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RESEARCH ARTICLE

Analysis of gravity anomaly decomposition and depth to basement, case study: Cenozoic Bogor Basin, Indonesia.

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Abstract

The Cenozoic Bogor Basin situated on the SE edge part of Sunda shelf is presumed to have hydrocarbon potential on its turbidite deep-water play. The deep subsurface geometry of this basin may play an important role, yet unexplored, to the hydrocarbon exploration. The gravity method is advantageous to illuminate the subsurface structure on the arbitrary depth and various sources. Eight-hundred-thirty-eight points of ground-based gravity survey were collected on roughly one kilometer spacing in the North of Bandung to Pamanukan region covering the Cenozoic Bogor Basin on the Subang-Purwakarta segment to generate complete Bouguer anomaly (CBA) map. This study examines the two robust methods of gravity anomaly decomposition (i.e., polynomial trend surface and upward continuation) by using multiple parameters to match the geological background. Radially averaged power spectrum was used to estimate the depth of anomalous source corresponds to the top of basement layer and resulting 4 km basement depth in North West Java basin and below 1 km on Tangkuban Parahu volcanic zone. The resulting estimated depth of Cenozoic Bogor Basin was evaluated by the matched *a priori* published data on those two areas and revealed the depth of depocenter (deepest sediment) on the Cenozoic Bogor Basin is up to 9 km, quite a deeper extent than previously assumed.

Keywords: Bouguer, Upward, Polynomial, Bogor Basin, Depth, Basement

1. Introduction

The Cenozoic Bogor Basin situated in Java island, Indonesia (the SE edge part of Sunda-land) was formerly a fore-arc basin (Middle Eocene) sunk in the Indian Ocean and evolved into the Oligo-Miocene's back-arc basin (Martodjojo, 2003). The evolution affected by thrusted regimes and volcanic activities constituted various stratigraphy units from deep to shallow marine facies such as shale, sandstone, breccia, volcanic products, and carbonate (Armandita et al., 2002). The deep-water play of the basin has the potential of hydrocarbon reservoir in its turbidite facies from the eroded sediment of the proven oil North West Java basin and volcanic sediment products (Satyana and Armandita, 2004).

Basement geology (i.e., depth, density, structure) are essential for hydrocarbon exploration, which related to sedimentation, petroleum play, and reservoir potential (Tonkin and Himawan, 1999). Several basement feature on the Java Cenozoic basin have been extensively studied by using gravity method, such as on the North West Java basin (Kamtono and Wardhana, 2012; Setiadi and Pratama, 2018), Majalengka sub-basin (Wardhana et al., 2016), and Banyumas basin (Setiadi, 2018). Specifically on the studied region, the existing forward 2D subsurface density model (Patmosukismo and Yahya, 1974) elongates northwardly from Tangkuban Parahu to Pamanukan was subject to several limitations on the unexplained gravity processing sequence (i.e., anomaly decomposition method) and indicated an underestimate interpretation of Bogor Basin basement depth (~4-km) compared to another back-arc basin basement depth on Java island (~10 km) (Smyth et al., 2008). On the other hand, the integrated analysis of the gravity anomaly decomposition and, *a priori*, geological constrain on the Bogor Basin, has never been explained and analyzed.

The gravity method utilizes the complete Bouguer anomaly (CBA) which might correspond to the subsurface bulk density, from near-surface rock to deep Moho structure, depending on the survey scale and mode. Regional-residual decomposition of this anomaly should be carefully commenced to filter the intended target from the unwanted sources which suit *a priori* features (e.g., regional geology, seismic, well-log data, etc.). The upward continuation (Arisona et al., 2018; Kebede et al., 2020), polynomial fitting (Handayani, 2019), minimum curvature (Kanthiya et al., 2019), and finite element method (Martyshko et al., 2018) were among the separation techniques of regional (deep layer) and residual (shallow layer) anomaly which considered best on their areas, respectively. These indicate that the method has their own advantage and drawbacks according to specific objectives and areas.

