IDENTIFICATION OF SEDIMENT-BASEMENT LAYER STRUCTURE IN WEST PAPUA PROVINCE INDONESIA BASED ON GRAVITY AND MAGNETIC INVERSION MODELING AS A STRESS INDICATOR OF EARTH CRUST

by Richard Lewerissa

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Abstract

Due to the convergence of the Australian, Pacific, and Eurasian tectonic plates, the province of West Papua in eastern Indonesia is situated in a complicated tectonic setting. Many major strike-slip faults exist in this interaction, including Koor, Sorong, Ransiki, and Yapen, where large and damaging earthquakes occur frequently. According to regional geological conditions, rocks in the northern part of West Papua are the contribution of the Pacific oceanic plate, which is composed of ophiolite and island arc volcanic, while those in the southern part are dominated by quaternary and siliciclastic sedimentary rocks bounded from west to east by the Sorong fault. Our research utilizes gravity and magnetic methods based on the availability of regional satellite data to study the subsurface geological structure of sedimentary layers and bedrock in the study area as an indication of stress on the earth's crust. The subsurface model was obtained through three-dimensional (3-D) inversion modeling of gravity and magnetic anomalies data by first performing separation and gradient analysis to improve the image of geological features. Gravity inversion produces rock density contrasts ranging from -0.348 gr/cm^3 to 0.451 gr/cm^3, while magnetic inversion produces rock susceptibility values between -0.363 SI to 0.223 SI, which are described in depth variations. The gravity and magnetic inversions show the subduction of the Pacific Ocean plate in the northern part of the bird's head of West Papua, massive intrusion of igneous rock, and the presence of low density and susceptibility anomalies associated with the Bintuni Basin which is rich in oil and gas in eastern Indonesia.

The boundaries of the sedimentary and bedrock layers are estimated at a depth of between 15 - 20 km, where the northern part of the bedrock layer is rock from the uplifted mantle, while in the southern part it is mainly composed of the Silurian-Devonian Kemum formation.

Keywords: Gravity and magnetic; Inversion modeling; Sediment; Basement; West Papua.

1. Introduction

The western part of Papua Island is administratively one of the provinces in Indonesia. Tectonically, this island is one of the most complex areas at the convergence boundary of the Australian and Pacific plates and is at the forefront of understanding the overall tectonic process on Earth (Baldwin et al., 2012). The Manokwari trough in the northern part of West Papua province is a subduction boundary of the Caroline-Pacific oceanic crust beneath the Australian continental crust. This trough is assumed to be a source of earthquake activity in the Bird's Head area of Papua, which is linked to significant strike-slip faults including the Koor, Sorong, Ransiki, and Yapen (Daniarsyad & Suardi, 2017; Lewerissa et al., 2021). There were 2807 earthquakes with magnitudes ranging from 3.5 to 7.7 between 1964 and 2021, most of which were shallow earthquakes, while several large earthquakes caused significant damage in the area. An earthquake hazard study is essential for determining the characteristics of future earthquake-prone sites and preventing the negative impacts on civilization (Kalaneh & Agh-Atabai, 2016).

Previously, several seismic and geoscience studies in the West Papua region were conducted, including determining the source mechanism of the 6.7 Mw earthquake at Ransiki in 2012 (Serhalawan & Sianipar, 2017), fault studies to evaluate quaternary activity and indications of seismic hazard in West Papua (Watkinson & Hall, 2017), and mapping of seismic hazard on Papua island in two regions, including Indonesia and Papua New Guinea using probabilistic seismic hazard analiysis (PSHA) (Makrup et al., 2018). Furthermore, terrane gravity and tectonic measurements have been conducted in the New Guinea region, indicating that the gravity method is an essential approach for terrane analysis but cannot be employed for isolated structures (Milsom, 1991). According to the information, the research that has been conducted is still restricted to studies on the ground surface and has not thoroughly investigated the subsurface structure. Our research uses a potential field of geophysical method that aims to understand and identify the structure of sediments and basements based on the availability of gravity and magnetic satellite data.

The study was conducted to identify the stress level of the earth's crust in the West Papua region. In 2021, we have estimated the variation of Mc and b values from the USGS and ISC earthquake catalogs for the period 1960 – 2021 and obtained the b values to be at the intermediate level for the West Papua region. In general, the value of b is related to variations in stress and strain, fracture, and the rate of deformation. This parameter can also indicate a high-stress level if the value of b is small (Lewerissa et al., 2021).

Geophysical data plays a significant part in the prediction and evaluation of seismic risks, which give guidance about the geological formation of the crust. Gravity data aids in the development of models of the crust and lithosphere at various scales, showing the density distribution of the upper crustal layers. On the other hand, it provides a better understanding of the basin as a source of oil, gas, and water also detects major tectonic features or structures (Saibi et al., 2021). Differences in crustal density are frequently related to faults and tectonic features, which show a geological framework for seismic risk study. The density defining of each layer that makes up the earth is critical for many investigations, including earthquake studies, tectonic plate reconstruction, and modeling the petroleum system (Gómez-García et al., 2019; Tian et al., 2020). It is known that in the study area there are two main basins producing the largest amounts of oil and natural gas in eastern Indonesia, including the Salawati and Bintuni basins.

Satellites can detect fluctuations in the earth's magnetic field caused by various geological characteristics of the lithosphere. Magnetic anomaly maps can provide critical things about tectonic structures and the lithosphere in general. The gravity and magnetic techniques are relatively inexpensive, non-invasive, and are non-destructive remote sensing methods. Furthermore, it involves information about the density and variation of the magnetic susceptibility of rocks. This research uses the examination of the earth's gravity gradient in the form of vertical, horizontal, and tilt angle derivatives to identify the borders of geological formations such as major faults. The sedimentary and basement layer are derived from 3-D inversion of regional gravity and magnetic anomalies data. These results are expected to be a support for disaster mitigation or the search for new natural resources in West Papua region.

