Basin Study in Atambua, West Timor, Indonesia from Gravity Data

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Abstract. Timor Island, Indonesia has complex geological structures related to its tectonic history. There is an existing subsurface geological model that is based on geophysical data. It is limited to the regional crustal scale and has a relatively low spatial resolution. The objective of our study was to delineate the sedimentary basin configuration of the area, both laterally and vertically, based on gravity data. Spectral analysis of the Bouguer anomaly allowed for anomaly enhancement by wavenumber domain filtering. Two main basins were identified from elongated low gravity anomalies that follow a SW-NE trend, i.e., the Central Basin and the Atambua Basin. The 2½D gravity modeling of selected profiles perpendicular to the regional structural direction revealed the sedimentary fills of the basins and the basement based on their densities. The Bobonaro mélanges and Viqueque sequences dominate and overlay the syn-rift (Kekneno sequences) and post-rift (Kolbano sequences) with varying lithology. These para-autochthon sediments are dominated by shale and carbonaceous rocks. Their respective thicknesses and depths of burial imply the possibility of hydrocarbon generation. The underlying basement may be associated with the Australian crust protruding from the south.

Keywords: *2.5D modeling; Atambua; basement; basin; gravity; Timor Island.*

1 Introduction

Timor Island is part of the Lesser Sunda Islands (Nusa Tenggara), Indonesia, and has very complex tectonic settings due to the relative movement of the Indo-Australian continental plate to the north. In that particular area, the northwest Australian continental plate collides with the Banda Island Arc, creating the Timor Through and the Tanimbar Through (Figure 1). The Banda Island Arc is the result of the convergence of three tectonic plates with quite different

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characteristics, i.e., the Indo-Australian Plate, the Pacific Plate, and the Eurasian Plate [1-3]. The complexity of Timor Island's tectonics has been described in detail by several authors (e.g., Audley-Charles in [4]; Villeneuve *et al.* in [5]; Charlton *et al.* in [6]). The geological condition of the west Timor area is interesting related to the possible occurrence of hydrocarbon potential [7-9]. However, the geological knowledge of the subsurface of the West Timor area, in particular Atambua and its surroundings, is very limited.

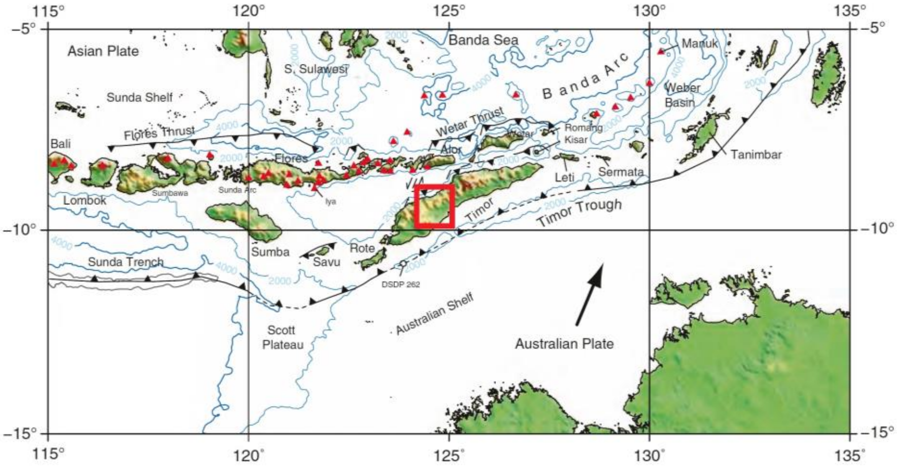

Figure 1 Location of Timor Island within the regional tectonic context (modified from Harris in [3]). The red box outlines the approximate study area.

Many seismic surveys have been conducted in off-shore areas in the southwestern part of Timor Island with a relatively limited depth target related to hydrocarbon explorations [10]. On-shore seismic surveys around Atambua with a similar objective have also been performed. The rough topography led to poor-quality data obtained. In addition, the seismic waves were scattered and did not reach the adequate depth for detailed basin delineation due to the presence of very complex near-surface formations [11,12]. Recent studies based on earthquakes that have occurred around Timor Island, i.e. ambient noise tomography, were done with good results at the crustal-mantle scale [13,14]. The resolution of such studies is more appropriate for regional tectonics than for basin studies. Land gravity studies [15,16] and airborne gravity survey [17] have proven effective in mapping the basement topography. In this study, we propose an interpretation of newly acquired gravity data to delineate basin structures around the Atambua area (Figure 2).

