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Gravity Disturbance Analysis of Geodynamics in East Indonesia

Al Shida Natul [1,*], T. Rykard Yudha Pratama [2], Annisa Kurnia Shalihat[1]

[1] Department of Survey and Mapping, Faculty of Engineering, Indo Global Mandiri University, Palembang, 30129
[2] Graduate Program in Disaster Science, Syiah Kuala University, Banda Aceh, 23111

*Corresponding author e-mail: alshida@uigm.ac.id

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Abstract

Gravity satellites can be used for geodynamic studies in large and hard-to-reach areas. This study conducts gravity disturbance analysis from GOCE and EGM2008 satellite data for geodynamic interpretation in eastern Indonesia. The results of this research can be used as a basis for geodynamic studies and disaster mitigation in eastern Indonesia. Gravity disturbance processing results from GOCE data with values around -300 to 260 mGal and EGM2008 with values around -350 to 450 mGal. Gravity disturbance maps of the GOCE and EGM2008 can clearly show fault patterns in the sea. However, the EGM2008 gravity disturbance map shows the fault pattern in the sea more clearly than the GOCE gravity disturbance map due to the higher spatial resolution of EGM2008 than GOCE. The cross-section of the GOCE and EGM2008 gravity disturbance maps represents the gravity signal of the study area; the GOCE graph represents the signal and forms the EGM2008 gravity disturbance signal components. The novelty of this research is related to the comparison of gravity disturbance maps from GOCE and EGM2008 data, which can be used to detect regional geological structures in eastern Indonesia.

Keywords: GOCE, EGM2008, gravity disturbance, fault, eastern Indonesia

1. Introduction

The eastern part of Indonesia is occupied by two large islands, namely Sulawesi and Papua, as well as a group of small islands consisting of the South Banda Islands and the Lesser Sunda Islands of Nusa Tenggara, Maluku, and Halmahera (Arief Troa *et al.,* 2016). The geodynamics of Eastern Indonesia is more complicated than Western Indonesia (Naryanto, 2019). On the western part of Indonesia, the Indo-Australian plate meets the Eurasian plate. Meanwhile, in eastern Indonesia, the confluence of three active tectonic plates, namely the Pacific, Indo-Australian, and Eurasian (Hinschberger *et al.,* 2005). These plates move in different directions (DeMets et al., 2010). The movement of these three tectonic plates resulted in the formation of megathrusts and faults in eastern Indonesia.

The geodynamics of eastern Indonesia is interesting to study using various methods because there are complex faults with the potential for high and intensive levels of seismicity. One method that can detect faults is the gravity method, which measures variations in the Earth's gravity caused by differences in subsurface density (Syafnur, 2019). Geological structures that cause significant gravitational effects by contrasting size and density (Götze & Pail, 2018). Gravity measurements can be carried out using gravity satellites that have broad observation areas, precision, spatial resolution, and high levels of spectral resolution and are not limited to topography (Saraswati & Anjasmara, 2010), such as The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE).

The GOCE satellite is a gravity satellite launched by the European Space Agency (ESA) on March 17, 2009 with a 3-axis gravity gradiometer instrument for measuring gravitational gradients, a spatial resolution of less than 100 km and has an accuracy of up to 1 mGal (European Space Agency, 2014). Its mission is in geodesy and geodynamics, a combination of Satellite Gravity Gradiometry (SGG) and Satellite-to-Satellite Tracking (SST) (Daraputri *et al.,* 2015).

Apart from GOCE, high-resolution geopotential model data such as Earth Gravitational Model2008 (EGM2008) is also used. The Development of the EGM2008 model was completed in late March 2008, and on April 17, 2008, EGM2008 was released and presented to the scientific community (Pavlis et al., 2008). The EGM2008 gravity model is a spherical harmonic model of the Earth's gravitational potential, developed by a combination of least squares of the ITG GRACE03S gravity model and the associated fault covariance matrix, using gravity data from a global set of area-average free air gravity anomalies defined on a 5-arc-minute equilateral lattice (Pavlis *et al.,* 2012).