2. Geology and Tectonic Setting

New Guinea or Papua island is defined as having the shape of a bird from west to east, consisting a bird's head, neck, body, and tail. The bird's head, tail, and part of its body are found in Papua and West Papua, Indonesia, while the rest of the tail is found in Papua New Guinea (Gold et al., 2017b). Regionally, the Papua island is influenced by two main activities that collide simultaneously until now. The Pacific plate is moving southwest relative to the Australian plate at a speed of 11 cm/year, resulting in a complex tectonic structure (Handyarso & Padmawidjaja, 2017).

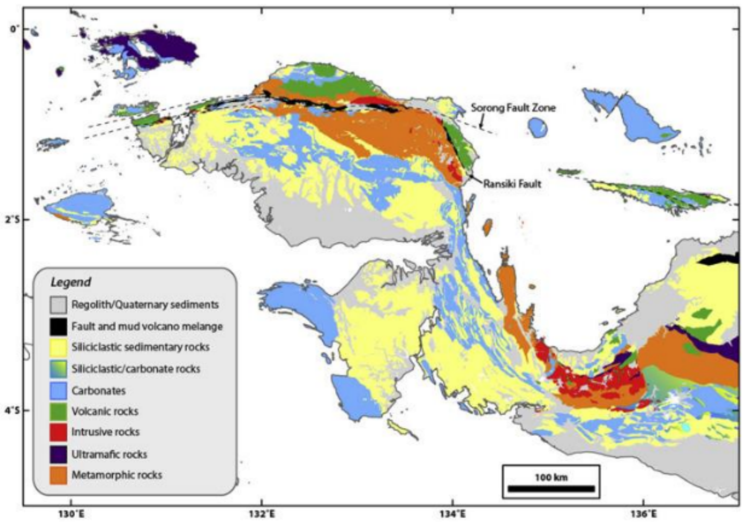


Figure 1. Lithological map of western Papua, Indonesia depicting the main fault structure, dominated by volcanic, metamorphic, and sedimentary rocks (Gold et al., 2017b).

The neck is mostly made up of limestone and siliciclastic rocks that were shortened during the formation of the Lengguru fold belt. The rock is distorted as part of the mountain belt, which stretches from western Bird's Head to the eastern end of the island via the Lengguru fold and the central mountain range.

In southern part of Papua island, rocks mainly from Australian continental plate, while the northern part consists of ophiolite and island volcanic arcs from the Pacific plate. These two domains are separated by a sedimentary wedge in the middle, as well as a variety of metamorphic and granitic rocks (Figure 1). This alignment is characterized by the presence of sutures formed during arc and continental collisions in the Oligocene and early Miocene. The Ransiki fault, located to the east of the bird's head, is thought to be due of a collision between an island arc and Australian continent, restricting into Cenderawasih Bay, east of Wandamen, and connecting with the Weyland overthrust in a Central Mountains (Gold et al., 2017a; Milsom, 1991; Milsom et al., 1992). Currently, the dominant arc rock forms the basement at the northern margin of Papua, the eastern bird's head, Cenderawasih Bay, and its islands. The Ransiki Fault is estimated to be a dextral shear zone with a NNW trend, connecting the Sorong Fault and the Yapen Fault, estimated to be inactive (Charlton, 2010). The length of a typical segment of this fault ranges from 20 -50 km, while the maximum is around 100 km (Watkinson & Hall, 2017).

3. Methodology

Our study looks at the bird's head region in the Indonesian province of West Papua, which has unique and complex tectonic features. The coordinates of the research area are between 131° E – 135° E and 0° – 4° S, which is an area that is prone to earthquakes due to the collision of the Australian, Pacific, and Eurasian plates, as well as several other microplates.

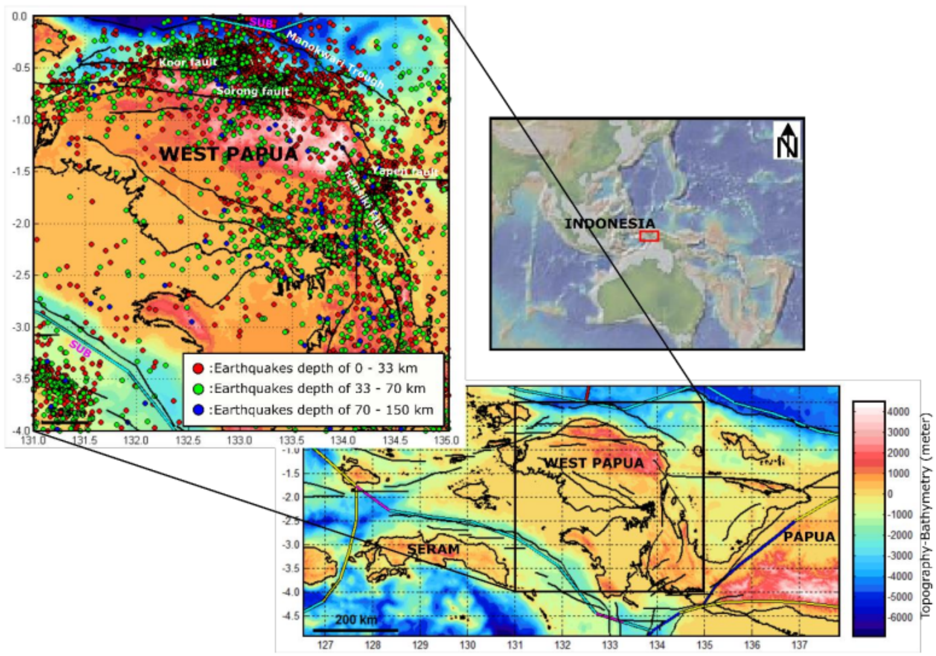


Figure 2. The research site in West Papua, Indonesia, is overlaid with topographic and bathymetric maps, as well as the main fault structures, which include the Sorong, Koor, Ransiki, and Yapen faults.

