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ASIAN JOURNAL OF
SCIENCE AND TECHNOLOGY

ISSN: 0976-3376

Asian Journal of Science and Technology
*Vol. 12, Issue, 03, pp.11570-11574, March, 2021*

## RESEARCH ARTICLE

# GRAVITY FIELD AND STRUCTURE OF THE MANTLE PLUME BENEATH KALIMANTAN ISLAND, CENTRAL INDONESIA

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**ARTICLE INFO**

***Article History:***
Received 17th December, 2020
Received in revised form
18th January, 2021
Accepted 14th February, 2021
Published online 27th March, 2021

***Key words:***
Kalimantan Island,
Mantle Plume Structure,
Primary Source of Diamonds.

**ABSTRACT**

A speculation on the existence of a mantle plume structure was raised when alluval diamonds were first found in Kalimantan about a century ago. The upward rising bouyant flow of mantle plumes has been recognised as one of the mechanism on the genesis of diamonds. Following the discovery however, the search for diamonds has been limited to placer deposits only, carried out on small-scale and traditional mining practices. The information on the primary source of diamonds, up to the present moment, was unavailable. The study presented in this paper made use of gravity data in the attempt to reveal the structure of the mantle plume. The work comprised of processing of gravity data for the spatial analysis and modelling to produce maps of images as well as sections of mantle plume models at a lithospheric scale. Result of the study demonstrates the presence of a mantle plume structure beneath Kalimantan Island. The structure is elliptical in shape, with the long axis oriented SW-NE, approximately 600 km long, 300 km wide and about 40 km thick. The depth to the top of the plume structure is about 160 km below sea level.

**Citation:** ***Sardjono.*** **2021.** "Gravity Field and Structure of The Mantle Plume Beneath Kalimantan Island, Central Indonesia", *Asian Journal of Science and Technology*, 12, (03), 11570-11574.



## INTRODUCTION

The island of Kalimantan hosts abundant diamond-bearing alluvial deposits for centuries but the location of their primary igneous source remains unknown[3,4,7]. Dense vegetation rain forests and intense weathering have restricted the efforts in finding the relatively small diamond-bearing intrusive bodies. The failure to find the local primary source has led to a number of concepts to explain the presence of diamonds in Kalimantan. These include that, the deposits were carried from the north-western part of the Australian continent by rifting processes, or the deposits were transported along great distances from south-eastern part of Eurasia southwards through the major Asian river systems, or the deposits were brought to the surface through ophiolite obduction or exhumation of ultra high pressure metamorphic rocks, or the deposits were derived from local intrusive bodies[9]. Processing and analysis of a gravity dataset were carried out in the attempt to reveal the presence of the mantle plume structure, which is known to be one of the lithospheric feature responsible to the formation of diamonds[6]. The gravity data were obtained from the public domain data source at the website of topex.ucsd.edu. The processing of the gravity data includes the computation for gridding and levelling of the topex dataset to the Regional Gravity Maps of Kalimantan published by the Agency of Geology, the Ministry of Energy and Mineral Resources, Republic of Indonesia[1].

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The levelled gravity dataset were subsequently reduced to obtain the extended or complete Bouguer gravityfor further analysis. The analysis comprised of assessing the spatial aspects of the gravity field and the modelling of the gravity effects generated by the mantle plume structure.

## MATERIALS AND METHODS

**Computation and Levelling of Gravity Data:** The downloaded dataset comprised of the topography and the free-air gravity grids. The dataset was obtained in the form of ASCII textfiles at a grid-size of one minute of arc, covering parts of the surrounding off-shore and land areas of Kalimantan Island, spanning the geographic coordinates of 106°E – 120°E ; 5°S – 8°N[8]. The dataset were converted to the UTM coordinates of Zone 49N and regridded at a size of 2000 m prior to the further processing. The computation of the dataset was performed firstly by evaluating the best-density fit for calculating the Bouguer and the regional terrain corrections. The best density value was obtained through the linear regression analysis of free-air gravity against topography grids. Using the value of the best-density fit, corrections for Bouguer slab were carried out to obtain the Simple Bouguer Gravity (SBG). The levelling of the dataset to the regional gravity maps of Kalimantan was performed on the recalculated SBG as the Regional Gravity Maps of Kalimantan were published in this format[1]. The levelling to the Regional Gravity Maps of Kalimantan was carried out by subtracting an average value of 4 mGal from the processed topex dataset. Following the levelling of the SBG maps, corrections for the regional terrain effects were performed. The regional terrain corrections are, in general, small. More than 90 percents of grid stations of Kalimantan land area have terrain corrections of less than 0.9 mGal.

