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USING THE COMBINATION OF THE 3D GRAVITY INVERSION METHOD WITH THE DIRECTIONAL ANALYTIC SIGNAL DERIVATIVES AND THE CURVATURE GRAVITY GRADIENT TENSOR METHOD TO DETERMINE STRUCTURE OF THE PRE-CENOZOIC BASEMENT ON SOUTHEAST CONTINENTAL SHELF OF VIETNAM

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Abstract. In this paper, we present some new results of the Pre-Cenozoic basement structure on the Southeast continental shelf of Vietnam based on the combination of some modern methods to analyse and interpret gravity data. They are the 3D gravity inversion method, the directional analytic signal derivatives and the curvature gravity gradient tensor. The results obtained include the density distribution, the fault system and the main structural blocks inside of the Pre-Cenozoic basement on Southeast continental shelf of Vietnam. The initial results about density distribution show that it relatively clearly reflects the shape of basins in the area: The contours that have value σ =2.7 g/cm^3 and value σ = 2.76 g/cm^3 are near the edges of the Cuu Long basin and the Nam Con Son basin, respectively. The density value reaches the maximum at the center of basins. For the Cuu Long basin, the maximum value is σ_{max}= 2.76 g/cm^3 and the Nam Con Son has maximum value σ_{max} = 3.0 g/cm^3. Many faults that appear in the study area have the existence depth in the wide range from 6 km to 30 km, even above 30 km and the faults that have the existence depth from 8 to 10 km are in the majority. In particular, the boundary of anomalous sources existing in the Pre-Cenozoic basement is shown by the better resolution, at which more edge points are identified than the maximum horizontal gradient amplitude method that is widely used. The results also show that the combination of individual results complements each other and creats the sufficient and clearer picture inside of the Pre-Cenozoic basement.

Keywords: Determine, combine, the source boundary, new methods, Pre-Cenozoic basement, density, fault, structural block.

INTRODUCTION

In recent years, in addition to determining the depth to the Cenozoic basement, the structural studies such as the density variation along with fault system characteristics inside of the Pre-Cenozoic basement have become important and attracted the interest of many national and international geophysicists. However, until now, the density distribution of the Pre-Cenozoic basement on the continental shelf of Vietnam has been only determined by the method of correlating or modeling the Earth's crust structure [1, 2].

Therefore, the accuracy has many limitations. In order to overcome these limitations, a part of this paper used a combination of anomaly layer removal with solving the 3D inverse problem by the chosen method of Bott [3] to determine the density distribution of the Pre-Cenozoic basement. Computer algorithms and programs to determine the density distribution by the gravity data were built and tested on the 3D model [4] and were also applied to the real data [5].

The density distribution, existence or absence of faults inside of the Pre-Cenozoic basement on the continental shelf of Vietnam in particular and on the East Sea of Vietnam in general have particularly important role in the basement structure map. The location of the faults on the surface of the Cenozoic basement has been shown quite comprehensively and in detail by many studies [6–10]. However, most of the studies on faults focus on the Cenozoic sedimentary layer and the methods used are mainly the classical methods such as: The horizontal gradient, maximum horizontal gradient, normalized full gradient,... Although the results obtained from these methods are very effective, but compared with more modern methods they cannot avoid their weakness. Thus, along with the density distribution, in order to supplement information about the fault system inside of the Pre-Cenozoic basement, we used the combination of the directional analytic signal derivative of the gravity tensor components and the Euler deconvolution method of this data with the gravity field transformation method to determine location and estimate the existence depth of anomaly source boundary inside of the Pre-Cenozoic basement on the Southeast continental shelf of Vietnam.

The Southeast continental shelf of Vietnam has two main basins: Cuu Long basin and Nam Con Son basin, they are bounded by the coordinates from 6°N–11°N and 106°E–111°E belonging to the continental shelf of Vietnam. This area has tectonic structure, many major faults, uplifts and trenches such as Song Hau fault, Song Dong Nai fault, Song Cau fault, Mang Cau trench, Nam Con Son trench, Dua uplift zone, Dong Son uplift,... Therefore, studying more accurately, confirming additional geological information on the area will make the geological picture in general and the Pre-Cenozoic basement in particular plentiful and more complete.

Individual results may not be sufficient if we consider them with different respects. The integrative interpretation of the individual results that are determined by the modern analysis and processed methods will have more information and mutual assertion to increases the accuracy as well as information of the obtained results. Hereafter, the paper presents the combination of modern methods to clearly determine the interior structure of the Pre-Cenozoic basement including the characteristics: Density distribution, existence of fault and structural blocks on the Southeast continental shelf of Vietnam.

