Subsurface geological model of Malay basin using free air anomaly

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Abstract. The aim of gravity survey is to assist in the detection and delineation of subsurface geological features such as salt domes and faults. In this study, free air anomaly (FAA) data was adopted for mapping and modelling process to delineate subsurface geological features and basement depth in Malay Basin. FAA is the measured gravity anomaly after a free air correction is applied, and it is used for elevation correction. The data of FAA in this study is obtained from Earth Gravitational Model (EGM) 2008 released by the National Geospatial-Intelligence Agency (NGA)-EGM Development Team. Oasis Montaj software was used in the mapping and modelling process whereby the base map which constructed by the Oasis Montaj is used to form the FAA map of Malay Basin. Typically, the positive anomaly is associated with the high-density intrusion at the base of the crust, while in contrast (negative anomaly), it is related to the sedimentary basin in the upper crust. On top of that, the regional-residual anomaly, total horizontal derivative (THD) and 3D Euler Deconvolution enhanced maps were produced and interpreted to acquire comprehensive insight of subsurface geological features. To conclude, this study showed 5 % deviation as compared to previous reported works and the deepest basement depth encountered is 14.5 km.

Keywords: Free Air Anomaly, Malay Basin, 2D Gravity Model, 3D Euler Deconvolution

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1. Introduction

Applications of gravity method in oil and gas exploration are essential and beneficial whereby this method could significantly enhance any targets exploration which possess the density contrast at different depth such as salt domes, ore bodies, structure, and regional geology [1]. In addition, the basement rock depth data in the oil and gas industry could also be used to determine the depth of the basin as well as the maximum well drilling depth [2]. Generally, gravity method passively measures natural variation of the earth's gravity over a map area and correlate them with the variation of geological subsurface features. This method basically offers advantages such as relatively economical, non-invasive, non-destructive remote sensing and at the same time, capable in providing information related to the densities of subsurface rocks [3,4]. Fundamentally, gravity anomaly can be defined as small deviation from the average gravity force due to the density variation of subsurface rock. The average gravity force or commonly called as the standard gravity possess the value of 9.80665 m s^{-2} (equivalent to 980665 mGal) and it is measured as free fall acceleration of an object at above sea level [5]. There are several methods of acquisition in obtaining gravity anomaly which include airborne, shipborne, and inland. For this study, free air gravity anomaly or commonly named as free air anomaly (FAA) is used in the mapping and modelling, in which consider free air correction for the measured gravity anomaly for elevation correction [6] and the unit used to measure the FAA is mGal whereby 1 mGal is one over thousands of 1 cm s^{-2}.

The implementation of gravity method (FAA) in the oil and gas industry basically enhances the exploration of any targets specifically the targets with density contrast at different depth such as salt domes, ore bodies, structure, and regional geology [7]. This is due to the fact that the integration of gravimeter instrumentation provides more accurate FAA data as compared to the solely airborne (satellite) and marine acquisitions. Common practice exhibits that the FAA method is often applied in oil exploration involving salt due to the huge density difference of salt with the surrounding sediment, whereby it yields in positive value when in shallow and negative value when in deep [8]. On top of that, this FAA also capable to provide the information related to the densities of subsurface rocks. Inference about the distribution of underground strata can be made using the concept of different rock types possess different ranges of densities [9]. Furthermore, the FAA also could determine the faults as the faults often juxtapose rocks of differing density.

To our knowledge, previous scholars only reported the FAA on Malay Basin using the ERS-1 satellite data [10] and no FAA works has been performed on Malay Basin using the latest Earth Gravitational Model 2008 (EGM 2008) satellite data. Thus, it is essential to investigate the differences between them in terms of geological features and basement depth. For that purpose, the qualitative and quantitative interpretations of FAA data on Malay Basin using the EGM 2008 data were performed using Oasis Montaj software. Qualitative interpretations include regional anomaly, residual anomaly, total horizontal derivative (THD) and Euler Deconvolution, while quantitative interpretation include the 2D gravity crust model.

