GEOLOGICAL INTERPRETATION OF NORTH MADURA OFFSHORE SEDIMENTARY BASIN BASED ON GRAVITY DATA ANALYSIS

INTERPRETASI GEOLOGI CEKUNGAN SEDIMEN PERAIRAN UTARA MADURA BERDASARKAN ANALISIS DATA GAYABERAT

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ABSTRACT: The area of north Madura offshore is one of the sedimentary basins within the North East Java Basin which has interesting paleogeographical developments. These developments are the result of various sedimentation processes and changes in the depositional environments. The purpose of this study is to identify subsurface geological structures, delineate sedimentary sub-basins, and estimate sediment thickness. For that, we do spectrum analysis, optimum upward continuation filtering, spectral decomposition analysis, 2D forward modeling and 3D inversion of gravity data. The results of the spectral analysis show that the average thickness of sedimentary rocks in the study area is around 3.788 km. From the gravity data analysis, 10 sedimentary sub-basins were delineated, indicating structural patterns of basement high, grabens, and faults. 2D and 3D modeling revealed four layers of stratigraphy, in order from youngest to oldest are Tertiary-Neogene sedimentary rocks with a density value of 2.1 gr/cc, the Tertiary-Neogene sedimentary rocks with a density of 2.3 gr/cc, the Tertiary - Paleogene sedimentary rocks with a density of 2.45 gr/cc, and the basement layer identified as volcanic igneous rock with a density of 2.67 gr/cc.

Keywords: Gravity method, optimum upward continuation filter, modeling, spectral analysis decomposition, 2D forward modeling and 3D inversion

***ABSTRAK**: Wilayah lepas pantai utara Madura merupakan salah satu daerah cekungan sedimen pada cekungan Jawa Timur Utara yang memiliki perkembangan paleogeografi yang menarik. Hal ini didasarkan pada proses sedimentasi yang bervariasi serta perubahan lingkungan pengendapan yang beragam. Tujuan dari penelitian ini adalah untuk mengidentifikasi struktur geologi bawah permukaan, mendelineasi subcekungan sedimen serta memperkirakan ketebalan sedimen. Analisis data gayaberat yang digunakan yaitu analisis spektrum, filter optimum upward continuation, analisis dekomposisi spektral, serta pemodelan 2D forward modeling dan inversi 3D. Hasil analisis spektral menunjukkan bahwa tebal batuan sedimen rata rata di daerah penelitian adalah sekitar 3.788 km. Delineasi sub-cekungan dari analisis data gayaberat ditemukan 10 sub-cekungan sedimen, pola struktur berupa tinggian batuan dasar, graben dan patahan. Adapun berdasarkan hasil pemodelan 2D dan 3D yang dilakukan diperoleh model lapisan yang terdiri atas empat lapisan dari lapisan paling muda ke lapisan paling tua yaitu batuan sedimen berumur Tersier-Neogen dengan nilai densitas 2.1 gr/cc, lapisan batuan sedimen TersierNeogen dengan densitas 2.3 gr/cc, batuan sedimen Tersier-Paleogen dengan densitas 2.45 gr/cc, serta lapisan basement yang berupa batuan beku vulkanik dengan densitas 2.67 gr/cc.*

***Kata Kunci:** gayaberat,* filter optimum upward continuation*, analisis dekomposisi spektral,* 2D forward modeling*, inversi 3D*

INTRODUCTION

Geologically, the North East Java Basin is part of the back-arc basin located in the southeastern region of the Sunda microplate. This basin is flanked by a series of mountains (known as the volcanic arc) and the Indo-Australian plate to the south (Walidah, 2011). The formation of the North East Java Basin resulted from the collision of the Australian continent Plate which subducted to the northwest under the Asian plate (Walidah, 2011). Regarding its constituent rocks, this basin is a geosyncline comprising Tertiary deposits with a layer thickness of up to 6000 meters (Koesoemadinata, 1978).

As one of the main objectives of hydrocarbon exploration in Indonesia, the Middle Miocene sediment of the North East Java Basin have been studied extensively. However, studies on sub-basin delineation and basement configuration based on gravity analysis in the northern region of Madura have not been conducted. Nevertheless, from a stratigraphic and structural perspective, this area exhibits significant potential for oil and natural gas production. The diverse deposits ranging from fluvial faces to marine, along with deltaic and shallow sea depositional environments, suggest potential hydrocarbon sources. Furthermore, the structural history of the basin is characterized by significant influences from rifting and tectonic activities during the Cretaceous Age (Fatahillah, 2016).

Many geophysical methods can be used to explore sedimentary basins, including the gravity method. The gravity method is one of the geophysical methods that can be used to determine subsurface geological conditions based on the physical parameters of rock mass density. This technique, with its sensitivity to changes in both lateral and vertical directions, proves to be an applicable method for studying geological structures, bedrock, rock intrusions, and sedimentary basins (Grant and West, 1965). However, due to the significant ambiguity in gravity data, spectral analysis is conducted during the modeling to estimate the depth of the anomaly source (Setiadi et al., 2010).

In this study, spectral analysis was used (Setiadi and Marjiyono, 2018) to determine the depth of bedrock (basement) within the research area. Furthermore, spectral decomposition analysis was conducted (Setiadi et al., 2019) to reveal the anomalous structural patterns at different depths in the study area. To characterize the subsurface conditions, two-dimensional (2D) forward modeling was executed (Talwani et al., 1959) using Oasis Montaj software. Additionally, three-dimensional (3D) inverse modeling was conducted using Grablox software (Pirtijarvi, 2008). The study aimed to identify a sub-basin pattern, bedrock depth, basement high pattern, subsurface