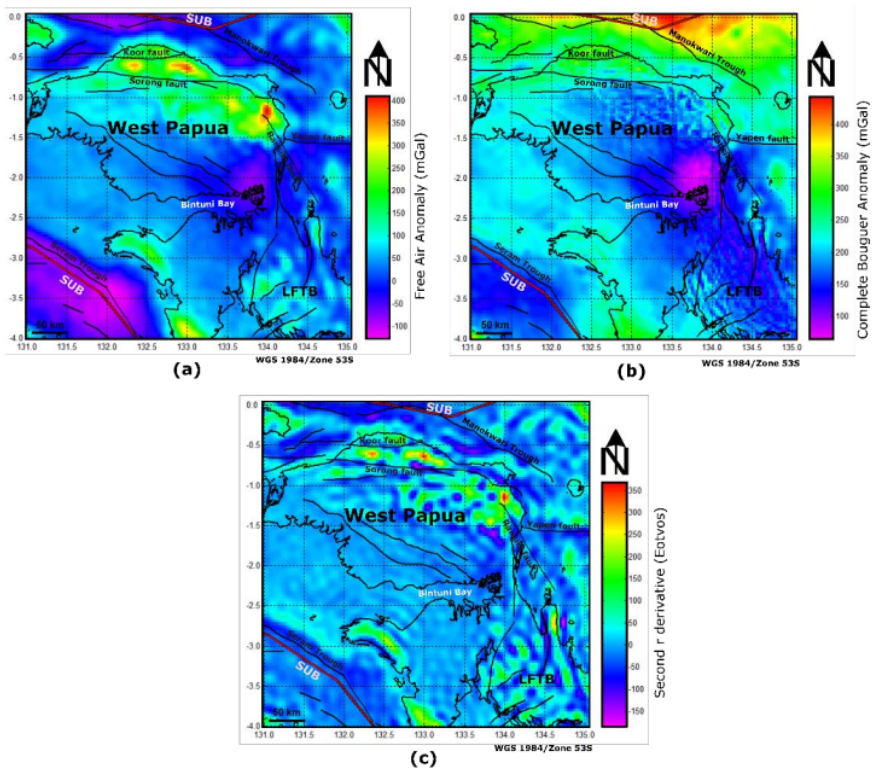
The historical seismic data from 1960 to 2021 obtained from the IRIS Data Management Center (http://service.iris.edu/fdsnws/event/1) shows that earthquakes mainly occurred in Koor, Sorong, Ransiki, and Yapen (Figure 2). This study integrates the interpretation and combination of regional gravity and magnetic potential field data based on satellite measurements to obtain the subsurface structure of West Papua.

The gravity data is from the 2012 World Gravity Map (WGM), and it includes free air anomaly data as well as the complete Bouguer anomaly (Balmino et al., 2012; Lewerissa et al., 2020). The second vertical radial derivative data is from the XGM2019e model (Zingerle et al., 2020), and a magnetic data is from NOAA's geomagnetic anomaly grid 2 version 3 (EMAG2-v3), with a spatial resolution of 2 arc minutes (Lewerissa et al., 2020; Meyer et al., 2017). Moreover, the Global CRUST 1.0 model is used as a constraint in 3D gravity and magnetic inversions (Laske et al., 2013).

3.1 Earth Gravity Data

The study utilizes the Earth's gravity method for mapping and delineating sedimentary and basement structure boundaries in a West Papua using satellite gravity data from the 2012 WGM model. Global gravity fields can be measured via satellite, which can reach areas where direct measurement is expensive and time-consuming as in the sea (Gómez-García et al., 2019). WGM is a global gravity anomaly grid map calculated with spherical geometry. It is derived from global earth gravity models like EGM2008 and DTU10, as well as a 1' x 1' resolution field correction from the ETOPO1 model, which accounts for the majority of the surface mass (Balmino et al., 2012). Free air and complete Bouguer anomalies of West Papua based on the 2012 WGM model are shown in Figure 3. Furthermore, XGM2019e is a model of the combined global gravity field represented by spherical harmonics of degrees and orders of up to 5399 with a spatial resolution of 2' arc minute (~4 km).

The model consists of the GOCO06s satellite model with wavelength ranges of up to degrees and order of 300, combined with a gravity grid model on the surface covering short wavelengths (Zingerle et al., 2020). Surface data consists of gravity anomalies on land and ocean provided by the NGA with a resolution of 15', plus topographically derived gravity information above the ground (EARTH2014). We use static model calculations from an International Center for Global Earth Model (ICGEM) to obtain a second radial derivative model (Ince et al., 2019) to define the boundaries of regional geological structures in the West Papua region (Figure 3c). The complete Bouguer anomaly was then separated to obtain regional and residual anomalies using an upward contiuation technique at 4 km altitude from the surface.



SUB: Subduction zone **LFTB**: Lengguru Fold Thrust Belt

Figure 3. The WGM 2012 and XGM2019 models of West Papua province. (a) Free air; (b) complete Bouguer; (c) Second r derivatives.

3.2 Earth Magnetic Data

The magnetic data utilized in this study is based on NOAA's EMAG2-v3 model, which is a collection of magnetic observations from satellites, ships, and aircraft. EMAG2-v3 is an updated model of the World Digital Magnetic Anomaly (WDMAM) map, which is gridded every 2 arc minutes and consists of two types of data, namely magnetic anomalies at sea level and upward continuation anomalies at 4 km from geoid (Meyer et al., 2017). We utilize Geoscience data services from Geosoft Seequent, which provide access to Geosoft Public DAP Server data (https://public.dap.seequent.com/GDP/Search), one of which is EMAG2-v3 data at sea level (Figure 4a) and upward continuation (Figure 4b) extracted for West Papua region.

