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Study on structure of the Earth's crust in Thua Thien-Hue province and adjacent areas by using gravity and magnetic data in combination

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Abstract
This paper presents the structural characteristics of the Earth's crust in Thua Thien-Hue province and adjacent area based on interpretation of gravity and magnetic data in combination. Research results have shown that: The depth of crystalline basement varies complicatedly, in the range of 0–11 km. The depth of Conrad surface increases from Northeast (12 km) to Southwest (18 km) and the depth of Moho surface is 23–34 km; The density of sedimentary layer changes from 2.61 g/cm^3 to 2.65 g/cm^3. Meanwhile, the density of granitic layer is in the range of 2.68–2.73 g/cm^3. The basaltic layer has the density value of 2.88–2.93 g/cm^3 and the average density of lower layer of the Earth's crust is about 3.30 g/cm^3; The depth of second-order faults, Red River and A Luoi - Rao Quan, is through the Earth's crust. Meanwhile, the depth of influence of third-order faults, Chay river, Dong Ha - Phu Vang, Vinh Linh, Hue - Son Tra and Tam Ky - Phuoc Son, is within the thickness of the Earth's crust.

Keywords: Gravity, magnetic, fault, the Earth's crust, Thua Thien-Hue.

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INTRODUCTION

The structural characteristics of the Earth's crust in the whole territory of Vietnam at 1/1,000,000 scale was established by Cao Dinh Trieu, 2005 [1] on the basis of analysis of obtained gravity data (with reference to aeromagnetic and satellite magnetic data). At a scale of 1/500,000, Lai Hop Phong (2009) [2] studied the structural characteristics of the Earth's crust in Northern Vietnam on the basis of analysis of ground Bouguer gravity data combined with two obtained deep seismic lines. The researches at 1/200,000 scale are mainly carried out by Pham Nam Hung (2013) in Ca river - Rao Nay [3] and Phan Thanh Quang in Da river hydroelectric ladder region [4].

Thus, the structural characteristics of the Earth's crust in the mainland of Vietnam and coastal areas were studied at a small scale (1/1,000,000). The researches at the scales of 1/500,000 and greater have not been adequately conducted. Meanwhile, the previous studies have not fully met the requirements of seismic zoning in the whole territory of Vietnam at 1/500,000 scale and in separate regions at 1/200,000 scale. Therefore, the state-level independent project (code: DTDL.CN.51/16) has set up the task of studying the structural characteristics of the Earth's crust (deep fault system and crystalline basement surfaces, Conrad surface and Moho surface) in Thua Thien-Hue at 1/250,000 scale. This paper presents the major results of the project: "Assessment of earthquake hazard for territorial development planning, and ensuring the safety of hydropower plants, irrigation works and cultural relics in Thua Thien-Hue".

The research process is conducted according to the following steps:

Analyze and transform gravity and magnetic data according to lines and planes for fault identification, establish the model of direct problem for solving the inverse gravity problem and studying the structural characteristics of the faults.

Establish 11 sections along 11 lines by using the method of solving 2.5D inverse gravity problem (fig. 1).