A GOCE data study for geodynamics in the Indonesian region was conducted by Dewanto et al. (2022) in West Sumatra; Natul & Heliani (2022) on Sumatra Island; Álvarez *et al.,* (2021) in Sumatra and Andaman; Saraswati & Anjasmara (2010) in the Subduction Zone in the West of Sumatra Island. However, no one has yet conducted research on GOCE and EGM2008 data for the Eastern Indonesia region.

This study aims to determine the distribution of gravity disturbance from GOCE and EGM2008 data on the geodynamics of eastern Indonesia. The main advantage of comparing GOCE with EGM2008 data is for GOCE model validation. The information from this research will be helpful as a basis for disaster mitigation efforts in Eastern Indonesia and become an effective method for analyzing geodynamics over large areas and saving time.

2. Tectonic Setting

Research locations in the eastern part of Indonesia include Sulawesi, Sumba, Timor, the Molucca Sea, the Banda Sea, Halmahera, and Papua (Figure 1). Eastern Indonesia is in a convergent zone between three main plates: South East Asia, the Australian, and the Pacific–the Philippine Sea. (Hinschberger *et al.,* 2005). The Australian Plate is moving north-northeast relative to Eurasia at a rate of about 70 mm/yr. In contrast, the movement of the Pacific relative to Australia is about 120 mm/yr westward (DeMets *et al.,* 2010). The main driving force for controlling the active tectonics of eastern Indonesia is the westward movement of the Pacific plate, which causes a series of faults such as the Yapen, Sorong, Matano, and Palu-Koro faults that cross the northern part of eastern Indonesia (Bock et al., 2003; Stevens *et al.,* 2002).

The Banda arc is a continuation of the Sumatra-Java subduction system to the east, which has morphological characteristics that characterize convergent plate boundaries, trenches, trench slope breaks, upper slope basins, volcanic arcs, and marginal basins (Cardwell & Isacks, 1978). The Timor Trough is located south of the Banda arc, with water depths of up to 2000 meters. In this region, the Australian Plate subducts northward under the Asian Plate, which produces an accretion complex. The extension of the Timor Trough leads to the South of the Tanimbar Islands to form the Tanimbar Through (Darman, 2012).

Sulawesi Island comprises complex tectonic structures and actively moves at different speeds (National Center for Earthquake Studies, 2017). To the north of Sulawesi Island is the North Sulawesi Megathrust, with a shifting speed of around 40–50 mm/year (Socquet *et al.,* 2006). The Palu Koro Fault, the Sorong Fault, and the Matano Fault are in the mainland area. The Palu Koro Fault is about 220 km long and moves about 42 mm/yr-1 relative to the main boundary of the Makassar thrust and the North Sulawesi Megathrust (Patria & Putra, 2020; Socquet *et al.,* 2006). To the north, the Palu-Koro Fault continues along the coast and terminates at the western end of the North Sulawesi subduction zone (Hamilton, 1973; Hall & Wilson, 2000).

The Molucca Sea is located in a complex region due to the interaction of the Pacific Plate, Philippine Plate, Eurasian Plate, and Australian Plate (National Center for Earthquake Studies, 2017). The Molucca Sea plate subducts eastward in the Halmahera subduction zone and westward in the Sangihe subduction zone to form an inverted U, which causes the oceanic domain to almost disappear (Hinschberger *et al.,* 2005; Hall & Wilson, 2000). To the west of the Maluku Sea lies an active volcano in the Sangihe Arc, which can be traced from North Sulawesi to Mindanao. In contrast, on the northeastern side of the Moluccas, volcanic activity in the Halmahera Arc has ceased to the north of Halmahera (Hall & Wilson, 2000).