2. Geological Setting

Generally, the Malay Basin in Figure 1 (grey shaded area) is located at the North Peninsular Malaysia (completely offshore), South Cambodia, and Vietnam, and extend across the Gulf of Thailand and the South China Sea. The dimension of this basin is approximately 500 km long and 200 km width, and the total area is about 83,000 km^2 with broad range of FAA value is about -20 mGal to -30 mGal [11]. Arrows along the faults in Figure 1 (a) shows the initial movement on the Dungun Faults, Hinge-line Fault, and Tenggol Faults. Each dextral slips associated with the faults are due to its slight wrench depression [12]. The slip was reverted during the Late Oligocene to the Early of Miocene due to transpressional stress regime and compressional structures formation. The E-W trending anticlines (anticline that contain most hydrocarbons) was relocated up to 35 km as the Malay Basin is cross by major N-S faults [13]. Nonetheless, Paleogene wrench together with left-lateral movement of 30 to 35 km fault zone (also represents the axis of basin) form the E-W inclination of the large folds with Moho depth in Figure 1(b) is approximately ranging from 29 to 32 km [14].

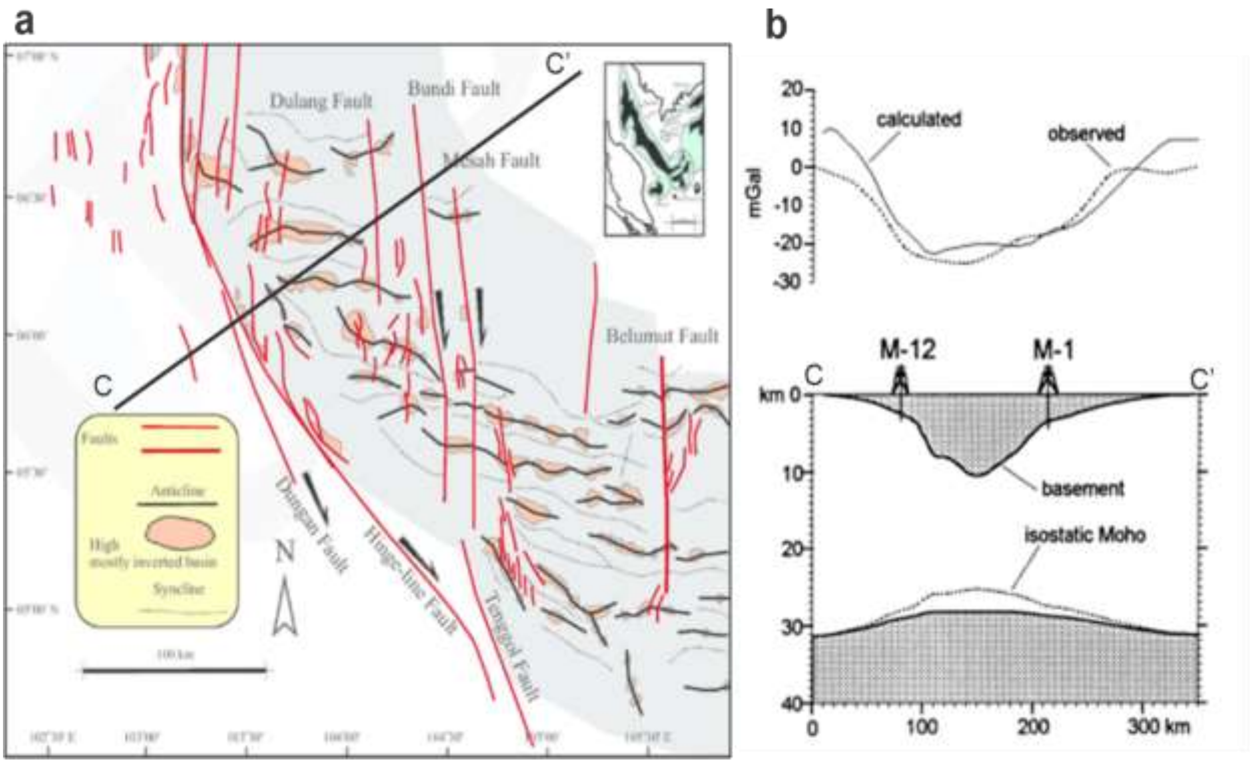

Figure 1. (a) Major structure of Malay Basin (after Tjia,[12]), (b) Gravity profile estimated Moho depth across northern part of Malay Basin (after Madon [22]).