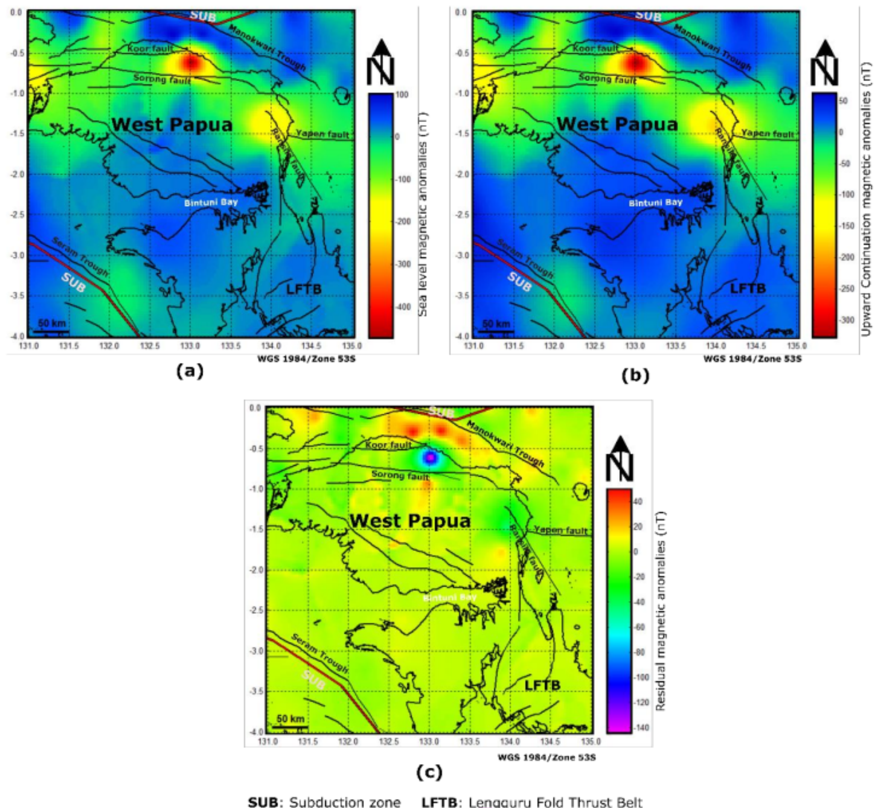


Figure 4. EMAG2-v3 model in West Papua province (a) Sea level; (b) Upward continuation; (c) Residual anomaly.

The EMAG2-v3 model is very beneficial for obtaining a synoptic perspective of the magnetic field, and repeated observations of overlapping orbits may be used to reduce ionospheric extraneous magnetic fields caused by lithospheric abnormalities. These measurements are used to learn about the nature and history of other terrestrial entities (Hinze et al., 2013). Furthermore, the residual magnetic anomaly is determined by subtracting the sea level and the upward continuation anomalies (Figure 4c). The upward continuation data is then used for further analysis and inversion modeling without reduction to pole (RTP) because the study area is large enough that it will experience distortion in the application of RTP.

3.3 Earth Gravity Field Gradient

The gradient method of the Earth's gravity field, such as vertical, horizontal, and tilt angle derivatives, is used in this study to enhance near-surface geological features that are not yet visible on a complete Bouguer anomaly of West Papua. Gradient techniques using vertical and horizontal derivatives are also used to describe the boundaries of geological structures and source objects buried in gravity fields. The boundaries of geological structures and source objects buried in gravity fields are described using gradient techniques in the form of vertical and horizontal derivatives (Eshaghzadeh et al., 2018). Vertical gradient is commonly utilized highlight near-surface of geological structure and increase a component of wavenumber spectrum, with a zero value corresponding to the geological structure's boundary (Ibraheem et al., 2019). The vertical gradient equation is written as:

$$VG = \frac{\partial g}{\partial z} \tag{1}$$

Furthermore, a density contrast boundaries of the gravity field data are determined using a horizontal gradient. When compared to vertical gradient, this approach is more effective for depicting shallow or deep sources (Abderbi et al., 2017). 2-D horizontal gradient equation is showed as:

$$\mathrm{HG}\,(x, y) = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \tag{2}$$

g is complete Bouguer anomaly. Another analysis conducted on gravity field data in the West Papua region is Tilt angle (*TA*). This technique is applied to enhance and sharpen the anomalous form of gravity or magnetic. Tilt angle is a ratio of vertical and horizontal derivatives with a range of -90° to 90°. TA is denoted by the following equations:

$$TA = tan^{-1}\left(\frac{VG}{HG\,(x, y)}\right) \tag{3}$$

TA is positive above the source object, close to zero or zero characterizing the source boundary, and negative values are generally outside the source (Eshaghzadeh et al., 2018; Ibraheem et al., 2019). Overall, the gravity field gradient in the study area was analyzed using a 2-D fast Fourier transform by Fourpot software (Shandini et al., 2018).

3.4 Inversion Modeling of Potential Field Data

In West Papua, subsurface structures in the form of density and susceptibility distributions of rocks were obtained through inversion modeling of gravity and magnetic data. Process of inversion was performed using Geosoft Oasis Montaj software version 9.10, which was based on several inversion equations (Li & Oldenburg, 1996). Inversion is a numerical computational process used to create models of physical variables from the subsurface, such as density contrast and susceptibility fo gravity and magnetic data. This technique produces a quantitative solution that is easier when compared to forward modeling, which involves iterating through trial and error (Saibi et al., 2021). This research utilizes the VOXI earth modeling facility from Oasis Montaj for 3-D inversion modeling in West Papua (Figure 5a).

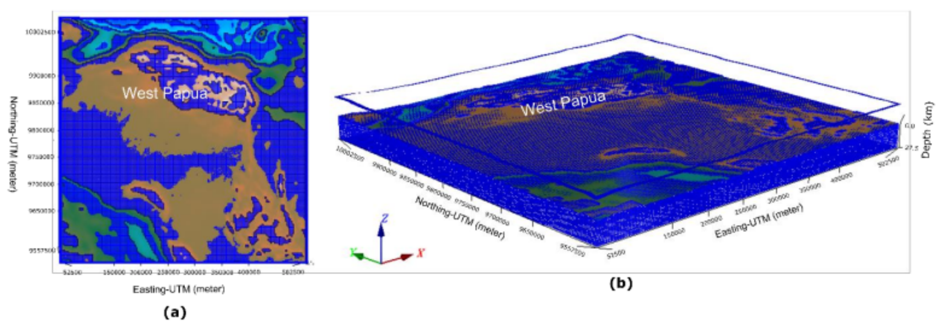


Figure 5. Reconstruction of a 3-D mesh model for the West Papua region (a) Digital Elevation Model; (b) 3-D grid model in the *x*, *y*, and *z* directions (blue lines indicate model boundaries).

