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Integrated Magnetotelluric (MT), Gravity and Seismic Study of Lower Kutai Basin Configuration

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Highlights:

- New insights from an integrated sedimentary basin study with MT and gravity data supporting the seismic method
- Establishment of a workflow incorporating non-seismic geophysical data with seismic data in hydrocarbon prospecting
- Improvement of interpretation results of seismic data suffering from strong scattering effects due to the stratigraphy of the study area

Abstract. This work describes a subsurface basin configuration of the Lower Kutai Basin (hereinafter LKB) in East Kalimantan, Indonesia, as inferred from combination of magnetotelluric (MT), seismic, and gravity data. LKB is structurally controlled mainly by the Samarinda Anticlinorium extending in a NNE-SSW direction and is one of the most prolific hydrocarbon basins in Indonesia. The phase tensor analysis of MT data from most stations and frequencies exhibited a 2D character with a relatively low skew ($-3° < \beta < 3°$). The geo-electrical strike direction was estimated at N30°E, which is in good agreement with the regional geological strike with a NNE-SSW direction. 2D MT inversion modeling was performed to infer the subsurface resistivity distribution associated with LKB's configuration. From the integration of MT, seismic and gravity models it was shown that LKB's configuration is composed mainly of sandstone, black shale, claystone, and basement rocks. The conductive zones of the MT models are associated with thermal alteration of black shale, which changes its mineralization, leading to lower resistivity. Hence, the black shale may be interpreted as potential hydrocarbon source rock in LKB.

Keywords: *basin configuration; gravity; magnetotellurics; MT; seismics.*

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1 Introduction

The delineation of basement structures within a sedimentary basin plays an important role in oil and gas exploration, i.e. identification of possible source rocks, migration pathways, and hydrocarbon accumulation in reservoirs. Gravity surveys are often employed to decipher the basin configuration due to a significant density contrast between the sediments filling the basin and the basement rocks. However, gravity data lack vertical resolution and suffer from inherent ambiguity of potential field data interpretation, unless additional constraints are incorporated [1,2]. In hydrocarbon prospecting, regional or sub-regional gravity surveys are frequently followed up by seismic surveys to provide a more detailed image of the subsurface within the basin. Seismic data may not reach the deeper parts of the basin since they are often focused on the first 2 to 3 km related to limited-source geophone offset in data acquisition. In some cases, a smeared seismic image of the deeper parts may also be due to the presence of karstified rock formations responsible for scattering of the seismic signals [3,4].

Kutai Basin in East Kalimantan is one of the major hydrocarbon provinces of Indonesia, located mostly onshore of the eastern part of Kalimantan island, while a minor part extends offshore, well-known as the Mahakam Delta in the Makassar strait. This basin is the largest and deepest Tertiary basin in Indonesia. The study area was located at approximately 50 km west of Mahakam Delta (thick box in Figure 1). This particular location is known as the Lower Kutai Basin (LKB), with fair to excellent hydrocarbon potential, i.e. gas from black shale as the source rock [5,6]. In this paper, we analyzed magnetotelluric (MT) data from LKB acquired by the Geological Survey of Indonesia (PSG), Ministry of Energy and Mineral Resources of Indonesia (KESDM) in 2010.

The existing seismic data in the study area are very limited in coverage and do not reach an adequate depth for detailed basin delineation. This is mostly due to seismic wave scattering, which may be caused by the presence of the black shale formation. Therefore, we determined the basin configuration of LKB by using the magnetotelluric (MT) method, even though it has a lower resolution than the seismic method. Physically, the electrical conductivity of black shale depends on its thermal maturity. In particular, the electrical conductivity is high if the black shale is mature [7]. It is from this perspective that the use of MT is complementary to seismic and gravity data for an integrated interpretation.

We performed 2D inversion modeling of the MT data to obtain the subsurface resistivity distribution along representative profiles. The subsurface resistivity model from the MT data combined with interpreted seismic sections were used to constrain the gravity modeling. In this case, we used available velocity data for time-to-depth conversions of the interpreted seismic time sections. The ambiguity problems in 2D or 2.5D gravity modeling were adequately overcome by integrating the results from MT and seismic investigations. The final models from the integrated interpretation enabled us to delineate the subsurface configuration and possible structural elements of the basin.

