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Subsurface modelling of Kei Kecil Island with 3D gravity inversion

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Abstract. Kei Kecil Island located at Kei Islands, Maluku Province, Indonesia and it is one of outer Banda Arc. Several compression and extension tectonic accoured in Kei Island that made complex regional structural geology there. Mapping of surface geology has been done by several geoscientists, but subsurface mapping is still challenging. This paper aims to image subsurface geological features in Kei Island and its surrounding. Gravity method carried out to obtain density configuration for interpretation of basin topography. Gravity data obtained from previous publication and the other collected through satellite-derived gravity. Result of analyses show Kei Kecil Island located at depocenter of the basin around the high of the surroundings. Trending of the basin is Northeast–Southwest to North-South. Interpretation reveals basin in the Kei Kecil Island situated in central part toward northern trending almost North-South direction. The higher density rock dominating southern area of the island caused by Weduar and Elat Formation from Kei Besar Island. The denser density dipping from Kei Besar Island to Kei Kecil Island with Northwest direction.The basins in Kei Kecil Island probably produce hydrocarbon.

1. Introduction

The Banda Arc has two big part, those are the inner that representing active volcanic and the outer as collisional front [1],[2]. Complex geological features in Banda Arc as interaction of the Australian, Eurasian, and Pacific plates each-others. The Kei Islands of Maluku Province, Indonesia, is located at Banda Arc, at the apex of an island arc system. There are three main geological provinces: eastern, central, and western. Active tectonics occurred in several phase influence configuration of basement or basin topography. The geological structure has been developing massively i.e. fold, fault, and anticline. Geological surface mapping had been done by Indonesian Geological Research and Development Central (GRDC) and other researchers. However, there are only a few of subsurface geophysical imaging in the Kai Islands, so this paper aims to exhibit subsurface geological feature with gravity method.

Subsurface mapping with the geophysical method will reduce the uncertainty of the existing geological model. Gravity investigations can also be used to map the geometry and features of the basin [3],[4],[5], detecting a giant fault or fold caused by tectonic [6],[7],[8] or reconnaissance hydrocarbon exploration [9],[10],[11]. Gravity method works when there is a variety of density in a lateral direction. Difference density and geometry of the geological feature will give a distinct gravity response. However, there is ambiguity in the gravity method that can be reduced by the constraint of input processing parameter. Constraints modelling can come from a geophysical or geological information. Good subsurface modelling will allow for exploring geological events or natural resources better.

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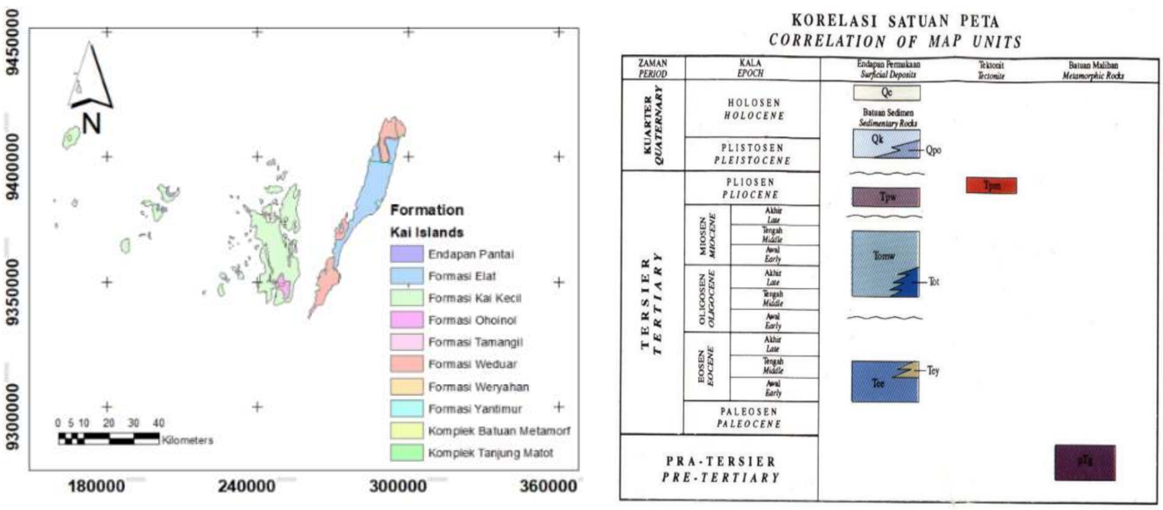
There are three parts of geological province in Kei Islands. Those are eastern, central, and western provinces. The Kei Kecil and Kei Besar Islands are eastern-most of Kei Islands and it is the passive margin of Australia continental crust. This feature due to extension tectonic of Aru Through. There is Nerong Strait separated Kei Kecil and Kei Besar islands as a result of thrust fault at Banda Arc in its frontal [12].