The gravity data modeling by inversion is generally limited to obtaining the geometry of a single interface between sedimentary layers and the underlying basement. In addition, the density contrast, either constant or varying with depth, should be assumed. Recently, the gravity-depth regression method has been introduced to overcome the necessity to set the density contrast a priori. However, this new technique needs information on the basement depth at several points [18,19]. Such an approach cannot be applied to our gravity data since knowledge of the subsurface in the survey area is very limited and no basement depth estimates exist. Therefore, we opted for trial-and-error adjustment of the geometry in 2½D models representing several interfaces of the rock formations [20]. To support the interpretation of the results from gravity modeling, we used published geological publications and surface geological data compiled by the field survey team of PPPTMGB LEMIGAS during geophysical data acquisition.

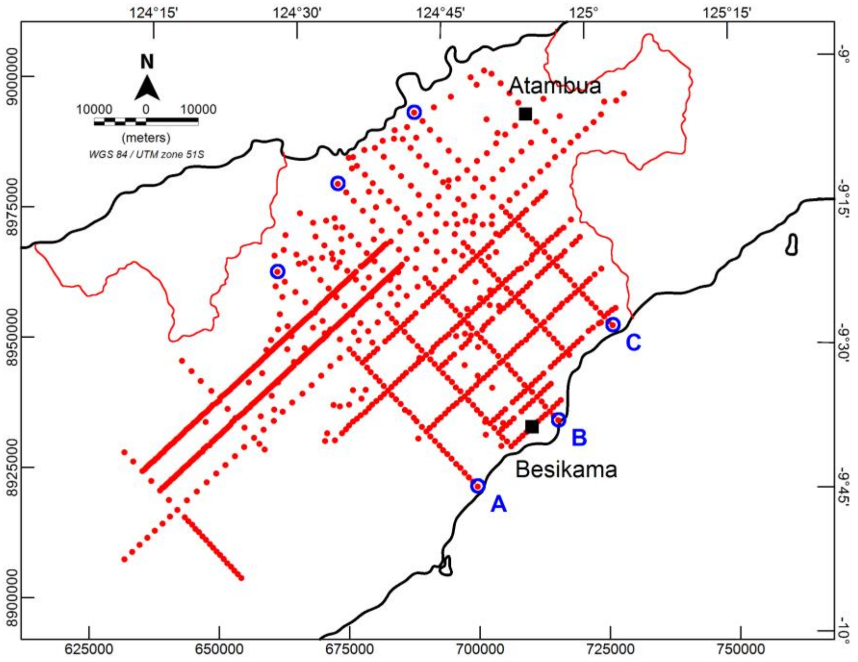

Figure 2 Distribution of gravity stations in Atambua, West Timor and its surroundings. The circled gravity stations are the beginnings and ends of the three profiles for 2½D gravity modeling. The thick black line marks the coastline, while the thin red line is the national border between Indonesia and Timor Leste.

2 Gravity Data Acquisition and Processing

In the survey area, gravity data were acquired at 900 stations distributed along traverse lines with an inter-station distance of around 0.5 to 3 km. The traverse lines were in the SW-NE and NW-SE directions with about 2.4 to 10 km separation (Figure 2). The gravity data acquisition was done by using Scintrex

CG-5 gravimeters. Differential Global Positioning System (DGPS) measurements, complemented by the Digital Elevation Model (DEM) from satellite imagery, were compiled as elevation data for processing the gravity data following the standard workflow [21,22].

The measured gravity data were corrected for the tidal effect and instrumental drift to obtain the station's gravity, referenced to the known gravity base-station. The normal or theoretical gravity at the reference ellipsoid g(ϕ) was calculated by using the well-known International Gravity Formula of 1980. Free-air, Bouguer and terrain (gTC) corrections were applied to the normal gravity. Then, the complete Bouguer anomaly (gBA) was obtained as the difference between the corrected normal gravity and the observed gravity (gobs), i.e.,

$$g_{BA} = g_{\mathrm{obs}} - g(\phi) + 0.3086\, h - 0.04192\, \rho\, h + g_{\mathrm{TC}} \qquad (1)$$

where h is the elevation of the gravity station above the datum level or MSL, and ρ is the representative rock density of 2.2 gr/cm^3 estimated from Parasnis' method [21,22]. The terrain correction in Eq. (1) was calculated using the Oasis Montaj software from Geosoft Inc. [23] with available DEM data. The SRTM data at 30-meter resolution were re-gridded to 250-meter and 500-meter resolution for local (up to 2-km radius) and regional (up to 20-km radius) terrain corrections, respectively. The gravity data are presented in Figure 3 as the Bouguer anomaly map.