Improving the subsurface image in the hydrocarbon potentially area is critical and challenging especially on the subvolcanic area such as Bogor Basin. The aim of this research is to analyze and compare the gravity anomaly decomposition method which suits for delineating the basement morphology and depth of the Cenozoic Bogor basin and surrounding geological background (Fig. 1a). The results were match with another published subsurface data from several methods and could amend the previous model derived from the gravity technique.

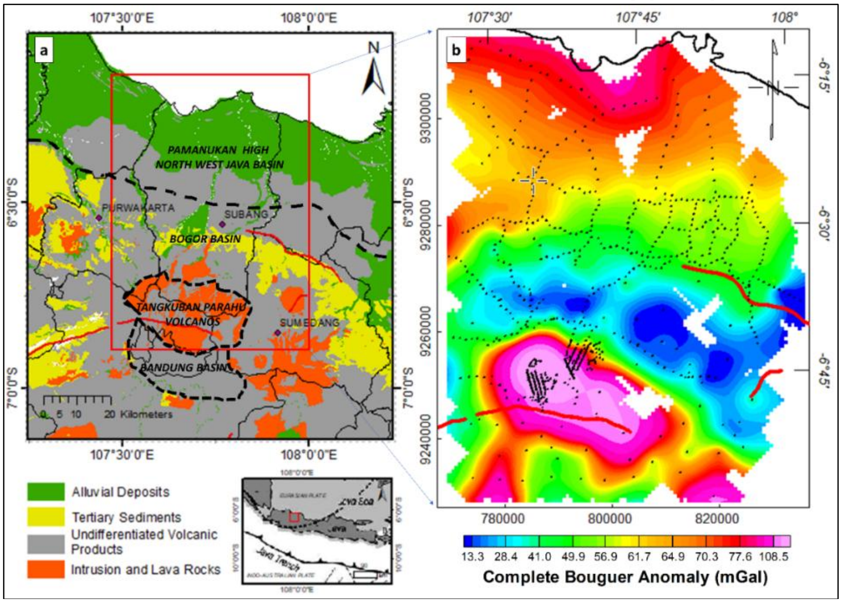

Fig. 1 (a) The study area (red rectangle) on the Java Island, Indonesia overlained by simplified geological map, active fault (red line) and the corresponding regional background of Pamanukan High, Bogor Basin, and Tangkuban Parahu Complex (black dashed lines) (after Irsyam et al., 2017; Martodjojo, 2003; Patmosukismo and Yahya, 1974; Sari et al., 2019; Sribudiyani et al., 2003),(b) The map of complete Bouguer anomaly (CBA) and 838 survey stations (black dots).

2. Data and Methods

2.1 Gravity data

The studied area was limited to the North of Bandung (Subang district) to Pamanukan region (107.43283°, -6.88465°; 108.03434°, -6.1938°) as the presumed Bogor Basin depocenter area sited (Satyana et al., 2002). Ground based gravity data were acquired by Lacoste-Romberg G-804 in the 838 points during October 16-25, 2019 (Fig. 1b). Those data were compiled with terrestrial repository data of BGI (Bureau Gravimetric International) and Indonesian Geospatial Agency (BIG). They were preconditioned to the equal reference point of BS-Geoteknologi LIPI station which has absolute gravity value of 977965.47 mGal (791 m elevation). Standard reduction routine was calculated using Bouguer and terrain density of 2670 kg/m^3 to generate the complete Bouguer anomaly map (Fig. 1b).

The CBA map was decomposed into regional using polynomial trend surface fitting and upward continuation which were chosen due to their robust performance. Particularly, the methods would illuminate the deep-broader geological feature indicated by low wave number from the shallow anomaly sources depicted by high wave number. Since the basement on this zone much more related to the regional anomaly, this study would focus on the regional anomaly.