The first is eastern province (Kei Besar) that elongated in an NNE-SSW direction. Figure 1 shows surface geological map and stratigraphic unit of Kei Islands. The oldest rock is Pre-Tertiary and the youngest is Holocene. The dominant formation there is Elat Formation that consists of flat-bedded poorly fossiliferous calcilutites and marls interbedded on a decimeter scale. This Formation is interpreted as product of pelagic or hemipelagic carbonates. The environmental depositional of Elat formation is a distal continental slope setting with possibly slightly shallowing upward [13].

The next is a central part that consists of Kei Kecil, Kai Dulah, and the Tayandu islands that predominantly of the Quaternary reef. The part is interpreted as the foremost part of the Banda Arc accretionary complex. The thrust related deformation in the central province occurred at pre-Quaternary. The final province is western province that interpreted as the innermost part of the west Kai forearc complex. It has high-grade metamorphic rocks founded together with Late Miocene-Pliocene claystone and sandstone [14] and Quaternary reef.

Kei Besar Island has the most complex of geological structure in Kei Islands; it at least has occurred three orogeny events. The first one occurred at Late Eocene that folds Elat Formation and Yamtimur Formation. The next orogeny event was Late Miocene that folding the older formations. The final orogeny event was during Plio-Pleistocene that folding of Weryahan Formation [13].



(a) (b)

Figure 1. Geological map and stratigraphy of Kai Island [13]

2. Methods

2.1. Gravity method

The gravity method is a geophysical method usually used in preleminary exploration. There are there parts of gravity method: acquisition, processing, and interpretasion. Gravity data processing is a process to obtain gravity anomaly. Gravity processing has many steps, those are: tide correction, drift correction, latitude correction, free air correction, Bouguer correction, and terrain correction are applied to obtain completed bouguer anomaly (CBA). The separation of regional and residual anomalies is needed to obtain gravity anomaly that correlating with geological structure. The method to do it in this paper is a bandpass filter. The residual anomaly obtained from previous step would used for the 3D inversion process using the UBC-GIF Grav3D.

Inversion process aimed to obtain a 3D spatial distribution model of density. The inversion process with UBC-GIF software should consider constaints: geologicals and physicals. The solution to the inversion problem using the Grav3D program is the problem of finding density $\rho(\boldsymbol{r})$ which minimizes data misfit according to noise. The solution involves the solution of the equation $\emptyset(\rho)$=$\emptyset d$+ $\mu\emptyset m$ where $\mu\epsilon[0,\propto]$ is the regularization parameter that controls the data misfit and the recovered model in the form of an objective function $\emptyset m$. The numerical solution of the objective function $\emptyset m$ can be written:

$$\phi m(\rho)=\|\boldsymbol{W}m(\rho(\boldsymbol{r})-\rho o)\|^2 \quad (1)$$

where $\rho(\boldsymbol{r})$ and ρo are vectors M which state the recover and reference models. The magnitude $\vec{\rho}$ that is used in the calculation to obtain a numerical solution objective function $\emptyset m$ has a lower and upper bound in the form of an equation:

$$\vec{\rho}min\leq \vec{\rho} \leq \vec{\rho}max \quad (2)$$

where $\vec{\rho}min$ and $\vec{\rho}min$ vector that contains lower and upper bounds on model values.