The remaining elevated points, especially in the Central Range region, terrain corrections may reach 1 to 5 mGal but become higher at stations on hill and mountain tops, which may register in excess of 10 mGal. The computed regional terrain corrections grid were added to the SBG grid to obtain the Extended or Complete Bouguer Gravity (XBG or CBG). For the reason of convenience, from this point on, the Extended or the Complete Bouguer Gravity shall be termed as the Bouguer gravity. Further analysis in this study made use of the Bouguer gravity grid.

**Spatial Analysis:** The spatial analysis deals with exploring the variations of the patterns of the images as well as classifying the levels of the Bouguer gravity in response to the lateral variations of sub-surface geology. The analysis aims at examining the shapes of the patterns of the images and classifying the levels of the Bouguer gravity, in the attempt to reveal the geometry of the mantle plume structure at depth. The analysis also attempts to investigate the conceivable traces of other structures which may have contributed to the occurrence of the diamonds.

**Modelling:** The modelling was performed in the manner of two-dimensional forward fitting, an approach in which, the computed gravity effects of a geometrically-designed model of a mantle plume structure were compared to the observed gravity along a selected transect line. The fitting of the computed model against the observed field was performed at the longest wavelength, throughout the entire observation window along the pertinent transect line. The analysis assumed that the modelled mantle plume is to have an average density of 2.87 gr/cc. The average density of the background manle is 3.07 gr/cc and the average density of the crust is 2.67 gr/cc. Adequate density contrast between the plume model and the background mantle results in the buoyance force exerting on the plume to flow upward. This mechanism is believed to have promoted the development of hot spots and the presence of the diamond-bearing intrusive bodies[6]. Estimates of the depth to the rheological boundaries were carried out by analysing the power spectrum of the Bouguer gravity field[5]. Results of the power spectrum depth estmate analysis were used for providing constraints to the modelling of the plume structure.

## RESULT AND DISCUSSION

Result of the processing and analysis are presented in Figs 1 through Fig 7. The map of the Topographic Images of Kalimantan is shown in Fig 1. The Map of the Free-air Gravity Images is depicted in Fig 2. The Linear Regression Analysis of free-air gravity against topography which results in the best-density fit of 2.19 gr/cc, is shown in Fig 3. Fig 4 shows the Map of the Bouguer Gravity Images. The result of the Depth Estimate Power Spectrum Analysis of the Bouguer gravity field is presented in Fig 5. Fig 6 shows the result of the modelling of the mantle plume structure and Fig 7 exhibits the Map of Depth Estimate of the Mantle Plume structure beneath Kalimantan Island. Throughout Kalimantan, the Map of the Topographic Images (Fig 1), is characterised by elevated zones of the Schwaner Mountains, the Muller Mountains and the Central Range Region, which occupy most of the south-west to central north-east part of the island, and to a narrower extent, of the Meratus-Bobaris Zone to the south-east. Smaller dimension of elevated areas also occur at Mount Niut in the west and the Mangkaliat Headland in the east.

The elevated regions which occupy about 25 percent of the overall land areas (coloured in bright yellow to deep reds) vary in altitude from about 300 m to 3000 m. The remaining low-land areas extend within the elevation range from about 300 m down to several metres encompassing the ridges, channels, plateaus, hinterlands and along the coastal zones (coloured in dark to pale blue).