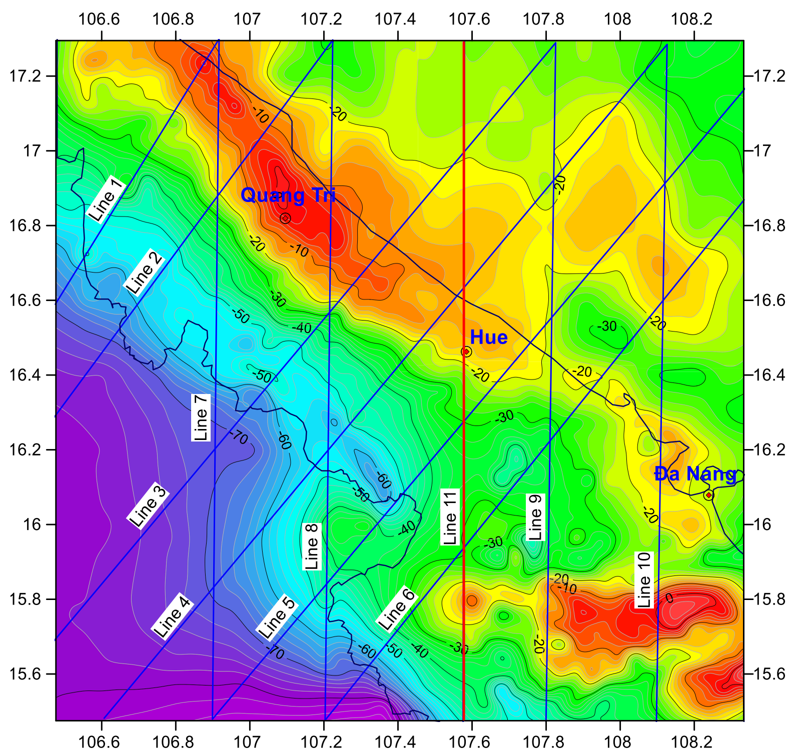

Fig. 1a. Bouguer gravity anomaly and lines of analyzing of gravity data in Thua Thien-Hue area at the scale of 1:250,000

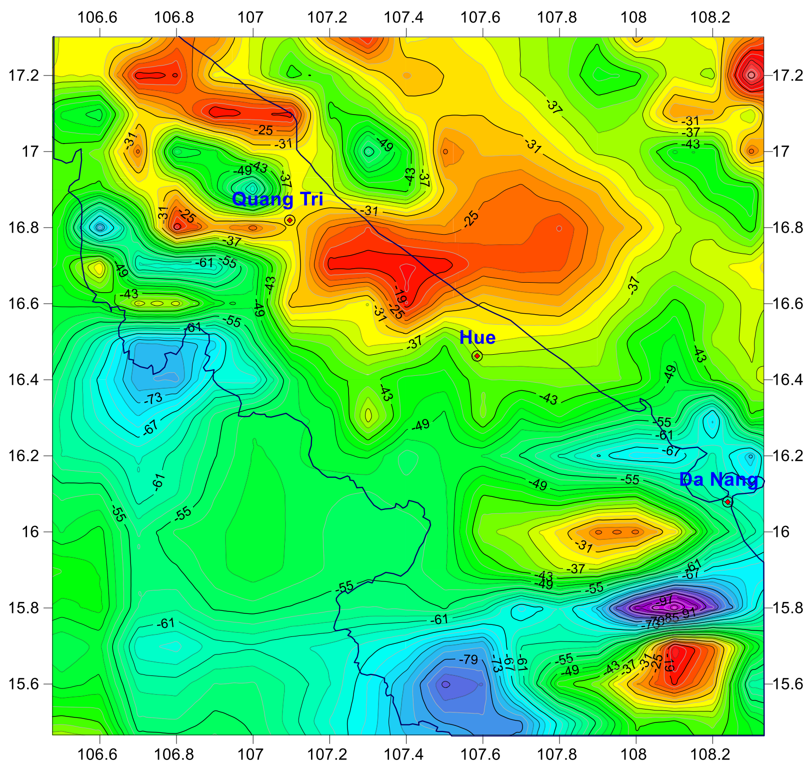

Fig. 1b. Aeromagnetic anomaly in Thua Thien-Hue area at the scale of 1:250,000

Establish the structural diagrams of basic boundary surfaces of the Earth's crust (crystalline basement, Conrad and Moho surfaces) based on the linear research results and the establishment of multi-dimensional linear correlation functions.

Establish the diagram of faults in the study area based on gravity and magnetic data.

The gravity and magnetic data used in this study include Bouguer gravity anomaly [5, 6] and satellite gravity anomaly [7], aeromagnetic anomaly [8] and satellite magnetic anomaly [9].

METHODOLOGY

Method of analyzing gravity and magnetic data for fault determination

The faults in Thua Thien-Hue province and adjacent areas are determined by using gravity and magnetic data according to the following indications and criteria [1, 3, 6, 10, 11]:

1. The indications of fault based on gravity and magnetic anomaly and anomaly field transformation include:

Faults associated with extended gradient field.

The boundary between two areas with different anomaly structure directions, or the intersection of anomalies with different structure directions.

The movement of extended linear anomalies and the appearance of flexures of contour line.

These are the initial indications according to primary identification method.

2. Using the calculation results of theoretical model: In case of three-dimensional and two-dimensional problems when applying methods of upward continuation, downward continuation, calculations of gradient at different upward continuation heights, horizontal gradient, vertical gradient and normalized full gradient of gravity anomaly to each specific model. In case of upward continuation and calculation of horizontal gradient to different heights, the gravity anomaly field will reflect the characteristics of uplifts and depressions, which are the criteria for fault identification. The calculation results of normalized full gradient of gravity anomaly provide the particular points which are related to the anomaly-causing blocks.