The modeling begins with the reconstruction of initial model with a cell discretization of 180 x 178 x 17 for the *x*, *y*, and *z* directions, with a cell size of 2.5 km for the *x* and *y*, while for *z* up to 2.9 km (Figure 5b). Regional gravity anomalies and upward continuation magnetic anomalies up to 4 km are used as measurement data in the inversion modeling. The goal is to obtain the basement structure as well as the main basin in the area. At the midpoint of the West Papua region, the total magnetic field, inclination, and declination are 40433.16 nT, -20.14^{o}, and 1.95^{o}, respectively. This study also includes the CRUST 1.0 model as a constraint for gravity and magnetic data inversion modeling, with a resolution of 1^{o} x 1^{o}, CRUST 1.0 provides data on global surface topography, seabed bathymetry, seismic refraction, ice sheets, sediments, and the thickness of the earth's crust (Laske et al., 2013; Lewerissa et al., 2020). The Geoscience data service from Geosoft Seequent provided access to Geosoft Public DAP Server data (https://public.dap.seequent.com/GDP/Search) in the form of subsurface density data (Figure 6a) and thickness of a crust (Figure 6b).

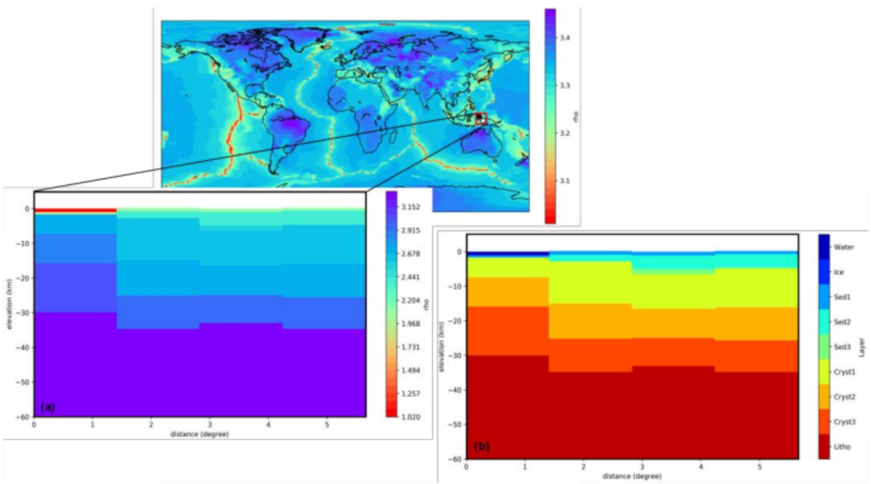


Figure 6. CRUST 1.0 cross-section in a West Papua, Indonesia, (a) Subsurface density distribution; (b) The earth's crust thickness.

4. Result and Disscussion

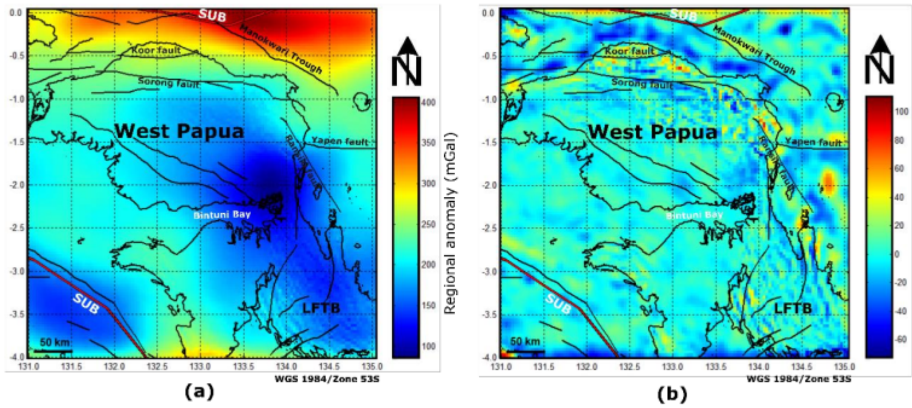
4.1. Regional and residual gravity anomalies in West Papua

The free-air gravity anomaly in the province of West Papua, Indonesia from the 2012 WGM model ranged from -127.64 mGal to 410.12 mGal (Figure 3a), while the complete Bouguer anomaly was positive between 63,830 mGal to 443.82 mGal (Figure 3b) covering land and sea areas. The free-air anomaly has a low value in the oceans to the north and northeast of the study area because they are in isostatic equilibrium, whereas it has a high value inland with higher topographic elevation, which is associated with mountain ranges. The complete Bouguer anomaly with high value is found in the northern and eastern parts of West Papua, and it is thought to be part of the mantle surface or Moho layer at shallow depths with high rock density. This high anomaly is also related to the northward subduction of the Pacific Ocean plate associated with the Manokwari Trough.

Furthermore, the value of the complete Bouguer anomaly decreased to the south and west, reaching a minimum value in the form of a circular shape at the neck of the bird, associated in the Bintuni basin with the main constituent composition of siliciclastic and quarter sedimentary rocks on the stratigraphy of the

Australian continental plate to the southeast on the Lengguru Fold Trhust Belt (LFTB). Low Bouguer anomaly is generally correlated with positive elevation, whereas high anomaly is associated with negative elevation. This correlation occurs because the Bouguer anomaly is directly related to the density distribution in the crust and mantle (Gushurst & Mahatsente, 2020). Bird's head stratigraphy is broadly defined as intra-Pacific island arc material to the north and east, followed by continental Australia material to the south and west (Gold et al., 2017b). A low anomaly is also seen in the southwest part associated with the Seram trough in Maluku province, thought to be a subduction zone of the Papuan bird's head microplate under the Banda Sea (Putra & Husein, 2019).