3. Methodology

3.1. FAA Input Data

The FAA input data used in this study is the satellite airborne data obtained from EGM 2008: publicly published by the National Geospatial-Intelligence Agency (NGA). This gravitational model is basically complete up to spherical harmonic degree and order 2159,and contains additional coefficients extending to degree 2190 and order 2159 [15]. The data version used in this study is WGS84 (Version of EGM 2008 released in July, 2008) which includes the grids and programs for computing geoid undulations relative to WGS84 Ellipsoid.

3.2. FAA Extraction

Google Earth software was used to set the area of study whereby four place marks were added within the area of Malay Basin. The airborne path was generated within the area of investigation in Google Earth in order to obtain the FAA value corresponding to the coordinates. The FAA data (anomaly data) in the Google Earth are shown in different colours. The FAA value for each points of the airborne path can be obtained through the colour as each colour range represents different values. Next, the coordinate of each point of the airborne path are extracted by the airborne path tab and then saved in kml format before converted to Excel using the TCX Converter. These coordinates are basically in decimal degree form of ellipsoid system for longitude and latitude in Global Positioning System (GPS, WGS84). The extracted coordinates in the form of GPS system are then converted to Universal Transverse Mercator (UTM) due to the requirement of Oasis Montaj software, whereby the coordinate grid data must be in the form of unit meter, projection of UTM [16].

3.3. Qualitative Interpretation

In Oasis Montaj, the grid of FAA data was constructed using the minimum curvature technique. Base map was built corresponding to all the data coordinates. The grid then was imported to the base map to form the FAA map. The regional anomaly map was used to determine the deep crust especially the lower crust depth. The component of the long wavelength in the gravity field is contributed by the depth of body which exceeded the limit of exploration of hydrocarbon and minerals [17]. The regional anomaly map was produced by applying a low pass filter on the FAA map. The filtering was carried out by MAGMAP in Oasis Montaj through MAGMAP 1-step filtering. The aim of this filter is to observe the cut off wavelength at deeper area. The cut off wavelength basically eliminates all the wavelength which possess less value than the cut off value. Residual anomaly is the anomaly which represent the short wavelength and related to the presence of shallow structure. It is formed by eliminating the long wavelength in the isotactic compensation effect from the source of different boundaries between the mantle and earth's crust [18]. Principally, the residual anomaly is capable to observe the clearer local anomaly which could be associated with the shallow structures. In this study, the residual anomaly map was constructed using the regional anomaly map with low pass filter of MAGMAP in Oasis Montaj through MAGMAP 1-step filtering. Total horizontal derivative (THD) was used to increase the delineation of the boundary based on density from the gravity data, and it estimates the drastic changes of density in lateral.

THD are generally has low susceptibility to noise in the data and possess robust delineation either in shallow or deep situation. Horizontal gradient filter was applied to produce dx and dy grids. THD map then were produced from dx and dy grids by using the grid math. The relationship between the dx, dy and THD map is shown in Equation 1 [16]:

$$G_0 = \text{sqrt}\,((g_1 * g_1) + (g_2 * g_2)) \ldots\ldots\ldots\ldots \quad \text{(Equation 1)}$$

Where G_0 represents the THD, g_1 represents the dx grid and g_2 represents the dy grid.

The 3D Euler Deconvolution was applied to estimate the mineral depth in 3D map by using the Structural Index (SI) input as listed in table 1 and suitable window size [19]. Briefly, the generated Euler deconvolution map illustrates the boundaries for geology features based on the difference in gravity and estimate the anomaly depth or fault location in measured area. Conceptually, this SI is necessary to form the required result, while for the window size, it is required for the Euler deconvolution map construction. Window size used for analysis and interpretation should be the optimum size (not too big or too small) whereby it requires all the gravity value need to be included. In this study, seven window size were used which were 3x3, 5x5, 7x7, 9x9, 10x10, 13x13 and 15x15. The reason for the variation of window size was due to the fact that the small window size is capable to detect the shallow anomaly while the bigger size is capable to detect deeper area anomaly. On the other side, the 2D Crust Model was constructed using the GM-SYS method for subsurface structure illustration, and that model was basically based on the value of gravity data with the average density of basement for the rock is set to 2.76 g cm^{-3}, seawater-1.03 g cm^{-3} and average sedimentary rock-2.65 g cm^{-3} [20].

Table 1. Standard Euler Deconvolution (Structural Index).