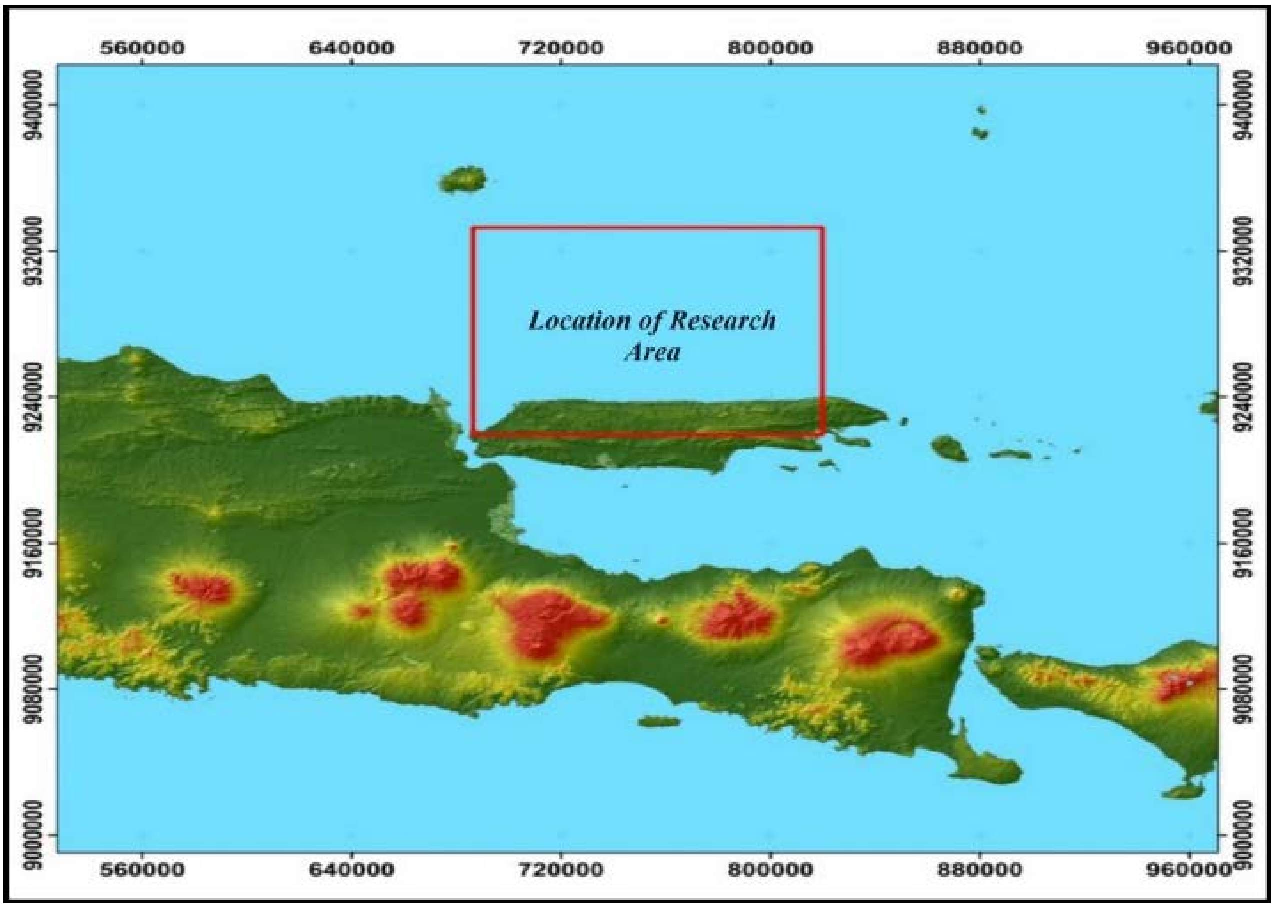

Figure 1. Location of research area of north Madura offshore.

structure pattern, 2D and 3D subsurface models that can be used as a reference or initial information in determining hydrocarbon sedimentary basin. The location of this study is in the offshore area of North Madura, North East Java Basin. Administratively, the research location is situated between coordinates (6º 03'34" - 7º 05' 38") S and (112º 41'10" - 113º 49' 32") E, including parts of Madura mainland and the north Madura offshore area (Figure 1).

METHOD

Ground gravity data used in this study was Geological Research and Development Centre data with a total of 526 data which measured using gravimeter G.826 as our primary data. The data was then integrated with free air anomaly (FAA) and bathymetry data from the Topex satellite. Spectral analysis was carried out to estimate the depth of sedimentary rocks and basement within the research area. Optimum upward continuation filters are applied to separate regional and residual anomalies from gravity data. This technique was carried out by doing an upward continuation of Bouguer anomaly data at several different heights, and then correlating it with the regional anomalies from other methods which are considered as references. The optimum height is obtained based on the highest correlation value. Moreover, spectral decomposition analysis was also conducted as an additional step to identify the structure and sub-basin patterns at specific depths and the depth determination was carried out sequentially from a shallower to a deeper depth. To obtain the expected basement depth, the cut-off value was set up from the graph of Ln A and K, which was then used to determine the window width for filtering.

2D forward modeling is used to calculate the effect of the subsurface model on gravity anomaly with an arbitrary in the form of a polygon, representing the subsurface state (Talwani et al., 1959). The density values utilized for generating sub-surface models in 2D forward modeling are based on Telford et al., (1990). Meanwhile, 3D inversion modeling is done by optimizing the Singular Value Decomposition approach on gravity anomaly. Singular Value Decomposition (SVD) is a matrix factoring method that is closely related to the singular value of the matrix, which is one of the well-known numerical analysis techniques for matrix diagonalization. The results of 3D inversion modeling appear as a distribution of rock mass density, providing a clearer depiction of the subsurface and enhancing the subsurface model information obtained from 2D forward modeling. Inversion modeling was carried out using Grablox 1.6 software (Pirttijarvi, 2008). The research flowchart is presented in Figure 2.

RESULTS AND DISCUSSION

Bouguer Anomaly

Bouguer anomaly illustrates the response to variations in subsurface rock mass density. Bouguer Anomaly values in the study area range between 8.9 - 49.5 mGal (Figure 3). The high anomaly is represented by a red color distribution in the southern and eastern parts of the area. These value are interpreted as uplifted bedrock and indicates the presence of high density rocks that occupy this area. The low anomaly values in the central to the northern areas are probably due to the presence of graben or depocenters, suggesting that the sedimentary rocks in that area are relatively thicker.