Table 1. Fault identification according to gravity and magnetic data

No.	Fault name	Rank of fault	Δg_B (mGal)	ΔTa (nT)	Gravity gradient	Magnetic gradient
1	Red river	II	–28–(–)15	–45–(–)25	0.1–0.8	0.5–1.3
2	A Luoi - Rao Quan	II	–63–(–)20	–80–(–)36	0.3–2.2	0.1–3.4
3	Chay river	III	–26–(–)17	–42–(–)33	0.3–0.7	0.3–0.9
4	Dong Ha - Phu Vang	III	–26–0	–55–(–)17	0.2–1.1	0.3–1.8
5	Vinh Linh	III	–29–(–)3	–42–(–)23	0.4–1.2	0.3–2.4
6	SePon - Cam Lo	III	–48–(–)2	–50–(–)33	0.6–1.6	0.3–2.5
7	Hue - Son Tra	III	–52–(–)13	–66–(–)30	0.5–2.1	0.1–4.2
8	Cu De river	III	–60–(–)14	–65–(–)48	0.3–1.5	0.2–2.1
9	Vu Gia river	III	–33–(–)20	–71–(–)41	0.7–2.7	0.6–4.5
10	Tam Ky - Phuoc Son	III	–32–0	–47–(–)21	0.4–2.4	0.2–2.3

3. Calculation of horizontal gradient of gravity anomaly: In regard to geological research environment, when the density separation boundary is vertical, the calculation result of horizontal gravity gradient allows determining the extreme points (maximum or minimum) whose location often coincides with the interface of two different geological units, and that is often the spatial vertical boundary. If the interface is not vertical, the extremum of horizontal gradient will be shifted towards the inclination; the positive extremum region is created just below the separation boundary and the negative one is on both sides.

