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Subsurface structural mapping from high-resolution gravity data using advanced processing methods

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Abstract

The Thua Thien Hue has a complex geological structure and is studied for mapping the subsurface structure using geophysical techniques. However, the Thua Thien Hue has not been studied for mapping geological structures, such as contacts and faults that appear as lineaments in gravity data.[1] In this study, the lineaments in the Thua Thien Hue area have been delineated using Bouguer gravity anomaly data, though some modern processing methods, such as horizontal gradient amplitude (HGA), tilt angle of horizontal gradient amplitude (THGA), and enhancement of horizontal gradient amplitude (EHGA), are also used.[0] Most of the identified lineaments are trending in the NW–SE direction and some WE-trending lineaments in the southeastern region.[0] This study provides new information for a better understanding of the structural framework and tectonic setting of the Thua Thien Hue area.

Keywords: Thua Thien Hue, lineaments, gravity, edge detection, EHGA

1. Introduction

Gravity data are critical for geological mapping, especially for information on geological structures (Nabighian et al.[0], 2005) and have signals with a large dynamic amplitude range that depend on the geometries, depths, and density properties of the sources (Ferreira et al., 2013).[38] Edge enhancement techniques are generally used to emphasize the characteristics of the gravity field to interpret the geology of gravity anomaly data (Pham et al., 2020).[0] Various techniques are available in the literature, most of which are based on gradients of gravity data (Nasuti and Nasuti, 2018; Pham et al., 2021a). Some edge detector techniques, such as the horizontal gradient amplitude (HGA) (Cordell and Graunch, 1985), analytic signal (Roest et al., 1992), tilt derivative (Miller and Singh, 1994), theta (Wijns et al.[4], 2005), normalized horizontal derivative (Cooper and Cowan, 2006), and tilt derivative of the horizontal derivative (Ferreira et al., 2013), are used to outline the boundaries of density structures. However, the boundaries detected by these techniques are rather diffuse (Pham et al., 2020; Pham et al., 2021b). Therefore, some filters, such as the improved normalized horizontal tilt angle (Li et al., 2014), improved theta method (Yuan et al.[2], 2016), improved enhanced tilt angle (Nasuti and Nasuti, 2018), the total directional theta method (Zareie and Moghadam, 2019), and enhanced horizontal derivative amplitude (Pham et al.[0], 2020) have been developed to improve the resolution of the edges.

The Thua Thien Hue area extends from latitude 15.47° N to 17.29° N and longitude 106.49° E to 108.30° E. A previous gravity study in the area focused only on estimating the depths to density interfaces by inverting gravity data (Hung et al., 2019).

[1]In this study, we applied the HGA, tilt derivative of the horizontal gradient amplitude (THGA), and enhanced horizontal gradient amplitude (EHGA) to the Bouguer data of the Thua Thien Hue to determine faults/lineaments. The results obtained from this work provide new elements to improve knowledge of the structure of the Thua Thien Hue area.

[32]2. Geological setting

The Thua Thien Hue is in the central region of Vietnam and is vital for socio-economic development and national defense security in the region. It has favorable natural conditions, rich mineral resources, unique culture, and especially, UNESCO has ranked the Hue Monuments Complex as a World Cultural Heritage.[45] In this area, the geological platform of the southwestern and southern parts belongs to the Indosinian geoblock, that of the central part belongs to the Truong Son fold system, and that of the northeastern part belongs to the Red River basin (Trang, 1996). The study area's strata include Paleozoic, Late Proterozoic-Early Paleozoic metamorphic, Neogene terrigenous, and Quaternary unconsolidated sediments. These formations include the Nui Vu formation of Late Proterozoic-Cambrian age, A Vuong formation of Cambrian-Ordovician age, Long Dai formation of Ordovician-Silurian age, Tan Lam formation of Early Devonian age, Co Bai formation of Middle-

Late Devonian age, Pliocene-Lower Pleistocene sediment, and A Lin formation. In the study area, the Quaternary unconsolidated sediment is composed of sand, breccia, silt, and pebble, predominantly distributed in the northeastern region along the coast and narrow areas along rivers and streams (Fig. 1).

3. Data and methodology

3.1. Data

The gravity data set used in this study was computed by Pham (2020) using $1' \times 1'$ grid gravity data derived from the CryoSat-2 and Jason-1 satellites, which has twice the accuracy than the previous gravity model (Sandwell et al., 2014). Fig. 3a displays the Bouguer anomalies after applying corrections to the free-air gravity anomaly data (Pham, 2020).[0] Recently, applications of edge enhancement techniques to satellite gravity data have shown great success (Vaish et al., 2015; Narayan et al. 2016; Kunnummal and Anand 2018; Kumar et al., 2020; Pham et al., 2021c).

3.2. Methodology

Extracting the lateral boundaries of the subsurface structures is a frequently required task in interpreting gravity data. The HGA is a commonly used technique, using peak values to extract the edges. The HGA of gravity data F is calculated from the two horizontal gradients using Cordell and Grauch's (1985) formula

$$\mathrm{HGA} = \sqrt{\left(\frac{\partial \mathrm{F}}{\partial \mathrm{x}}\right)^2 + \left(\frac{\partial \mathrm{F}}{\partial \mathrm{y}}\right)^2}. \quad (1)$$

Fig. 2b displays the HGA of the gravity data (Fig. 2a) of 2D sources that are shown at the bottom of Fig. 2. High amplitude responses dominate the HGA is dominated because of the shallower source G1.