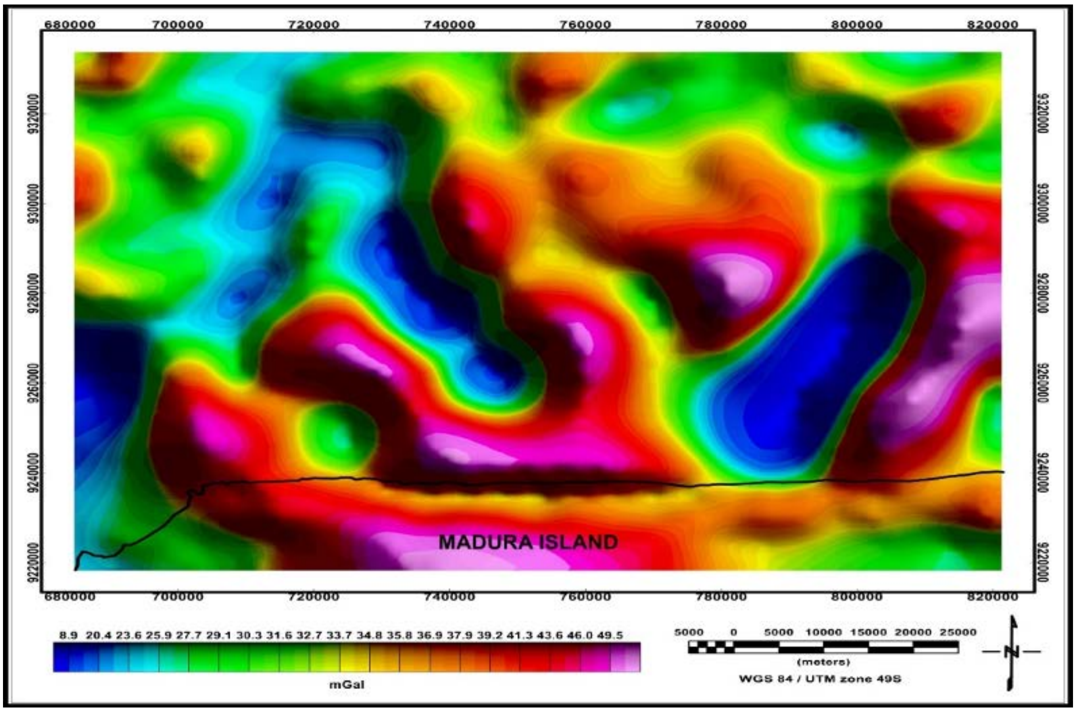

Figure 3. Bouguer anomaly map North Madura Offshore

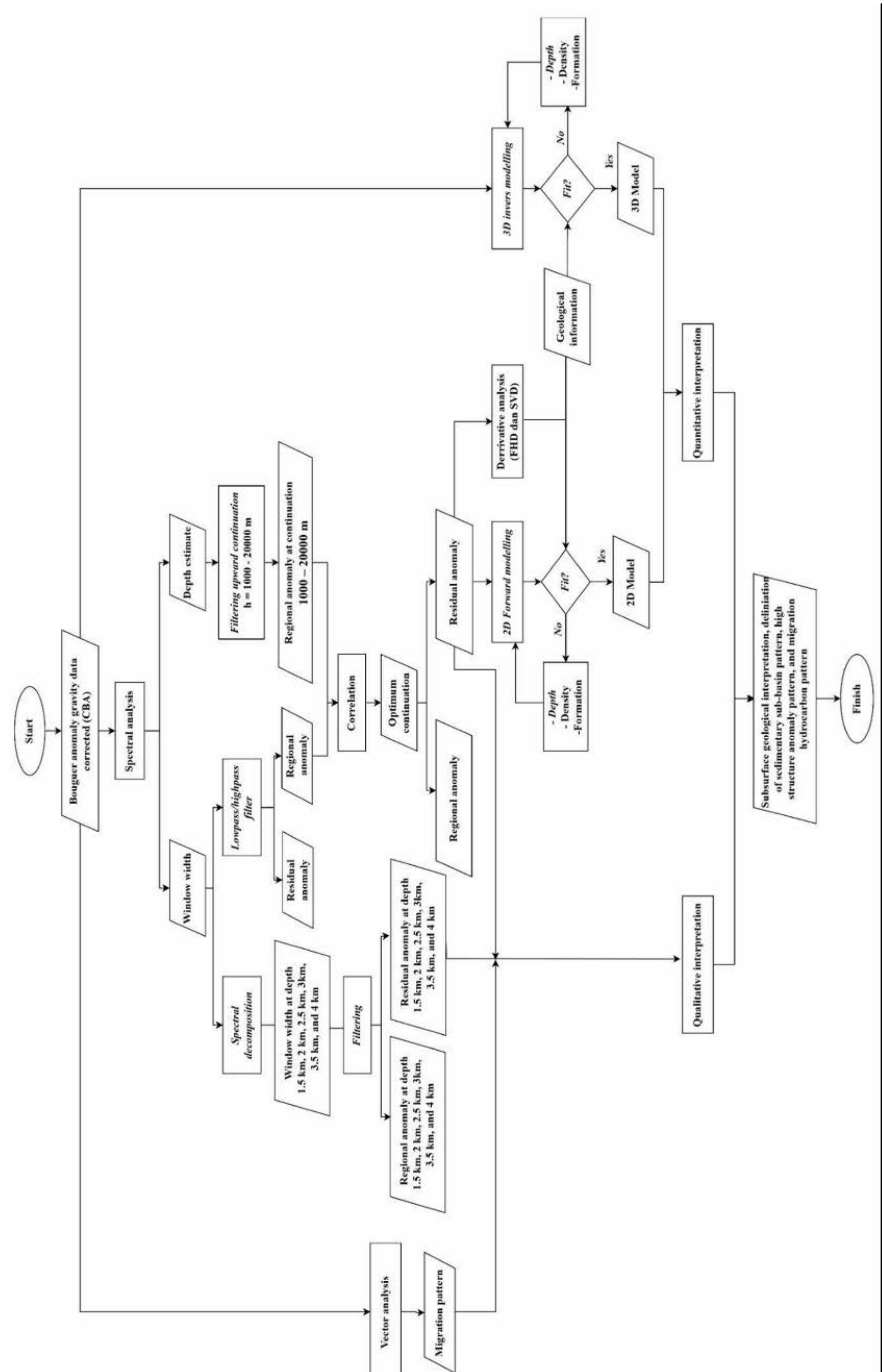

Figure 2. Research Flowchart

Spectral Analysis

Spectral analysis was carried out in order to estimate the depth of bedrock (basement) in the research area. In this study, 11 cross sections with northeast-southwest and northwest-southeast directions were analyzed by a Fourier transform (FFT) to determine the signal content along the lines (Figure 4(a)). The relationship between wave number (K) versus log normal amplitude (Ln A) is illustrated in Figure 4(b). On spectral analysis, the gradient or the slope of the line from the graph of ln A with respect to K is the depth of the discontinuity plane. A large gradient value reflects the discontinuity area of the regional (deep) anomaly, while a low gradient value indicates the discontinuity area of the residual (shallow) anomaly. The intersection of the regional and residual discontinuity plane gradients is the kc wave number (cut-off). The

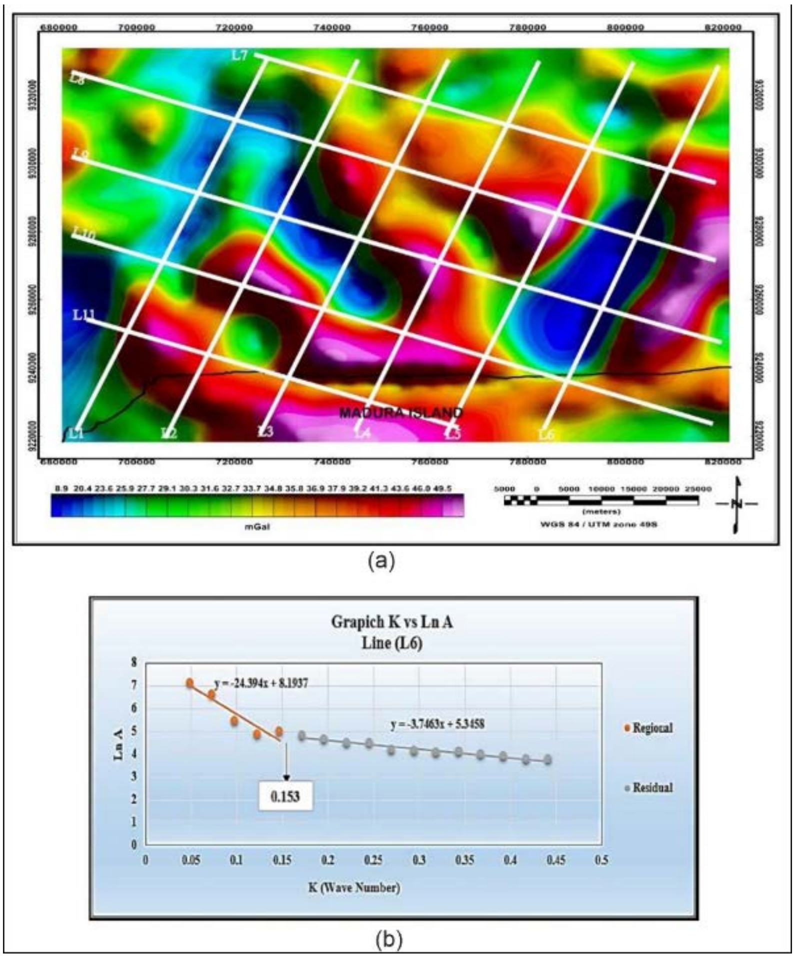

Figure 4. (a) Bouguer anomaly map and cross section direction of spectral analysis, and (b) Example of spectral analysis chart of the line L6

Table 1. Result of the calculation of regional and residual anomaly depth based on spectral analysis.

Line	Depth Reg (Km)	Depth Res (Km)	Kc	N	Window Width
L1	-22.62	-2.9727	0.151	21	40
L2	-18.443	-3.1577	0.181	19	36
L3	-14.578	-3.1216	0.181	19	36
L4	-24.325	-3.6123	0.158	21	40
L5	-22.801	-3.4334	0.172	19	36
L6	-24.394	-3.7463	0.153	21	40
L7	-24.764	-3.4386	0.158	21	40
L8	-17.79	-4.4386	0.151	21	40
L9	-27.457	-4.8654	0.141	23	44
L10	-38.97	-5.5182	0.147	23	44
L11	-24.604	-3.372	0.153	21	40
Average	**-23.704**	**-3.788**		**21**	**40**

average depth of the deep discontinuity field in the study area is -23.704 km which is estimated as the depth of the lower crustal discontinuity field (basement). The average depth of the shallow discontinuity field is -3.788 km, interpreted as the average depth of sedimentary rocks (border between bedrock and sedimentary rocks) in the study area (Table 1).