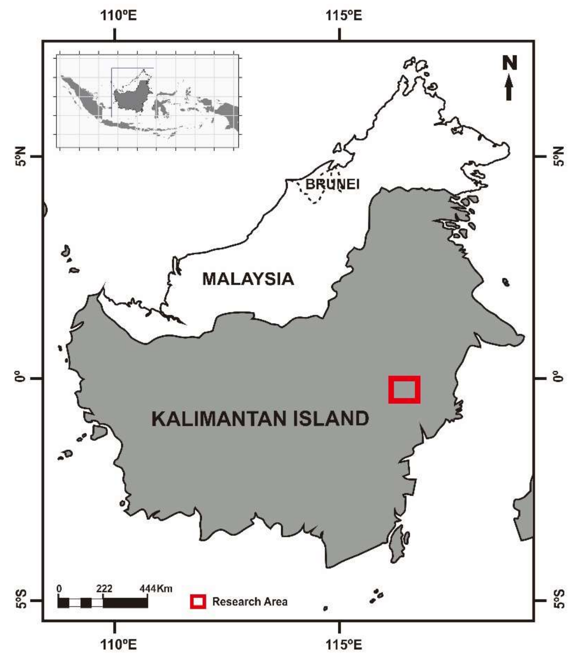

Figure 1 The Lower Kutai Basin as the study area (marked by the red thick box) is part of the Kutai Basin, East Kalimantan, Indonesia [6].

2 Geological Setting

Kutai Basin, covering an area of 43,680 km^2, has the Samarinda Anticlinorium as the main structure, extending from the NNE to the SSW direction (Figure 2). The anticlinorium is strongly folded, asymmetric and bounded by synclines. These synclines are filled with siliciclastic Miocene sediments [8,9]. The Kutai Basin's stratigraphy is shown in Figure 3. It consists of four main formations, i.e. the Pamaluan, Pulaubalang, Balikpapan, and Kampung Baru formations. The Pamaluan formation consists of coal, coaly shale, sandstone, and siltstone. The Pulaubalang formation is composed of sandstone, coaly shale, shale and limestone, while the Balikpapan formation consists of claystone, sandstone, shale, and coal. The youngest is the Kampung Baru formation, which is composed of sandstone, shale, siltstone, and coal [10].

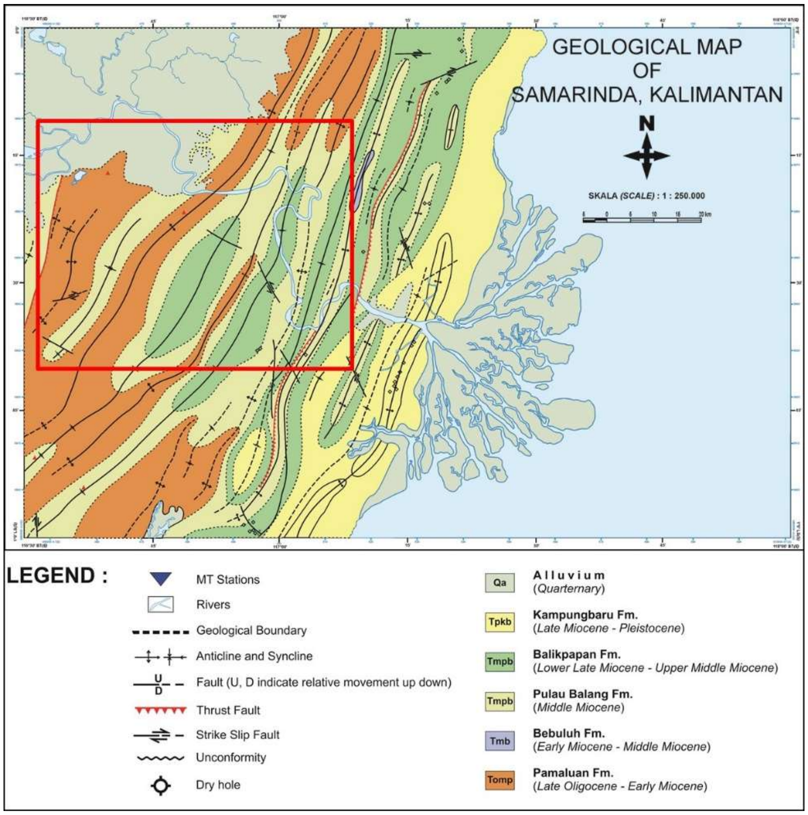

Figure 2 Simplified geological map of the Lower Kutai Basin (LKB), showing the Samarinda Anticlinorium as the main structure [8]. The red box outlines the study area.

3 Methods

3.1 MT Data Modeling

Thirty MT sounding sites were deployed at the Lower Kutai Basin (Figure 4). The MT stations covered the survey area with a relatively sparse spacing (about 5 km) due to difficulties of access and the limited number of stations that could be deployed by the survey team. Two units of MTU-5A equipment from Phoenix-Geophysics Ltd. were used for MT signal recording. Single site mode with overnight measurement was performed at each station to obtain adequate data stacks in the frequency range between 0.02 to 3000 Hz. Data processing from raw or time series data was carried out by employing the robust standard MT processing software provided by the equipment's manufacturer [11].