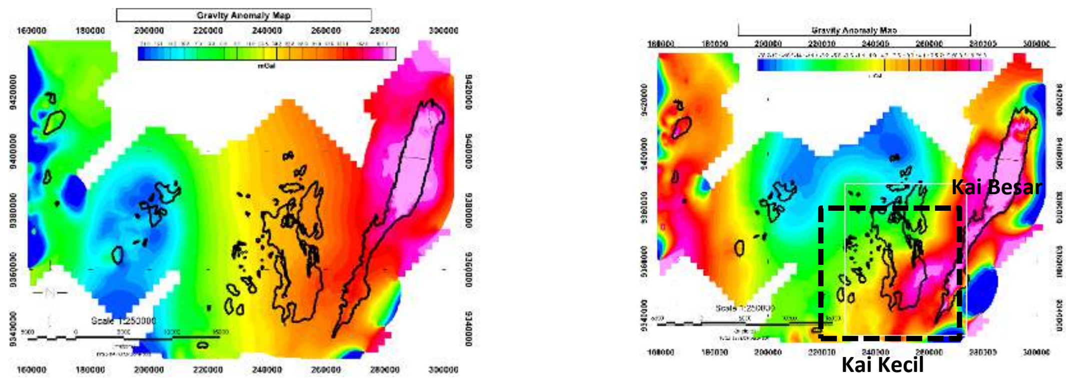
This paper used gravity data set collecting by [15] working with the University of London and Geological Research and Development Central, Bandung, Indonesia and together with the University of London and PT Corelab, Jakarta. We also applied satellite-derived gravity GGMPlus with distance each point is 200 meters with regular gridding. Topographic information was obtained using SRTM. Both of data used, after blending them, to obtain gravity anomaly map and its inversion modelling. Radial spectrum analysis and bandpass filter applied to obtain residual anomaly.

3. Results and Discussion

Gravity anomaly maps on Figure 2 show the distribution of various gravitational field horizontally. The gravity anomaly caused by different density value of rock in subsurface. Normally, rock with high density will produce high gravity anomaly. The density of rocks also influenced by depositional factor i.e. overburden pressure, sediment age, diagenetic, pores, porosity, etc [16]. Therefore, it needs careful interpretation when it deals with gravity method.

Based on completed Bouguer anomaly map, the high anomaly areas depicted by dark red to light red range value of 123–181 mGal dominating the eastern area. While the low anomaly gravity imaged with blue to green between -21–11 mGal located in the western province. Middle area is a transition zone where gravity anomaly has a moderate value from 11–123 mGal. Kei Besar Island has high gravity anomaly zone while Kei Kecil Island has moderate gravity values on otherside the Kur, Fadol and adjacent islands located in a western province dominated by low gravity anomaly zone. Residual gravity anomaly map shown in Figure 2b exhibits more clear about the local distribution of density area. There is the difference with regional anomaly with deal with all of the depth whilst residual anomaly prefers with shallow to a moderate depth of rocks. The residual anomaly reveals high anomaly in the western area which is shown high in regional map. It means such area has denser rock locally. In central province also has little chance especially at the area of Kei Kecil where there is dominated by moderate gravity anomaly in the regional map, but the residual map show two big parts. The northern part of Kei Kecil Island dominated by low gravity anomaly range from -38–1 mGal while in the southern value of 21–39 mGal representing high anomaly dominating this area.