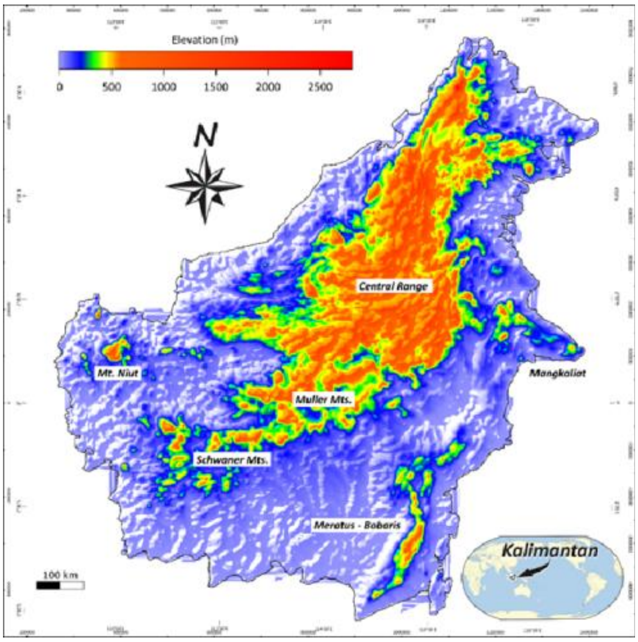


**Fig 1. The map of the Topographic images of Kalimantan Island, Central Indonesia (source: topex.ucsd.edu)**

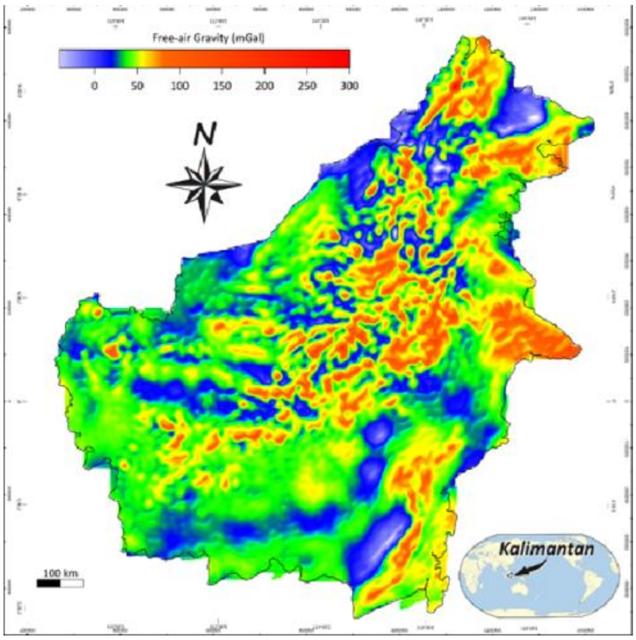


**Fig 2. The map of the Free-air Gravity Images of Kalimantan Island, Central Indonesia (source: topex.ucsd.edu)**

The Map of the Free-air Gravity Images of Kalimantan is depicted in Fig 2. Throughout Kalimantan, free-air gravity ranges in values from about -40 mGal to +300 mGal. Within the elevated zone of the Central Range Region where the mean altitude is 740 m, the mean value of the free-air gravity of +55 mGal indicates that, the region is not in an isostatic equilibrium.

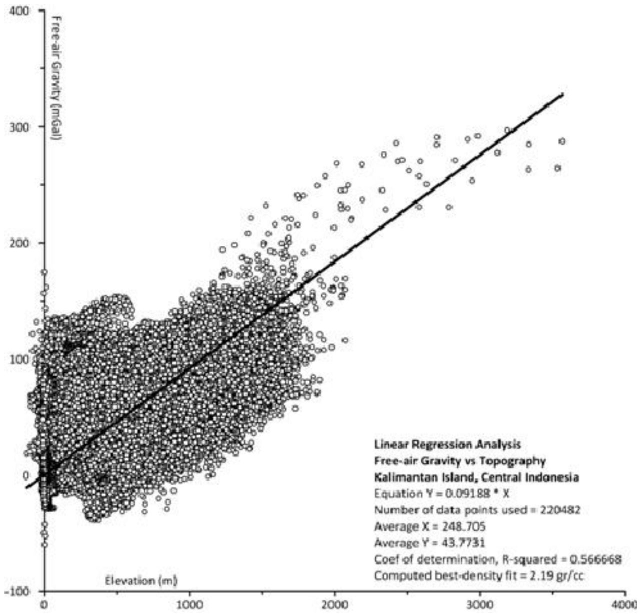


**Fig 3. The Linear Regression Analysis of Free-air Gravity against Topography, Kalimantan Island, Central Indonesia. The best-density fit for Bouguer gravity reduction was obtained by dividing the slope factor of the equation Y=0.09188 * X with the Bouguer slab constant of 2®G (approximately 0.042, where G is the gravitational constant). This approximately results in 2.19 gr/cc for the value of the best Bouguer reduction density, and was subsequently applied for recalculating the Bouguer slab corrections and the corrections for the regional terrain effects to produce the Extended Bouguer Gravity map shown in Fig 4.**