The Sorong fault line from west to east is the boundary between the Pacific oceanic crust in the north and the Australian continental crust in the south, according to the complete Bouguer anomaly map. A low Bouguer anomaly has been studied in relation to the low seismicity parameter b, whereas the opposite is thought to be related to the offshore free air anomaly. Temporal variations in the value of b are interpreted as a result of seismicity migration by changes in spatial petrological, geophysical, and rheological characteristics (El-Isa & Eaton, 2014). To emphasize the main regional geological structures in West Papua, including Koor, Sorong, Ransiki, and Yapen faults, a second radial derivative map is also analyzed based on the XGM2019e model. The value of the second radial derivative ranges from -184.93 Eotvos (mGal/km) to 364.80 Eotvos (mGal/km), as shown in Figure 3c. On the second r derivative map, it is clear that the main fault structure paths in the study area tend to be associated with zero values. In this route, earthquakes predominantly occur in the province of West Papua. Subsequently, regional and residual gravity anomalies were separated using an upward continuation technique at an altitude of 4 km based on a complete Bouguer anomaly map. The height of the continuity is adjusted to the availability of EMAG2-V3 data upwards of 4 km.



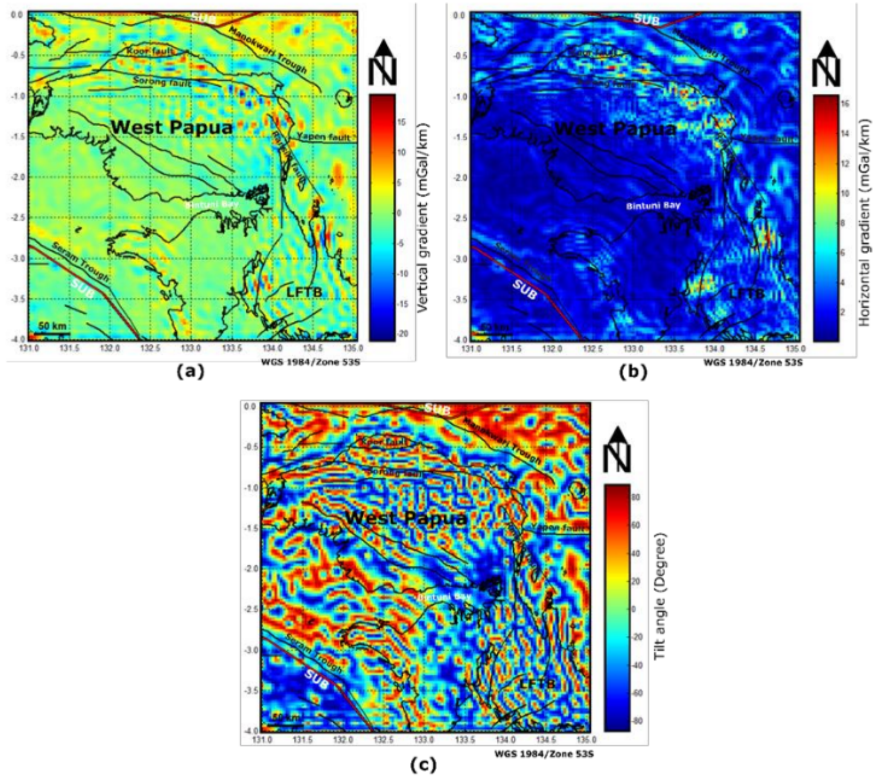
SUB: Subduction zone **LFTB**: Lengguru Fold Thrust Belt

Figure 7. Gravity anomalies separation in the West Papua region, (a) Regional anomalies; (b) Residual anomalies.

The process is carried out to obtain regional anomalies and eliminate the influence of small structures from the gravity data in form of residual anomalies. Regional gravity anomalies are used as input data for gravity inversion modeling to obtain a basement model in the study area. The positive regional gravity anomaly ranged from 85.90 mGal to 406.08 mGal (Figure 7a), while the residual gravity anomaly ranged from -72.45 mGal to 110.40 mGal (Figure 7b). The high regional anomaly is located in the north of West Papua and decreases towards the south with a circular pattern at the neck of the associated bird in the Bintuni basin. Residual anomalies are more complex than regional anomalies, with a predominance of moderate to low values. The high residual anomaly is distributed in several places, especially on the Koor fault line in the north, the Sorong fault and the Ransiki fault in the southeast, it is thought to be related to the volcanic rock lithology which has a high density (Figure 2). Regional gravity anomalies generally describe large and deep geological structures, while residual anomalies are associated with small and shallow structures.

4.2. Gravity Gradient in West Papua

The Earth's gravity gradient analysis aims to increase structural boundaries or geological contacts in the West Papua region not yet visible on the complete Bouguer anomaly map. The vertical gradient was negative to positive and ranged from -20.97 mGal/km to 19.61 mGal/km (Figure 8a). High gradient values were found in the north of the research area, while low values were distributed in several locations, such as the heads and necks of southern birds. In general, major fault structures and geological contact points in the study area are related with a zero value of the vertical gradient. Positive values for the horizontal gradient range from 0.039 mGal/km to 16.56 mGal/km.



SUB: Subduction zone **LFTB**: Lengguru Fold Thrust Belt

Figure 8. Earth's gravity gradient in West Papua; (a) Vertical gradient, (b) Horizontal gradient, (c) Tilt angle.

The maximum amplitude values on the horizontal gradient map of the West Papua region indicate geological contact boundaries, faults, and main geological structures (Figure 8b). Furthermore, tilt angle analysis is used to compute the arctan value of the ratio of vertical and horizontal gravity anomaly derivatives for the complete Bouguer anomaly data set. Tilt angle analysis has the advantage of not requiring physical parameters such as density, magnetic susceptibility, inclination, structural index, and so on in its calculations when compared to other methods. The tilt angle contour can be used to calculate the depth of the source (Akin et al., 2011). Tilt angle analysis of the complete Bouguer anomaly in West Papua produces more complicated values and patterns than vertical and horizontal gradients. The tilt angle value ranges from -87.03° to 88.50°, with positive values predominating in the study area's north, east, and west (Figure 8c), and negative values generally associated with the contact boundaries of geological structures and major faults in West Papua. The vertical limit of the source of the anomaly or geological structure is represented by the zero value of the tilt angle.

