition at depth of 1 km. In accordance with the theory previously that the frequency (f) has linear relationship with the wave number (k), so the higher frequency (wave number) the wavelength anomalous will shorter, otherwise the lower frequency (wave number), the wavelength anomalous is longer. From Figure 9 it can be seen that to determine a certain depth value of 1 Km by shifting the value of the wave number cutoff (k_c). The wave number cutoff results are used to calculate the optimum window width (N) so that anomaly patterns will be found at a depth of 1 Km. Processing is performed on each selected line and at other specified depths, so that wavelength anomaly patterns at a certain depth will be obtained as shown in Figure 10.

Figure 10 shows anomaly patterns of spectral decomposition results at several depths, namely 1 Km, 2 Km, 3 Km and 4 Km. In general, the anomaly pattern from top to bottom shows that the anomaly wavelength is getting wider and closer to the regional structure. The top picture is the anomaly pattern of spectral decomposition results at depth 1 Km, this anomaly shows a pattern with shorter wavelength and a more complex anomaly structure, it appears that the high anomaly is shown in red colour while the lower anomaly is shown in blue colour. High anomaly in the southern part at a depth 1 Km may be caused by the influence of volcanic rocks that intrude to the top which causes a more complex structure anomaly pattern. In the northern part of the high anomaly at a depth 1 Km may be due to the influence of the basement raised up which result high anomaly as basement high. The picture below is an anomaly pattern of spectral