The Sorong Fault is the Maluku and Philippine Sea plate's southern boundary with Australia. The Sorong Fault is part of the suture zone of the juxtaposed arc and continental crust in the North Maluku and Bird's Head Islands of New Guinea (Hall & Wilson, 2000). Active faults in Papua are divided into several zones, namely the Bird's Head Zone, the Yapen Fault Zone, the Mamberamo Fault Zone, the Papua Fold Thrust Belt Zone, and the Bird's Neck Zone (National Center for Earthquake Studies, 2017). In the Bird's Head zone, three faults are the source of earthquakes: the Sorong Fault, the Koor Fault, and the Teminabuan Fold Zone (Pamumpuni, 2006). The Yapen Fault zone is east of Ransiki and continues west-east to Yapen Island, which merges with the Mamberamo Fault zone in the north of Papua Island. The Papua Fault and Fold Zone extends from the eastern part of the bird's neck to Papua New Guinea. The Papua Fold Thrust Belt is in the southern part of the Papuan Central Range, which involves old to young rocks from the Paleozoic to Rasen (Pamumpuni, 2016). Active faults in the Bird's Neck region consist of the Tarera-Aiduna Fault, the Through Aru, and the Lengguru Fold Belt (Pamumpuni, 2006). In addition, the Papua region has the Waipoga Fault, whose structure is characterized according to the coastline of Cenderawasih Bay from the northeast-southwest.

The Subduction Zone in Papua is also a source of earthquakes such as the Manokwari Thrust and New Guinea Trench. The Manokwari Thrust is an asymmetrical depth (trending west to east on the west and southeast-northwest on the east) that extends in bathymetry to the north of the Bird's Head. The New

Guinea Subduction Zone results from the collision of the Pacific and Australian plates, which causes a change in the polarization of the subduction angle.