The gravity data were further processed for regional-local anomaly separation, which can be considered as the first step of the Bouguer anomaly interpretation. The regional and local anomalies are generally characterized by long-wavelength and short-wavelength anomalies, respectively. There are many methods for gravity anomaly separation based on their wavelengths. However, we opted for spectral- or wavenumber-based filtering. First, for computational purposes, the area with no data was filled by using a simple inverse distance interpolator. Then, the data were transformed from the spatial to the wavenumber domain by the Fast Fourier Transform (FFT) algorithm. In the final result, the added data were blanked to conform with the original data coverage [23,24].

The radially averaged spectrum of the Bouguer anomaly is presented in Figure 4. Based on the spectrum, we are more interested in the anomaly within a specific wavelength interval, representing the dominant basin structures of the area. Therefore, we used a combination of Butterworth and band-pass filters to enhance the anomalies between 100 km down to 5 km in wavelength, equivalent to the wavenumber between 0.01 and 0.2 km^{-1} (Figure 4). The enhanced gravity anomaly shown in Figure 5 was used to facilitate the preliminary and qualitative interpretation of the gravity data.

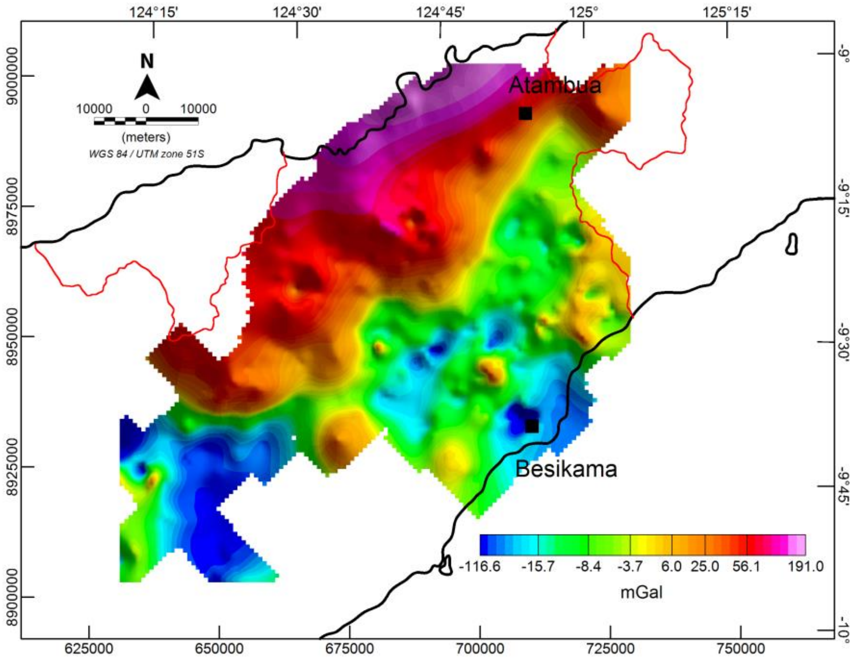

Figure 3 Bouguer anomaly map. The thick black line marks the coastline, while the thin red line is the national border between Indonesia and Timor Leste.

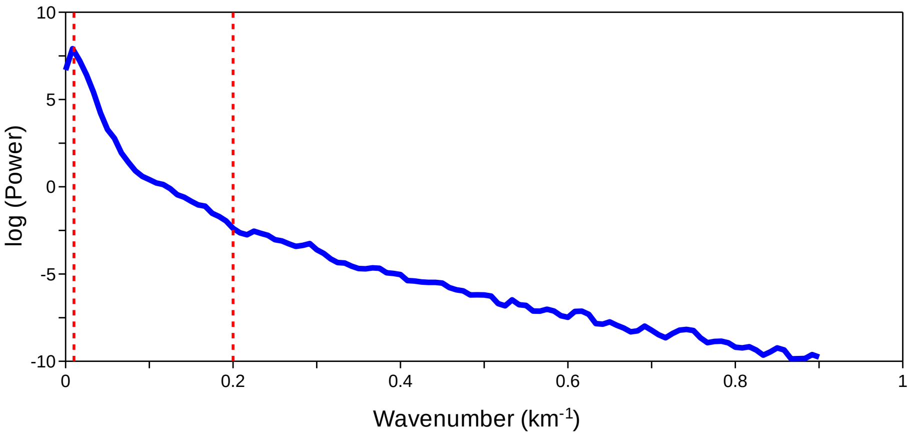

Figure 4 Radially averaged spectrum showing the content of the gravity data in the wavenumber domain. The anomaly with wavenumber less than 0.01 km^{-1} and above 0.2 km^{-1} was filtered out in the band-pass filtering.