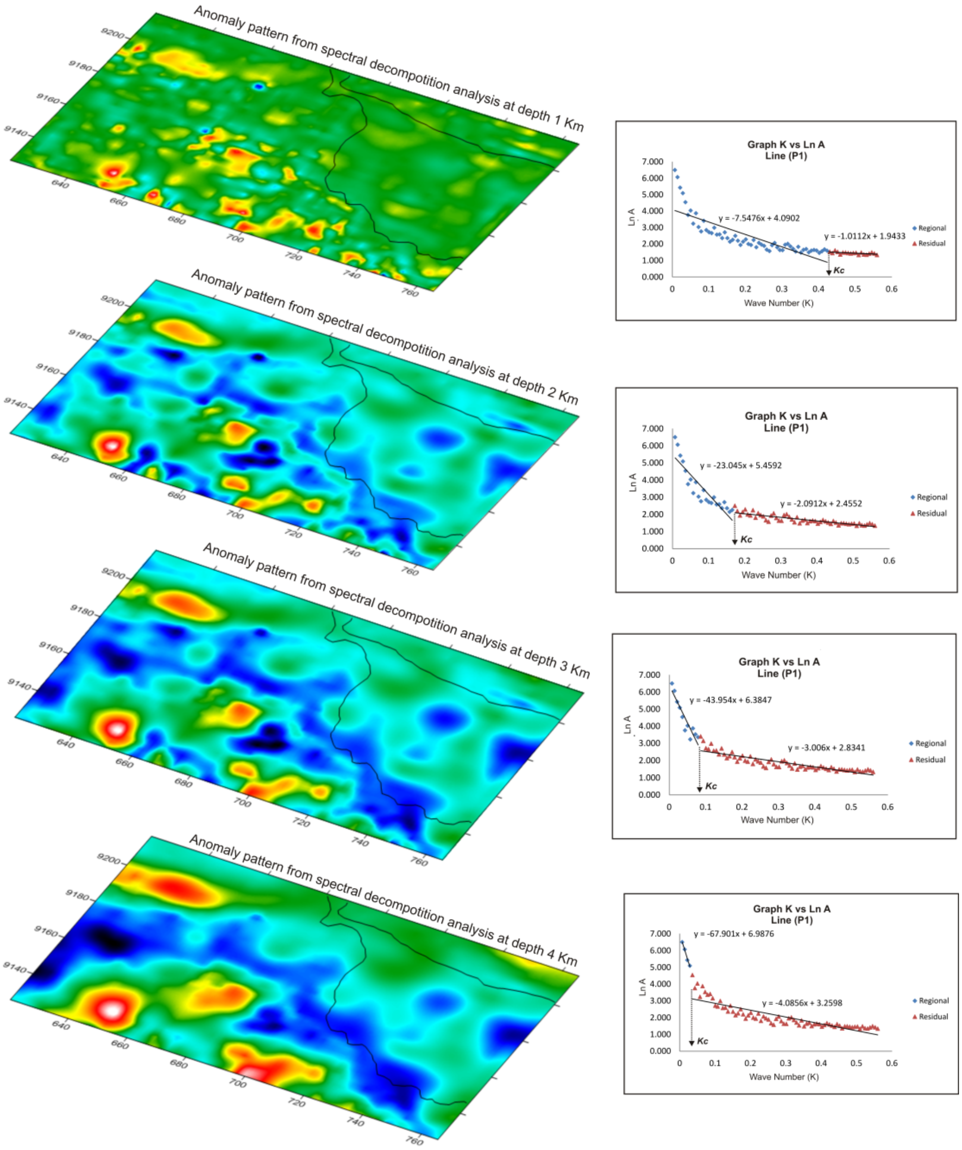


Figure 10. Anomaly patterns at depths 1 Km, 2 Km, 3 Km and 4 Km based on spectral decomposition analysis.

decomposition results at a depth 2 Km, the picture shows the pattern of anomaly structure at a depth 2 Km where the low anomaly (shown in blue colour) in the north part is probably due to the influence of sedimentary rocks, sedimentary rocks are spreaded in several locations which is supposed as a sedimentary sub basin in the northern part of East Java, while in the southern part, the low anomaly probably influenced by volcanoes with magma material so that the anomaly is low. The structure anomaly at a depth 3 Km and 4 Km is relatively simpler, not as complex as at a depth of 1 Km and 2 Km. At the deeper structure it is clearly seen that the pattern of high anomalies in the southern part shows the influence of the igneous intrusion of volcanic zones of the southern mountains of East Java that intrude to the top which is support with continuous anomaly from bottom to top.

Qualitative Interpretation