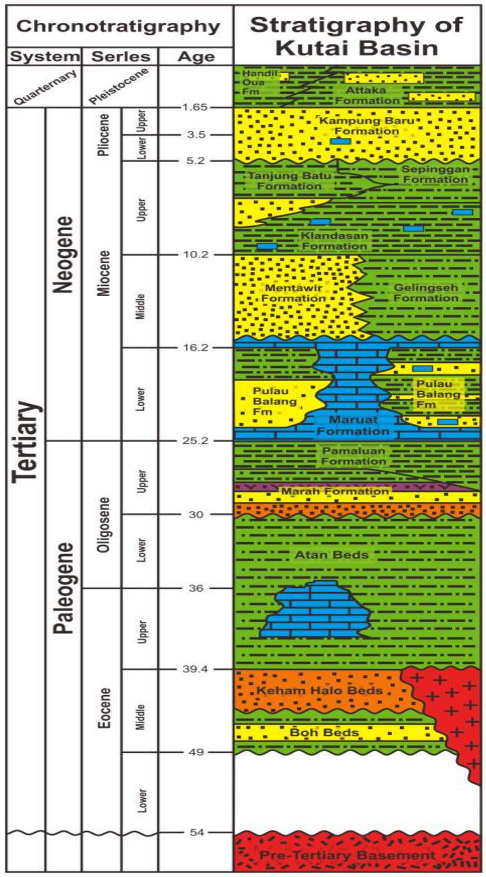

Figure 3 Stratigraphy of the Kutai Basin consisting of the Pamaluan, Pulaubalang, Balikpapan and Kampung Baru formations [10] (see text for more details).

Preliminary MT impedance tensor analysis was done by using phase tensor analysis to determine the geoelectrical strike of the study area. When the overall dimensionality of the MT data is 2D, the geoelectrical strike is likely related to the geological strike and can be used to choose profiles for 2D modeling [12,13]. The MT data from most stations and frequencies exhibited a 2D character with a relatively low skew ($-3° < \beta < 3°$). The estimated geoelectrical strike direction is N30°E, which is in good agreement with the regional geological strike, which has a NNE-SSW direction [6,10]. Therefore, we set up four profiles for 2D modeling oriented perpendicular to the estimated strike direction (Figure 4). Detailed results of the preliminary analysis can be found in Irawati, *et al.* [14].

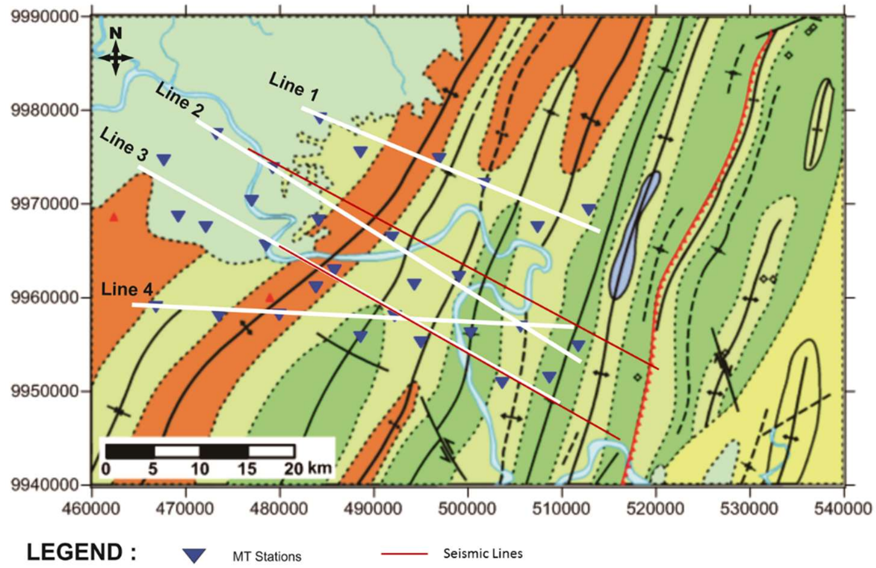

Figure 4 MT sounding stations, MT profiles for 2D modeling (white lines) and interpreted seismic lines (red lines) overlaid on a geological map of LKB similar to Figure 3. Coordinates are in UTM zone 49S.