2.2 Trend surfaces

The trend surface analysis, also called polynomial filter or surface fitting, is the least-square applications to define the large-scale pattern on the complete Bouguer anomaly which correspond to the geological background. The higher polynomial order of this method affects the smoothness of the result which means more local anomalies (residual) to be included on the result. Mathematically, the order-1 surface fitting could estimate the regional character ($\mathbf{B}_R$) of a map in x,y coordinates calculated by Eqn. 1 & 2 (Hinze et al., 2013).

$$(\alpha\beta\gamma)^t == (\mathbf{A}^t\mathbf{A})^{-1}\,\mathbf{A}^t\mathbf{B} \quad (1)$$

$$\mathbf{B} = \alpha + \beta x + \gamma y \equiv \mathbf{B}_R \quad (2)$$

The above α, β and γ, are respectively the plane's mean value, and the x-and y-directional slopes. The t transposition on the left-hand side of Eqn. 1 leads the matrix into the least square formula on the right-hand side. Additionally, the higher order which would compensate more local anomalies could be generated by modifying **B** with more unknown variables. In this study, the trend surface order was processed on the first, second, and third mode of polynomial fitting. Those multiple parameters were evaluated based on its matching on the geological background (Fig. 1a).

2.2 Upward continuation

The upward continuation filter enhances the low wave number signal by varying the vertical z-direction above the observation plane. The gravitational effect of an anomalous body mass (**bm**), at geoid level (x_0, y_0, z_0=0) is processed to the intended height h by Δgp (Eqn. 3).

$$\Delta \mathrm{gp} = G_{bm} \frac{z+h}{[(x-x_0)^2+(y-y_0)^2+(z+h)^2]^{3/2}} \qquad (3)$$

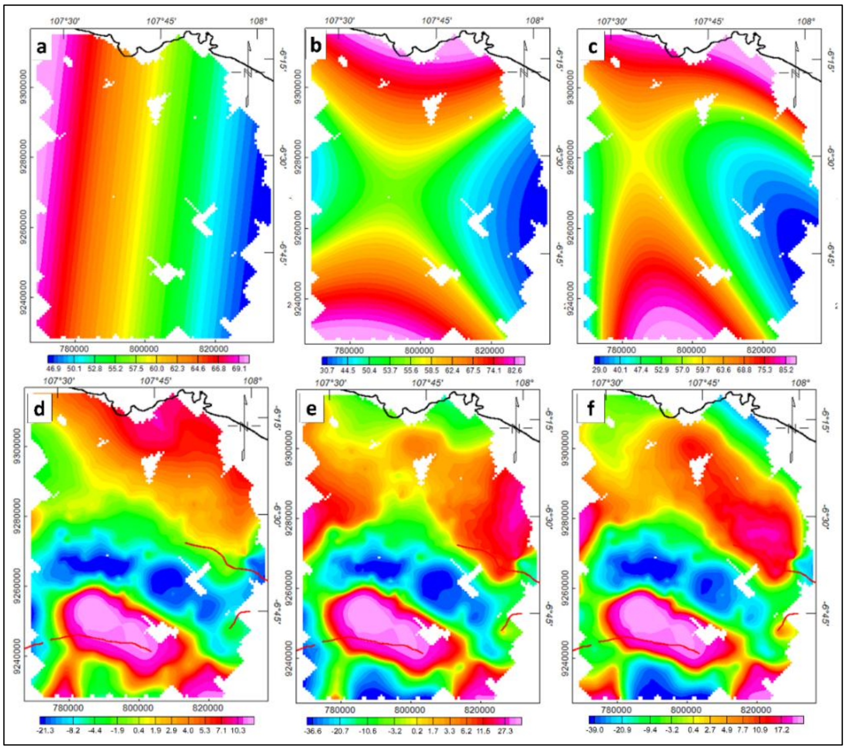

Fig. 2 The trend surface analysis result of regional anomaly (above) and residual anomaly (bottom) in different parameters: (a& d) first order, (b& e) second order, (c& f) third order (units in mGal). Among them,the first order denotes the best residual match on thegeologicalbackgroundin Fig. 1a

The applied upward continuation was conducted in the wave number domain by converting the grid data to the dual Fourier domain using the fast Fourier transformation (FFT) algorithm (Blakely, 1995). The method produced a folded 2D transform map that represents symmetry, linearity, shift and derivative properties which allow several computational operations to be performed more efficiently than in the spatial domain. Notably, this continuation method is preferable to indicate the geometry of anomaly sources at and below the arbitrary depth (z) of half a selected height (h) by z=h/2 (Jacobsen, 1987). In this study, the height parameters were tested on six different elevation from 1000 m to 10000 m.