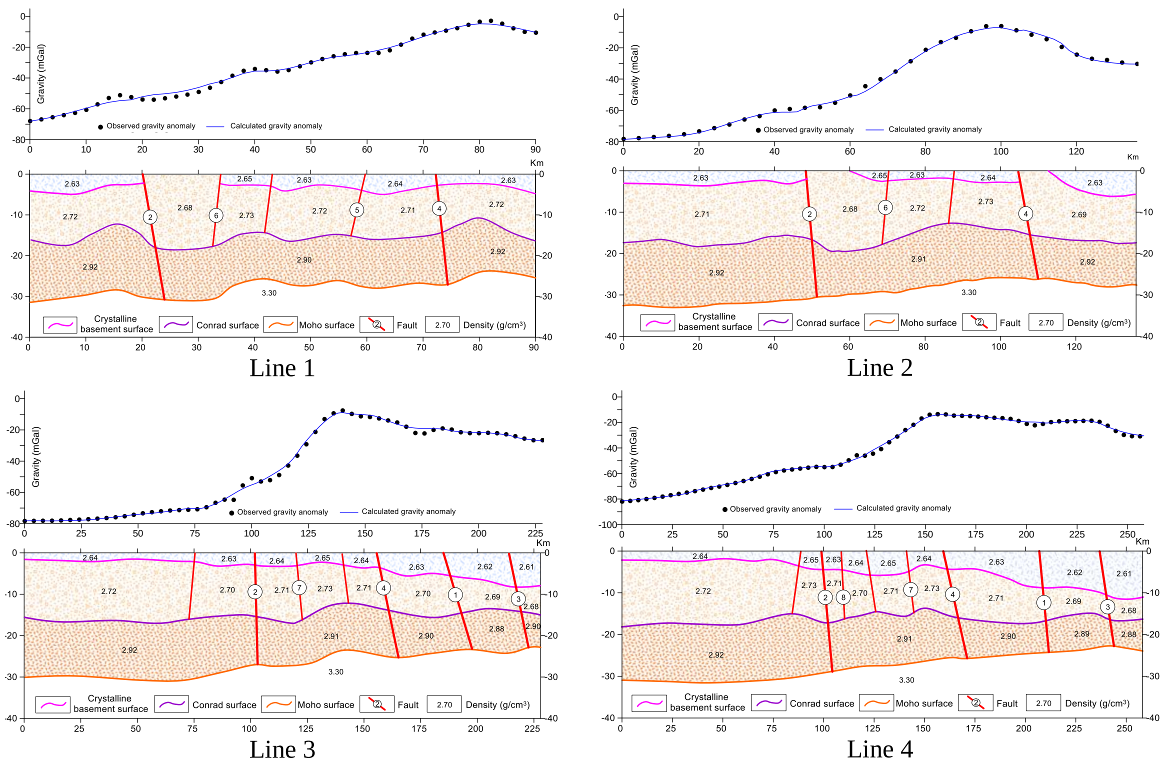

Fig. 2. Geological-geophysical sections (along 11 lines) in the study area

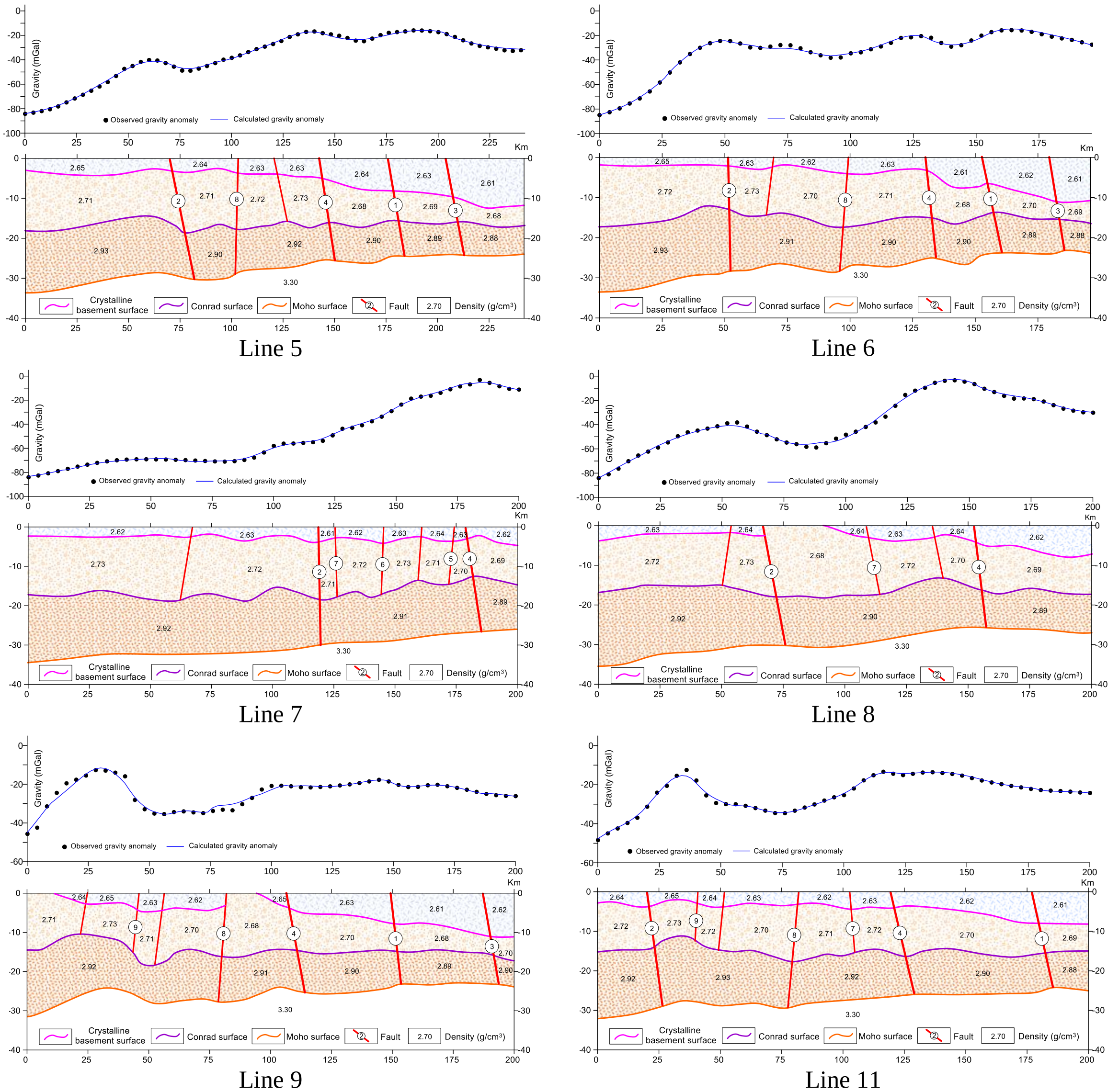

Fig. 2. Geological-geophysical sections (along 11 lines) in the study area (next)

4. Indications based on the calculation results of linear normalized full vertical gradient are particular points when calculating the field reduction through geological object. Particular points often appear in the object or coincide with the outer edges of geological object causing anomaly in the predetermined shape.