Optimum Upward Continuation

Filter upward continuation at an altitude of 1000 – 20000 m was conducted to determine the optimum regional anomaly. Upward continuation is calculated on the map at each altitude using the grid size (1.5 x 1.5) Km. The obtained regional anomaly was then correlated with regional anomaly from other methods (as a correlation reference), resulting in a regional anomaly from optimum upward continuation (Table 2). From Table 2, it can be seen that the highest correlation value is obtained at an altitude continuity of 5000 m (Figure 5). The height of this maximum correlation is the estimated optimum height of upward continuation that is used to calculate the residual anomaly. When the altitude upward continuation is lower than the optimum height, an anomaly upward continuation consists of two components, namely regional and residual anomaly. The residual anomaly decreases and almost disappears as it approaches the optimum value. In contrast, when the altitude of upward continuation is higher than the optimal height, the regional anomaly is attenuated and

Table 2. The correlation between the regional anomaly results of the continuation and the reference regional anomaly

UPWARD	HEIGHT	CORRELATION VALUE
UP_1000	1000	0.988182
UP_2000	2000	0.991887
UP_3000	3000	0.993896
UP_4000	4000	0.994779
UP_5000	5000	0.994959
UP_6000	6000	0.994679
UP_7000	7000	0.994121
UP_8000	8000	0.993402
UP_9000	9000	0.99254
UP_1000	10000	0.991711
UP_11000	11000	0.990875
UP_12000	12000	0.990008
UP_13000	13000	0.98911
UP_14000	14000	0.988418
UP_15000	15000	0.987724
UP_16000	16000	0.987008
UP_17000	17000	0.986311
UP_18000	18000	0.985696
UP_19000	19000	0.985156
UP_20000	20000	0.984623

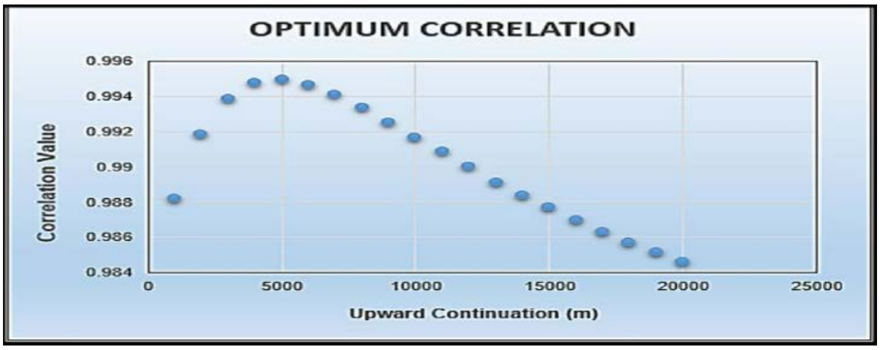

Figure 5. The optimum correlation curve between the regional anomaly of the continuation result and the reference regional anomaly

may reach a zero value. At the optimal height, this condition produces a regional component. Hence, the maximum correlation shows the optimum regional component because it is not affected by residual anomalies and has not experienced attenuation, as shown in Figure 5.

Regional and Residual Anomalies

Separation of regional and residual anomalies is carried out based on the results of the optimum upward continuation filtering of gravity data. The value of regional anomaly ranges from 19.4 to 43.3 mGal (Figure 6a). This anomaly pattern shows a relatively longer wavelength than the Bouguer anomaly, the regional anomaly reflects the rock structure with a deeper position. The high anomaly is suggested to be influenced by rock undulations at the depth of the lower crust or Moho which may rise upwards. The high anomaly pattern in the south is relatively west-east direction, while the high anomaly in the east part is relatively northeast-southwest ward. This high anomaly direction is estimated to be influenced by the RMKS fault zone (Rembang – Madura – Kendeng) and the Meratus pattern. Meanwhile, low anomalies are scattered in the central part to the southern part of the study area.

The residual anomaly pattern (Figure 6b) is obtained from the subtraction between the Bouguer anomaly and the regional anomaly resulting from optimum upward continuation filtering. From the figure, it can be seen that the anomaly value ranges from -11.7 to 7.2 mGal. The structural anomaly pattern is more complex than the Bouguer anomaly pattern because the residual anomaly represents an anomaly structure with a shallower depth

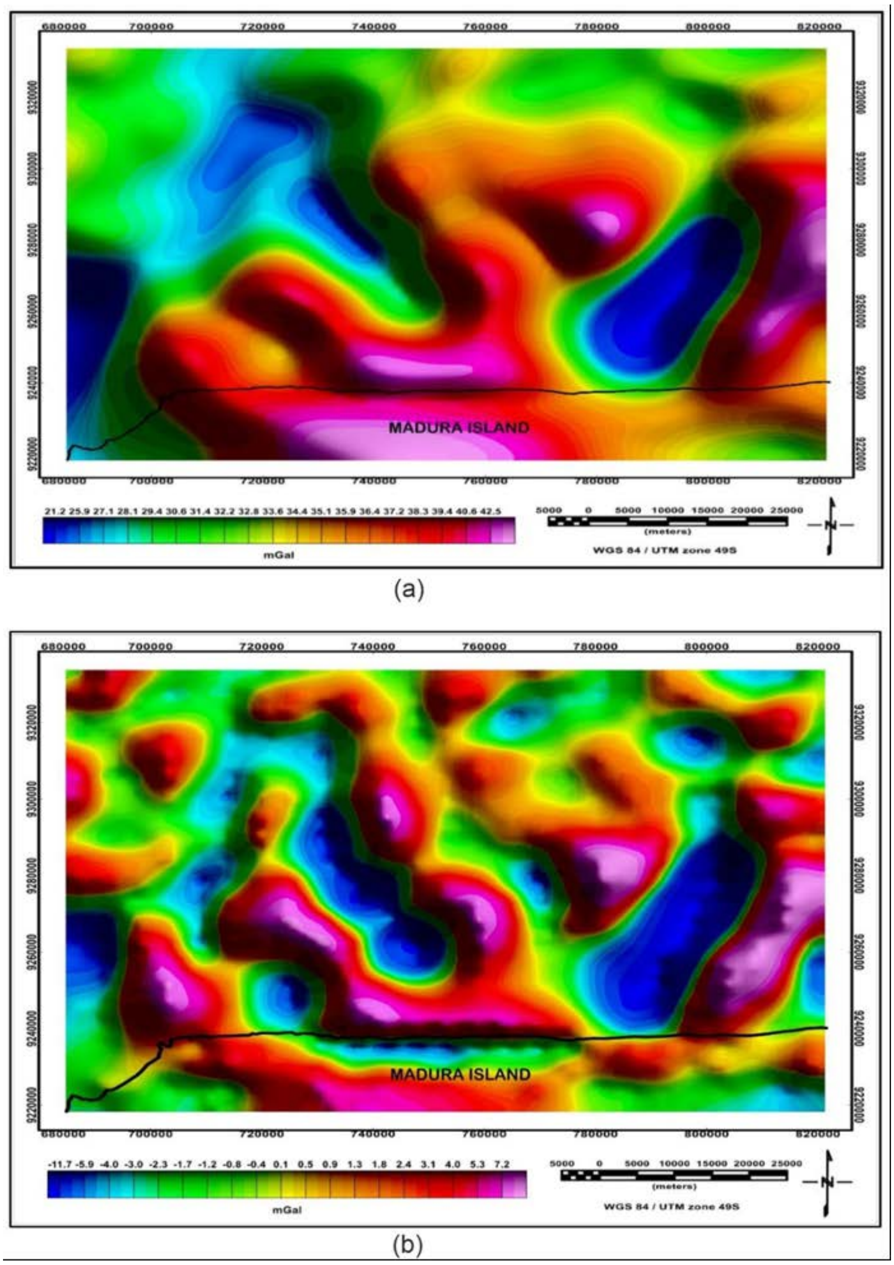

Figure 6. (a) Regional anomaly map, and (b) Residual anomaly map of North Madura Offshore

and shorter wavelength. The results of this residual anomaly will be used to make a qualitative interpretation.

Spectral Decomposition

Spectral decomposition analysis is carried out by parsing or making several cut-off wave numbers and window widths, which are divided into different depths. The purpose of spectral decomposition analysis is to identify patterns of anomalous structures at predetermined depths. In this analysis, the cut-off value is calculated based on the results of the Fourier transform on 11 paths that have been made previously in the spectral analysis. In this study, the depths of the residual anomalies selected for analysis were at depths of 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, and 4 km. The result reveals that shallower anomalies indicate more complex structures, in contrast, deeper anomaly reflects more homogeneous structure patterns (Figure 7).