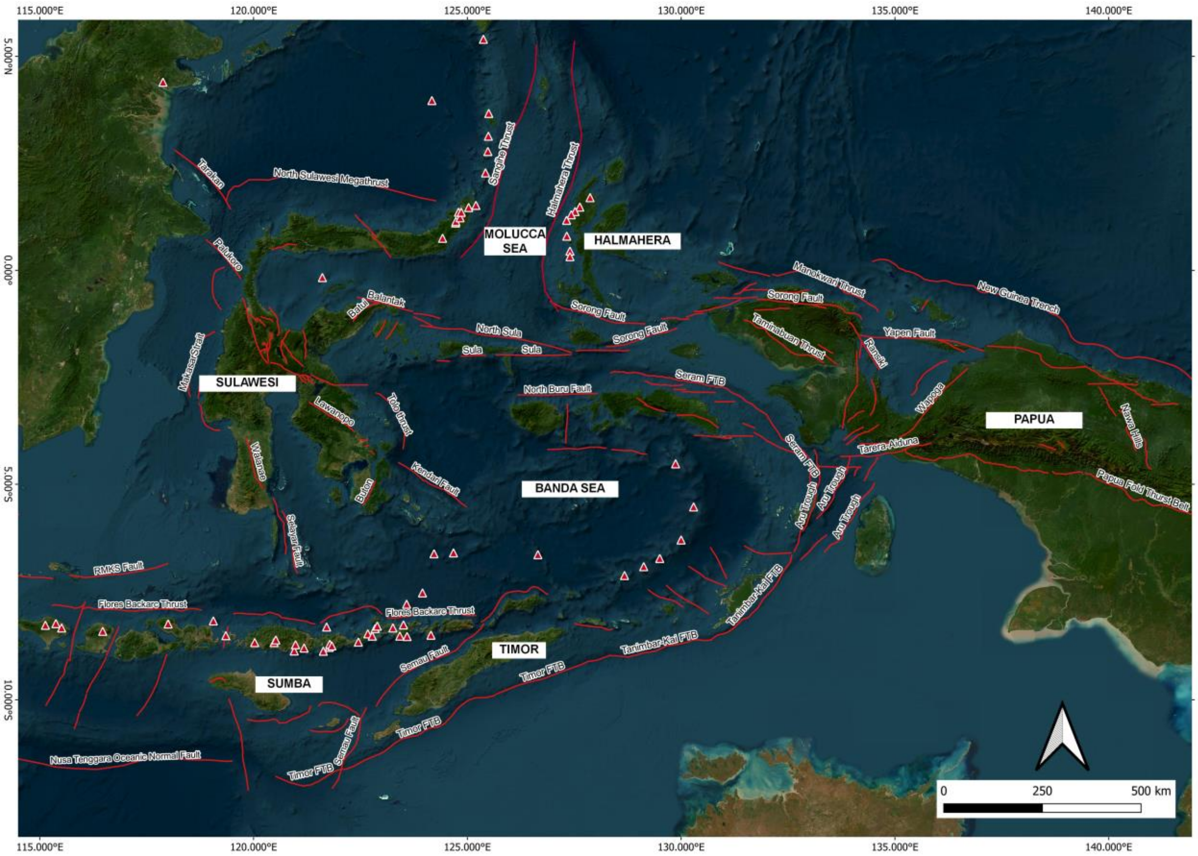

Figure 1. Tectonic map of Eastern Indonesia

3. Methodology

The location of this study is in Eastern Indonesia, covering the geographical position of -11^0 S to 5^0 N and 117^0 to 141^0 E. The data used in this study are GOCE (GO_CONS_GCF_2_TIM_R6e) in 2019 with degree 300 from the GOCE gravitational field model using the time-wise approach and EGM2008 in 2008 with degree 2190. EGM2008 data combines altimetry, satellite Grace, and terrestrial data. A series of spherical harmonic coefficients represent the earth's gravitational field model, the maximum degree/order that depends on the spatial resolution of the model. (Barthelmes, 2009).

GOCE and EGM2008 data can be downloaded at http://icgem.gfzpotsdam.de/. A spherical harmonic series, up to a maximum degree and order, is applied to the gravity field model (Yi & Rummel, 2014). The spatial resolution of GOCE and EGM2008 data is determined using the formula $\pi R/N_{max}$, where R is the earth's radius of approximately 6.371 km and Nmax is the maximum degree/order of the harmonic expansion. The spatial resolution of GOCE data is 67 km, while the spatial resolution is EGM2008 9 km. The software used is Goce User Toolbox (GUT). Additional data, namely DEM, fault, volcanic, tectonic map, and eastern Indonesian administrative.

Gravity disturbance, which is typically employed to measure the height of the geoid, is a type of free air anomaly reduced to the standard earth ellipsoid surface as a reference surface. The equation for gravitational disturbance δg is as follows (Bauer Marschallinger et al., 2015):

$$\delta g = g_p - \gamma_p \qquad (1)$$

with $g_p$difference between observed gravity g and normal gravity γ at the same point P on the geoid. Visualization of the gravity disturbance map using the Golden Surfer software. The GOCE and EGM2008 gravity disturbance map overlaps with additional data (faults, volcanoes, and administrative boundaries) to facilitate data interpretation and analysis.

4. Result and Discussion

Gravity disturbance can represent the gravitational effect produced by Indonesia's heterogeneous density distribution (Perozzi et al., 2021). According to Doğru & Pamukçu (2019) gravity disturbance map from gravity satellites can reflect tectonic elements. In Indonesia, a study on gravity disturbance maps was conducted by Julzarika et al. (2020) using GRACE satellite data to detect plate boundaries and faults in the Sunda Strait area. A geodynamic study using gravity disturbance has been carried out by Fadhilah & Heliani (2020) using airborne and EGM2008 data on the island of Sulawesi.

The results of the gravity disturbance processing from GOCE data are shown in Figure 2 with values around -300 to 260 mGal and from EGM2008 in Figure 3 with values around -350 to 450 mGal. The color range bar values in Figure 2 and Figure 3 are made the same; faults are symbolized by a red straight line, and volcanoes are represented by a red triangle. This examines the differences and similarities between the GOCE and EGM2008 gravity disturbances. In general, the GOCE and EGM2008 gravity disturbances have the same pattern.

The GOCE gravity disturbance map clearly shows fault patterns in the sea with negative values around -300 to -10 mGal. The faults detected on the gravity disturbance map (Figure 2) are based on patterns and changes in low gravity disturbance values, including the Tarakan Fault, North Sulawesi Megathrust, Palu-Koro Fault, Tolo Thrust, Kendari Fault, Sangihe Thrust, Halmahera Thrust, Manokwari Thrust, New Guinea Trench, Timor FTB, Tanimbar-Kai FTB, Aru Trough, Flores Backarc Thrust, Seram FTB, North Buru fault, North Sula, Balantak, and Makassar Strait. Faults on land that can be detected are the Papua Fold Thrust Belt, but they are not very clear.