We performed 2D inversion of the MT data by using the well-known WinGLink software from Geosystem, which implements the Non-Linear Conjugate Gradients (NLGC) algorithm [15,16]. A homogeneous medium close to the overall or average apparent resistivity data is usually proposed as the initial model. The subsurface 2D resistivity model is obtained from iterative refinement of the initial model while minimizing the objective function. In general, the objective function can be represented as follows:

$$\phi(\mathbf{m}) = (\mathbf{d} - F(\mathbf{m}))^T \mathbf{V}^{-1}(\mathbf{d} - F(\mathbf{m})) + \tau \, \mathbf{m}^T \, \mathbf{L}^T \mathbf{L} \, \mathbf{m} \qquad (1)$$

where **d** is the data vector, *F* is the forward modeling operator for model vector **m**, while **V** is the diagonal matrix with data variance, and τ is a regularization parameter. The matrix **L** represents the differences of the adjacent model parameters in **m** such that the second term on the right-hand side of Eq. (1) is the model's roughness to be minimized along with the misfit. The regularization parameter will determine the importance of the model smoothing relative to the data fitting [17]. A plot of model smoothness and misfit for different τ values, the so-called L-curve, is commonly used to select the optimum value for τ in the 2D MT inversion. We tested 9 different values for τ, logarithmically sampled from 0.1 to 300, and chose τ = 3 for all 2D MT modeling lines. The choice was determined by the balance between a relatively low misfit and model smoothness as well as model plausibility from the regional geology's point of view.

Figure 5 shows the 2D resistivity models for line-1 to line-4 using the chosen regularization parameter. In addition, a horizontal to vertical smoothness ratio of 2 was used to enhance the horizontal layering of the resistivity models [15]. The latter is common in the modeling of basins with sedimentary formations, which usually tend to have a layered character [4,18]. The models show that there are conductive areas, indicated as C1, C2 and C3, that reach the deeper part of the subsurface and are consistent with four almost parallel profiles, especially for line-1, line-2 and line-3. In general, the conductors are deeper towards S-SW of the profiles. The thickest and deepest reaching conductor C2 may be correlated with the black shale formations as source rocks for hydrocarbon prospecting. The thinner conductors C1 and C3 can be associated with the upper part of sedimentary formations due to the shallower depth. There is no presence of C1 at line-1 since it is a shorter profile than the other ones. On the other hand, the extension of C3 to a great depth at line-4 appears to be an edge effect less constrained by the MT data.

3.2 Seismic Data Interpretation

Seismic reflection data are records of the seismic wave response from the source reflected by subsurface rocks with different physical parameters, i.e. seismic wave velocity and rock formation density. The available seismic data are limited to only two profiles of time sections and coincide with line-2 and line-3 of the MT profiles (see Figure 4). To integrate the results of seismic data interpretation, the seismic time sections were converted to depth sections. In this case, the seismic wave velocity propagation of sandstone and shale were estimated at 2500 m/s and 3000 m/s, respectively. After well-seismic tie and time-to-depth conversion, two main horizons were identified.

In Figure 6, the uppermost horizon represents the interface between superficial layers (alluvium) and sandstone, while the lower horizon is between sandstone and shale formations. Interpretation of more detailed formations within the basin is very difficult due to the low quality of the seismic data and is beyond the scope of this paper. The main horizons identified from the seismic sections along with the resistivity distribution from MT 2D modeling were further used to constrain the 2D gravity modeling. However, only a horizon associated with the interface between sandstone and shale formations was used in the subsequent modeling and interpretation. A shallower horizon was considered too detailed and insignificant in our larger-scale modeling.