THE METHODOLOGY

The methodology discussed below includes a combination of three modern methods for analyzing and processing gravity data, namely the directional analytic signal derivative, the curvature gravity gradient tensor (the method determine the boundary of the anomalous sources by eigenvalue) and the method of solving the 3D inverse problem to determine the density distribution of the Pre-Cenozoic basement by anomaly layer removal. All three methods have been studied from theoretical basis, building the computational program, testing on the digital model, and have been successfully applied on the Song Hong basin [4, 5, 11, 12]. So, this paper is not the representation of the models that only introduces the theoretical basis of each method.

The method of solving the 3D inverse problem to determine the density distribution. This method is based on solving the 3D gravity inverse problem by the chosen method [5] combined with anomaly layer removal as follows: Considering the observed gravity anomaly as the total field consisting of the anomalies that are caused by sedimentary surface boundaries, the density variation inside of the Pre-Cenozoic basement and the Moho surface topography change. Therefore, to solve the 3D inverse problem for determining the density distribution of the Pre-Cenozoic basement, first of all it is necessary to remove the gravity field that is caused by the upper sediment surface boundary and the regional field that is caused by the Moho topographic change. Then, the redundant field:

$$\Delta g_{(i,j)}^{bas} = \Delta g_{(i,j)}^{obs} - \Delta g_{(i,j)}^{reg} - \Delta g_{(i,j)}^{sed} \qquad (1)$$

Will be the anomaly that reflects the heterogeneity of density distribution of the Pre-Cenozoic basement.

To determine the density distribution of the Pre-Cenozoic basement, this basement layer was approximated as vertical rectangular blocks (box blocks) that are placed close together. Each box block (*i*, *j*) has the distance between two observation points Δx (on *x*-direction), Δy (on *y*-direction), has the height $\Delta Z_{(i,j)}$ (is distance from the bottom of the Cenozoic sediments ($Z_{(i,j)}^{t}$) to Moho surface topography ($Z_{(i,j)}^{b}$)) and has the corresponding residual density $\sigma_{(i,j)}^{bas}$. The calculation process is as follows [4]:

From residual anomalies, the initial estimate of excess residual distribution of basement was performed based on the direct determination of Bott [3]. Accordingly, the excess density of each box block is determined by:

$$\sigma_{(i,j)}^{bas} = \frac{\Delta g_{(i,j)}^{bas}}{2\pi f \Delta Z_{(i,j)}^{bas}} \qquad (2)$$

If the residual density inside of Cenozoic sedimentary layer does not vary from depth to depth ($\lambda = 0$). And when it varies according to the exponential law of depth ($\lambda \neq 0$), the excess density of each box block is given by the formula:

$$\sigma_{(i,j)}^{bas} = -\left(\frac{1}{\lambda}\right)\ln\left[1 + \frac{\Delta g_{(i,j)}^{bas}}{2\pi f \Delta Z_{(i,j)}^{bas}}\right] \qquad (3)$$

Where: $i = 1, 2, \ldots M$, $j = 1, 2, \ldots N$ is the sequence number of observation points on *x*, *y* directions; $\Delta g_{(i,j)}^{bas}$ is residual anomaly that is caused by the heterogeneity of the excess density of the Pre-Cenozoic basement at the (*i*, *j*) point: $\Delta Z_{(i,j)}^{bas} = Z_{(i,j)}^{b} - Z_{(i,j)}^{t}$ is the thickness of the Pre-Cenozoic basement at the observation point (*i*, *j*) and *f* is the gravitational constant.

According to Bhaskara Rao's algorithm [13], determining the gravity anomaly of each box block and then calculating the total gravity anomaly of *M*N* box block to obtain the calculated anomaly of basement $\Delta g_{(i,j)}^{cal}$ at all observation points.