The purpose of qualitatif interpretation is to know the spread of lateral anomalies pattern, interpretation was done based on residual anomalies that obtain from the of spectral analysis results. Qualitative interpretation of residual anomalies is to know the pattern of basement high and delineation of sub basin as shown in Figures 11 and 12.

Figure 11 shows that the pattern of height structure anomaly is relative east-west direction, however there are some structures having a relative north-south direction. The structure pattern in the relative east-west direction is most likely due to regional tectonic influence, which is due to the compression force of the subduction from the south of Java to the north so that causes the structure height to relatively east-west direction. The basement high pattern as seen from the residual gravity anomaly reflects the undulation of the basement which is relatively upward position so that of the sedimentary rocks in this area is depleting. In hydrocarbon exploration activities, the location of basement high is very interesting to know because hydrocarbons that have already mature usually will migrate from sediment depocenter (lower location) to a higher location.

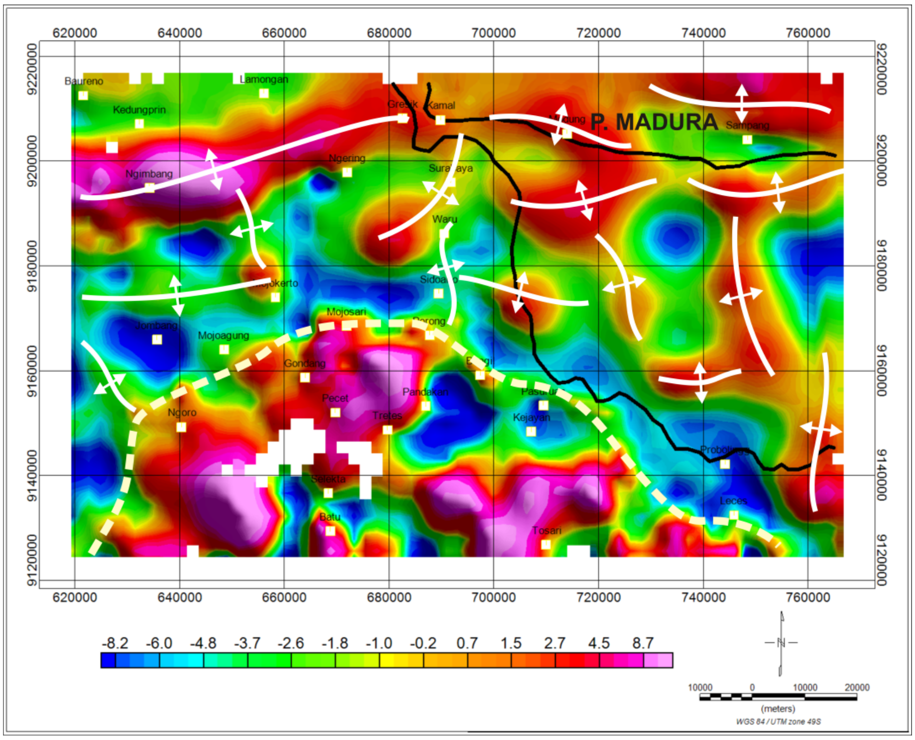


Figure 11. The height structure anomaly pattern of the study area based on residual anomaly