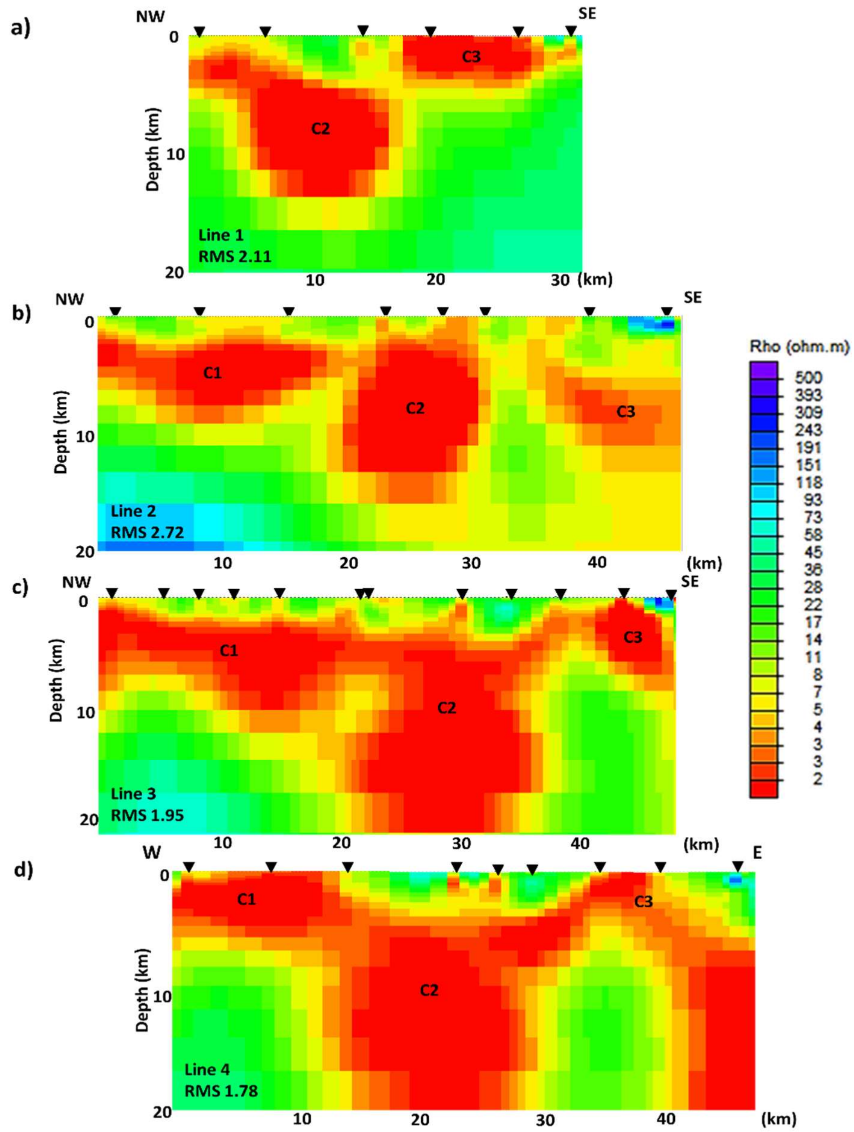

Figure 5 2D resistivity models of the Lower Kutai Basin showing dominating conductors, a) line-1, b) line-2, c) line-3, d) line-4. The inverse triangles at the top of the profiles indicate the positions of the MT sounding sites.

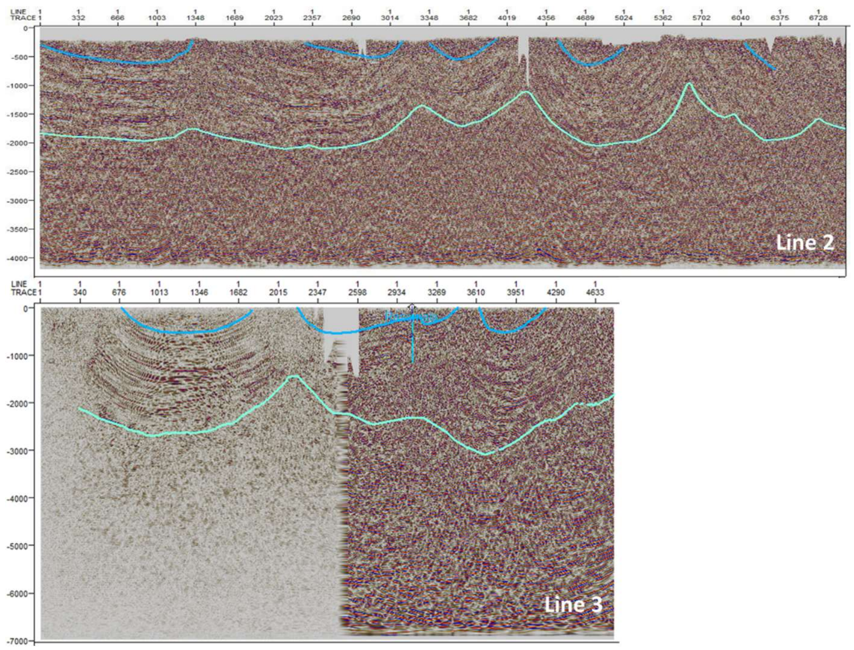

Figure 6 The result of seismic data interpretation for line-2 and line-3, consisting of two horizons. The upper horizon is soil to sandstone boundary, while the lower horizon is sandstone to shale boundary.