Research methodology of structural characteristics of the Earth's crust

The process of analyzing Bouguer gravity data along the study lines is conducted as follows [1, 3, 6, 10, 11–13]:

1. Calculate the section of horizontal gravity gradient;

2. The section of normalized full gradient;

3. The section of structure/density coefficient based on the problem of horizontal cylinder model.

The results of analysis of above sections allow determining the location as well as the angle of fall and dip direction of the fault. Based on these analysis results, we can also build an initial model for solving the 2.5D gravity problem.

4. Solve the 2.5D inverse gravity problem (using GM-SYS software from Geosoft) for studying the structural characteristics of the Earth's crust along the study lines.

The results of analysis of 11 gravity lines are shown in fig. 2, providing a primary picture of density structure of the Earth's crust in the study area.

STRUCTURAL CHARACTERISTICS OF THE EARTH'S CRUST IN THE STUDY AREA

In the study area, there are very few published data on the depth to basic boundary surfaces of the Earth's crust, including deep seismic data and magnetotelluric data. Therefore, we use the gravity lines analyzed in fig. 2 as a basis to build multi-dimensional linear correlation functions, with the aim of determining the depth of basic boundary surfaces of the Earth's crust in the study area.

The calculation results have determined the correlation functions between the depth of surfaces and the value of transformed gravity fields as follows:

The depth of Moho surface in the study area is established on the basis of multiple regression equation:

$$H_{MH}(km) = 28.42 + 0.13\Delta g_B - 0.02\Delta g_D \quad (1)$$

Correlation coefficient: $R_{MH} = 0.83$

Where: Δg_D is the value of residual gravity anomaly at the upward continuation levels of 10 km and 20 km.

The depth of Conrad surface is determined by multiple regression equation as follows:

$$H_{CR}(km) = 15.63 - 0.03\Delta g_B - 0.05\Delta g_D \quad (2)$$

Correlation coefficient $R_{CR} = 0.82$

Where: Δg_D is the value of residual gravity anomaly at the upward continuation levels of 5 km and 10 km.

The depth to the crystalline basement surface is determined by regression equation as follows:

$$H_{KT}(km) = 2.02 - 0.03\Delta g_B + 0.05\Delta g_D \quad (3)$$

Correlation coefficient $R_{KT} = 0.84$

Where: Δg_D is the value of residual gravity anomaly at the upward continuation levels of 2 km and 5 km.

Structure of crystalline basement

The structural morphology of crystalline basement surface in the study area is presented in fig. 3. The result shows that:

The distribution of crystalline basement surface is relatively complicated, increasing gradually towards the Southwest and Northeast directions. The isometric uplift structures (with crystalline basement exposed on the surface) are commonly distributed in the study area.

The maximum depth of crystalline basement surface in the mainland does not exceed 5 km. Meanwhile, the depth of this boundary surface can reach 2.0–3.5 km in the territory of Laos and 11 km in the Red river basin.

The difference in density between the sedimentary layer above (2.61–2.65 g/cm^3) and the granitic layer below (2.68–2.73 g/cm^3) is about 0.07 g/cm^3.

Structure of Conrad surface

The depth to the Conrad surface ranges between 12–18 km, increasing gradually from Northeast to Southwest. Conrad surface is uplifted highest at about 12 km in Nong Son-Quang Nam zone, about 16 km along the coast and subsided along the Vietnam - Laos border. The difference in density between the granitic layer above (2.68–2.73 g/cm^3) and the basaltic layer below (2.89–2.93 g/cm^3) is about 0.09 g/cm^3.

Structure of lower boundary surface of the Earth's crust (Moho surface)

The depth of the Moho surface varies from 23 km to 34.5 km, increasing gradually from Northeast to Southwest. In the mainland of Vietnam, the depth of Moho surface changes from 27 km along the coast to 31–34 km along the Vietnam - Laos border. The difference in density between the basaltic layer above (2.89–2.93 g/cm^3) and the mantle layer below (3.30 g/cm^3) is about 0.42 g/cm^3.