Gravity 3D inversion has carried out by UBC-GIF Grav3D software. Gravity inversion mesh was built with same dimension of x and y. The dimension of the mesh is 45x1000 meters and 55x1000 meters toward x and y respectively while the size of z or depth is 10x250, 4x500, and 6x750 meters. The mesh sides were aligned along E–W, or N–S with geographic coordinates of UTM WGS 1984 zone 53S. The purpose of this inversion was to obtain the morphology of the subbasin at depth. Surface geological environment is known as quarternary to tertiary sedimentary rocks [11]. The gravity data, as expected, shows the density contrast between the lower density in sedimentary rocks comprising such as the formation of Kei Kecil against the surrounding with high density older sedimentary rock or basement.



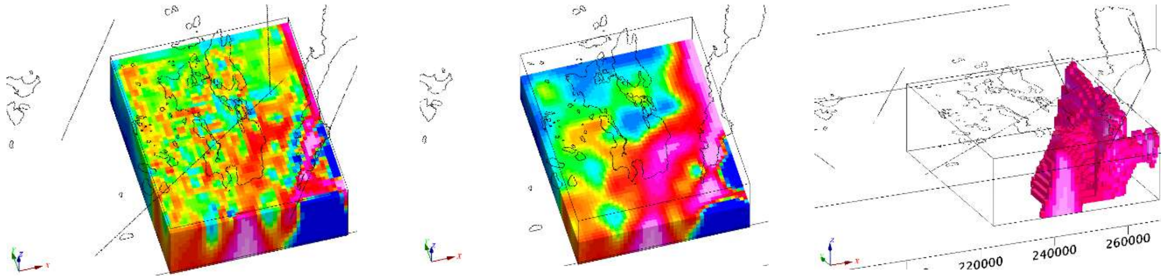
(a) (b)

Figure 2. CBA Map (a) and Residual Anomaly Map with a white square is area of inversion (b)

Figure 3 and 4 reveal 3D inversion modelling concerning density. The density varies from 2.0 to 3 g/cm^3. The inversion model picts the 3D geometry of the basin is located at central to northern of Kei Kecil Island. This basin represents the density value from 2–2.5 g/cm^3. While the denser rocks with range density of 2.67–3 g/cm3 located at the southern area and continue to Kei Besar Island (Figure 3). The denser rocks are dipping toward Northwest and it is separated with lower density zone at the Nerong strait between Kei Kecil Island and Kei Besar Island. It is suitable with [12] stated the Nerong Straits suggests that structurally simple thin-skinned frontal folds.

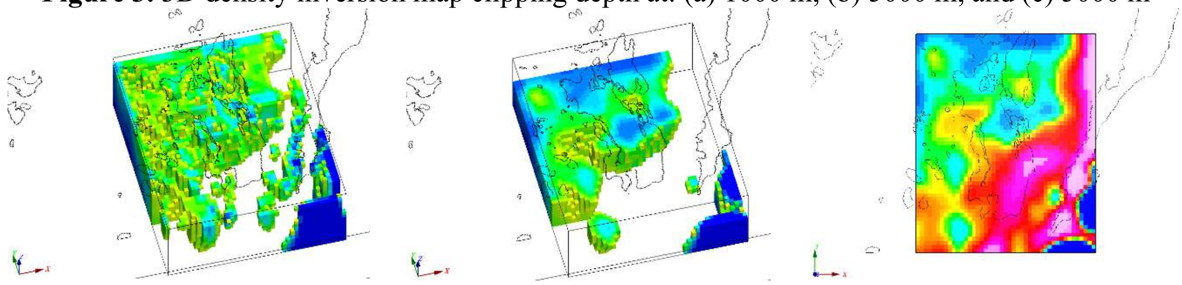
Low-density zone located in Kei Kecil Island is interpreted as Kei Kecil Formation. The formation covers most of the island. The Kei Kecil Formation composed predominantly of the Quaternary reef. [13] reported reef limestone to consist of corals, molluscs, algae, and bryozoans. It forms low undulated hill, karst and low hills with a steep slope. Kei Kecil Formation has lower density because the age of Kei Kecil Formation is Quaternary and it has not been influenced by a massive compressional force which may change rock density significantly. It agree with [11] stated that the thrusting on accretionary complex made the deposited of Quaternary reef unconformably. The others formation exist with a small portion in central to northern Kei Kecil Island that provides low-density zone are Coastal Deposit, Ohoinoi and Weryahan Formation. The Coastal deposit composed of sands, gravel, and muds. This formation deposited in Quaternary as a product of fluvial to a deltaic system [13]. That formation less contributes to density there because of the small size of their geometry.