2.3 Power spectrum analysis

The radially averaged power spectral (RAPS) analysis method utilizes the fast Fourier transform method to express CBA map's spatial mode into the wave number domain. This method is well-established to distinguish low and high wave number features which resemble shallow and deep-seated sources, respectively. The spectral analysis explains the variation of the energy as a relation to wave number and estimates the depth of basement (high contrast density) layer by Eqn. 4 (Spector and Grant, 1970).

$$h = -\frac{1}{4\pi}\left(\frac{\log E_1 - \log E_2}{k_1 - k_2}\right) \qquad (4)$$

The h is depth to interfaces while $E_1$and E_2 are gravity field power spectra whose wave number are k_1 and k_2.

3. Results and Discussion

3.1 Trend surface analysis

The trend surface method utilizes the polynomial order techniques to filter out the long-wavenumber (short wavelength) feature on the CBA map. The corresponding first to third order surface fitting of the anomaly indicated their ability to highlight the basement morphology which denoted in the regional anomaly.

The resulting regional anomaly (Fig. 2a-c) have different characteristics on illuminating the profound feature. The 2nd order regional anomaly (Fig. 2b) was best illuminating the regional geology than the other two such as in the north basement high anomaly of Pamanukan, middle part of Bogor basin low anomaly, and bottom part high anomaly of Tangkuban Parahu volcanic complex (Fig. 1a). The regional results in 1st anomaly (Fig. 2a) has contradicting result to the regional information since the anomaly striking on NS direction. On the other hand, the 3rd order regional result (Fig. 2c) has much more flexure feature than on the geological reference.

Although its regional has no significance to the geological background, the 1st order residual anomaly (Fig. 2d) exceeded the performance than the other two according to the regional map of West Java (Fig. 1a). The northernmost and southernmost anomaly in second and third-order residual trends (Fig. 2e,f) depict far distorted results from the regional view. Those EW trend low anomaly on the northernmost area has no reasonable geological means to the geological shallow or deep background on the onshore Sunda-land since no E-W striking fault or discontinuities on the related area reported by seismic section or systematic geological map. In addition, the slightly same south most low anomaly range (-40 to -20 mGal) to the middle-part (Fig. 2e,f) contradicted with the regional geological background as the Bogor basin should have much smaller low anomaly indicating its reasonably much deeper basement, ~8 km (Waltham et al., 2008) than the Bandung basin's feature of up to 1 km depth (Pranata et al., 2019).

Despite the lack of result in the north and southern part, the low anomaly in the middle part on both trend fitting orders (Fig. 2d-f) might be appropriately related to the Bogor Cenozoic basin. The lack performance of high order fitting result (Fig. 2e,f) might correspond to the limited data on the edge of the CBA grid, whereas the 1st order fitting (Fig. 2d) concentrates only on passing the major low wavenumber that best corresponds to the basement geomorphic. This edge effect is a common artifact in the polynomial analysis (Hinze et al., 2013) and needs a further filter such as data tapering to tolerate the lack of information on the edge map.

3.1 Upward continuation

The upward continuation method was compared on several elevations to examine its ability to pass the low wavenumber on the CBA anomaly (Fig. 3). The higher selected elevation parameter would express the smoother regional anomaly. Based on Jacobsen (1987), the resulting upward continuation model represents geological features at or below the depth of a half selected height (z=h/2). Therefore, the selected height parameter of 1000, 3000, 5000,6000, 7000, 10000m might represent the geological character at or below the depth of500, 1500, 2500, 3000, 3500, or 5000 m, respectively. The whole resulting upward continuation regional models (Fig. 3) were a match with the three - main geological characteristics of Pamanukan High, Cenozoic Bogor basin, and Quaternary volcanos complex (Fig. 1a).