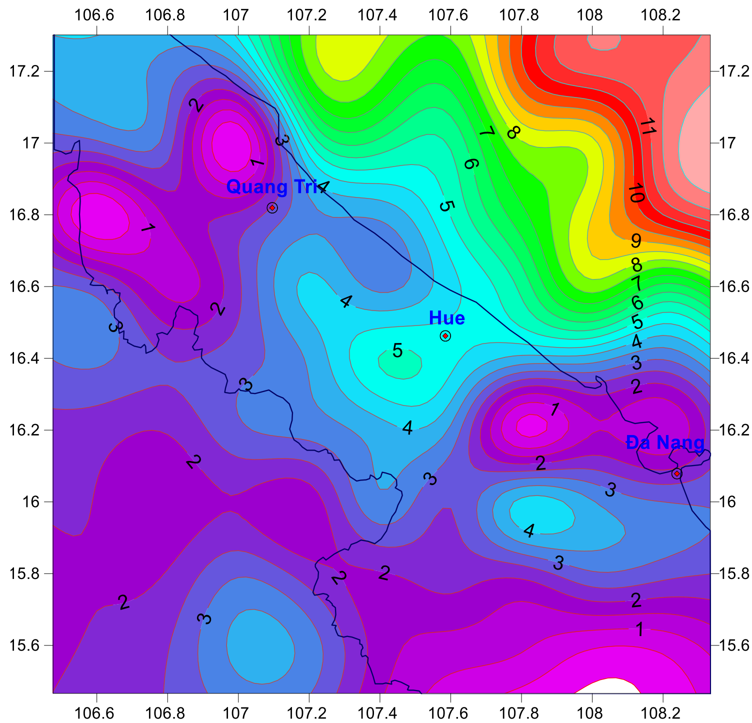

Fig. 3. Crystalline basement surface depth (km) in Thua Thien-Hue province and adjacent area at the scale of 1:250,000

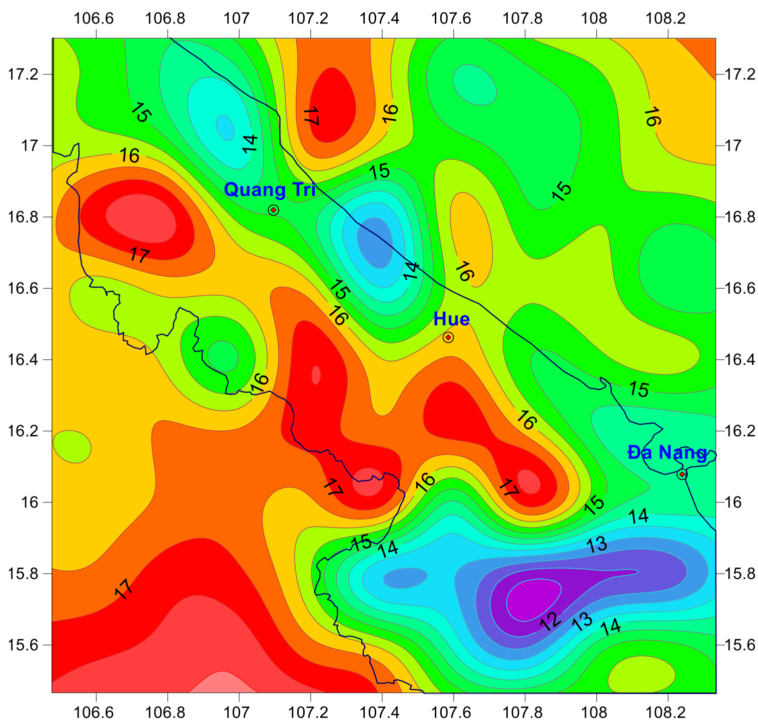

Figure 4. Conrad surface depth (km) in Thua Thien-Hue province and adjacent area at the scale of 1:250,000

Deep fault system

The deep faults in the study area are presented in the fig. 6 and table 2, indicating that:

There exist 10 deep faults with the depth of influence of 15 km or greater (within and through the Earth's crust):

There are 2 regional second-order faults (local first-order) with depth through the Earth's crust (25–30 km and greater, depending on the depth of Moho surface): Red river and A Luoi - Rao Quan;

There are 8 regional third-order faults (local second-order) with depth of influence within the Earth's crust, to Conrad surface (15–20 km and greater, depending on the depth of Conrad surface): Chay river, Dong Ha - Phu Vang, Vinh Linh, Hue - Son Tra and Tam Ky - Phuoc Son.