3.3 Gravity Modelling

Gravity data were used to infer the subsurface density distribution of LKB. The Bouguer anomaly map published by the Geological Survey of Indonesia was digitized, re-gridded and reprocessed by performing the standard method, i.e. spectral analysis and filtering in the spatial frequency domain [19,20] to enhance the residual anomaly. The radially averaged power spectrum of the gravity anomaly determined the band-pass filter parameters, i.e. wavelengths between 5000 m and 50000 m for the lower and upper bounds, respectively. The residual anomaly showed high anomaly values over the central basin with a NE-SW direction (Figure 7), which represents thickening or shallowing of the shale formation, as evidenced from 2D gravity modeling.

Gravity forward modeling was performed using the GM-SYS module of the Oasis Montaj software from Geosoft [20]. Seismic data were not available on line-1 and line-4 (see Figure 4). Therefore, the initial model for gravity modeling of these lines was only due to the MT results. When seismic data were available, for line-2 and line-3, the formation interface from the seismic data along with resistivity units from MT modelling were used to initiate a density model of the subsurface. Then, adjustments of the latter were made to minimize gravity modeling errors.

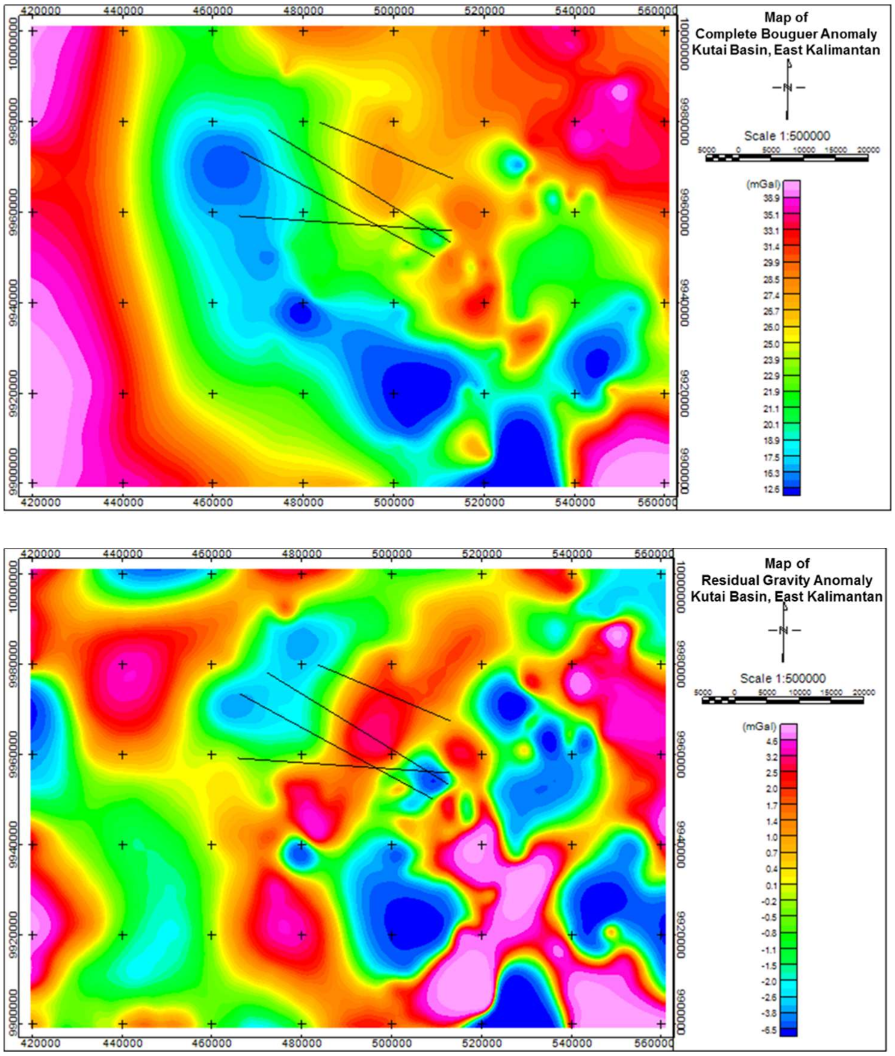

Figure 7 Bouguer anomaly of the Lower Kutai Basin (top) and residual anomaly (bottom) showing an elongated high anomaly pattern with a NE-SW direction. MT modeling profiles are also shown to indicate the study area.