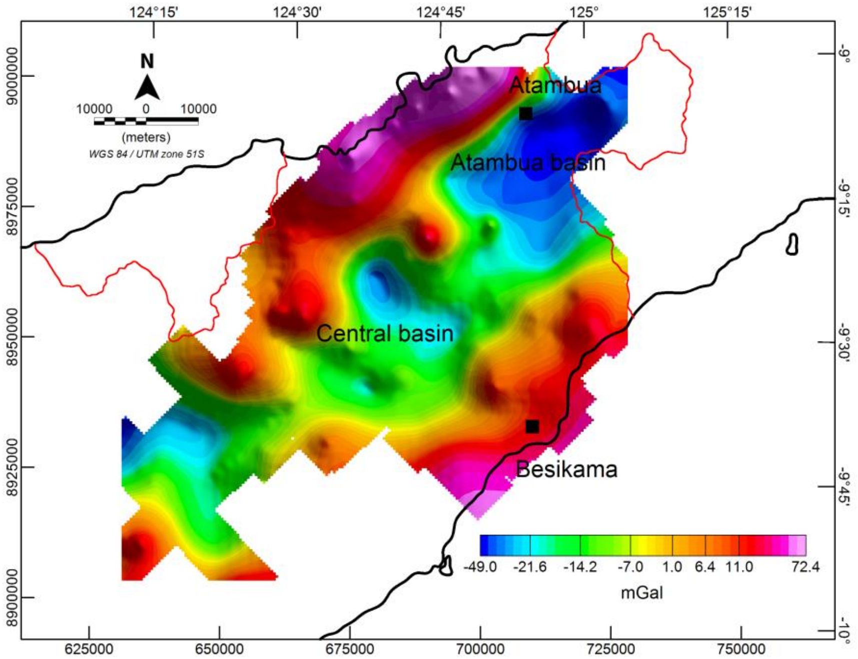

Figure 5 Enhanced gravity anomaly map showing the regional trend of a low anomaly in the SW-NE direction. As with the Bouguer anomaly map, the extreme of minimum and maximum values in the color bar may be localized in very restricted areas only. The thick black line marks the coastline, while the thin red line is the national border between Indonesia and Timor Leste.

3 Gravity Modelling

We performed 2½D gravity forward modeling by using the GM-SYS Gravity and Magnetic Modelling Software Module embedded in the Oasis Montaj Software from Geosoft Ltd. [20,23]. In a 2D model, the density varies in the vertical and horizontal (along profile) directions, while it is constant along the strike of the structure, which is considered infinite. The term 2½D means that we essentially have a 2D model with a limited length along the strike. In this case, we used 10 km for the length along the strike, or 5 km to each side of the profile. This choice was based on the distance between the profiles and the geometry of the basin. The overall thickness and densities of the sedimentary layers overlaying the basement were estimated by considering the subsurface knowledge from geology (e.g. [9]). In addition, we also considered the preliminary results from 2D modeling of MT data from the same study area [25].

We were interested more particularly in the gravity data of three profiles (line A, line B and line C) perpendicular to the regional SW-NE structural direction. The geometry of the anomalous sources representing different density units of the subsurface were adjusted to minimize the misfit between the observed and the calculated gravity; the latter is the theoretical response of the model. The results are presented in Figures 6, 7 and 8 for line A, B and C, each with misfit represented as the root-mean-squared error of 2.04, 1.65 and 2.66 mGal, respectively. We chose for modeling the general features of the subsurface, i.e., by using blocks with significant thickness to represent rock formations with similar physical characteristics. Therefore, there are only two main sediment layers with densities of 2.3 gr/cm^3 and 2.5 gr/cm^3 overlaying the basement with 3.0 gr/cm^3 density. Only at line A, there are two additional units, i.e., volcaniclastic (2.6 gr/cm^3) and crystalline (2.8 gr/cm^3) rocks.