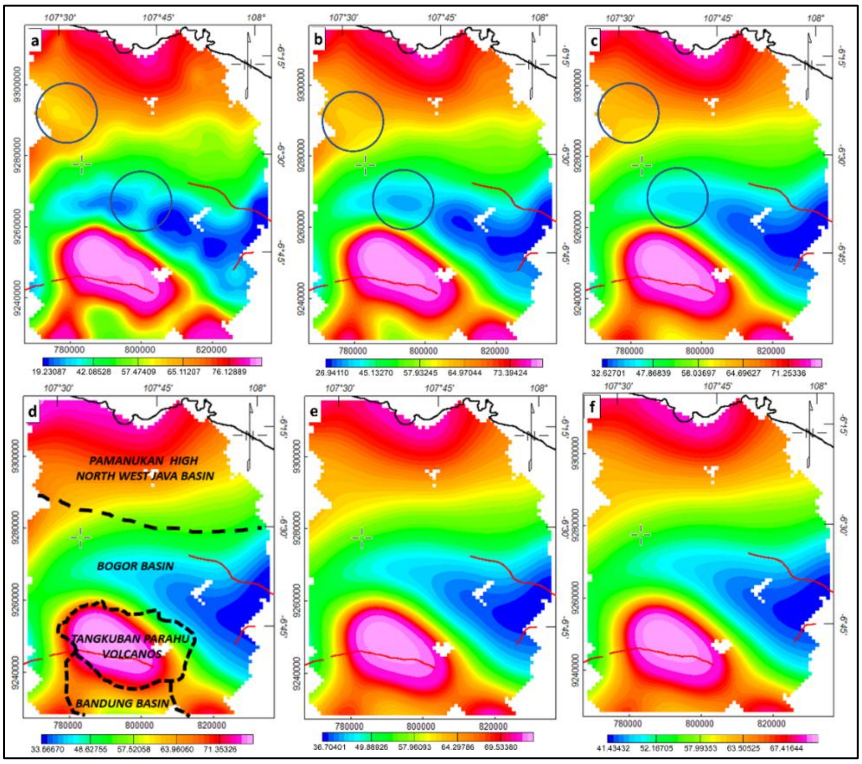

Fig. 3. The regional anomaly of upward continuation on six different height parameters: (a) 1000 m, (b) 3000 m, (c) 5000 m (d) 6000 m (e)7000 m (f) 10000 m (units in mGal). The high wavenumber of local anomalies on (a) to (c), depicted by blue circle, has been effectively removed on 6000 m (d). Since the 7000 m (e) and 10000m (f) have no more significant anomaly change,the 6000 m (d) denotes the most suitable basement feature and closely matches with the regional geology (black dashed line) showed in Fig. 1a

However, a suitable option should be carefully picked to generate the best subsurface representation, otherwise it would end up with a km-scale deficiency on the interpreted result.

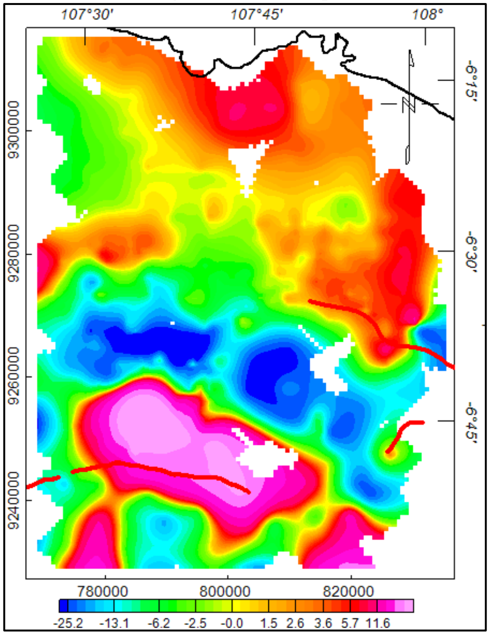

Fig. 4 The residual anomaly from the 6000 m upward continuation (Fig. 3d) indicates short wavelength undulation related to shallow anomaly source.