SI	Gravity Field
0	Sill / Dyke / Ribbon / Step
1	Cylinder / Pipe
2	Sphere
3	NA

4. Results and Discussion

In this study, the analysis and interpretation of the Malay Basin has been made on the FAA map as shown in Figure 2. The qualitative enhanced map including the regional anomaly, residual anomaly, THD, and 3D Euler Deconvolution has been constructed using the Oasis Montaj software. These enhanced maps were then further analyzed and interpreted to estimate and to understand the major structure and faults of the Malay Basin. In addition, the 2D modelling has also been done by GM-SYS in Oasis Montaj for Malay Basin basement depth estimation.

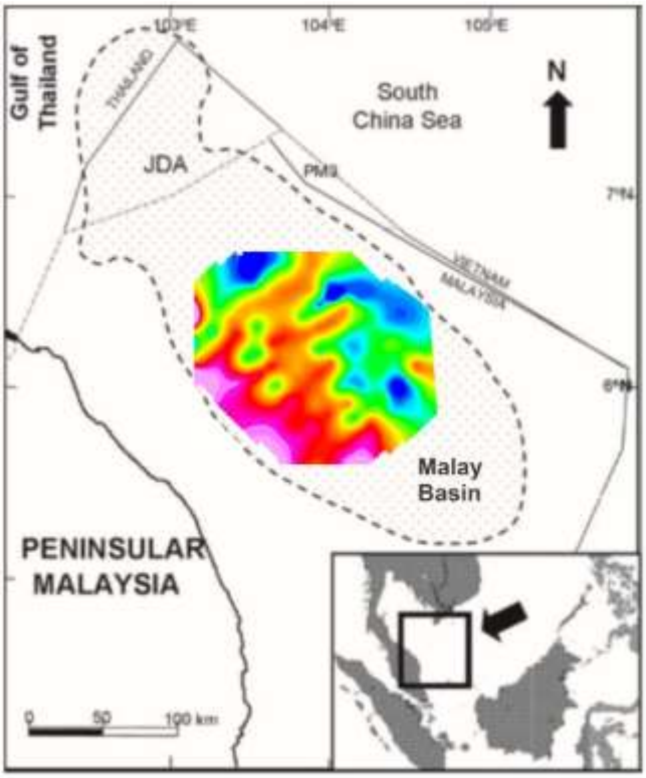

Figure 2. FAA map display in central part of Malay Basin.

4.1. Regional and Residual Anomaly Map

To determine the accurate cut off wavelength, several regional anomaly maps with different cut off wavelength values were constructed until the contour of the anomaly map became smooth. The cut off wavelength with the smooth contour line in the map will be the value of cut off wavelength for regional anomaly map. The value of cut off wavelength was determined as 125000 ground unit since the maps showed no changes from regional anomaly map with the cut off wavelength at 125000 (Figure 3a) and onwards. Hence, the cut off wavelength of 125000 is used for interpretation of residual anomaly within the study area (Figure 3b).

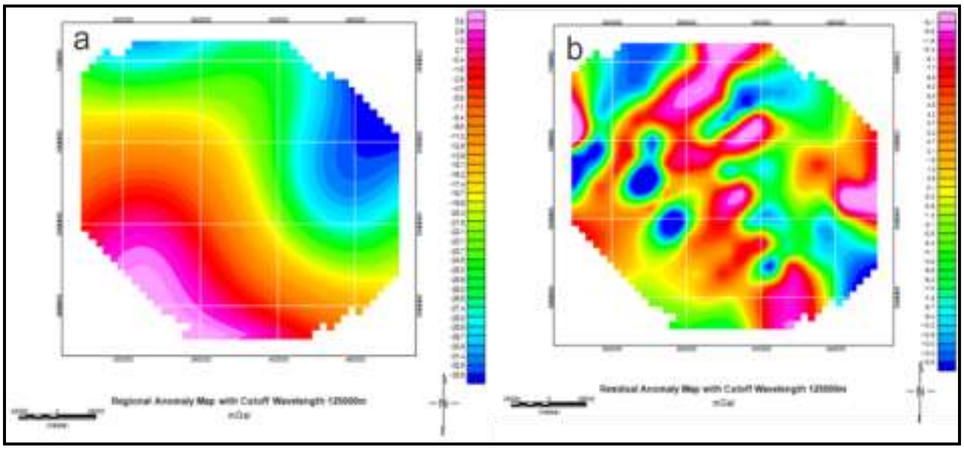

Figure 3. Regional anomaly map with (a) cut off wavelength at 125000 m and (b) residual anomaly map after cut off wavelength at 125000 m.