4.3. Magnetic Anomaly in West Papua

The EMAG2-v3 model provides two types of magnetic anomaly data extracted for the West Papua region, including sea level anomalies and an upward continuation of 4 km above sea level. The sea-level magnetic outliers ranged from −472.75 nT to 101.94 nT (Figure 4a), while the upward continuation magnetic anomalies at 4 km altitude ranged from −328.178 nT to 62.001 nT (Figure 4b). Overall, the patterns of magnetic anomalies for both models are relatively the same, with high anomalies predominant in the north associated with the Manokwari Trough subduction zone, and then high anomalies are also found at the bird's neck in the south. Low magnetic anomalies dominate Bird's Head from west to east, mainly on the Koor, Sorong, Ransiki, and Yapen strike-slip fault lines.

The high-to-low magnetic anomalies in both models suggest west-to-east subduction from the north of Bird's Head, a contribution from the Pacific Plate. Low negative anomalies with circular shapes were found on the main Sorong and Koor fault lines and at two locations on the Ransiki fault line in the South Manokwari District, possibly due to igneous intrusions in the study area. Such low magnetic anomalies are generally associated with low rock susceptibility values in which volcanic rocks lose their magnetism due to high temperature and high pressure. To further emphasize the magnetic anomalies that can describe smaller geological structures, residual anomalies were also calculated based on the difference between sea-level outliers and results that carried over up to 4 km. Residual outliers ranged from -144.57 nT to 49.86 nT (Figure 4c). The high residual anomaly further emphasizes the geological contact boundary indicating subduction in the northern part of the Papuan bird's head, associated with the Manokwari trough of Pacific oceanic crustal rocks.

4.4. Gravity and Magnetic Anomlies Inversion

Figure 9 depicts the results of a three-dimensional inversion of regional gravity anomaly data in the province of West Papua. The rock density contrast values obtained range from -0.348 gr/cm3 to 0.451 gr/cm3. The results of the gravitational inversion are represented as layers at various depths, including 5 km (Figure 9a), 10 km (Figure 9b), 15 km (Figure 9c), and 20 km (Figure 9d) (Figure 9d). At a depth of 5 km, rock density contrast is generally moderate to low, with low-density contrast found in several locations in the north, bird's neck, southwest, and southeast. This low value is thought to be a result of the study area's tectonic activity. The geological structures of the main faults, such as the Sorong, Koor, Ransiki, and Yapen faults, are generally found at the boundary of low and high-density contrasts, particularly in the northern part of the bird's head from west to east.

In particular, the low-density contrast in a neck is associated with the Bintuni Basin which is the largest oil and gas producing basin in eastern Indonesia. The basement rocks of the Bintuni Basin are composed of the Kemum formation of Silur-Devon (Paleozoic) age, consisting of claystone, graywackes, and coarse clastics. The Kemum Formation is estimated to have experienced the folding and intrusion of granite rocks (Handyarso & Padmawidjaja, 2017). At a depth of 10 km, high-density contrast is seen starting to dominate in the entire study area. At this depth, the Bintuni basin begins to be seen with low-to-minimum density contrast. At this depth, the contrast of low rock density is also still visible. The contrast of rock density at a depth of 15 km and 20 km generally has the same pattern, where high-density contrast reaches a maximum that dominates the entire area. When compared with the global crust model CRUST 1.0 for the West Papua region (Figure 6), this layer is estimated to be the boundary between the sedimentary layer and the upper crust, presumably as the basement layer in the study area.

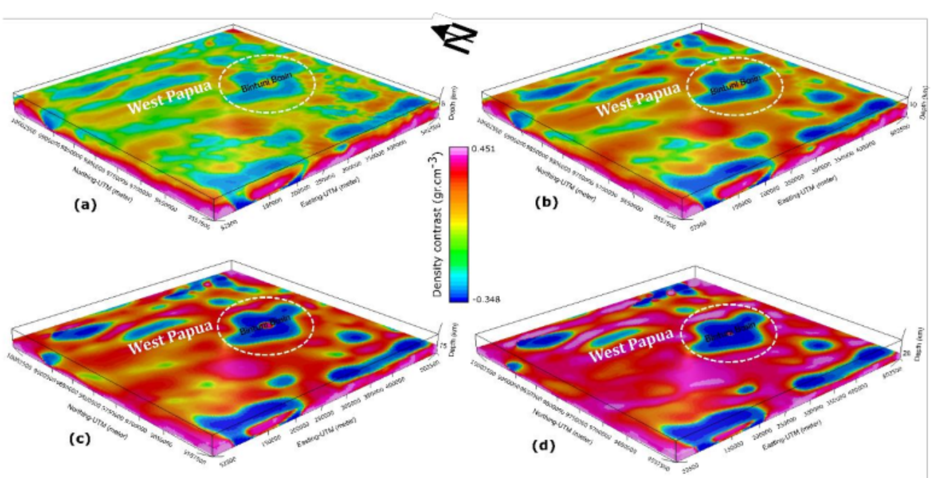


Figure 9. Rock layering model at various depths based on regional gravitational anomaly inversion modeling in West Papua: (a) 5 km; (b) 10 km; (c) 15 km; (d) 20 km.

The EMAG2-v3 model also performed a 3-D inversion of regional magnetic data up to 4 km to support the results of the three-dimensional (3-D) inversion of gravity data. Magnetic susceptibility physical parameter values range from -0.363 SI to 0.223 SI. Depth changes, such as gravity data inversion, comprise the rock formation system. The pattern of rock susceptibility at 5 km depth (Fig. 10a) is more complex, with moderate to high susceptibility values in the north and south, and low susceptibility in the middle of the bird's neck in Papua. High rock susceptibility can be found primarily to the north and south at a depth of 10 km (Figure 10b). Rock susceptibility generally follows the same pattern at depths of 15 km (Figure 10c) and 20 km (Figure 10d), with high susceptibility in the north, west to east, and south in the middle. This high susceptibility is thought to be due to the Pacific oceanic crust's high rock density and richness in magnetic minerals. This layer is thought to be West Papua's basement layer. The low rock susceptibility of the oil and gas-rich Bintuni Basin corresponds to quarter and siliciclastic sedimentary deposits.