The sign $\Delta g_{(i,j)}^{dev}$ is the difference between the residual anomaly $\Delta g_{(i,j)}^{bas}$ of the Pre-Cenozoic basement and the calculated anomaly $\Delta g_{(i,j)}^{cal}$ at the point (*i*, *j*) on the observation plan. This deviation is used to adjust the excess density of the basement after each selection:

$$\Delta\sigma_{(i,j)}^{bas} = \frac{\Delta g_{(i,j)}^{dev}}{2\pi f \Delta Z_{(i,j)}^{bas}} \text{ when } \lambda = 0;$$

$$\Delta\sigma_{(i,j)}^{bas} = \frac{\Delta g_{(i,j)}^{dev}}{2\pi f \Delta Z_{(i,j)}^{bas} \exp(-\lambda \Delta Z_{(i,j)}^{bas})}$$

when $\lambda \neq 0$ (4)

The selection process only stops when the average squared error between the residual anomaly and calculated anomaly of basement is less than the allowable error or exceeds the predetermined selection numbers.

Based on this theory, an automatic computation program was developed in the Matlab language and has been successfully tested on the numerical model [4] and has been also applied to determine the density distribution of the Pre-Cenozoic basement on the Song Hong basin [5], it allows calculating for both $\lambda \neq 0$ and $\lambda = 0$.

The directional analytic signal derivative method. This method is derived from the analysis and processing of gravity gradient elements (GGT), GGT is the 2nd order tensor that contains the 2nd order derivative of the gravitational potential on the scales *x*, *y* and *z* in the Cartesian coordinate system: g_{xx}, g_{xy}, g_{xz},… and the analytical signals in *x*, *y* and *z* directions are the functions that are defined by [14]:

$$\begin{bmatrix} A_x(x,y,z) \\ A_y(x,y,z) \\ A_z(x,y,z) \end{bmatrix} = \begin{bmatrix} g_{xx} & g_{xy} & g_{xz} \\ g_{yx} & g_{yy} & g_{yz} \\ g_{zx} & g_{zy} & g_{zz} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ i \end{bmatrix} \qquad (5)$$

Debeglia and Corpel (1997) [15] have indicated that the derivative of the directional analytic signal intensity will separate the anomaly more effectively in case they are interfered by multiple anomalies:

$$\frac{\partial |A_\alpha(x,y,z)|}{\partial x} = \frac{\frac{\partial g_\alpha}{\partial x}\left(\frac{\partial^2 g_\alpha}{\partial x^2}\right) + \frac{\partial g_\alpha}{\partial y}\left(\frac{\partial^2 g_\alpha}{\partial x \partial y}\right) + \frac{\partial g_\alpha}{\partial z}\left(\frac{\partial^2 g_\alpha}{\partial x \partial z}\right)}{|A_\alpha(x,y,z)|} \qquad (6)$$

$$\frac{\partial |A_\alpha(x,y,z)|}{\partial y} = \frac{\frac{\partial g_\alpha}{\partial x}\left(\frac{\partial^2 g_\alpha}{\partial y \partial x}\right) + \frac{\partial g_\alpha}{\partial y}\left(\frac{\partial^2 g_\alpha}{\partial y^2}\right) + \frac{\partial g_\alpha}{\partial z}\left(\frac{\partial^2 g_\alpha}{\partial y \partial z}\right)}{|A_\alpha(x,y,z)|} \qquad (7)$$

$$\frac{\partial |A_\alpha(x,y,z)|}{\partial z} = \frac{\frac{\partial g_\alpha}{\partial x}\left(\frac{\partial^2 g_\alpha}{\partial z \partial x}\right) + \frac{\partial g_\alpha}{\partial y}\left(\frac{\partial^2 g_\alpha}{\partial z \partial y}\right) + \frac{\partial g_\alpha}{\partial z}\left(\frac{\partial^2 g_\alpha}{\partial z^2}\right)}{|A_\alpha(x,y,z)|} \qquad (8)$$

Here α is the index of *x*, *y* and *z*. The function that represents the combination of the directional analytical signals of A_{xz} and A_{yz}:

$$|ED| = \sqrt{|A_{xz}|^2 + |A_{yz}|^2} \qquad (9)$$

Will allow determining location of the source boundary better than the function of the gravity gradient tensors that is used previously:

$$HGA = \sqrt{(g_{xz})^2 + (g_{yz})^2} \qquad (10)$$

The depth to the source boundary is determined by the combination of Euler deconvolution method of the directional analytic signal data with the window sliding method, in which the window center is the maximum point of the ED function. The method was also tested on the model and was successfully applied to real data [5, 11].