By using the elastic thickness of the crust of 30 km and the assumed denities of the topography 2.19 gr/cc (Fig 3), the crust 2.67 gr/cc and the mantle 3.07 gr/cc, the Airy isostatics suggest that the Central Range Region is, at present , compensated only by about 20 percents, impliying the depth of the crustal root of less than 31 km. A total isostatic compensation may be achieved when the mean value of the free-air gravity is very close to 0 mGal at which, the depth of the compensating crustal root reaches 34 km below sea level[2]. Free-air gravity maps are sensitive to elevation and tend to masked the deep geological bodies. The analysis of deeply seated geological features was carried out using the Bouguer gravity in which, effects of surface geology which masked the target of interest at depth were removed.

The map of the Bouguer Gravity Images (Fig 4) demonstrates a broad, SW-NE elongated pattern of low level gravity which ranges in values from about -100 mGal to +10 mGal, covering about 25 percents of the overall land area of Kalimantan. This extensively broad pattern of low Bouguer gravity is interpreted as to represent the existence of the deep seated mantle plume beneath Kalimantan (Fig 5). Other patterns of gravity low which extent within the range from 0 mGal to about -15 mGal prominently show up in the area to the south, forming the two distinctive circular patterns of about 50 km in diameter, possibly expressing the presence of the lower density intrusive bodies. The top of the intrusives is estimated at about 2 km below sea level and the height is about 15 km.Further to the south-east, the gravity low of about 0 mGal to -15 mGal marks the extent ofthe Meratus-Bobaris Zone. The SW-NE oriented zone of gravity low is interpreted as to represent the Barito sedimentary basin. It extends for about 150 km long and 40 km wide with a total sedimemt thickness of about 8000 m. The obscured pattern of gravity low over the Mount Niut area in the west, which ranges in values from about 0 mGal to -10 mGal, is interpteted as the representation of a low density intrusive body. The intrusive body is about 8 km in diameter, 11 km high and the top of the structure is situated approximately at 600 metres below sea level. Within the area of the Mangkaliat Headland, the Bouguer gravity ranges from about +60 mGal to +120 mGal and higher. The gravity high over the Mangkaliat Headland is interpreted as to correspond to the locally elevated Mohorovičić discontinuity beneath the peninsula. The remaining land areas of Kalimantan are characterised by low to high gravity levels, registering from about +20 mGal to +110 mGal. In some areas where gravity level is within the range of about +20 mGal to +30 mGal and, in general, show elliptical patterns, they are interpreted as to represent sedimentary basins. Elongated patterns with gravity level of about +40 to +60 mGal, oriented W-E in the central west and oriented SW-NE in south-east parts of the island may be interpreted as to correspond to the obducted ophiolites or exhumed ultra high pressure metamorphic rocks.