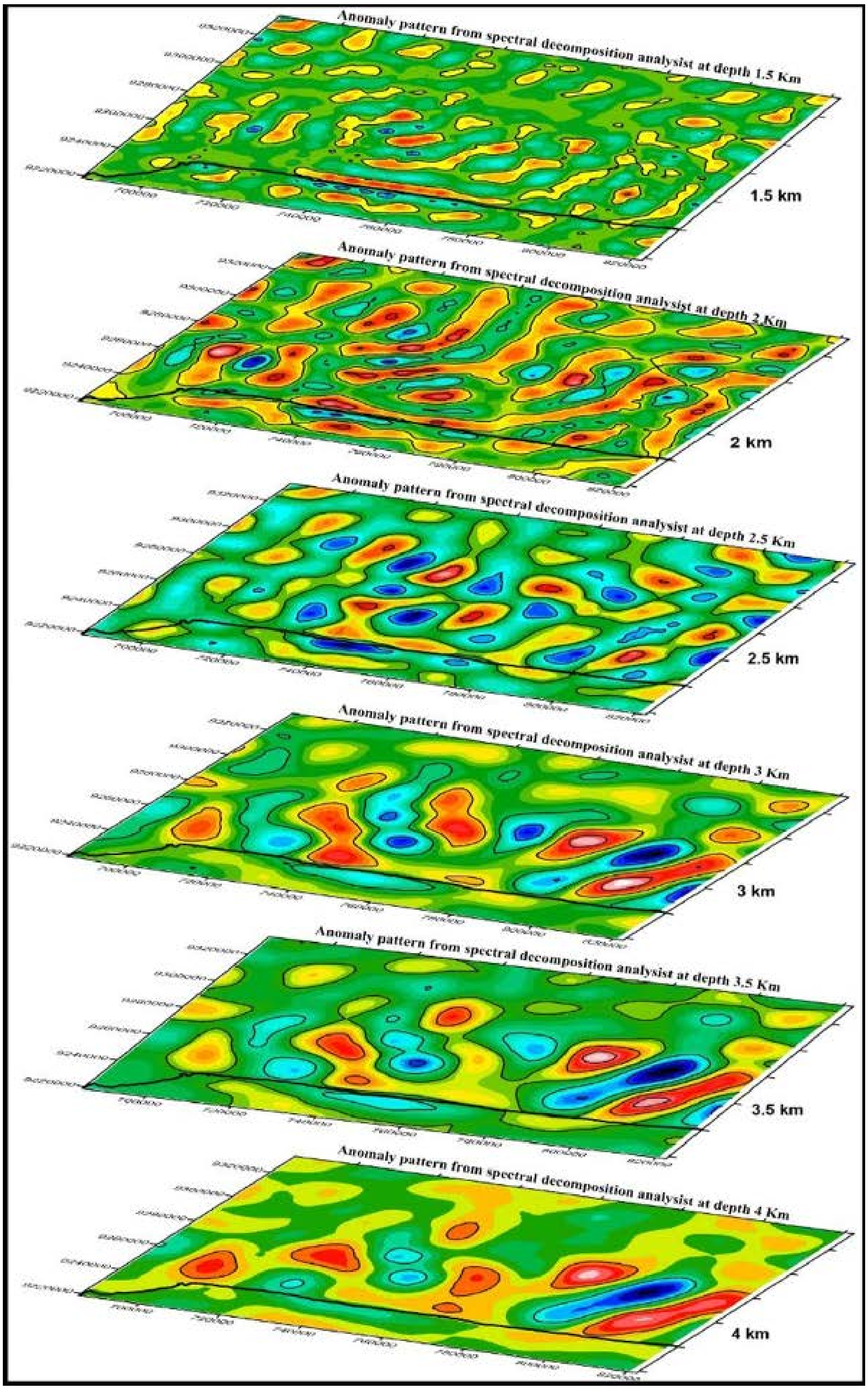

Figure 7. Anomaly pattern at 1.5 km, 2 km, 2.5 km, 3 km, 3.5 km, and 4 km depths based on spectral decomposition analysis

This result is in line with the theory suggesting that a deeper density of the subsurface rock characterizes a homogenous pattern (Febriansyah et al., 2017). Analyzing the anomaly pattern for each depth, the residual anomaly at 4 km depth appears more regional, while the anomaly pattern at 1.5 km depth still shows complexity, forming a closures pattern. The results of the residual anomaly in the spectral analysis show that the boundary of the discontinuity field between the sedimentary rock and the basement is at a depth of 3.78 km. This finding aligns with the results of spectral decomposition analysis, where at 4 km depth the anomaly pattern is similar to residual anomaly from spectral analysis. Meanwhile the residual anomaly pattern of the spectral decomposition analysis, at 3 km and 3.5 km depths exhibits relatively similar to the one that resulted from the separation of the anomaly with optimum upward continuation filtering.

Qualitative Interpretation of Sedimentary Basins

Qualitative Interpretation was conducted to determine the lateral changes of anomalies based on residual anomaly using optimum upward continuation filtering. Furthermore, the structural pattern, basement high and sub-basin delineation can be recognized by this qualitative interpretation. In general, the structural pattern in the study area (Figure 8c) consists of two main directions, namely east-west and northeast-southwest. The west-east trending structure might be affected by the RMKS fault zone (Rembang – Madura – Kendeng) (Satyana et al., 2004), while the northeast-southwest trending structure pattern might be affected by the Meratus pattern, which is the dominant structural pattern in the East Java region. The height pattern (basement high) as shown in the residual anomaly (Figure 8a) shows a relatively east-west and northeast-southwest direction.