The GOCE gravity disturbance value in volcanic areas is predominantly high, with around 150 to 260 mGal as seen on the mainland of Halmahera Island and northern Sulawesi, which have positive anomalies. Apart from that, high gravitational disturbance values also occur in high topographic areas such as Papua, Sumba, West Sulawesi, and Central Sulawesi.

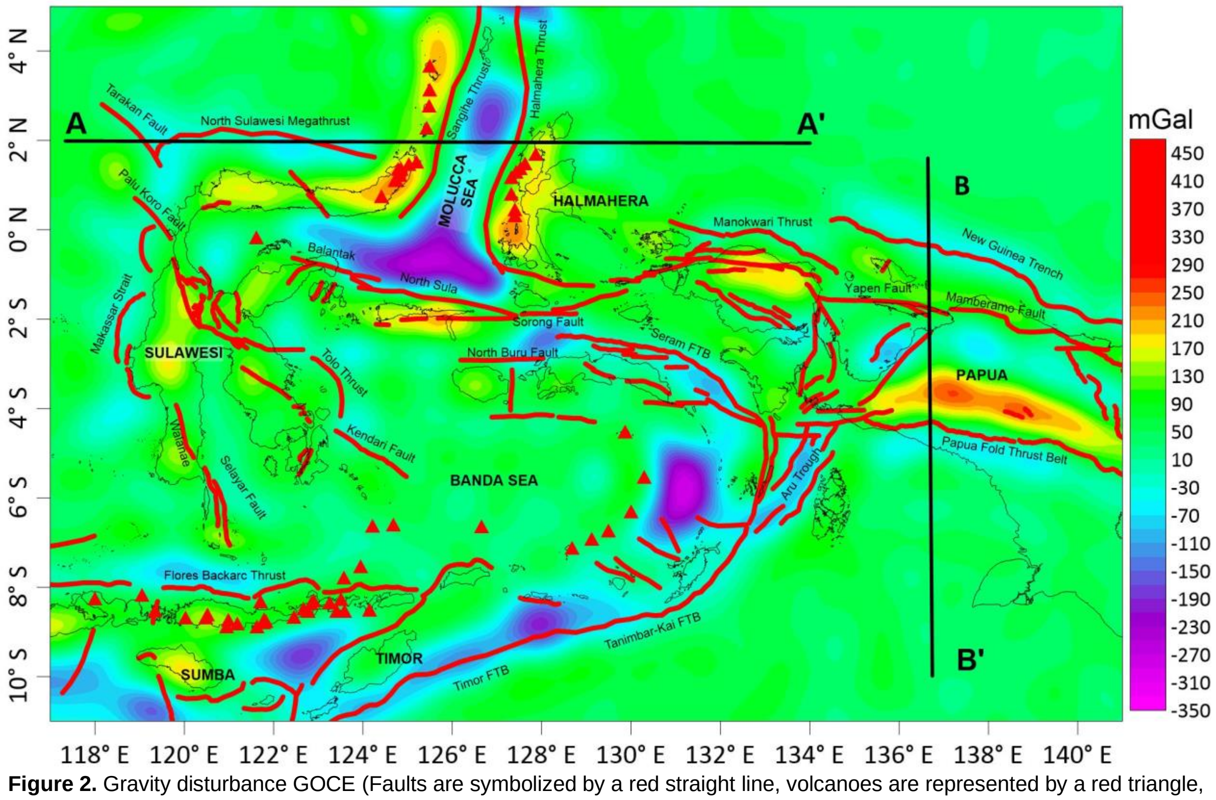

Figure 2. Gravity disturbance GOCE (Faults are symbolized by a red straight line, volcanoes are represented by a red triangle, and a black straight line symbolizes slicing)