The superficial layer present at all profiles consists of Viqueque sequences dominated by carbonates (Tertiary to Quaternary) overlaying Bobonaro mélanges (Tertiary) with various matrixes of clay and shale. The second layer combines syn-rift (Permian-Jurassic) and post-rift (Cretaceous-Tertiary) sequences. The syn-rift (Kekneno) sequence is dominated by shale and carbonaceous rocks. The other members of the syn-rift sequence have lithologies from shale to sand, calcareous and volcanic rocks. The post-rift (Kolbano) sequence is dominated by carbonaceous rocks from calcilutite, calcarenite, and calcirudite. The basement (Pre-Permian) is generally part of Australia’s crust formed by crystalline rocks, i.e., schist, phyllite, serpentine, and basalt. A layer that exists only at line A is the volcaniclastic (Jurassic-Tertiary) layer dominated by tuffs, agglomerates and carbonated clastic rocks. Additionally, the crystalline rocks (Jurassic-Tertiary) consist of metamorphosed rock from the Banda Arc because of obduction during collision between the Australian Arc and the Banda Arc and the intrusion of diorite [4,5,9].

4 Results and Discussions

From the Bouguer anomaly map, the study area was divided almost diagonally into high (up to 191.0 mGal) and low (down to -116.6 mGal) gravity anomalies in the north-western and south-eastern parts, respectively. The extreme of minimum and maximum values of the gravity anomalies shown in the color bar in Figure 3 (also in Figure 5) are only intended to cover the whole range of the data. They may be localized in very restricted areas only. The border between these dominating anomalies extends from SW to NE, almost parallel to Timor Island (Figure 3). From the compiled gravity data of the whole Banda Arc area by Kaye in [26] and Chamalaun *et al.* in [27], the transition from high to low gravity anomalies with a similar pattern extends to East Timor (Timor Leste).

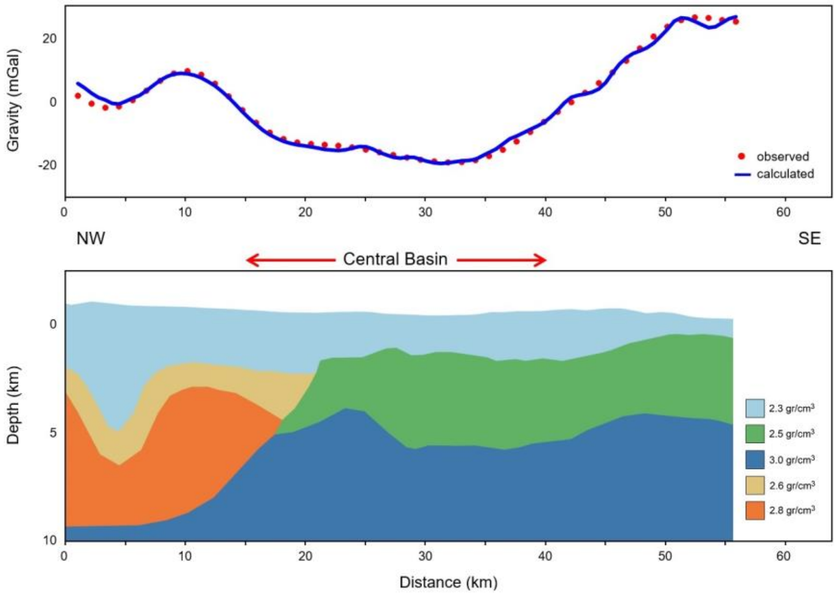

Figure 6 Gravity modeling result for line A (RMS error 2.04 mGal). The legend for density is also applicable for modeling of line B and line C.