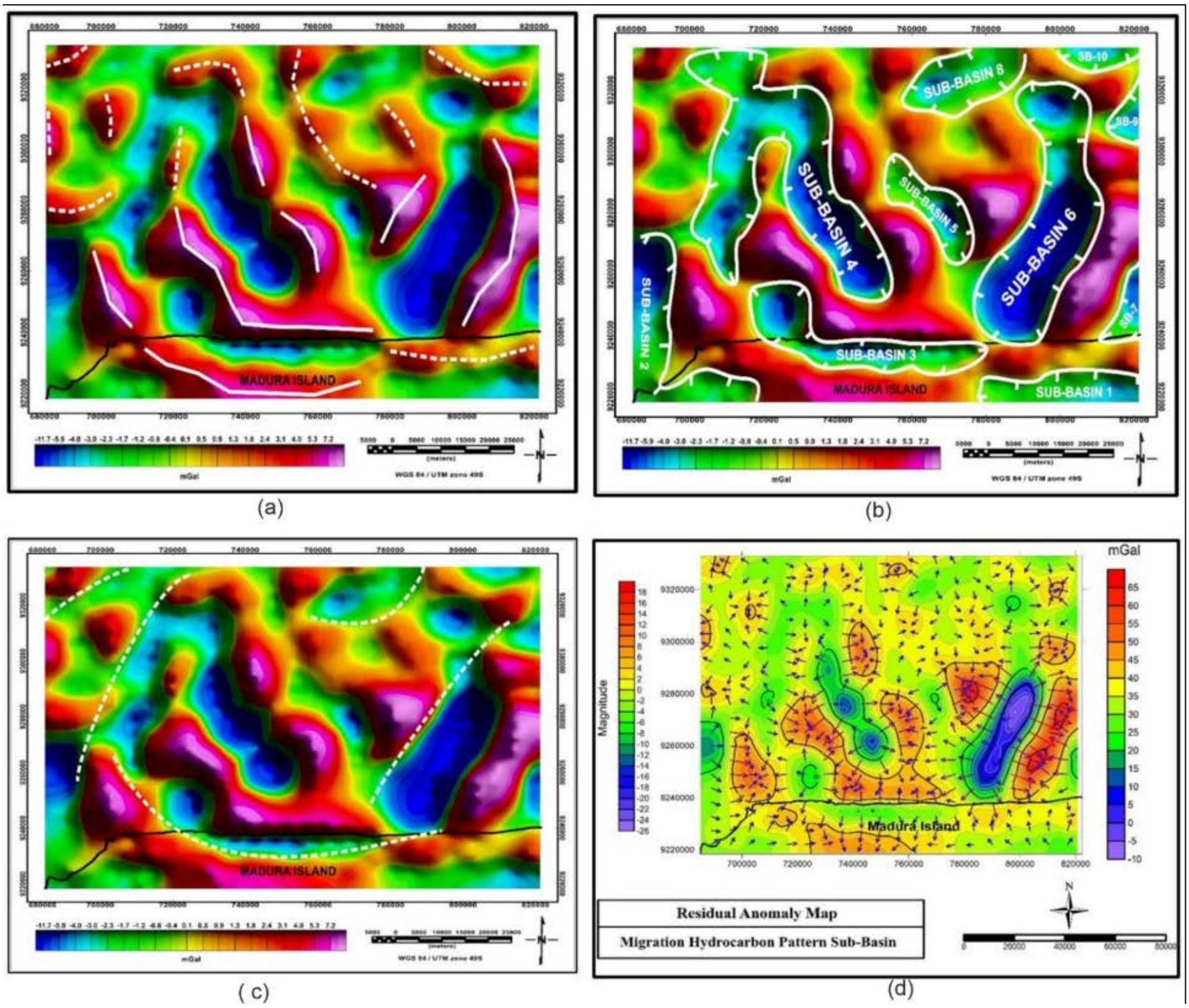

Figure 8. (a) Basement high pattern, (b) sub-basin delineation, (c) Lineament structure pattern, (d) Migration hydrocarbon pattern North Madura Offshore.

These basement high patterns will later be developed into anticlinal structures which are important for the petroleum system analysis. In the southern part of the study area, the relative basement high pattern appears to be oriented east-west, likely influenced by the RMKS fault zone (Rembang – Madura – Kendeng). Meanwhile, in the southern to the northern part of the study area, the high anomaly is relatively northeast-southwest direction. This might be due to the influence of the Meratus pattern.

The delineation pattern of the sedimentary sub-basins determined based on residual anomaly consists of 2 (two) large sub-basins and 8 (eight) small sub-basins (Figure 8b). These sub-basins are bounded by the surrounding basement high patterns, and characterized by low anomalies, indicated by blue to dark blue colors with the anomaly values ranging from -11.7 to 7.2 mGal. Figure 8(d) shows the alleged migration patterns of hydrocarbons identified based on vector analysis on the residual Bouguer anomaly map using Surfer software. Furthermore, the flow patterns can be predicted which tend to migrate from the low anomalies to the high anomalies, since the fluids move from high-pressure area to that of lower pressure.

Quantitative Interpretation

To determine the subsurface geological model, which includes the dimensions or size of the subsurface model, the types of constituent rocks based on the geology of the study area and rock density parameters, quantitative interpretation was conducted. The results are expected to reveal the bedrock depth and the composition of the sedimentary rock above it. This quantitative interpretation involved 3D inversion modeling using the Grablox program (Pirttijarvi, 2008) and visualizing the 3D model using rockwork. The inversion results (Figure 9a) show that the density values of the model range from 2.37 to 3.0 gr/cc which is an illustration of the subsurface rock mass density in the north Madura offshore area, North East Java Basin. While Figure 9(b) displays the cross-sectional direction of the 2D model.

In the 2D model, Line A-A' (Figure 9c) is a northeast-southwest ward, while Line B-B' shows a northwest-southeast direction (Figure 9d). Within this path, the

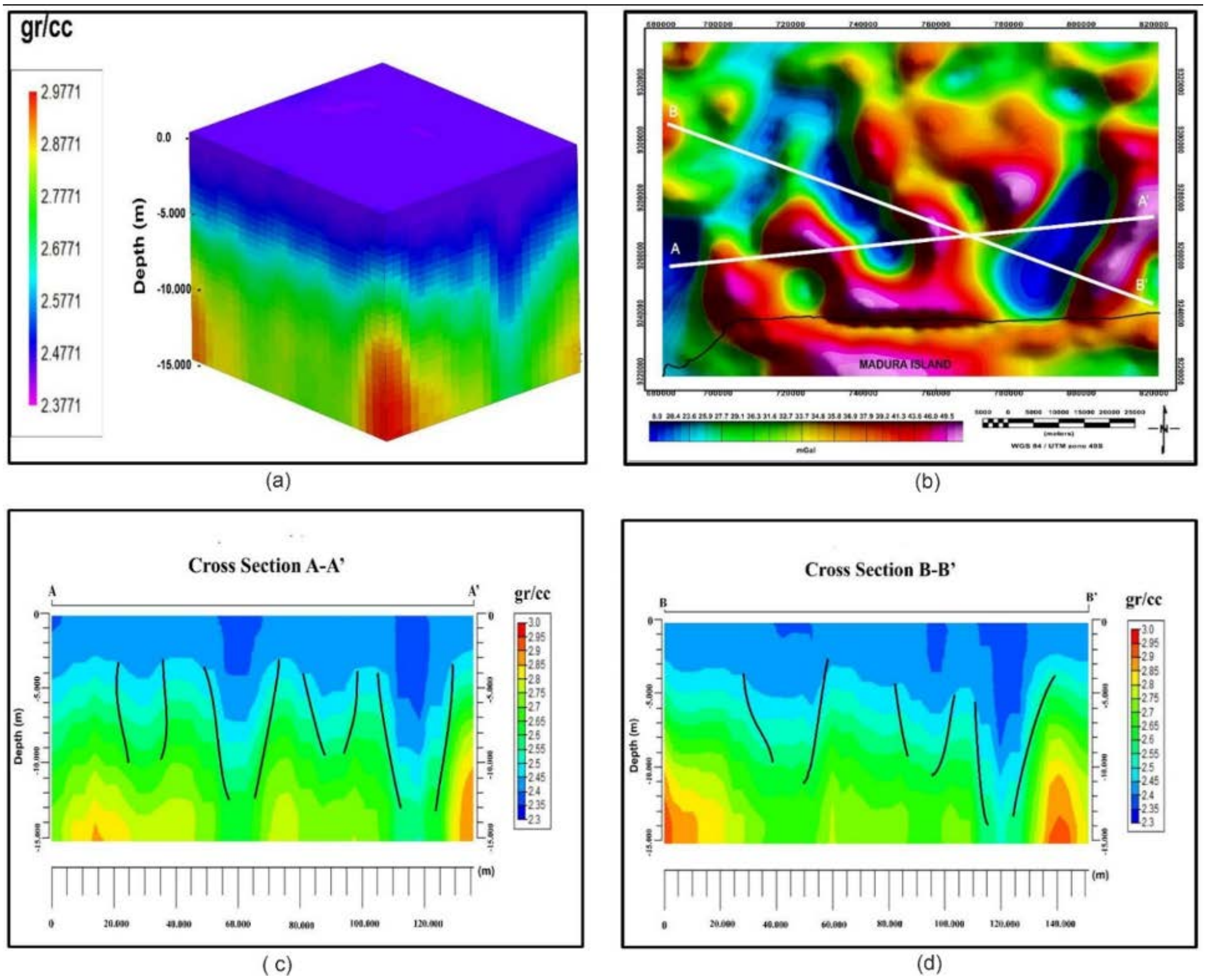

Figure 9. (a) 3D inversion modeling, (b) Line direction of 3D inversion modeling (c) 2D modeling of cross section A-A’, (d) 2D modeling of cross section B-B’.

presence of highs and lows anomalies can be identified, resembling sub-basins as indicated by the anomaly patterns along the modeling trajectory. From the model (Figures 9c and 9d), low-density values represent sedimentary rocks, identified as sub-basins within the study area, while higher-density values correspond to the basement underlying the sedimentary layers. In the A-A' and B-B' cross sections, two large sub-basins are bounded by basement high, which are interpreted as depocenters. To validate the 3D inversion modeling result, 2D modeling is used with forward modeling. This modeling is done by creating a subsurface model with an arbitrary cross-section in the form of a polygon that is considered to represent the subsurface state (Talwani et al, 1959). The density values used for making subsurface models on 2D forward modeling are based on references from Telford et al., (1990). Figure 10 displays a cross-section of the 2D forward modeling path (A-A' and B-B'), which is in a similar position to the path in the 3D inversion modeling.