The curvature gravity gradient tensor. In addition to determining the density distribution along with determining the fault system of the Pre-Cenozoic basement, studying to determine the types of structural block inside of the Pre-Cenozoic basement is also essential. It helps to know the location of the uplift zones, trenches, main structure of the Pre-Cenozoic basement. It contributes to the clarification of the internal structure of the Pre-Cenozoic basement. The theoretical basis of the Curvature Gravity Gradient Tensor method (CGGT) is introduced by Oruc, B. et al., [16]. This method determines the anomalous source boundary based on the eigenvalue of the matrix consisting of four horizontal components of the gravity tensor:

$$\Gamma = CGGT = \begin{pmatrix} g_{xx} & g_{xy} \\ g_{yx} & g_{yy} \end{pmatrix} \qquad (11)$$

And we get eigenvalue Γ:

$$\lambda_1 = \frac{1}{2}\left(g_{xx} + g_{yy} + \sqrt{(g_{xx} - g_{yy})^2 + 4g_{xy}^2}\right) \qquad (12)$$

$$\lambda_2 = \frac{1}{2}\left(g_{xx} + g_{yy} - \sqrt{(g_{xx} - g_{yy})^2 + 4g_{xy}^2}\right) \qquad (13)$$

$$\det(\Gamma) = \lambda_1 \lambda_2 \qquad (14)$$

At value $\det(\Gamma) = 0$ is the object edge, or in other words, the contour maps $\det(\Gamma) = 0$ will outline the geological structure boundaries. The method has been tested on model and also applied to real data of the Song Hong sediment basin [12].

THE RESULTS OF APPLICATION TO REAL DATA OF SOUTHEAST CONTINENTAL SHELF OF VIETNAM

Data sources used. In this paper, for the resolution and homogeneity of the data source, D.T. Sandwell's satellite gravity data with data grid spacing of 1'×1' along with sea bottom topography data source [17] were used to determine the Bouguer gravity field. In addition, data sources of sediment thickness and the depth of Cenozoic sediment bottom that are being stored at the Institute of Marine Geology and Geophysics [8] have been also used to remove anomaly of Cenozoic sediment layer. The bottom depth of Cenozoic sediment is used to solve the 3D inverse problem for determining the density distribution. In addition to gravity data, Cenozoic sediment thickness, the sea bottom topography,... the paper also references and uses some research results on geology, tectonics, wells, seismic sections in the study area that are collected from the articles and projects by many authors [6–10, 18, 19, 20]. Because data sources are different, the paper used algorithms that have the same resolution, equivalent to 1:500,000 to obtain all data sources.

Based on data sources and modern methodologies that were presented above together with computer program that was built, tested on digital models and effectively applied on Song Hong sedimentary basin [5, 11, 12], hereafter, we apply these methods to determine the density distribution, faults and the structural blocks that exist inside the Pre-Cenozoic basement (internal structure of the Pre-Cenozoic basement layer) on the Southeast continental shelf of Vietnam.

Density distribution: The density distribution of the Pre-Cenozoic basement is determined by solving the 3D inverse problem combined with anomaly layer removal that was presented above in the theoretical basis. The anomalous field components caused by the sediment layers are removed by a 3D mathematical problem of Bhaskara Rao [13], in which the excess density of the Cenozoic sedimentary layer on each prism does not vary from depth to depth (is constant, $\Delta\sigma$ = -0.27 g/cm^3) and prism height is Cenozoic sediment layer.

The regional field is eliminated by calculating the correlation between gravity fields at upward continuation levels of observation field and field obtained by approximating the observation field by a 7th order polynomial (is calculated for the whole East Sea of Vietnam with coordinates: 100^{o}E–120^{o}E, 4^{o}N–24^{o}N). The field transform level that has the highest correlation coefficient was selected as the regional field. Specifically in this result the 100 km level has the correlation coefficient r = 0.91481 and it was selected as regional field. The Moho surface depth was cited from the results of the national research projects, codes: KC09.02 and KC09.24 [8]. The field that is obtained after removing the Cenozoic sediment field and regional field is thought to well reflect the anomaly caused by the Pre-Cenozoic basement layer (fig. 1a) and it is used to solve the 3D inverse problem for determining the density distribution of the Pre-Cenozoic basement along with the bottom surface depth of Cenozoic sediment and Moho surface depth.