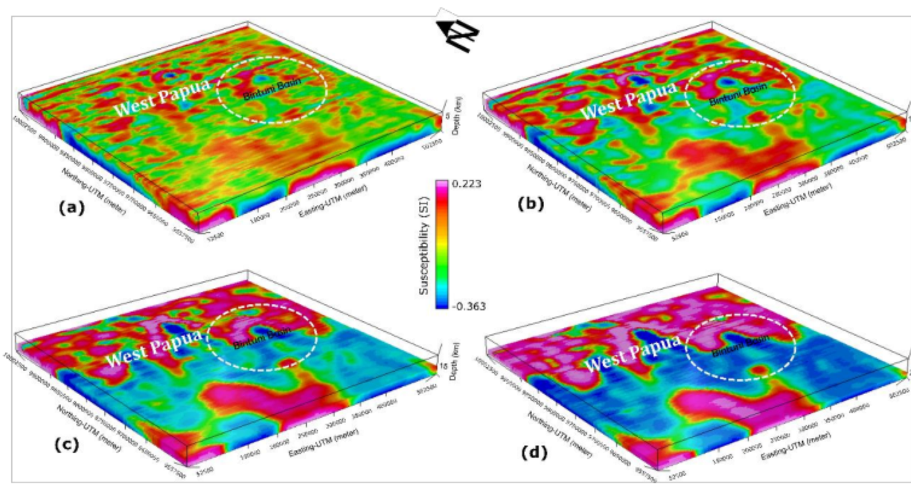


Figure 10. Rock layering model at various depths based on the upward continuation 4 km magnetic anomaly inversion modeling in West Papua: (a) 5 km; (b) 10 km; (c) 15 km; (d) 20 km.

The subsurface model is shown in the form of a north-south cross-section from the results of a three-dimensional (3-D) inversion to demonstrate the presence of tectonic activity in the province of West Papua (Figure 11). Figure 11a depicts a gravity inversion cross-section showing the subduction of the Pacific plate with high rock density contrast under the Australian continental plate with lower density contrast from the north.

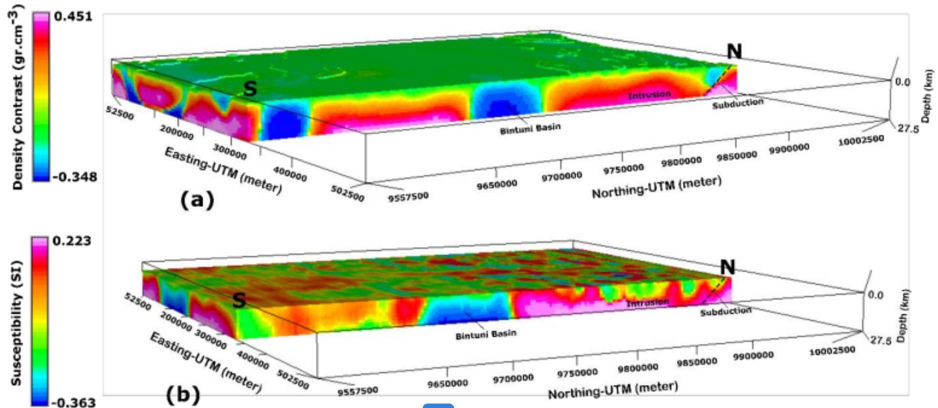


Figure 11. North to south cross-sectional model showing the subduction pattern of the Pacific plate beneath the Australian plate in West Papua: (a) Gravity inversion results; (b) Magnetic inversion results.

There is also an intrusion pattern of granite rocks, particularly in the mountain clusters in the study area. Papua's bird's head experienced intense volcanic activity during the Triassic period, with evidence of granite found at several locations on the bird's head and the western and southwestern parts of Cenderawasih Bay. Anggi granite, Wariki granodiorite, and Warjori granite are all part of the Netoni intrusion complex (Gold et al., 2017b; Webb & White, 2016). The gravity inversion cross-sectional model also clearly shows the Bintuni basin with negative density contrast, presumably having good oil and gas potential in the area. Figure 11b is a cross section of the magnetic inversion which shows the same pattern as the earth's gravity inversion. The subduction of the Pacific plate is characterized by the presence of high rock susceptibility under the Australian continental plate with lower susceptibility. Granite intrusion patterns are also depicted through rocks with high susceptibility. A cross section model of the gravity and magnetic data shows the appropriate results regarding the subsurface geological structure in the province of West Papua.

5. Conclusion

Utilization and analysis of gravity and magnetic data based on satellite measurements from the 2012 WGM model and EMAG2-v3 provide significant results for understanding tectonic activity and determining the subsurface structure model for sediment-basement layers in West Papua. High gravity and magnetic anomalies in the northern part of the study area indicate subduction of the high density and magnetic mineral-rich Pacific plate under the Australian plate in the southern part which is associated with low gravitational and magnetic anomalies. Gravity gradient analysis in the form of vertical, horizontal, and tilt angle derivatives provides results that confirm the boundaries of major geological structures such as the Sorong, Koor, Ransiki, and Yapen faults, which are the paths of earthquakes in West Papua.

The three-dimensional (3-D) inversion of gravity and magnetic data shows conformity of the subsurface model that describes the subduction of the Pacific Ocean plate in the northern part of the bird's head of West Papua, the presence of massive intrusion of igneous rock, as well as the presence of density anomalies and low susceptibility indicating the presence of a basin. Bintuni is rich in oil and gas in eastern Indonesia. The boundary of the sedimentary and basement layers is estimated at a depth of between 15 – 20 km with rock from the mantle in the north as the basement, and the Kemum formation consisting of Silur-Devonian metamorphic siliciclastic rocks in the south.

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Author Contributions: R.L has developed the research concepts and designs, as well as written the manuscript. S.S. writes and assesses research findings in the form of a published manuscript.

Data availability

The datasets used in this study are available upon reasonable request from the corresponding author.

Competing interests

The authors state that they do not have any competing interests.

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