To equalize the anomalies with different amplitudes, Ferreira et al. (2013) proposed using the THGA as follows

$$THGA = atan\left(\frac{HGA_z}{\sqrt{HGA_x^2 + HGA_y^2}}\right), \quad (2)$$

where HGA_x, HGA_y, and HGA_z are the gradients of the HGA. From Fig. 2c, the THGA filter is effective in equalizing the anomalies with different amplitudes. The peaks of the THGA are directly positioned over the source edges.

Pham et al. (2020) recently introduced another filter, the EHGA, which is defined as follows

$$\mathrm{EHGA} = \mathcal{R}\left(\mathrm{asin}\left(\mathrm{k}\left(\mathrm{P}-1\right)+1\right)\right) \qquad 3)$$

where

$$P = \frac{HGA_z}{\sqrt{HGA_x^2 + HGA_y^2 + HGA_z^2}}$$

and k is a positive number defined by the interpreter. A value of k that is ≥2 will produce the best result. The EHGA value is limited to between $-\pi/2$ and $+\pi/2$, where its peaks over the source lateral boundaries. As shown in Fig. 1c, the EHGA produces a sharper image on the body edges than the HGA and THGA filters.

4. Results and discussions

The HGA, THGA, and EHGA methods were applied to the Bouguer gravity data in Fig. 3a. Fig. 3b displays the HGA image of the gravity data. Because the HGA technique depends on the burial depth of the source, it does not produce a balanced image for the gravity lineaments. The northeastern portion of the area has lower HGA amplitude values, which might be related to increasing basement burial depths in the East Sea. Conversely, the increase in amplitude in the southwestern and southern parts of Thua Thien Hue could be related to the basement (Hung et al., 2019). Fig. 3c and 3d show the THGA and EHGA maps, respectively. Unlike the HGA method, the THGA and EHGA methods can equalize the amplitudes of small and large anomalies. Although the THGA and EHGA methods are more effective in enhancing the main gravity structures than the HGA method, the EHGA can bring lineaments with higher resolution. The obtained results indicate that several trends exist in the data, with the NW–SE trend being dominant. These results detected by the THGA and EHGA methods correlate well with the trend of geology structures in the area (Fig. 1). The boundaries of the intrusive rocks are well extracted by the THGA and EHGA methods. The results also reveal N-S trending lineaments in the East Sea and NE–SW trending lineaments in the southeastern region. Furthermore, the THGA and EHGA maps demonstrate the existence of many lineaments that are not extracted by geological mapping alone.

[9]To reduce the noise effect and improve the effects of deep structures, we applied a 5 km upward continuation filter to the gravity data in Fig. 3a before using edge detection techniques. Fig. 4a shows the Bouguer gravity data after the upward continuation of 5 km. Fig. 4b, 4c, and 4d show the results determined by applying the HGA, THGA, and EHGA methods, respectively.[1] Although the HGA method is more effective in enhancing the deep structures in the East Sea than its previous result, the detected result is faint. Again, the THGA and EHGA methods provide more detailed features than the HGA method. Here, the NW–SE trending lineaments in the THGA and EHGA maps appear more distinctly. The southeastern region displays the E–W trending lineament, indicative of a deep subsurface feature in the region. Although the THGA and EHGA methods can equalize different amplitude anomalies, the results detected using the EHGA provide sharper lineaments. As can be observed from Fig. 4c and Fig. 4d, most of the extracted lineaments are NW–SE trending and some E–W, N–S trending lineaments in the southeastern region. We anticipate that the lineaments trending NW–SE extracted in this study are related to the same activity of tectonic plates. In other words, this could be because of the collision between the Eurasian and Indian plates (Tapponnier et al., 1982; Lacassin et al., 1997).

5. [0] Conclusions

Different edge enhancement methods (HGA, THGA, and EHGA) are applied to the Bouguer gravity data to extract the structural features of the Thua Thien Hue area. The obtained results show that the THGA and EHGA methods enhanced the lineaments of all anomalies, whereas the HGA method extracted the lineaments mostly of large-amplitude anomalies. Furthermore, the EHGA method can produce lineaments with higher resolution than the HGA and THGA methods. We also found that most boundaries delineated in this study are lineaments with the NW–SE trend being dominant, sympathetic to the known geologic information of the area. The results of this work will immensely help understand the tectonic and structural framework of Thua Thien Hue.

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Figure captions

Figure 1. Schematic geological map (Trang, 1996).

Figure 2. (a) Gravity of the 2D gravity model, (b) THG, (c) THGA, and (d) EHGA with k = 8.

Figure 3. (a) Bouguer gravity data of the Thua Thien Hue area, (b) HGA, (c) THGA, and (d) EHGA.

Figure 4. (a) Bouguer gravity data of the Thua Thien Hue area after upward continuation of 5 km, (b) HGA, (c) THGA, and (d) EHGA.