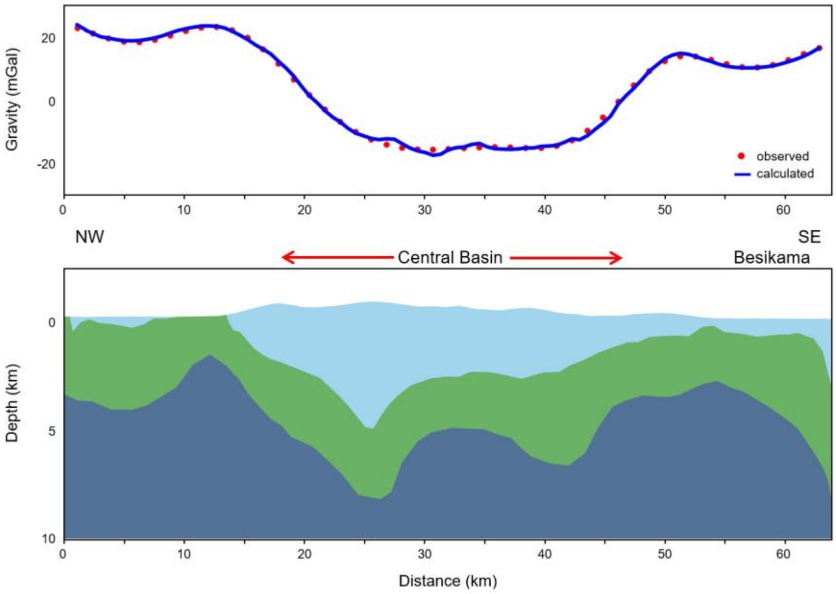

Figure 7 Gravity modeling result for line B (RMS error 1.46 mGal) with the same legend for the density as Figure 6.

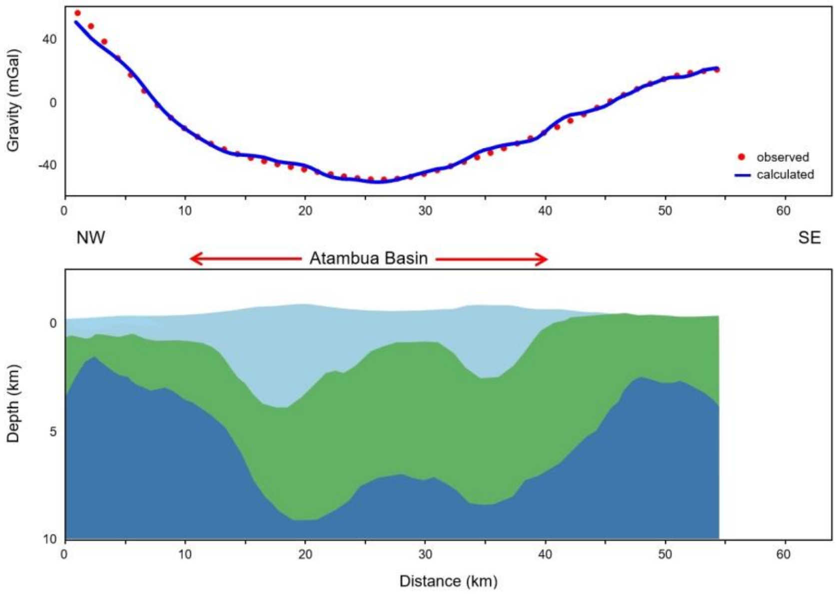

Figure 8 Gravity modeling result for line C (RMS error 2.66 mGal) with the same legend for the density as Figure 6.

The high gravity anomaly indicates a relatively shallower basement in the northern/north-western area compared to the central and southern area. On the other hand, the low gravity anomaly dominating the central area toward the southern/south-eastern area can be associated with the thick Australian continental crust or a deeper basement [27]. Our gravity data are in good agreement with the ambient noise tomography results, showing low S wave velocity at varying depth related to a crust/upper mantle transition [13,14].

The regional structural trend from SW to NE is more obvious in the enhanced gravity anomaly map resulting from the filtering process (Figure 5). Following that trend, elongated low gravity anomalies (less than -7.0 mGal) indicate the presence of basin structures with apparent deepening toward NE (down to -49.0 mGal). The low gravity anomalies are separated by moderately higher anomalies of around -15 to -10 mGal, crossing perpendicularly to the SW-NE trend (Figure 5). Although having a different basin geometry from the surface geology, i.e., in size [4,9], the south-westernmost low anomalies can be associated with the Central Basin, while the one in the NE is the Atambua basin.

The subsurface geological models from gravity data for lines A, B and C represent regional sedimentary depositional fill resulting from tectonic events that occurred in Timor Island. At line A (Figure 6), there are three different layers that reveal emplacement sequences. The top layer with dominant density 2.3 gr/cm^3 represents the Bobonaro mélanges and Viqueque sequences dominating the surface of the study area. The density of these formations covers a range from 2.0 to 2.3 gr/cm^3. The middle layer consists of syn-rift and post-rift sequences or para-autochthon with dominant density 2.5 gr/cm^3. The variation of density representing various lithologies in this layer is in the range of 2.5 to 2.7 gr/cm^3. The allochthonous layer (2.6 gr/cm^3) and rootless former basement of the Banda Volcanic Arc or Banda Terrane (2.8 gr/cm^3) are juxtaposed with the middle layer in the NW of the area [1-9]. The Banda Terrane was folded, faulted, and detached from the Australian basement (3.0 gr/cm^3) during the collision phase [3-7].