In addition to seeing the basement high structure pattern, qualitative interpretation was used to know the sedimentary sub-basin distribution patterns in the study area as shown in Figure 12. From the picture can be seen that the sub-basin pattern is spread in the middle and north parts which are marked in green-blue color, the sub-basin in blue color is relatively thicker in sedimentary rocks than to the green one. The sub-basin pattern reflecting the presence of sedimentary rock depocentre which is sedimentary rock is accumulated. The thick sedimentary rock will be better, due to the possibility of the existence of a higher petroleum system, although there is no guarantee that thick sedimentary rocks will be found the hydrocarbon.

Quantitative Interpretation

Quantitative interpretation was done by make 2D models of residual gravity anomaly, the purpose of modeling is to find out the depth of basement, thickness of sedimentary rocks, and the density value of rock in the study area. Quantitative interpretation is carried out in three different line-sections as shown in Figure 13.a. Line section AA 'and CC' is relatively east-west direction while BB' line section has perpendicular AA' and CC' that is relatively north-south direction. Figures 13b, 13c and 13d are subsurface 2D models created along the line section.

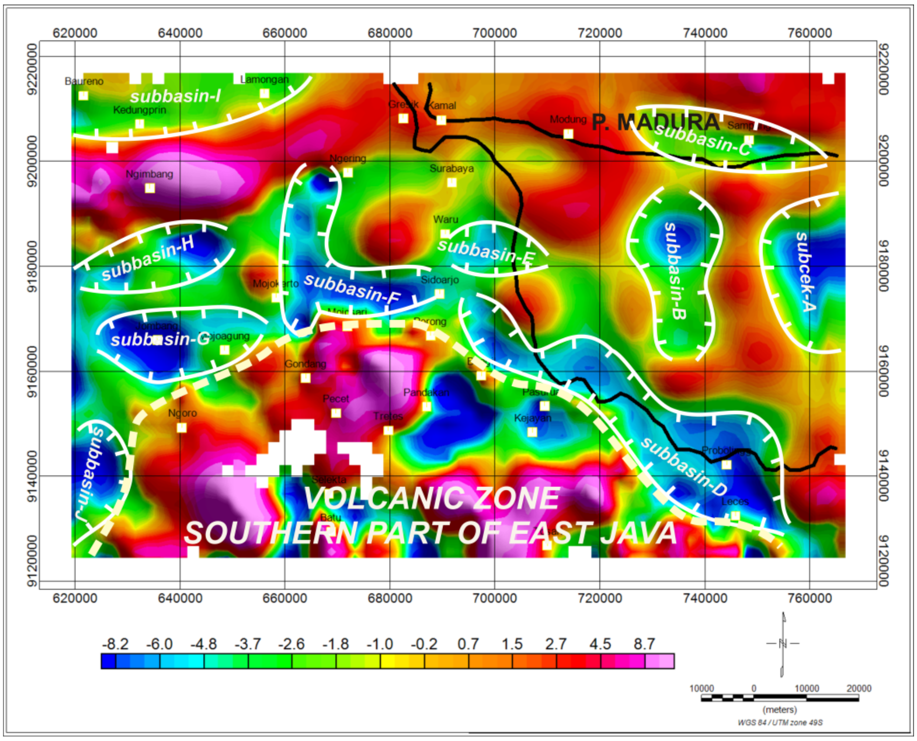
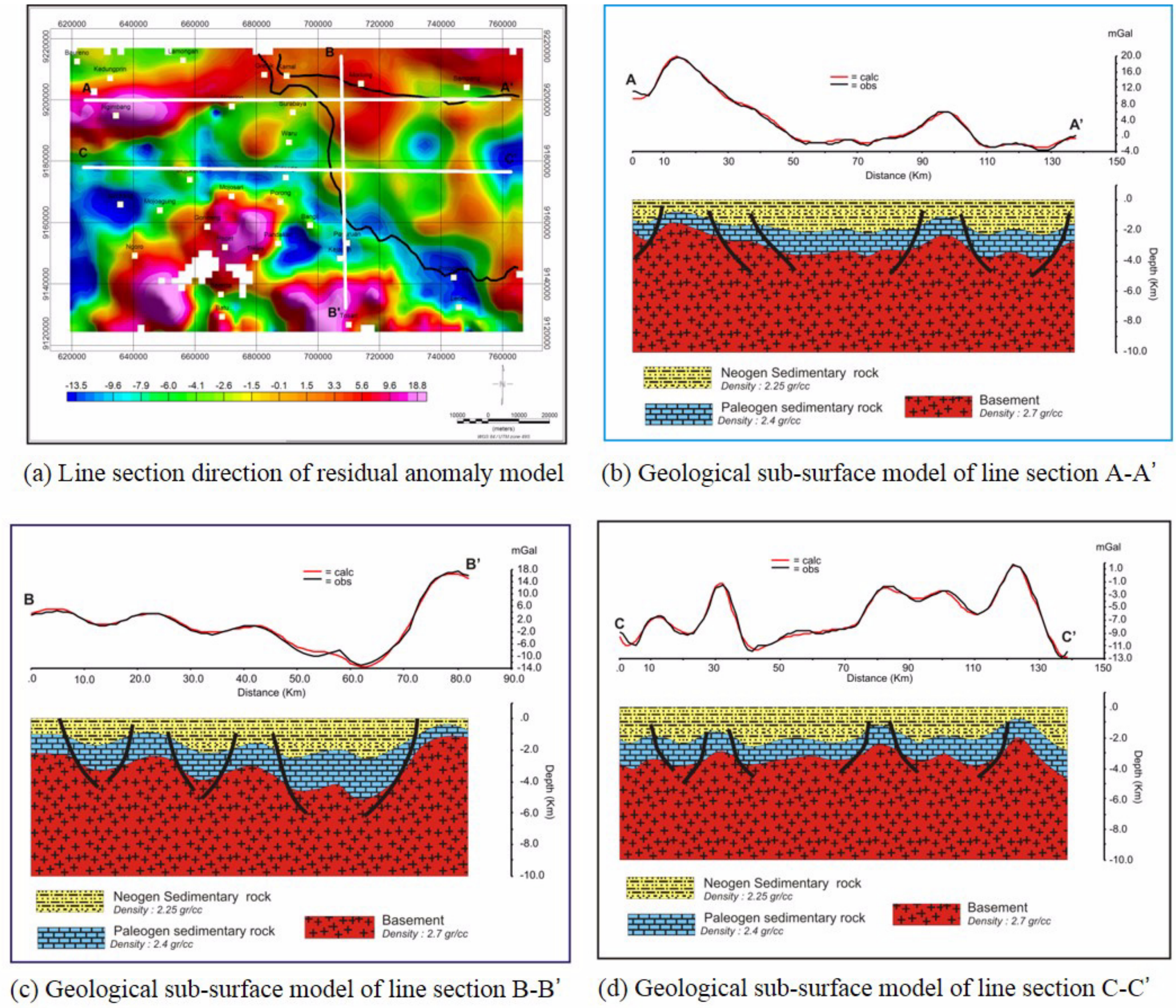


Figure 12. Delineation of sedimentary sub-basin pattern in the study area based on residual gravity anomaly