Based on the profound geological features (Fig.1a), the 6000-m upward continuation result (Fig. 3d) is interpreted as the most suitable regional model expressed by the upward continuation method, principally due to the eliminated high wavenumber on most part of the CBA maps. The high wave number or short wave length anomaly (blue circled on Fig. 3a-c) were gradually eliminated from the 1000 m to 6000 m upward continuation. Those features emerged on the north and south border of Bogor basin might reflect the non-regional features such as local sediments or structures. While the result of 7000 and 10000 m (Fig. 3e,f) depicted no more significant local anomalies removal, the right preceded 6000 m upward continuation (Fig. 3d) resolved the best delineation of regional basement morphology among others. The slightly different feature between the black dashed line border and the anomaly (Fig. 3d) might corresponds to the rough physiography and surface geological method used to produce the map (Fig. 1a). The resulting residual map from the 6000 m anomaly subtraction (Fig. 4) might related to shallow surface sediment distribution and structures.

The proportional result of 6000 m upward continuation filter (Fig. 3d) is closely match with the broader regional feature surrounding the basin explained in previous literature (Martodjojo, 2003; Satyana and Armandita, 2004). Northwardly, a smooth flexural high anomaly zone denotes the Pamanukan high of North West Java basin, which relates to the Sunda-land SE edge. The middle part of lowest anomaly indicates a deep basement feature of Bogor basin (depocenter) and the gradually north to middle decreasing anomaly indicates the slope of the basin. The southern part indicates the Quaternary Tangkuban Parahu volcanic complex, which is depicted by the high gravity anomaly and the slight decrease to the southern most part of this complex indicates the north border of the Bandung basin which begin to thicken to the south.

In comparison to the upward continuation regional anomaly results (Fig. 3), the best regional anomaly from the polynomial trend surface method (Fig. 2b) has minor means to the geological background. Moreover, the best residual result of polynomial surface trend analysis (Fig. 2d) still depicted some edge effect artifacts which need a further filtering process to illuminate a proper subsurface feature. Therefore, the upward continuation, specifically the 6000-m height, was the best method to delineate the basement layer on this zone.

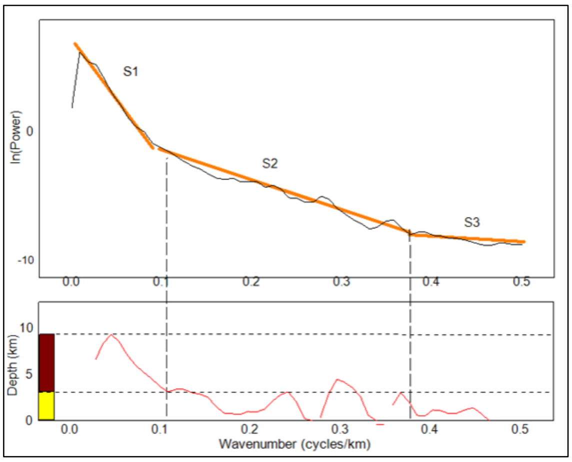

Fig. 5 The radially averaged power spectrum graph showing wavenumbers (cycle/km) to ln (P) relation (above) and the interpreted source depth from slope line analysis (bottom). Depth to the deep anomaly is 9 km (S1), whereas the shallow and near-surface anomaly are 4 km (S2) and below 1 km (S3), respectively. Yellow and brown depict the sediment thickness range from the shallow and deep sources, respectively.