The subsurface at line B (Figure 7) is quite similar to the south-eastern part of line A. There is a relatively deeper basin in the middle of line B compared to line A. The basin is associated with the Central Basin, although it is smaller compared to the one defined previously based on syn- and post-orogenic sediment [9]. The difference is located around the east shoreline, surrounding Besikama, where a high gravity anomaly indicates probable basement rock or another tight rock, which could not be determined based on previous surface data. It is possible that the surface geological data do not reveal the continuity of the syn- and post-orogenic sediment vertically.

The model from line C (Figure 8) is in general analogous to line B in terms of age and lithology. The basin in this area can be associated with the Atambua Basin, which is slightly larger than the basin identified by Charlton in [9]. The sediment of para-autochthon is thicker at line C than at the other lines. This layer is equivalent to syn- and post-rift sequences at Line B and is dominated by the Aitutu and Wailuli formations that were formed before the breaking up of the Australian continent from the Gondwana supercontinent by rifting processes [4,28]. The Aitutu formation (shale and carbonaceous rocks) has proven to generate hydrocarbon and could expel oil and gas [29]. Charlton identified the Wailuli formation (mostly shale) as a regional seal rock of Timor Island [9]. Therefore, there is a possibility of the presence of a hydrocarbon system in the study area.

5 Conclusion

Atambua, West Timor, Indonesia and its surrounding area exposes a mix of young and old rocks on the surface. Such complex geological features are influenced by the deeper structure resulted from the regional tectonic evolution of the area. Despite the regional and sub-regional scale results, newly acquired gravity data clearly revealed the deeper geological features represented by the regional trend or lineament and basin configuration.

The lineament in the SW-NE direction divides Timor Island into three parts. The north-western part, with high gravity anomalies, coincides with a rough mountainous area and is probably the first area where collision between NW Australia and the Banda Volcanic Arc occurred. The modeling result to the NW of line A confirmed this hypothesis previously proposed by several authors [3,4]. The central part is dominated by the Central Basin as a result of tectonic processes in the syn- and post-orogeny phases. In addition, the existence of the Atambua Basin located in the north-eastern part of the study area is emphasized. These basins are delineated qualitatively by a residual gravity anomaly and quantitatively by 2½D gravity modeling. The south-eastern part has a thick crust, presumed to be the former NW Australian passive margin.

Finally, thick pre-collisional sediments were revealed from the modeling of the gravity data on lines A, B and C. The sediments associated with the former NW Australian passive margin have previously been identified from surface data as good petroleum system elements [9,29]. This research provides locations where thick sediments should be further explored for hydrocarbon.

Acknowledgments

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References

[1] Hamilton, W., *Tectonics of the Indonesian region*, Geological Society of Malaysia Bulletin **6**, 3-10, 1973.

[2] Hall, R. and Wilson, M.E.J., *Neogene sutures in eastern Indonesia*, Journal of Asian Earth Sciences **18**(6), 781-808, 2000.

[3] Harris R., *The nature of the Banda Arc–continent collision in the Timor region*, In: Brown, D. and Ryan, P.D. (eds.) Arc-Continent Collision. Frontiers in Earth Sciences, 2011.

[4] Audley-Charles, M.G., *Tectonic post-collision processes in Timor*, Geological Society London Special Publications **355**(1), 241-266, 2011.

[5] Villeneuve, M., Bellon, H., Martini, R., Harsolumakso, A.H. and Cornée, J.J., *West Timor: A key for the eastern Indonesian geodynamic evolution*, Bulletin de la Société Géologique de France **184**(6), 569-582, 2013.

[6] Charlton, T.R., Barber, A.J. and Barkham, S.T., *The structural evolution of the Timor collision complex, eastern Indonesia*, Journal of Structural Geology **13**(5), 489-500, 1991.

[7] Sawyer, R.K., *The stratigraphy and sedimentology of West Timor, Indonesia*, 22nd Annual Convention Proceedings of Indonesian Petroleum Association (IPA), 1993.

[8] Charlton, T.R. and Wall, D., *New biostratigraphic results from the Kolbano area, southern West Timor: implications for the Mesozoic-Tertiary stratigraphy of Timor*, Journal of Southeast Asian Earth Sciences **9**(1), 113-122, 1994.

