Regional Bouguer anomaly gravity data: 3-D modelling of subsurface structures of the Flores and Timor earthquake risk area

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Abstract. Regional anomaly gravity data are very useful for determining deep subsurface structures due correspond deep surface anomalies. This research aims at analyzing qualitatively to map the gravity anomaly of the island of Flores, modelling shallow surfaces, and interpret surface structures based on the gravity anomalies. In this research, the gravity method used was the secondary gravity data from the Bureau Gravimetric International (BGI) that would be applied using Upward Continuation techniques to interpret deep surfaces for 3D modelling of earthquake risk areas on the islands of Flores and Timor. The modelling was performed by an inversion technique applying the method of singular value decomposition (SVD) and Occam inversion. The result showed that the subsurface structure of the volcano area of the Flores island consists of sandstone, breccia, and andesite with density values of 2.42 g/cm³ - 2.62 g/cm³ and basaltic and lava with density values of 2.65 g/cm³ - 3.24 g/cm³. The most dominating rock in the study area was basaltic rocks with the average density of 2.73 g/cm³. Based on 3D models of regional Bouguer gravity anomalies, the Flores back arc fault was estimated at a depth of 30 km, the thickness of the earth's crust in the Flores back arc fault zone was estimated to be up to 30 km while the thickness of the earth's crust in the fore arc was estimated to be more than 60 km. The existence of magma chamber in the volcanic arc of Flores island was estimated at depth of 30 km in accordance with the seismicity map Flores and Timor areas.

1. Introduction
Indonesia has high volcanic and tectonic activities caused by the position of the Indonesian archipelago between tectonic plates. There are three tectonic plates under the Indonesian territory that have the same type of plate boundary plane, which is the convergent boundary plane that forms subduction zones, namely are Indo-Australian plate, the Pacific ocean plate and the Eurasian plate [8] [7] [11]. Indo-Australian plate subduction moving north with the Eurasian plate moving south is considered to correlate with many various fault systems, folds, basins and active volcanoes that stretch from Sumatra, Java, Bali to Nusa Tenggara as shown in Figure 1(a) [11] and also produce mountains folds, volcanic paths, faults systems and various types of sedimentary depressions such as troughs, fore arc basins, inter-mountain basins and back arc basins as shown in Figure 1(b) [14].
Flores Island is located between the Sunda arc in the west and the Banda arc in the east, and it is also between the Flores basin in the north and the Savu basin in the south. In general, the geological order of the northern part of Flores Island is very complicated, composed of Tertiary aged rocks such as igneous rocks, volcanic clusters and sedimentary rocks, while the southern part has many active volcanoes. The Banda arc extends from Bali to the east through Sumbawa, Flores and the small islands of East Flores and bend to the north resembling a spoon [8] [5] [6].

Figure 1. (a) Indonesian Tektonic Map [11], (b) Subduction Zone [14].

The fractures of the Flores back arc was first reported by Hamilton (1979) based on several reflection profiles. He reported to find a fault on the north of Alor Island and the east side of the Java back arc subduction zone known as Wetar back arc thrust fault. Silver et al. (1986) estimated that the fault on the west side continued into Bali basin located in the North of the Bali island known as Flores back arc thrust fault. Wetar back arc thrust fault and Flores back arc thrust fault occur as a reaction to the pressure arising on the Nusa Tenggara archipelago due to collisions of the Indo-Australian Plate [4], [10].

The Bali-Flores back arc basin has been studied and identified using geophysical methods by several researchers including Hamilton (1979), Silver et al. (1986), McCaffrey (1988), Prasetyo (1992), Zen et al. (1993), Audley-Charles (2004), Daryono (2011). They define the characteristics and presence of the Bali-Flores back arc basin thrust zones from studies of reflection profiles, side scan mapping, seismicity, and other data.

Gravity research conducted from the Indonesian ocean to the North of the Nusa Tenggara Islands shows that there is a change in Bouguer gravity anomaly patterns in the area between Sumbawa and Flores [15]. Hamilton (1979) and Darman (2000) state that in the southern part of the Nusa Tenggara islands there is a positive anomaly which is a subduction with a continuous increase that causes volcanoes to form. In the northern part of the Nusa Tenggara islands, a low anomaly forms a basin.

The gravity method is one of the geophysical methods that can describe subsurface geology based on variations in the earth's gravitational field caused by differences in rock density. This method has the ability to distinguish the density of an anomalous source from the density of the surrounding environment [9].

2. Method

In this research, a three-dimensional modelling of the subsurface structure of Timor and Flores and back arc thrust had been carried out using the Singular Value Decomposition (SVD) inversion method. This study used secondary data in the form of complete Bouguer anomalies and topography data obtained by the Bureau Gravimetric International (BGI) of France based on the 2012 World Gravity Map (WGM) and National Geospatial-Intelligence Agency (NGA). Location of the study area is at 7°-9.5° South and 120°-125° East.