4.2. *THD and Euler Deconvolution Map*

Three THD maps were constructed which named as THD from FAA map (Figure 4a), THD from THD from residual anomaly map (Figure 4b). By observing the THD map generated from the FAA map both maps display several lineaments have similar dominant trend of anomaly reading in the direction to the reference lineament provided by Tjia [12]. These results are in agreement with the previous works same dominant trend in the central axis of Malay Basin which trending from northwest (NW) to southeast (SE)) [12] with some minor anomaly trends observed in the North-South direction.

All the three maps generally show similar major trend of the fault at the axial Malay fault zone, which trending from NW to SE. Furthermore, those maps also resemble major faults in Malay basin such as Dungun Fault, Hinge-line fault, Dulang Fault and Bundi Fault.

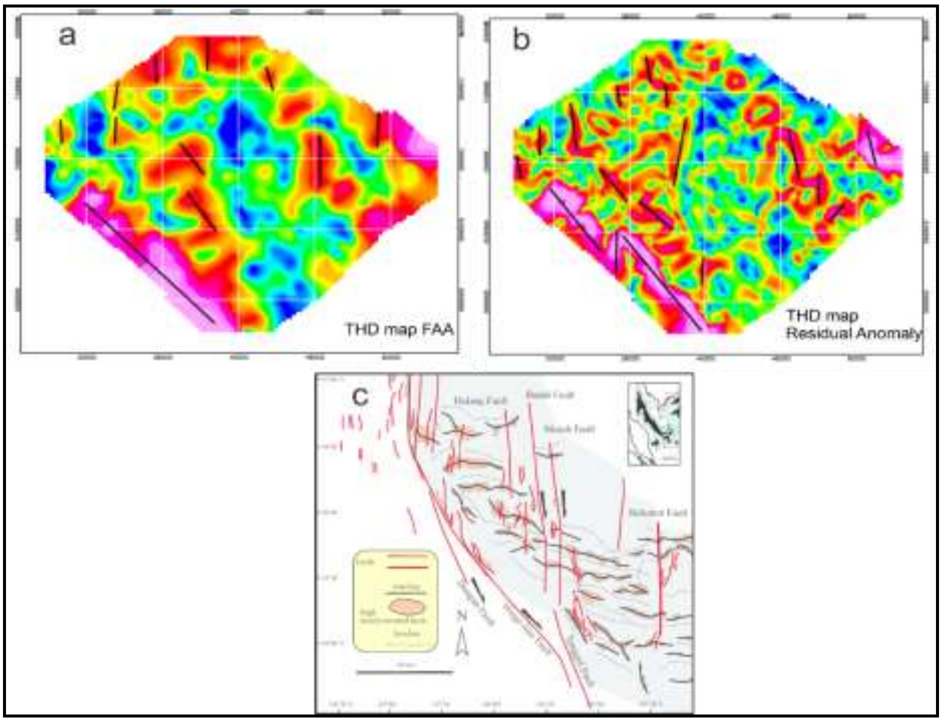

Figure 4. THD with lineament generated from (a) the FAA, (b) the residual anomaly, and (c) the reference lineament by Tjia [12].

The Euler Deconvolution map with the window size of 7x7 and 0 SI indicates that more anomalies (distributed in the whole map) observed for the depth of 2000-4000 m as shown in Figure 5. Meanwhile for the anomalies in the depth of 4000-6000 m and 6000-8000 m, all of them are distributed in the east direction and NW of the map, respectively.