The major development direction of the faults is Northwest - Southeast (Red river, A Luoi - Rao Quan, Chay river, Dong Ha - Phu Vang, Vinh Linh, Hue - Son Tra and Tam Ky - Phuoc Son). Some faults follow the sub-latitudinal direction (SePon - Cam Lo, Cu De river and Vu Gia river) and the sub-longitudinal direction.

The faults are mainly normal faults with nearly vertical dip angle (60–75^{o}).

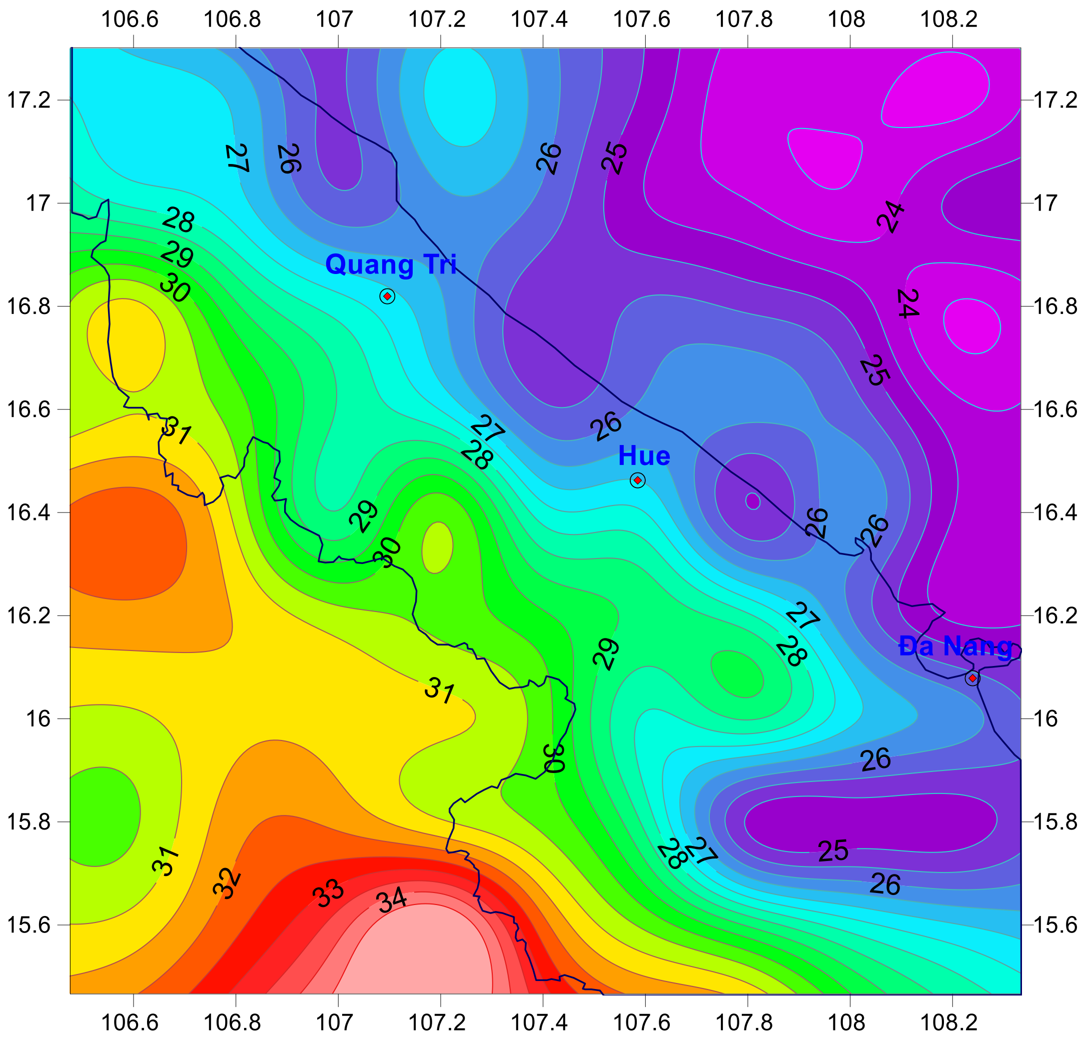

Fig. 5. Moho surface depth (km) in Thua Thien-Hue province and adjacent area at the scale of 1:250,000