[9] Charlton, T.R., *The petroleum potential of West Timor*, 28th Annual Convention Proceedings of Indonesian Petroleum Association (IPA), 2001.

[10] Bailie, P. and Milne, C. *New insights into prospectivity and tectonic evolution of the Banda Arc: Evidence from broadband seismic data*, 38th Annual Convention Proceedings of Indonesian Petroleum Association, 2014.

[11] Mansfield, G., Chandra, S. and Carver, P. (2016) *Where's the data?*, Acquisition and Processing of Seismic Data in the PNG Highlands, *AAPG/SEG*, 41762.

[12] El Redini, N.A.H., Bakr, A.M.A. and Dahroug, S.M., *Seismic data interpretation for hydrocarbon potential, for Safwa/Sabbar field, East Ghazalat onshore area, Abu Gharadig Basin, Western Desert, Egypt*, NRIAG Journal Astronomy and Geophysics **6**(2), 287-299, 2017.

[13] Porritt, R.W., Miller, M.S., O'Driscoll, L.J., Harris, C.W., Roosmawati, N. and Teofilo da Costa, L., *Continent-arc collision in the Banda Arc imaged by ambient noise tomography*, Earth and Planetary Science Letters **449**, 246-258, 2016.

[14] Zhang, P. and Miller, M.S., *Seismic imaging of the subducted Australian Continental Margin beneath Timor and the Banda Arc Collision Zone*, Geophysical Research Letters **48**(4), 1-11, 2021.

[15] Abdullayev, N.A., Kadirov, F. and Guliyev, I.S., *Subsidence history and basin-fill evolution in the South Caspian Basin from geophysical mapping, flexural backstripping, forward lithospheric modelling and gravity modelling*, Geological Society London **427**, 175-196, 2017.

[16] Ali, M.Y., Watts, A.B. and Farid, A., *Gravity anomalies of the United Arab Emirates: Implications for basement structures and infra-Cambrian salt distribution*, GeoArabia **19**(1), 85-112, 2014.

[17] Li, W., Liu, Y., Zhou, J., Zhou, X. and Li, B., *Sedimentary basin analysis using airborne gravity data: a case study from the Bohai Bay Basin, China*, International Journal of Earth Sciences **105**(8), 2241-2252, 2016.

[18] Florio, G., *Mapping the depth to basement by iterative rescaling of gravity or magnetic data*, Journal of Geophysical Research: Solid Earth **123**, 9101-9120, 2018.

[19] Florio, G., *The estimation of depth to basement under sedimentary basins from gravity data: Review of approaches and the ITRESC method, with an*

application to the Yucca Flat Basin (Nevada), Survey in Geophysics **41**, 935-961, 2020.

[20] Northwest Geophysical Associates Inc., *GM-SYS Gravity and Magnetic Modelling Software User's Guide*, ver. 4.9, 2004.

[21] Long, L.T. and Kaufann, R.D., *Acquisition and Analysis of Terrestrial Gravity Data*, Cambridge University Press, 2013.

[22] Fairhead, J.D., *Advances in Gravity and Magnetic Processing and Interpretation*, EAGE Publishing, 2015.

[23] Geosoft Inc., *Oasis Montaj How-To Guide*, 2013.

[24] Grandis, H., and Dahrin, D., *The utility of free software for gravity and magnetic advanced data processing*. IOP Conference Series: Earth and Environmental Science **62**(1), 012046, 2017.

[25] Wijanarko, E., Arisbaya, I., Sumintadireja, P., Warsa and Grandis, H. *Subsurface geology of West Timor, Indonesia based on gravity and magnetotellurics* (*MT*) *Study* (*submitted*), 2021.

[26] Kaye, S.J., *The Structure of Eastern Indonesia: An Approach via Gravity and Other Geophysical Methods*. Ph.D. thesis, University of London, 1989.

[27] Chamalaun, F.H., Lockwood, K. and White, A., *The Bouguer gravity field and crustal structure of eastern Timor*, Tectonophysics **30**, 241-259, 1976.

[28] Charlton, T.R., Barber, A. J. and Barkham, S. T., *The structural evolution of the Timor collision complex, eastern Indonesia*, Journal of Structural Geology **13**(5), 489-500, 1991.

[29] Shaylendra, Y., Adlan, Q. and Kesumajana, A.H.P., *Petroleum system play failure on Triassic source rock in the west Timor onshore area: Basin modeling and oil to source rock correlation*, 41st Annual Convention Proceedings of Indonesian Petroleum Association (IPA), 2017.