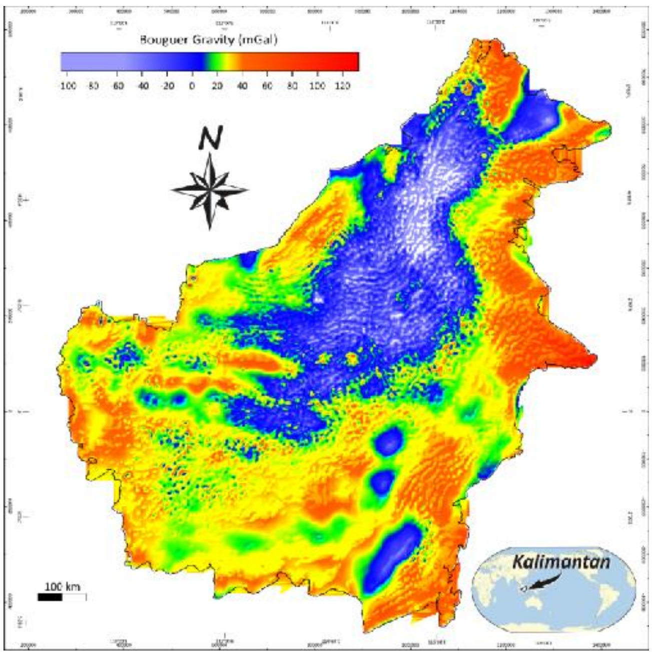


**Fig 4. The map of the Bouguer Gravity images, Kalimantan Island, Central Indonesia. The map was produced by reprocessing and levelling of the topex gravity datasetto the Regional Gravity Maps of Kalimantan[1].**

Fig 5 illustrates the power spectrum analysis of depth estimates to the rheological boundaries beneath Kalimantan. The graph shows three distinct clusters of the power spectrum trends, along with the indicated depths to the corresponding rheological boundaries. The first cluster consists of 9 power spectrum values (white circles) with the best-depth line fit $d_1$ = 158.9 km (thick black line) and corresponds to the depth of the top of the mantle plume. The second cluster contains 71 power spectrum values with the best-depth line fit $d_2$ = 23.8 km and corresponds to the depth of the Mohorovičić discontinuity. The third cluster has 84 power spectrum values with the best-depth line fit of $d_3$ = 7.9 km and corresponds to the depth to to the top of the granitic crust. These depth estimate values were subsequenly used for providing constraint to the modeliling of the mantle plume structure (Fig 6).

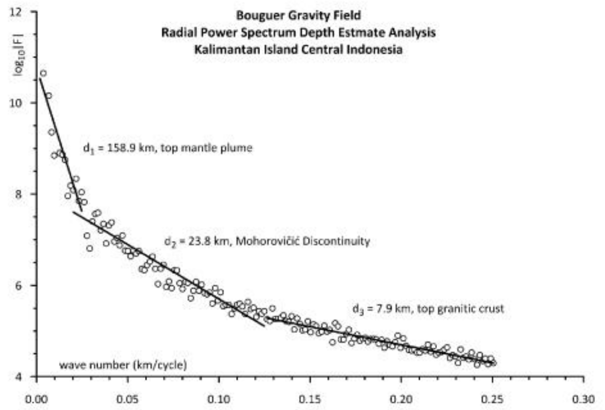


**Fig 5. Bouguer gravity radial power spectrum plot of depth estimate analysis to rheological boundaries beneath Kalimantan Island, Central Indonesia. The graph shows three distinct clusters of power spectrum trends (white circles), along with the manually fitted lines for each cluster (thicker black lines) and the indicated depths to the corresponding rheological boundaries ($d_1$, $d_2$ and $d_3$). The estimated depths in this analysis were subsequently applied to provide constraints to the modeling of the mantle plume structure shown in Fig 6.(Adapted from Pirttijärvi2014).**

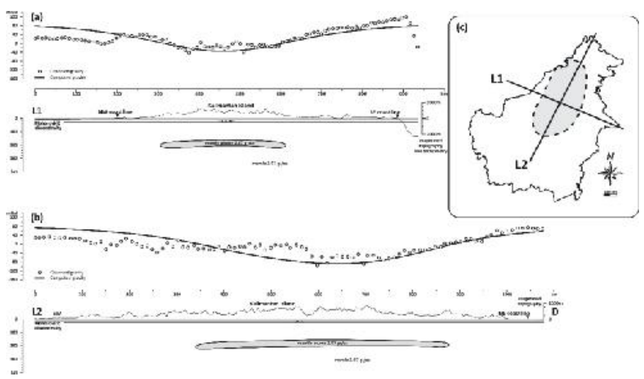


**Fig 6. Lithospheric scale gravity models of the mantle plume beneath Kalimantan Island, Central Indonesia. Showing model sections of transect analysis L1 (a) and L2 (b), and the geometry of the plume structure (c). Lightly shaded area bounded by thick dashed line illustrates the approximate shape of the plume sructure at depth**