The results are presented in Figure 8 for line-1 and line-4 and in Figure 9 for line-2 and line-3. In these figures, the residual anomaly profile is also plotted to confirm its association with the Samarinda Anticlinorium, which thickens and becomes shallower, leading to a positive residual anomaly. Figures 8 and 9 show that the subsurface of LKB consists of four layers, i.e. sandstone, shale, claystone and basement rocks, respectively, from the surface to the deep layers. The interface between sandstone and shale formations was resolved from interpreted seismic data for line- 2 and line-3. Furthermore, the interface between the shale and claystone formations was determined only from the resistivity model, since the seismic data did not cover greater depth. The basement geometry and adjustment of the interfaces of the shallower layers were determined to obtain the gravity data fit. The misfit between observed and calculated data from the forward gravity modeling for line-1 and line-4 was 0.978 and 0.519, respectively, while for line-2 and line-3 it was 0.932 and 0.945, respectively.

4 Discussion and Conclusion

MT 2D modeling was performed with a preference to obtain layered models for the sedimentary basin environment. The resulting models revealed undulated and possibly faulted low resistivity layers, interpreted as black shale as the main conductivity anomaly. The conductive zones were consistent at all lines and located at more than 2000 m depth. The top of the shale formation from MT coincided approximately with the horizon from the seismic reflection data. Furthermore, 2.5D gravity modeling was done to infer a subsurface density distribution that was consistent with the MT resistivity models and interpreted seismic horizons. Adequate constraints in gravity modeling are crucial, whether for basin delineation or isolated anomalies, as stated in [21].

The integration of MT, seismic and gravity data can be used as a tool to delineate the configuration of the Lower Kutai sedimentary basin. The interpreted main formations in LKB are: sandstone in the Kampung Baru formation, black shale in the Pamaluan formation, claystone in the Atan Beds and Pre-Tertiary basement, from the top to the bottom of the basin, respectively. These models also show structures in the subsurface, i.e. undulated layers with significant vertical offset. These structures hidden from the surface geology may be associated with concealed faulting in the sedimentary basin at greater depths. As Figures 8 and 9 show, positions of anticlines and synclines from the surface geology are not always obvious in the model due to the different scale between the surface geology and our model. In addition, the low resistivity of the black shale from MT modeling may indicate its maturity as the source rock for hydrocarbon potential of LKB. Basically, black shale is a resistive material. However, thermal alteration reduces the bulk resistivity of black shale, which is rich in organic materials.