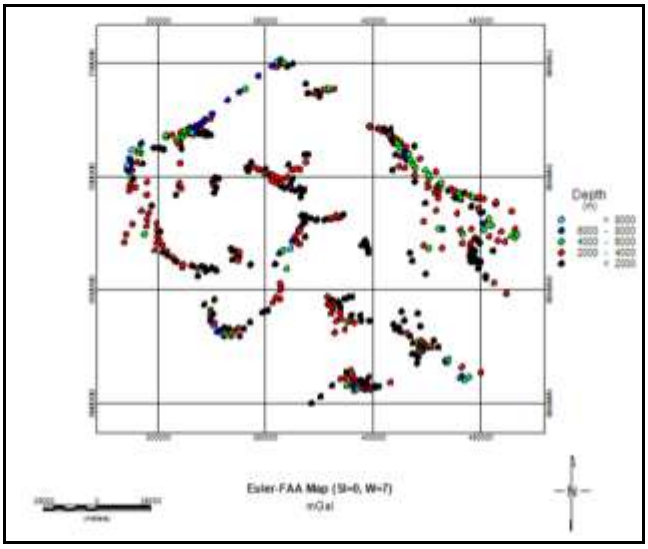

Figure 5. Euler Deconvolution map (SI=0, Window=7).

4.3. 2D Gravity Model

Figure 6 illustrates the 2D gravity profile of AA' directed from SW to NE which was modelled on the study area. The modelling shows the width of the profile is about 160 km and the range of depth encountered is 0-14.5 km with the deepest basement depth generated by GM-SYS is 14.5 km. The reference to built this 2D model was referred to Madon [21] with differentiate from observed and calculated error is acceptable below than 0.3.

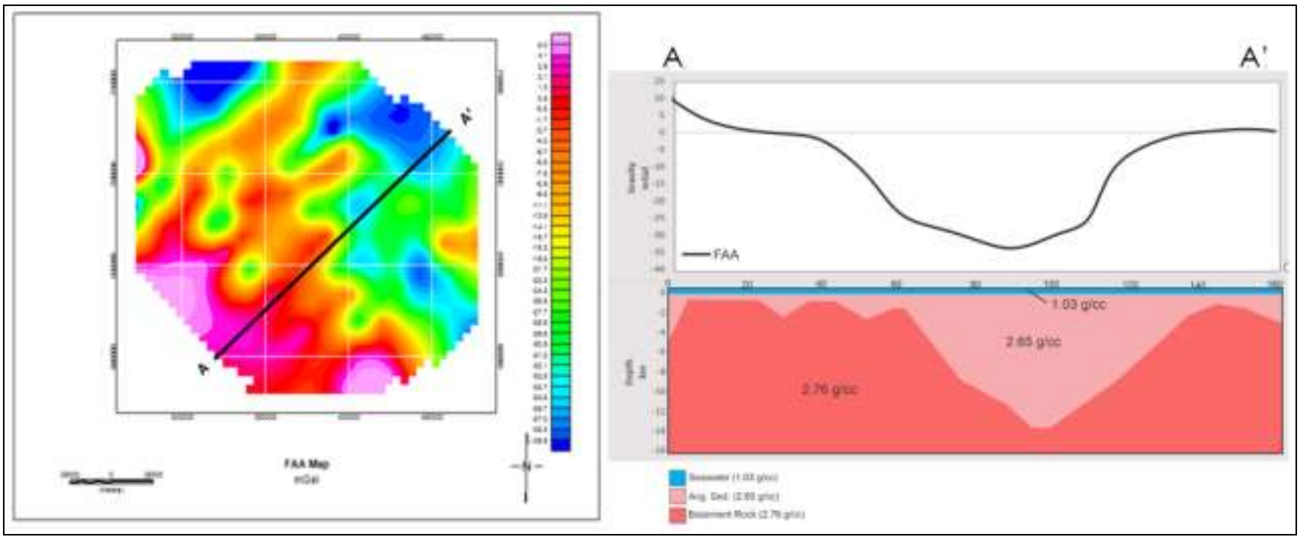

Figure 6. 2D gravity model for the central of Malay Basin.

5. Conclusions

Maximum anomalies were observed in the South (S) and SW direction while for the minimum anomalies, they could be seen in the East (E), NE and SE direction. Regional anomaly map shows the trend of NW-SE, while the THD maps detect the faults at similar locations as the geological map. From the study of Euler deconvolution, the most suitable window which produce efficient and clear anomalies was found to be 7x7. By comparing the Euler map with the geological structure map, similar faults at 2000-4000 m and 4000-6000 m were detected. The 2D gravity model reveals that the deepest basement depth found is 14.5 km which is about 5 % deviation from previous works using the the ERS-1 satellite data. For future works, it is suggested to match this FAA study with the seismic line and magnetic anomaly.

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