The lithospheric scale gravity model of the mantle plume structure is shown in Fig 6. Transect analysis L1 (a) extends NW-SE for about 900 km. It starts in the off-shore area to the north west, passes over the landmass of Kalimantan and terminates in the off-shore area to the south east. Along transect L1 (a), Bouguer gravity varies from about -40 mGal to +120 mGal and the longest wave length of the signal is about 600 km. The gravity low which ranges from 0 mGal down to about -40 mGal clearly marks the presence of the plume structure at depth. The depth to the top of structure is about 160 km below sea level. Transect analysis L2 (b) extends SW-NE for about 1200 km. It starts in the land area to the south west, continues over the mountaineous areas of the Schwaner, Muller and Central Range Region of Kalimantan and terminates in the off-shore area to the north east. Along transect L2 (b), Bouguer gravity varies from about -90 mGal to +80 mGal and the longest wave length of the signal is approximately 1200 km. The gravity low which ranges from 0 mGal down to about -40 mGal visibly indicates the existence of the plume structure at depth. The apex of the structure is approximately situated at 160 km below sea level. The mantle plume structure is elliptical in shape with the longer axis orientates SW-NE of about 600 km long and the shorter axis extends NW-SE of about 300 km wide (c). Fig 7 shows the map of the Depth Estimate of the Mantle Plume structure beneath Kalimantan Island. The map was generated using depth constraints obtained from the gravity modelling (Fig 6).

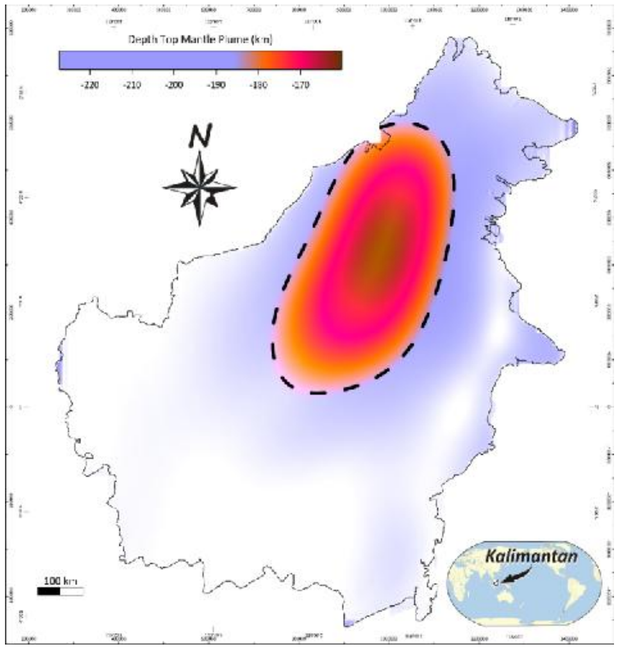


**Fig 7. The map of Depth Estimate of the Mantle Plume structure beneath Kalimantan Island, Central Indonesia. Warm colours enclosed by dashed line, approximately delineate the plume geometry. The structure is elliptical in shape, with the longer axis orientates SW-NE, approximately 600 km long and the shorter axis extends NW-SE of about 300 km wide and approximately 40 km thick (Fig 6a and 6b). The depth to the top of the plume structure is about 160 km below sea level**

## Conclusions and Recommendation

The gravity data processing and analysis presented in this study successfully demonstrate the presence of the mantle plume structure beneath Kalimantan Island. The existence of the mantle plume structure was speculated when first alluvial diamonds were found about a century ago[3,4]. The upward rising bouyant flow of mantle plumes has been recognised as one of the mechanism on the genesis of diamonds[6]. Although limited on the resolution, the gravity dataset used in this study were able to pin-point the low-density tubular features most possibly expressing the structures of diamond-bearing intrusive bodies. Using the presently available data, other features such as hot spots and smaller intrusive bodies which may presence above the mantle plume are unresolvable. Higher resolution geophysical data are required in order to discriminate and pinpoint the relatively smaller size diamond-bearing structures above the mantle plume. Airborne gravity gradiometry and magnetics surveys at 50 m sampling intervals and 100 m line spacings is greatly recommended in order to obtain an adequately high resolution dataset for the exploration of primary diamonds in Kalimantan.

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