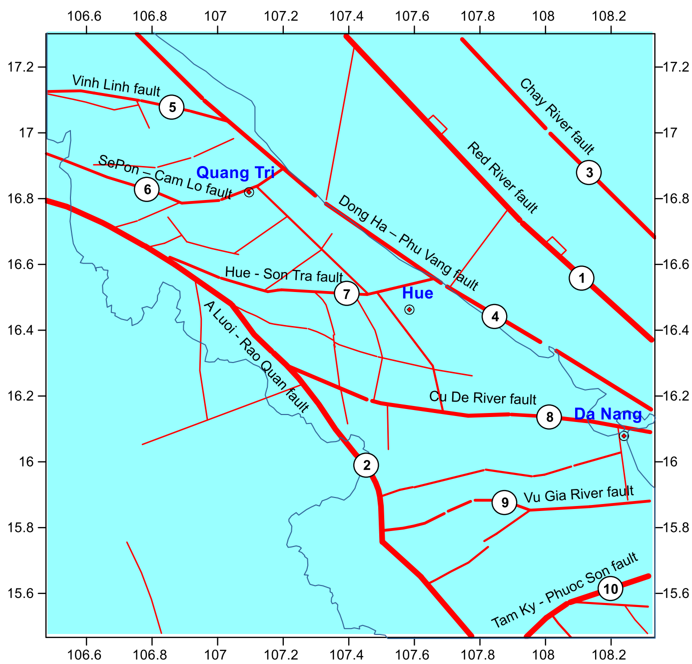

Fig. 6. Tectonic faults in Thue Thien-Hue province and adjacent area at the scale of 1:250,000. Legend of fig. 6: (1) Red river fault; (2) A Luoi - Rao Quan fault; (3) Chay river fault; (4) Dong Ha - Phu Vang fault; (5) Vinh Linh fault; (6) SePon - Cam Lo fault; (7) Hue - Son Tra fault; (8) Cu De river fault; (9) Tam Ky - Phuoc Son fault; (10) Vu Gia fault

Table 2. Fault parameters according to geophysical data

No.	Fault name	Rank of fault	Strike direction	Dip direction, Dip angle (degree)		Maximum depth (km)
1	Red River	II	NW-SE	NE	$\frac{60-80}{76}$	25–30
2	A Luoi - Rao Quan	II	NW-SE	NE	$\frac{61-82}{70}$	30–35
3	Chay River	III	NW-SE	NE	$\frac{67-83}{76}$	15–20
4	Dong Ha - Phu Vang	III	NW-SE	NE	$\frac{59-80}{71}$	15–20
5	Vinh Linh	III	NW-SE	S	$\frac{62-74}{66}$	15–20
6	SePon - Cam Lo	III	Sub-latitudinal	S	$\frac{65-78}{72}$	15–20
7	Hue - Son Tra	III	NW-SE	NE	$\frac{62-82}{72}$	15–20
8	Cu De River	III	Latitudinal	S	$\frac{60-78}{71}$	15–20
9	Vu Gia River	III	Latitudinal	S	$\frac{72-76}{74}$	15–20
10	Tam Ky - Phuoc Son	III	NE-SW	NE	$\frac{64-76}{71}$	15–20

CONCLUSION

Based on the data used, the research methodology and the results of structural characteristics of basic boundary surfaces of the Earth's crust, the paper can draw some conclusions as follows:

1. The crystalline surface in the study area varies quite complicatedly, from exposed on the ground to the maximum depth of over 11 km. The depth of Conrad surface changes from 12 km to 18 km, gradually increasing towards the inland area and decreasing towards the sea. Meanwhile, the depth of Moho surface has the greatest value of about 34 km in the mainland and only reaches 23–24 km in the Red river basin.

2. The density of sedimentary layer changes from 2.61 g/cm^3 to 2.65 g/cm^3. Meanwhile, the density of granitic layer ranges between 2.68 g/cm^3 and 2.73 g/cm^3. The basaltic layer has the density value of 2.88–2.93 g/cm^3 and the average density of lower layer of the Earth's crust is 3.30 g/cm^3.

3. There are 10 deep faults, including 2 regional second-order faults (local first-order) with depth through the Earth's crust (Red river and A Luoi - Rao Quan) and 8 regional third-order faults (local second-order) with depth of influence within the Earth's crust (Chay river, Dong Ha - Phu Vang, Vinh Linh, Hue - Son Tra and Tam Ky - Phuoc Son). The faults are mainly normal faults and developing in the Northwest - Southeast direction with nearly vertical dip angle (60–75^o).

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