The EGM2008 gravity disturbance map can clearly detect fault patterns at sea and on land with negative values around -10 to -350 mGal (Fig.3). Although not all faults on land can be detected. Faults at sea that can be detected clearly are Tarakan Fault, North Sulawesi Megathrust, Palu-Koro Fault, Sangihe Thrust, Halmahera Thrust, Manokwari Thrust, New Guinea Trench, Timor FTB, Tanimbar-

Kai FTB, Aru Trough, Flores Backarc Thrust, Semau Fault, Seram FTB, North Buru Fault, North Sula, Balantak, Tolu Thrust, Kendari Fault, Selayar Fault, Makassar Strait, Yapen Fault, and Palu Koro Fault. Meanwhile, the faults on land detected were the Papua Fold Thrust Belt, Nawa Hills, and Mamberamo Fault.

In the volcanic area and high topographic areas, the EGM2008 gravity disturbance values were detected at around 200 to 450 mGal. Volcanic areas with high anomalies, such as Halmahera Island and northern Sulawesi. The high topographic areas with high anomalies are in Papua, Sumba, West Sulawesi, and Central Sulawesi.

The EGM2008 gravity disturbance map more clearly detects anomalous changes in fault areas, volcanoes, and high topography compared to the GOCE gravity disturbance map. Figures 2 and 3, show the differences in color contrast and patterns in the Selayar Fault, Sorong Fault, Yapen Fault, and Mamberamo Fault areas. The EGM2008 gravity disturbance map can detect these faults with low anomalies, while the GOCE gravity disturbance map can not detect these faults. The EGM2008 data has a higher spatial resolution than the GOCE data. In addition, the EGM2008 data presents the variable quality of the original terrestrial data, while the quality of the GOCE data is locally homogeneous (Álvarez et al., 2014).