The 2D modeling of the residual anomaly on the Line A-A' was conducted along 132 km length (Figure 11a), while the length of the Line B-B' model was 148 km (Figure 11b). The model result exhibits a subsurface model consisting of four layers including the basement and some sedimentary rock layers. The topmost layer is interpreted as Tertiary-Neogene sedimentary rock with a density value of 2.1 gr/cc. This layer is indicated as the Lidah Formation which is dominated by marine shale with some limestones formed from the decomposition of older limestones. This formation is the result of rapid deposition from the Paciran and Kalibeng Formations to the northeast (Putra, 2007). According to the regional stratigraphy of the North East Java Basin by Pringgoprawiro (1983 in Sribudiyani et al., 2003), this formation is younger from the early Pliocene to the Pleistocene. The second layer is interpreted as Tertiary-Neogene sedimentary rock with a density value of 2.3 gr/cc. This layer consists of alternations between sandy claystone with sandstone and foraminiferal-rich limestone, belonging to the orbitoid group from the Tawun formation. It is also composed of orbitoid limestone and claystone at the bottom and sandstone with the insertion of orbitoid limestone at the top from the Ngrayong formation. Additionally, it consists of unlayered marl and claystone, with sandy limestone and calcareous sandstone at the bottom of the Wonocolo formation.

The third layer is interpreted as Tertiary-Paleogene sedimentary rock with density a value of 2.45 gr/cc. This layer age ranges from the Late Oligocene – Miocene, composed of carbonate platforms from the Late Oligocene Prupuh Formation and followed by the growth of reef limestones in the Early Miocene. The lowest part is the basement layer which comprises volcaniclastic igneous rock with a mass density value of 2.67 gr/cc. This volcaniclastic layer covers the southern part of the basin area, dominated by eroded rocks from "Old Andesite

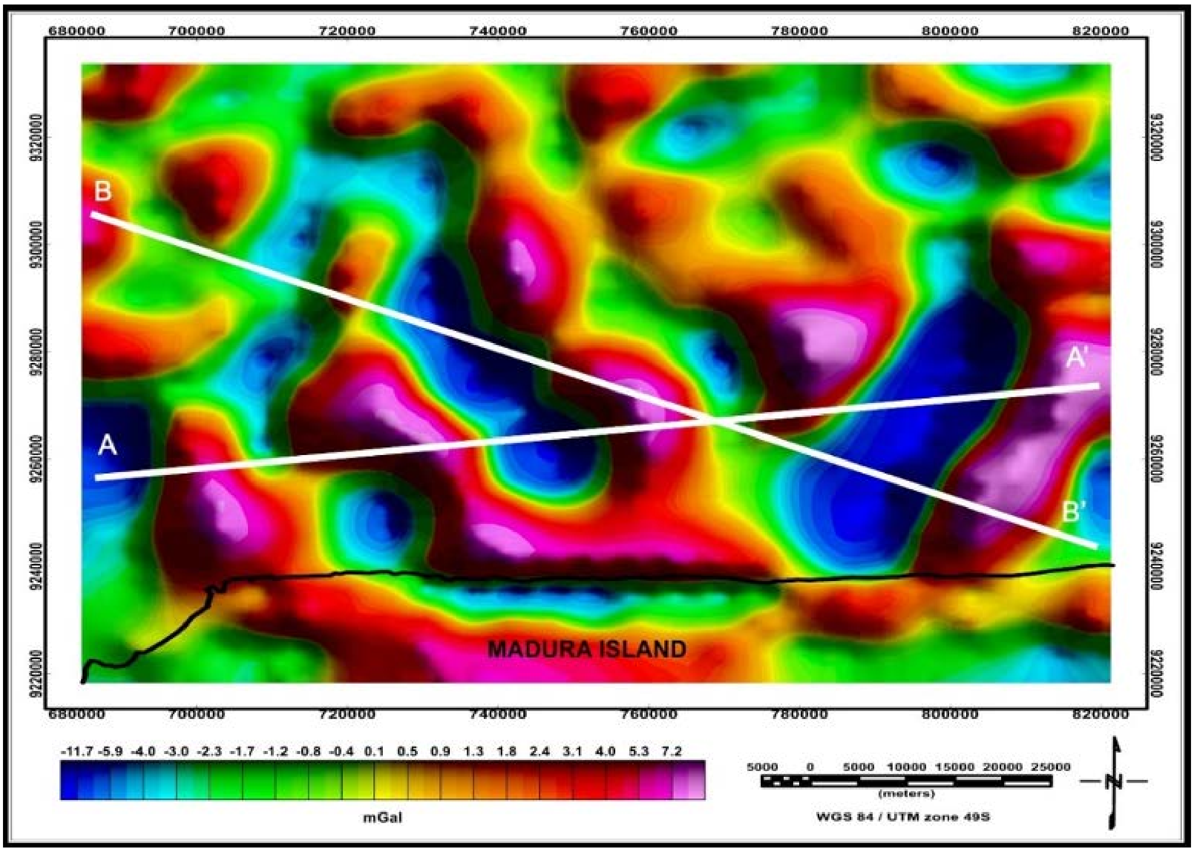

Figure 10. Line direction of 2D subsurface geological modeling of the North Madura Offshore

Formations" in the Cepu – Tuban area along the north coast and granite rock erosion, producing sandstone deposits from the Ngrayong Formation (Putra, 2007). Furthermore, to determine the fault structure, we conducted the second vertical derivative (SVD) analysis. Thrust faults are identified if the positive SVD value is lower than the negative SVD value, whereas, normal faults are identified when the positive SVD value is greater than the negative SVD value. The results indicate that the fault in the basin area is dominated by normal faults.

The results of qualitative gravity data analysis show two quite large sub-basins, namely sub-basin4 and sub-basin6 with a sedimentary rock thickness of around (5-6) Km. The results of the second vertical derivative analysis and 2D modeling in these two basins show the existence of a normal fault structure which is characteristic of back-arc basins. These sedimentary basins are something of interest for the development of the petroleum system in this area. The results of the spectral decomposition of gravity data show different structural patterns at several depths. The sub-basin pattern clearly appears at a depth of 4 km,