The reference of density value that is used in 2D modeling is based on stratigraphic information and book literature density according to Telford *et al.*, (1990). Figure 13.b shows the line-section of the 2D subsurface geological model along the AA' profile, from the figure can be seen that the basement in the study area interpreted as a continental and metamorphic crust with a mass density value of 2.7 gr/cc. Above the basement interpreted as Paleogen-aged sedimentary rocks with a mass density value of 2.4 gr/cc. This Paleogen sedimentary rock is combination of the Ngimbang, Kujung and Prupuh Formations consist of sandstone, shale, limestone and coal. Above it deposited Neogene-aged sedimentary rocks which are combination of the Tuban Formation, Ngrayong, Wonocolo, Ledok, Mundu consist of sandstones, shale, marl, limestone, claystone, siltstone with mass density values of 2.25 gr/cc. The BB' line section has a north-south direction perpendicular to the AA' line section, this cross section passes through the southern Madura Island, the Madura Strait, the mainland of Java in Pasuruan to the south of East Java area. The subsurface geological model of BB' line section as shown in Figure 13c, the figure shows that the bedrock is continental crust with a mass density value of 2.7 gr/cc, the upper layer is a Paleogene sedimentary rock with a mass density value of 2.4 gr/cc and the top layer is a Neogene-aged sedimentary rock which has a mass density value of 2.25 gr/cc. The CC' line section is located in the south of the BB' line section, same as the AA' and BB' line section, in the CC line section the bedrock is probably as continental crust that have to metamorphism process with a mass density value of 2.7 gr/cc, upper layers of bedrock Paleogen-aged sedimentary rock consist of sandstone, shale, limestone and coal with a mass density value of 2.4 gr/cc, and the top layer is Neogen-aged sedimentary rock consist of a combination of the Tuban, Ngrayong, Wonocolo, Ledok, Mundu Formations comprising of sandstone, shale, marl, limestone, claystone, siltstone with a mass density value of 2.25 gr/cc. The geological history of the East Java basin is closely related to the tectonic activity in the Southeast Asian region and controlled by the interaction of the Indo-Autralia Ocean plate which move to north, the Pacific ocean plate move to the west and the relatively stable Eurasian plate. This tectonic plate movement activity resulting the basement high and graben structure as shown at (Figures 11 and 12). The East Java Basin was formed in the Eocene, starting with rifting and spreading of the basement then filling by the sedimentary rock and continued by formed of anticline structure. Basement configuration that have been deformed into heights and lows structure make the basins in this area rich in hydrocarbon (Panjaitan, 2010). The result of spectral decomposition analysis (Figure 10) shows the pattern of anomaly structures from 1Km to 4Km depth, at 1Km depth the structure of the anomaly is more complex, it can be seen from the number of anomaly closure both high anomaly and low anomaly. The red colour anomaly in the southern part is probably caused by the presence of volcanic rocks that have high density, while in the northern part of the high anomaly is probably due to the lifting of the basement rock. The structure of the basin is clearly visible at 2Km and 3 Km depth, at this depth the basin shown in blue colour while the height is shown in green-red colour. This structure pattern at a depth of 2 Km and 3 Km is likely to be interesting for further research from the aspect of petroleum systems because there are many graben and anticline which are probably as a place for



(a) Line section direction of residual anomaly model

(b) Geological sub-surface model of line section A-A'

(c) Geological sub-surface model of line section B-B'

(d) Geological sub-surface model of line section C-C'

Figure 13. Line section direction and subsurface geological model of AA, BB, and CC sections in the East Java basin on the Madura Strait and surrounding area.

hydrocarbon accumulation. The structural pattern at depth of 4 Km shown a relatively homogeneous anomaly pattern where the low anomaly pattern in the middle is shown in blue colour which according to (Satyana, 2008) is a low axis (depression) which extend from Bogor, North Serayu, Kendeng to Madura Strait. Sedimentary rock with Miopliocene and Plistocene aged were quickly deposited on this low and compressed then resulting fold and thrust belt structure in the middle of Java island. Miopliocene and Plistocene-aged sediments were quickly deposited rapidly on this low and compressed resulting in folds and thrust belt in the middle of Java Island. The low anomaly in the middle part known as the Kendeng zone is interesting because sediment deposits in this area are quite thick and based on Satyana (2016), the East Java Basin and its surroundings area, it is possible for petroleum system in kenozoic-aged based on deep seismic, geochemical and tectonic data.

CONCLUSION

The result of spectral analysis from gravity data shows that the average basement depth of the study area is around 3.2 Km, the number of sub-basins detected based on the analysis of residual anomalies is 10 sub-basins. The result of spectral decomposition of gravity data shows that the subbasin is visible at depths of 1 Km, 2Km and 3 Km, whereas at a depth of 4 Km the subbasin pattern is not clearly visible, this is probably that at depth of 4 Km reflecting basement undulation. The structural pattern that can be found from the results of qualitative and quantitative analysis are basement high, graben, and fault. 2D modeling results shows that the basement of the study area interpreted as a continental crust and metamorphic rock with a mass density value of 2.7 gr/cc. The results of gravity analysis are useful for knowing graben patterns and basement high which are interesting for further research to find out the more detail of petroleum system in this area.

SUGGESTION

Detail geophysical method such as 3D seismic survey based on different physical properties need to be carried out to know structural patterns and hidrocarbon trap arround Madura Strait subbbasin and surrounding area, East Java.

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