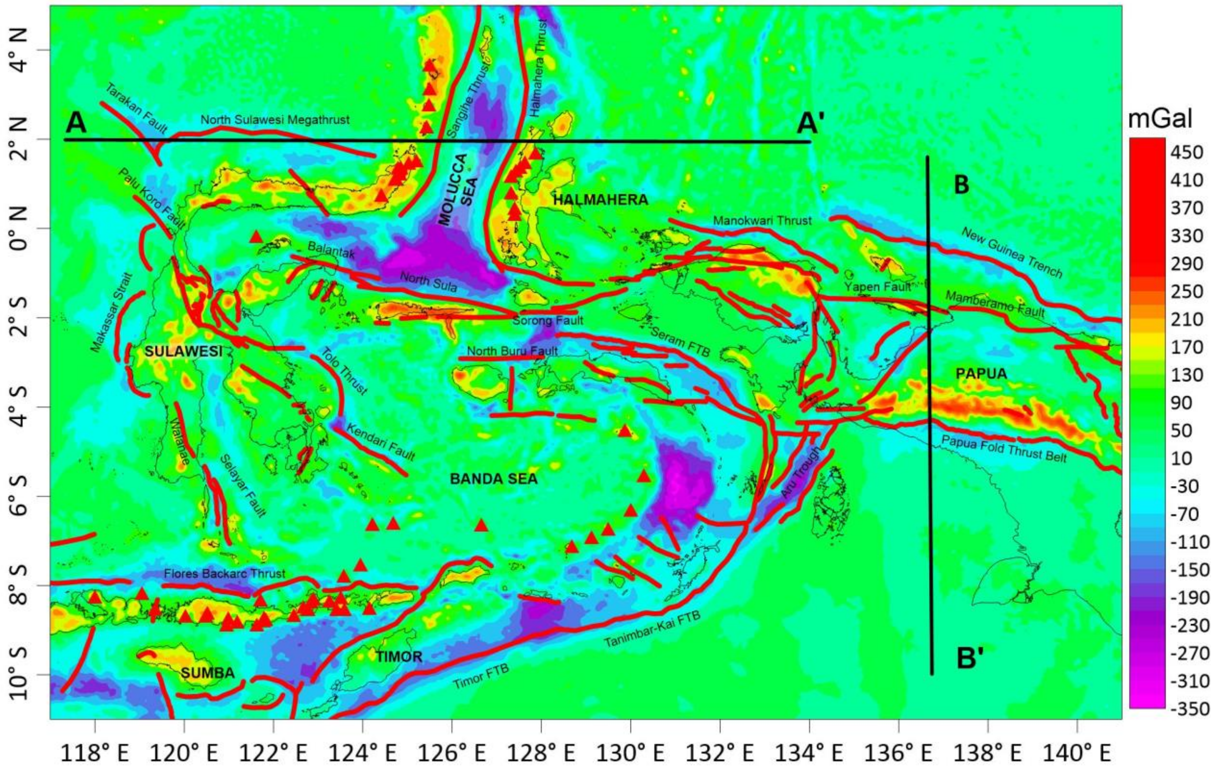

Figure 3. Gravity disturbance EGM2008 (Faults are symbolized by a red straight line, volcanoes are represented by a red triangle, and a black straight line symbolizes slicing)

To better understand the anomalous changes in the fault location, a cross-sectional analysis of gravity disturbance was performed, shown with AA′ and BB′ sections, as well as the red box (the location of the fault).

The AA' Slice (Figure. 4) shows in the fault location area (the red box) that the change in gravity disturbance values is low at the Tarakan Fault, Sangihe Thrust, and Halmahera Thrust. The Tarakan Fault has a GOCE gravity disturbance value of around -40 mGal, while EGM2008 is around -90 mGal. The Sangihe thrust has a GOCE gravity disturbance value of around -130 mGal and an EGM2008 gravity disturbance value of around -140 mGal. The Halmahera thrust has a gravity disturbance value of around -140 mGal, while EGM2008 is around 150 mGal. In addition, the gravity disturbance graph is also low in the Molucca Sea region, with GOCE gravity disturbance values around -150 mGal and EGM2008 -160 mGal. In addition, the gravity disturbance graph is also low in the Molucca Sea region, with GOCE gravity disturbance values around -150 mGal and EGM2008 -160 mGal. The low gravity disturbance value in the Molucca Sea region indicates the existence of a subduction zone where three tectonic plates meet, namely the Philippine Plate, Australian Plate, and Eurasian Plate.

On the BB' Slice (Figure 5) in the New Guinea Trench, Yapen Fault, and Papua Fold Thrust Belt regions (the red box), the graphs of the GOCE and EGM2008 gravity disturbance values decrease. The

GOCE gravity disturbance value in the New Guinea Trench is around -40 mGal, while EGM2008 is around -80 mGal. The Yapen Fault has a GOCE gravity disturbance value of around 0 mGal, while EGM2008 is around -40 mGal. The gravity disturbance value for GECE Papua Fold Thrust Belt is around -10 mGal, while EGM2008 is around -40 mGal.

The conclusion from the results of this graph is that the areas detected by geological structures in gravity disturbance from GOCE and EGM2008 are at low gravity disturbance values. The GOCE gravity disturbance graph results represent regional signals in the study area and form the EGM2008 gravity disturbance signal components.