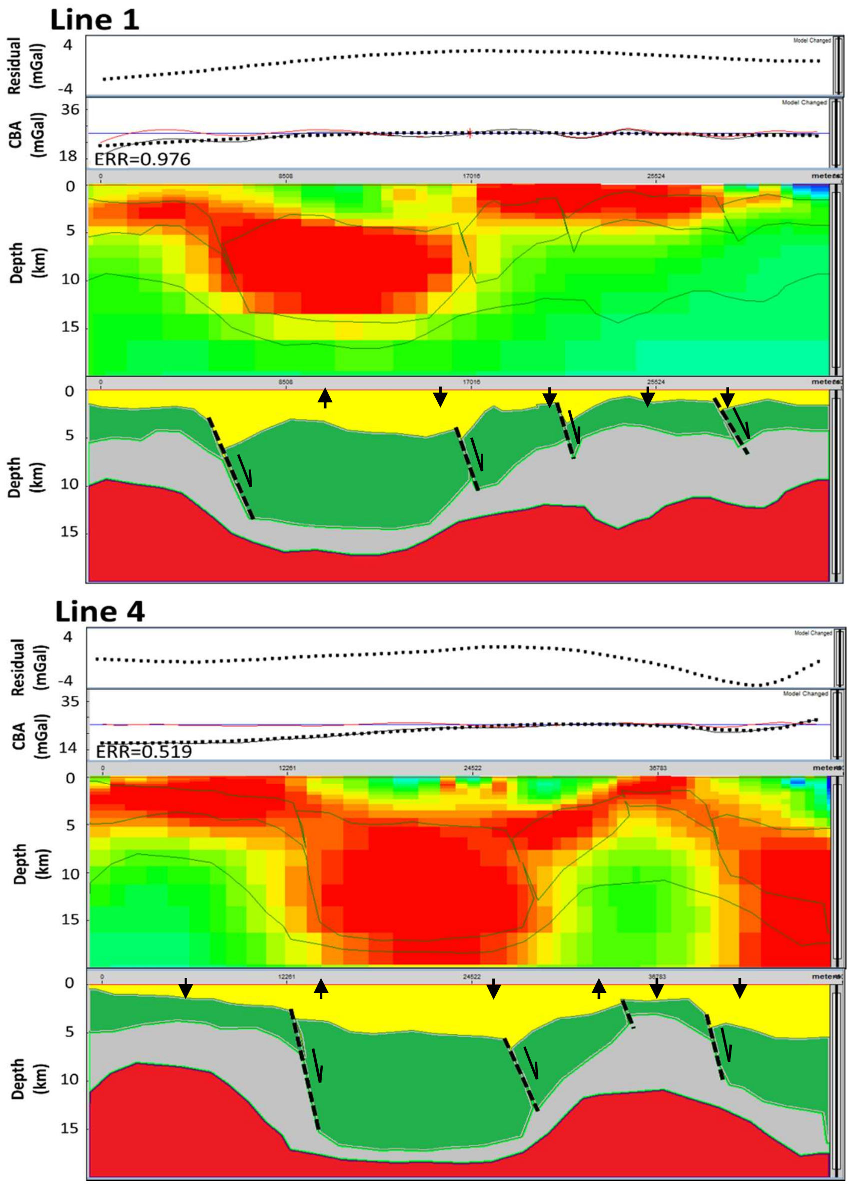

Figure 8 Integrated MT and gravity model for line-1 and line-4 showing sandstone (Kampung Baru Formation, yellow), shale (Pamaluan Formation, green), claystone (Atan beds, grey) and basement (Pre-Tertiary formation, red). Upward and downward arrows indicate anticlines and synclines, respectively.

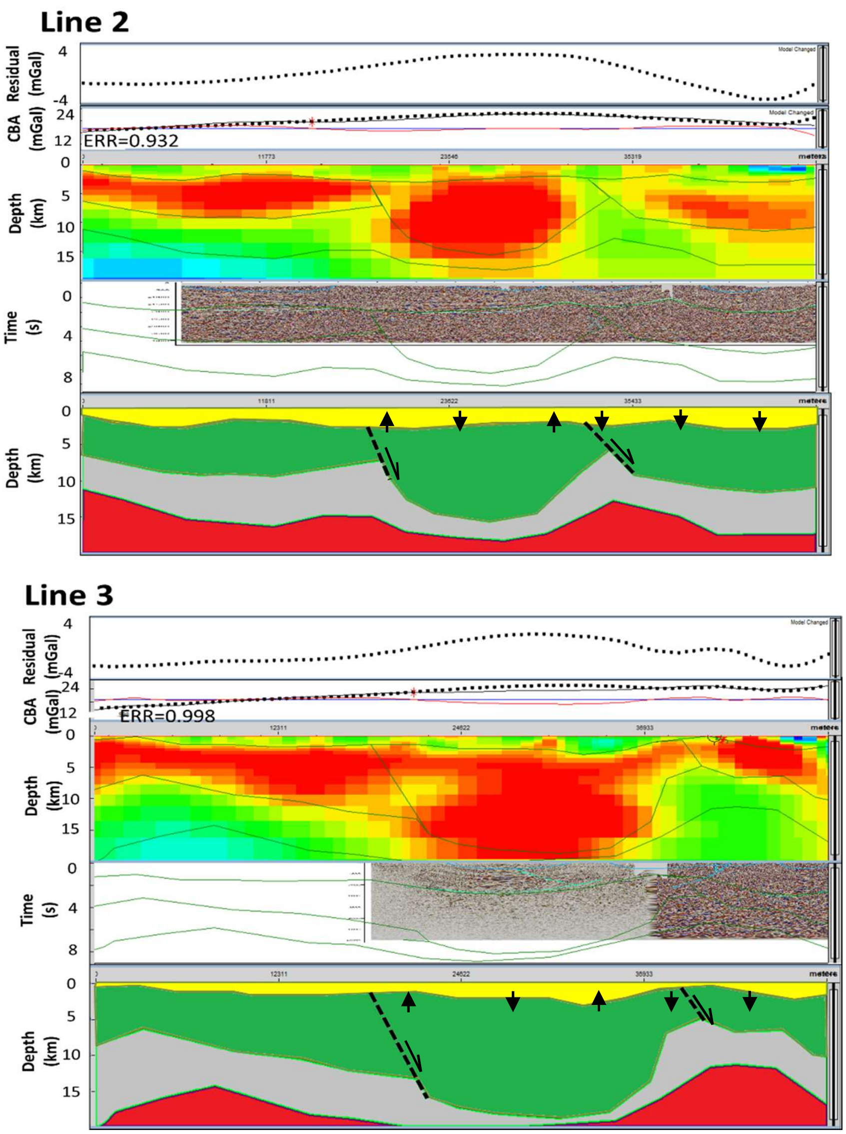

Figure 9 Integrated MT, gravity and seismic model for line-2 and line-3 with similar formations as in Figure 8. In both Figure 8 and Figure 9, discontinuities of the shale may be interpreted as concealed faults. Upward and downward arrows indicate anticlines and synclines from the surface geology, respectively.

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