Mapping of the complete Bouguer anomaly data and topographic contours of the study area was shown in Figure 2. The complete Bouguer anomaly map is a gravity anomaly map that reflects the distribution pattern of subsurface rock density. Based on the map, the complete Bouguer anomaly has positive values ranging from 150 mGal to 430 mGal with an interval of 20 mGal (Figure 2(a)). The
northern part of the map shows a high positive anomaly pattern, and it indicates that rocks in this area have a high density. Whereas in the southern part of Flores shows a low positive anomaly, which indicates a lower density than the area in the north which is a fault area up the back arc of Flores. Contour anomaly obtained is used to model subsurface structures. Regional Bouguer anomalies were used for subsurface modeling that encompasses the inner zone, while the residual Bouguer anomalies to model shallow structures near the surface of either the back arc fault zone the Flores island volcano. Topography of Timor and Flores island is at around 1700 m above sea level shown in Figure 2(b).

![Figure 2. (a) Complete Bouguer anomaly data and, (b) Topographic contours Flores and Timor.](image)

Projections to the flat plane are made to eliminate the topographic effect on the complete Bouguer anomaly data. The projection to the flat plane, in this study, used the method proposed by Dampney (1969) with the assumption that the equivalent point of mass was distributed to a flat plane with a certain depth. Gravity anomaly map in the flat field was shown in Figure 3 which had Bouguer anomaly values ranging from 180 mGal to 400 mGal.

![Figure 3. Bouguer anomaly at flat plane.](image)

The complete Bouguer anomaly is a combination of regional anomaly and residual anomaly. For the purposes of interpretation and modeling, residual anomalies caused by shallow sources are separated from regional anomalies caused by sources in using the upward continuation method. Contour maps of regional anomalies and residual anomalies are shown in Figures 3. Regional Bouguer anomaly values are in the range of 240 mGal to 355 mGal (Figures 3(a)). For residual anomalies, they were represented by positive and negative anomalies with the anomaly range at -95 mGal to 55 mGal (Figures 3(b)). High anomaly in the northern part which is a fault area back arc Flores is considered to occur due to plate collision.
3. Inversion

Interpretation is carried out on regional Bouguer anomaly data to determine the subsurface structure. The inversion method used was Singular Value Decomposition (SVD) which consists of base optimization, density optimization, block height optimization and Occam inversion method. It showed the phenomenon of the subduction of the Indo-Australian plate on the Eurasian plate. Regional Bouguer anomalies describe deep subsurface structures. The study area covered an area of 155,400 km² involving 280 km in the North-South direction and 555 km in the East-West direction, divided into 20 blocks in the Y direction and 25 blocks in the X direction, and also 10 blocks in the Z direction (Figures 5). The depth of interpretation was estimated at 60 km to model subsurface structures caused by deep mass distribution anomalies. Subsequently made slices in the direction of the X axis, Y axis and Z axis to determine the pattern of subsurface resistivity distribution shown in Figure 6 – Figure 13.

![Figure 4.](image)

**Figure 4.** (a) Regional Bouguer anomaly and, (b) Residual Bouguer anomaly Flores and Timor.

![Figure 5.](image)

**Figure 5.** Blocks subsurface 3-D model based on the regional anomaly modelling.
Figure 6. (a) Measured and, (b) Computed regional Bouguer anomaly.

Figure 6 showed the plot of the measurement and calculation of regional Bouguer anomaly inversion results. The similarity between the measurement data and calculated data was shown by the very small RMS value of 0.15% (Figure 7 (a)). Slices density of inversion results in the Y direction at X=69.00 km was shown in Figure 7(b) and Figure 8. A decrease in density occurred at 8960-9040 km which indicated a fault or subduction zone. It was shown in Figure 9, and Figure 10 was for block slices in the X direction. Whereas for horizontal slices, it showed that the decrease in density occured from a depth of 30 km (Figure 11-14).

Figure 7. (a) Computed and measured regional Bouguer anomaly (b) Slices density at Y direction.

Figure 8. Slices density of inversion results in the Y direction at X=69.00 km.
Figure 9. (a) Computed and measured regional Bouguer anomaly (b) Slices density at X direction.

Figure 10. Slices density of inversion results in the X direction at Y=9153.59 km.

Figure 11. (a) Slices of horizontal density distribution at Z= 0.0 km, (b) Distribution of density.
Figure 12. (a) Slices of horizontal density distribution at Z= 30.48 km, (b) Distribution of density.

Figure 13. (a) Slices of horizontal density distribution at Z= 42.79 km, (b) Distribution of density.

A seismicity map of the study area was shown in Figure 14. Earthquake data were obtained from the Incorporated Research Institutions for Seismology (IRIS) in the period from January, 1975 to December, 2015. From this map, it could be seen that seismic activity in the Flores area was dominated by deep earthquakes that occurred at the depths of 30-150 km due to the subduction of oceanic plates beneath the continental plates.

Figure 14. Seismicity maps of Timor and Flores (Iris.edu).
4. Result and Discussion
Based on the analysis of gravity anomaly data and three-dimensional modelling of the subsurface structure of the Flores fore arc fault zone, Bouguer gravity anomalies with the highest positive anomalies were in the northern part of the Flores back arc fault zone, while gravity anomalies with low positive anomalies were scattered in the south of the study area including the Flores volcano arc area.

Based on X-section, Y-section and horizontal slices 3D models of regional Bouguer gravity anomalies, the Flores back arc fault was estimated at a depth of 30 km, and the thickness of the earth's crust in the Flores back arc fault zone was estimated to be up to 30 km, while the thickness of the earth's crust in the forearc was estimated to be more than 60 km. The existence of magma chamber in the volcanic arc of Flores island was estimated at depth of 30 km in accordance with the seismicity map Flores and Timor areas.

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