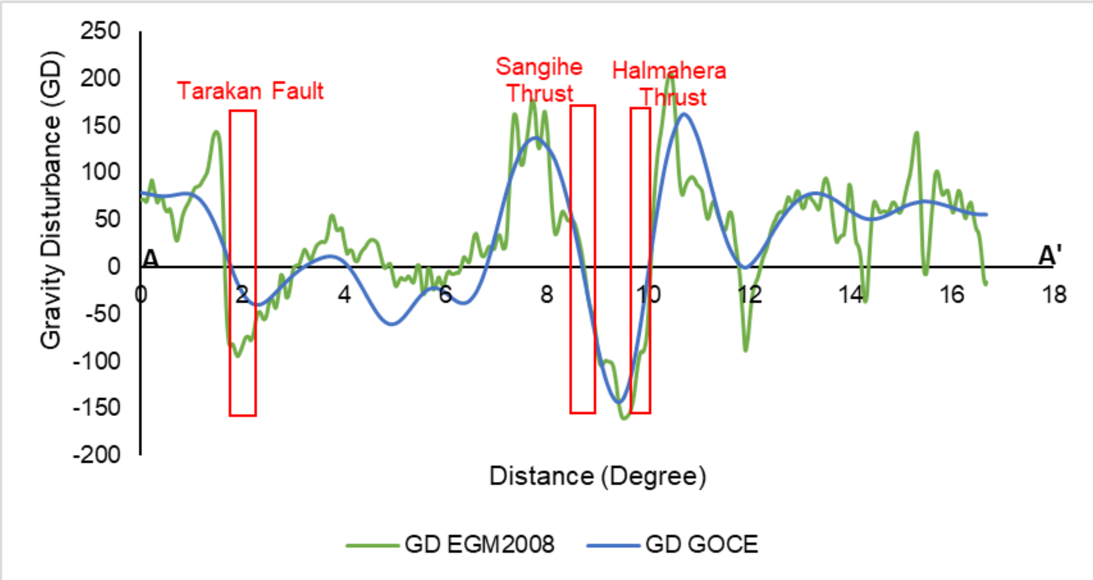

Figure 4. Cross section AA’

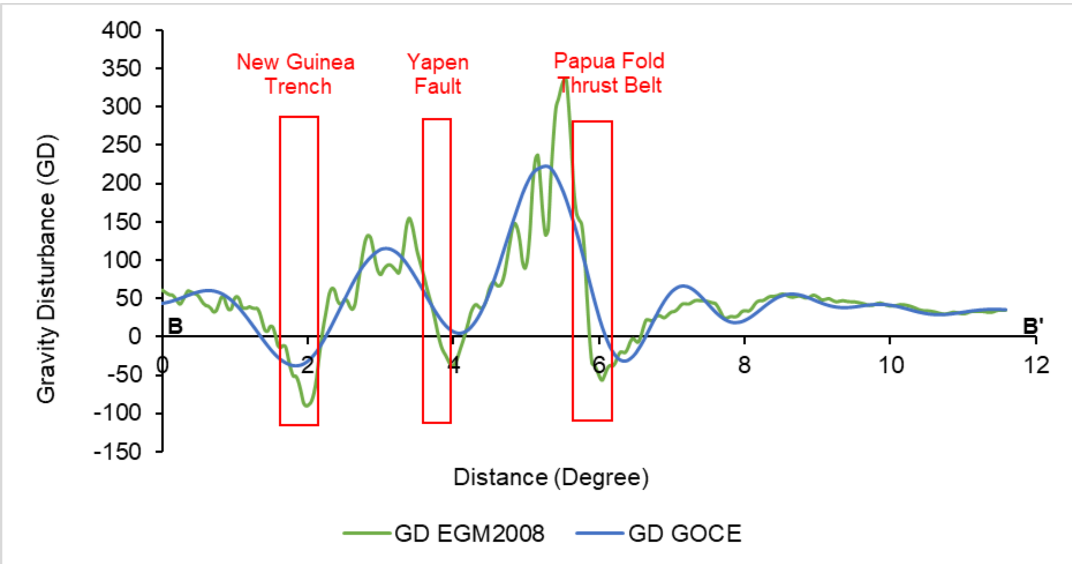

Figure 5. Cross section BB’

5. Conclusion

Based on this research, it can be seen that the GOCE and EGM2008 gravity disturbance maps can detect faults and subduction zones regionally in eastern Indonesia. However, the gravity disturbance map detects subduction zones and sea faults more clearly than land faults. The EGM2008 gravity disturbance map detects subduction zones and faults more clearly and in detail than the GOCE gravity disturbance map, supported by a graph of the slicing results of the EGM2008 gravity disturbance map. EGM2008 data resolution is higher than GOCE data resolution. The GOCE and EGM2008 data may be useful for large-scale tectonic determinations and complementary data sets for geophysical and geological data. The results of this study can be used for geodynamic studies and disaster mitigation. The novelty of research on gravity disturbance analysis in geodynamics is related to the comparison of gravity disturbance maps from GOCE and EGM2008 data, which can be used to detect regional geological structures in eastern Indonesia. This gravity disturbance map research can be developed to include a Bouguer anomaly map. Apart from that, validation is needed by adding remote sensing data or gravity measurement data in the field to make it more accurate.

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