Zone of denser rocks situated at the southern area of Kei Kecil Island and continue to Kei Besar Island (Figure 2 and 3). At the surface, it coincides with Kei Kecil, Ohoinoi, and Weryahan Formation with more proportional geometrical dimension. Similar to Kei Kecil Formation composed by reef limestone deposited in shallow neritic marine, the Ohoinoi Formation had also the same depositional system either Weryahan Formation. The difference is Ohoinoi and Weryahan Formation are older than Kei Kecil (Figure 1). The Ohoinoi Formation arranged of unconsolidated biocalcarenite interbedded with marl while the Weryahan Formation composed of marl and limestone. The east of Kei Kecil Island is Kei Besar Island that consists of Weduar and Elat Formation in its central to southern. The Weduar Formation has the age of Miocene to Oligocene whilst Elat Formation is Eocene. Weduar Formation has sedimentary rock from reef limestone and chalk to moderate grain of calcarenite and napal. Elat Formation in other hand has calcarenites that reached 700 meters thick. It exposed on the middle and south part of Kei Besar [13].



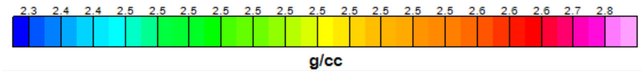
(a) (b) (c)

Figure 3. 3D density inversion map clipping depth at: (a) 1000 m, (b) 5000 m, and (c) 5000 m



(a) (b) (c)

Figure 4. 3D low-density inversion map clipping depth at: (a) 1000 m, (b) 5000 m, and (c) full density at 5000 m



Weduar and Elat Formation have significant contributions to make density higher in the Kei Islands. They have rocks formed in Tertiary that may give chance to diagenesis. The diagenesis of limestone can change the density of rock denser than previously. What processes occur when coral reef reveals at surface or shallow level terrain that possible rainfall reacts to carbonates mineral. The chemical reaction will change mineral from primary sedimentation product to others, for example, dolomite becomes calcite when it reacts to water rainfall. Changing mineral will finally become an accumulation of rocks with denser rock-forming mineral. The other factor is overburden pressure that decreases pore or porosity of rocks. Weduar and Elat Formation are older than the formations in Kei Kecil Island. It probably causes Weduar and Elat Formation lie beneath Kei Kecil, Ohoinoi, and Weryahan Formation. Figure 3 and 4 are evidence that Weduar and Elat Formation effect significant with the denser zone in Kei Besar and Kei Kecil Island especially at the southern areas.

The denser density zone is dipping from Kei Besar Island toward Northwest to Kei Kecil Island at southern to the center part. The dipping density estimated as Weduar and Elat Formation from Kei Besar that some parts of them penetrate under rock formations in Kei Kecil Island. This process similar to regional tectonic in the islands that the thrust that had correlation with deformation in the central geological province occurred at pre-Quaternary age [11]. Figure 3 images the distribution of denser density at the depth that spread from shallow to bottom.

4. Conclusion

Gravity 3D inversion with regular mesh applied in Kei Kecil Island and its surrounding reveals interesting geological feature such as the distribution of lower density coinciding with basin. Interpretation of basin in the Kei Kecil Island situated in central part toward northern trending almost North-South direction. The higher density dominating southern area of the island caused by Weduar and Elat Formation from Kei Besar Island. The denser density dipping from Kei Besar Island to Kei Kecil Island with Northwest direction.

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