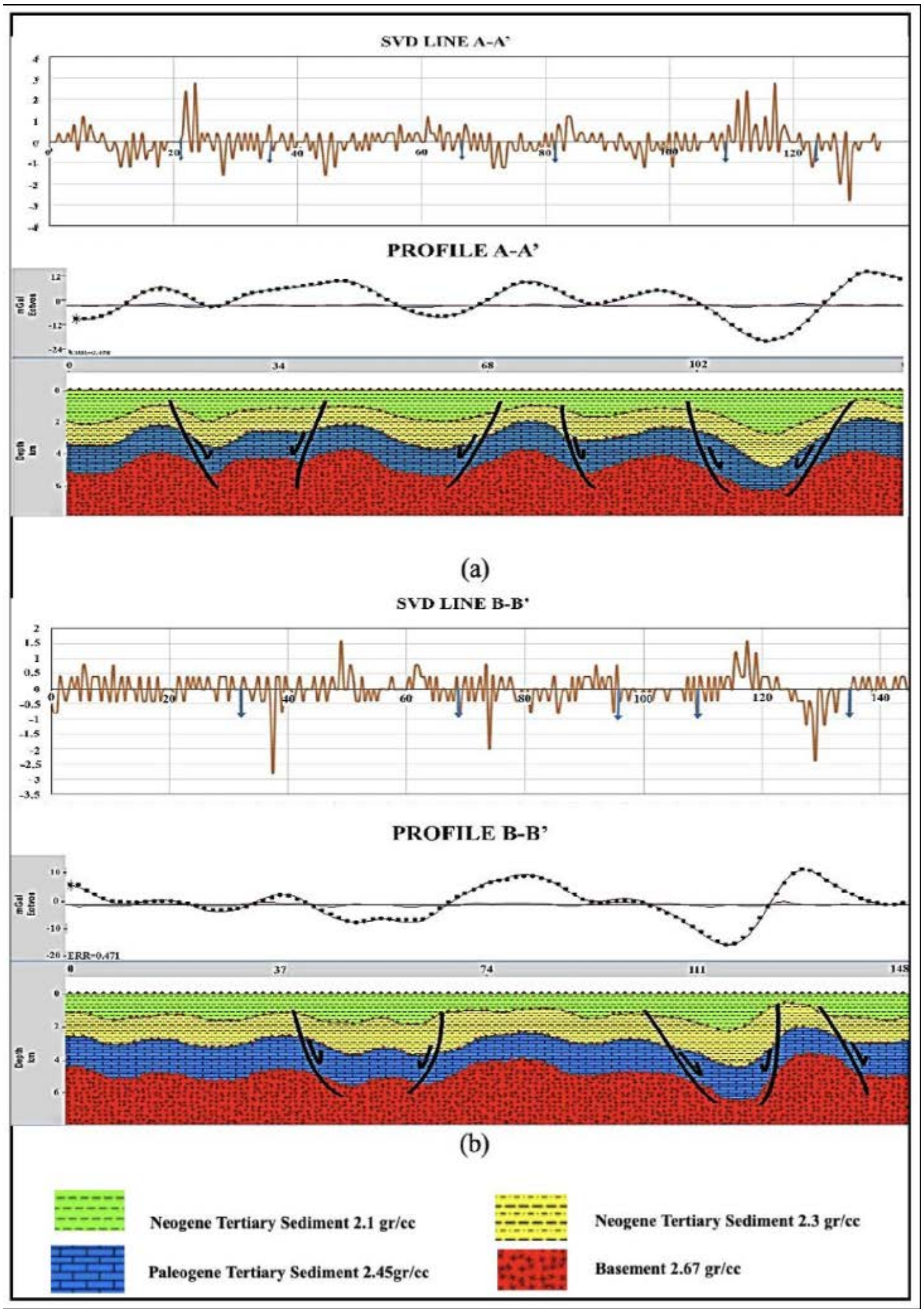

Figure 11. (a) 2D Model of subsurface geology A-A' line section, (b) 2D Model of subsurface geology B-B' line section of the North Madura Offshore.

characterized by a simpler structural pattern, more complex structures are visible at shallower depths. The basement highs pattern, fault structures, and depocenters are clearly visible in the 2D model (figure 11), the anticline structure appears at a depth of 1.5 km, this is in accordance with the anticline structure seen in the spectral decomposition results (figure 7). The existence of fault structures, sub-basins, and basement highs in the north Madura offshore basin is interesting for further study to determine the potential of the petroleum system in this area.

CONCLUSIONS

The Bouguer anomaly map shows that the high anomalies are scattered in the southern and eastern parts of the study area, while the central to northern parts exhibit low anomalies surrounded by high anomalies. The results from spectral analysis indicate an average depth of 23.704 km for deep discontinuities field (representing lower crust) and 3.788 km for shallow discontinuities field (basement). Filtering upward continuation identified the optimal height at 5000 m, used in determining regional and residual anomalies. Regional anomaly indicates a long wavelength anomaly which is usually interpreted as a regional (deep) structure while residual anomaly reflects shorter wavelength anomaly which is interpreted as a local (shallow) structure. Based on the qualitative interpretation, the height pattern of the study area is relatively west-east direction in the southern part and relatively northeast-southwest in the central to northern parts. This might be due to the influence of the RMK fault in the south and the Meratus pattern in the central to northern parts. Additionally, sub-basin delineation identified 2 large sub-basins and 8 smaller sub-basins characterized by low anomalies. These sub-basins are limited by the surrounding basement high. The bedrock that underlies the research area is volcaniclastic igneous rock with a mass density value of 2.67 gr/cc. The modeling results reveal several thick sedimentary basins, fault structures, and anticlines that are interesting for further exploration in petroleum studies.

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REFERENCES

Fatahillah, Y., 2016. Penentuan Potensi Batuan Induk Menggunakan Model Log TOC, pada Formasi Ngimbang, Lapangan “Arrazi”, Cekungan Jawa Timur Utara. *Bachelor thesis*. Institut Teknologi Sepuluh Nopember. Surabaya. *Unpublished.*

Febriansyah, D., Haerudin, N., Suharno, and Setiadi, I., 2017. Studi Pola Sub-Cekungan Hidrokarbon Menggunakan Analisis *Spectral Decomposition*, Pemodelan 2D Dan Pemodelan 3D Berdasarkan Data Gayaberat Daerah Longiram, Kalimantan Timur. *Jurnal Geofisika Eksplorasi*, 3 (3): 1-16.

Grant, F.S., and West, G.F., 1965. *Interpretation theory in applied geophysics*. New York: MC Graw-Hill Book Company.

Koesoemadinata, R.P., 1978. *Geologi Minyak dan Gas Bumi*. Bandung, ITB.

Pirttijarvi, M. 2008. *Gravity interpretation and modeling software based on 3-D block models. User’s guide to version 1.6b.* Department of Physics Sciences. University of Oulu. Finland.

Putra, P. S., 2007. Sekuen Pengendapan Sedimen Miosen Tengah Kawasan Selat Madura. *Jurnal Riset Geologi & Pertambangan*, 17 (1): 20-36.

Satyana, A.H., Erwanto, E., and Prasetyadi, C., 2004. Rembang -Madura -Kangean -Sakala (RMKS) Fault Zone, East Java Basin: The Origin and Nature of a Geologic Border. *Proceeding the 33rd Annual Convention & Exhibition of Indonesian Association of Geologist.*

Setiadi, I., Setyanta, B., and Widijono, B, S., 2010. Delineasi Cekungan Sedimen Sumatera Selatan Berdasarkan Analisis Data Gayaberat. *Jurnal Geo-Sciences,* 20 (2): 93-106.

Setiadi, I., and Marjiyono. 2018. Interpretasi Geologi Bawah Permukaan dan Delineasi Cekungan Salawati wilayah Sorong dan Sekitarnya Berdasarkan Analsis Spektral serta Pemodelan 2D dan 3D Data Gayaberat. *Jurnal Geologi dan Sumber Daya Mineral*, 19 (3): 117-130.

Setiadi, I., Setyanta, B., Nainggolan, T. B., and Widodo, J., 2019. Delineation of Sedimentary Subbasin and Subsurface Interpretation East Java Basin in the Madura Strait and Surrounding Area Based on Gravity Data Analysis. *Bulletin of the Marine Geology*, *34* (1): 1-16.

Sribudiyani, Muchsin, N., Ryacudu, R., Kunto, T., Astono, P., Prasetya, I., Sapiie, B., Asikin, S., Harsolumakso, A. H., and Yulianto, I., 2003. The collision of the East Java microplate and its implication for hydrocarbon occurrences in the East Java basin. *Proceedings Indonesian Petroleum Association, 29th Annual Convention & Exhibition.*

Talwani, M. Worzel, J.L., and Ladisman, M. 1959. Rapid Gravity Computation for Two Dimensional

Bodies with Application to the Medicino Submarine Fractures Zone. *Journal of Geophysics Research*, 64 (1): 49 - 59.

Telford, W.M., Geldart, L.P., and Sheriff, R.E., 1990. *Applied Geophysics*. USA: Cambridge University.

Walidah, F. I. 2011. Penentuan Struktur Bawah Permukaan Berdasarkan Analisa dan Pemodelan Data Gayaberat untuk Melihat Potensi Hidrokarbon pada Daerah "FW1807" Cekungan Jawa Timur Utara. *Bachelor thesis*. Universitas Indonesia. Depok.