3.3 Spectral analysis and verification

The radially averaged power spectrum (RAPS) result denotes the subsurface structure (i.e., basin sediments thickness and basement depth) calculated by interpreted slope S over 4π on the selected *ln (P)* and wavenumber graph derived from Eqn. 4 (Fig. 5). The radially averaged power spectrum (RAPS) method considerably illuminates the profound extent of an anomalous source using fast Fourier transform spectral analysis (Spector and Grant, 1970). It was applied to control the interpreted depth on the suitable regional anomaly (the 6000 m upward continuation) to get more accurate basement depth prediction on the Cenozoic Bogor Basin.

Three slopes on Fig. 5 depicted depth interpreted from the method were 9 km (S1), 4 km (S2), and 1 km (S3). The most profound anomalous source (S1) delineated in the zone was 9 km most probably indicated the deepest basement top of Cenozoic Bogor Basin or depocenter, which was depicted by the lowest CBA and extensive low wavenumber. While the sediment thickness on the intermediate zone (S2) were varies from 2-5 km with mean value of 4 km and depicted the sediment thickness in the northward (i.e., Pamanukan High of the North West Java basin). The near-surface anomalous source (S3) lying between 0-1 km depth most probably related to the young intrusion of Quaternary volcanic Tangkuban Parahu and the Bandung Basin (Pranata et al., 2019). The results on the inferred North West Java part to Pamanukan High anomaly (~4 km basement depth) are in agreement with published studies by well-log data (Fansuri et al., 2019), seismic profile (Soulisa and Sujanto, 2006), and forward density model (Setiadi and Pratama, 2018).

The significant depth match between the RASP interpreted result to the subsurface data in North West Java basin and Tangkuban Parahu volcanic zone concluded the power spectrum method interpretation for the Bogor Cenozoic basin (~9 km) is preferable. Whereas the 6000 upward continuation of up to 3 km depth estimation based on Jacobsen (1987) is slightly match with the intermediate slope (S2) which denoted North West Java Basin depth. As the interpreted result of each upward continuation method is estimated on a single arbitrary depth, it would roughly predict the mean basement depth on the zone only. Therefore, the result of RASP has more reasonable detail of basement depth estimation which are suitable to estimate the basement depth of Cenozoic Bogor basin. In comparison to the published literature, the 9 km depth of Cenozoic Bogor Basin basement derived from spectral analysis is considered more reasonable than the presumed 4 km depth on lateral 2D density model of Patmosukismo and Yahya (1974). This depth result also in agreement with the hypothetic basement depth of the Cenozoic basin in the Bogor-Kendeng zone (Waltham et al., 2008).

4. Conclusions

The 6000m upward continuation technique had better performance than 1st to 3rd order trend surface methods according to the *a priori* geological background delineation of the Pamanukan High, Cenozoic Bogor basin, Quaternary Tangkuban Parahu complex, and northern border of Bandung Basin. The regional anomaly of 2nd order trend surface analysis has more reasonable result than the other two. However, the corresponding 2nd and 3rd order residual trend surface anomaly indicated inaccurate feature on the northernmost and southernmost due to the edge effect of the polynomial techniques. In comparison to the trend surface fitting, the upward continuation filter exceeded the performance on removing the local anomaly (low wavenumber) and has no edge effect result to illuminate the basement feature.

The north and southern part basement depth estimation by the radially averaged power spectrum method on the 6000 upward continuation was closely matched to published works. Therefore, the model was suitable to predict the middle part, Cenozoic Bogor Basin depth. The implied 9 km deepest sediment layer was most probably related to the Cenozoic Bogor Basin depocenter which in agreement with hypothetic Cenozoic basin depth (~10 km) on Bogor-Kendeng zone (Waltham et al., 2008) but considerably different from the previously interpreted 4-km (Patmosukismo and Yahya, 1974). This study seems more reasonable since it refined by well-explained parameter and model selection in comparison to the previous study and might suggest alternative estimation of subsurface depth of the Cenozoic Bogor Basin. Coupled geophysical methods (e.g., passive seismic, magneto-telluric, resistivity) with potential field-based methods might improve the regional delineation and filtering analysis.

Acknowledgements

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