The results obtained on the density distribution of the Pre-Cenozoic basement layer are shown in fig. 2a (the contour line after adding 2.67) and the convergence of the inverse problem process is shown in fig. 2d. It can be seen that the density distribution in this area fluctuates strongly from 2.64 g/cm^3 to 3.0 g/cm^3. High density values (over 2.76 g/cm^3, are covered by a dark yellow contour) are mainly concentrated on the Nam Con Son basin, the Tu Chinh uplift zone, and the deep trench of East Sea. In the area of the sediment, the density distribution varies with the basin morphology and reaches the maximum at the center of basins: On the Nam Con Son basin, the maximum value σ_{max}= 3.0 g/cm^3 and the

Cuu Long basin, σ_{max}=2.76 g/cm^3. The basin form is most likely characterized by a density contour: The density contour σ = 2.7 g/cm^3 is the boundary of the Cuu Long basin (violet contour line) and the density contour σ = 2.76 g/cm^3 (red contour line) is the boundary of the Nam Con Son basin. The low density values (less than 2.67 g/cm^3) can be found in the Vung May trench, Song Hau trench, North East trench and Con Son uplift zone. Fig. 2d shows that the convergence of the inverse problem solution for determining the density distribution is 32-loops, with the original error RMS1 = 143.5194 mgal, after 32-loops RMS32 = 0.0477707 mgal, this error value is less than the value RMS = 0.05 mgal (predetermined value).

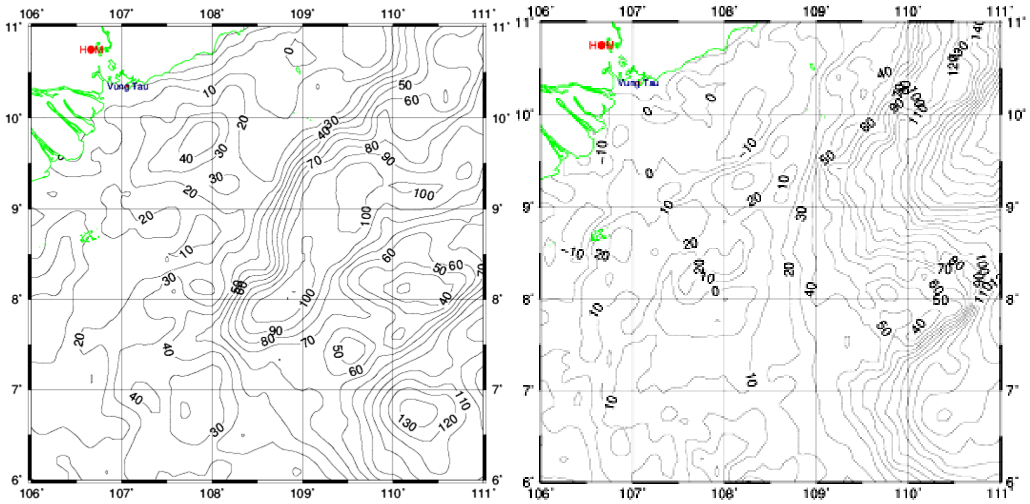

Fig. 1. a) The field was caused by the Pre-Cenozoic basement layer, b) Observation field

Fault system. The activity of faults is very complex, they can only appear in one stratum, or can penetrate and appear in many geologic strata on each segment even on the whole fault. Determining the depth at which the faults still exist (existence depth) is necessary so that we can interpret their activity, or their existence. In order to clearly see the picture of the basement structure, the faults existing inside the Pre-Cenozoic basement, we made upward continuation at higher level 20 km; with this level, the local anomaly of the Cenozoic sediment is removed and residual field will clearly reflect the Pre-Cenozoic basement structure. At this transform level, two functions: HGA function (Equation 10) and ED function (Equation 9) are calculated together with their maximum values. The edge location of the anomaly source is determined by two ways (the maximal points of HGA function and the maximal points of ED function). The faults system is determined as connecting line of the maximal points of ED function (modern method) or the maximal points of HGA function (traditional method) along with the long strip form of the gradient vector of the 2nd order vertical derivative G_{zz}. And the structural blocks are usually presented by nearly closed vectors and direct to the center of the positive anomaly mass (uplift zones) or direct to outside of the center of the negative anomaly mass (trench zones). The depth at these maximal points is determined by Euler deconvolution method of the directional analytical signal derivative along with the window sliding method in which the window centers are maximal points of the ED function and the structural index is assigned n = 0.05, window size w_x= w_y= 14 data points.

The determined results of the fault system along with the source edge points inside of the Pre-Cenozoic basement are presented in fig. 2a (color dots). In which, the position of the dots indicates the source edge position, different colors represent the different depths, they are placed on the background of the density distribution. White lines are the faults that are digitized for color dots in the study area, the red lines are reference faults [6], and the straight black line is the seismic cross section.

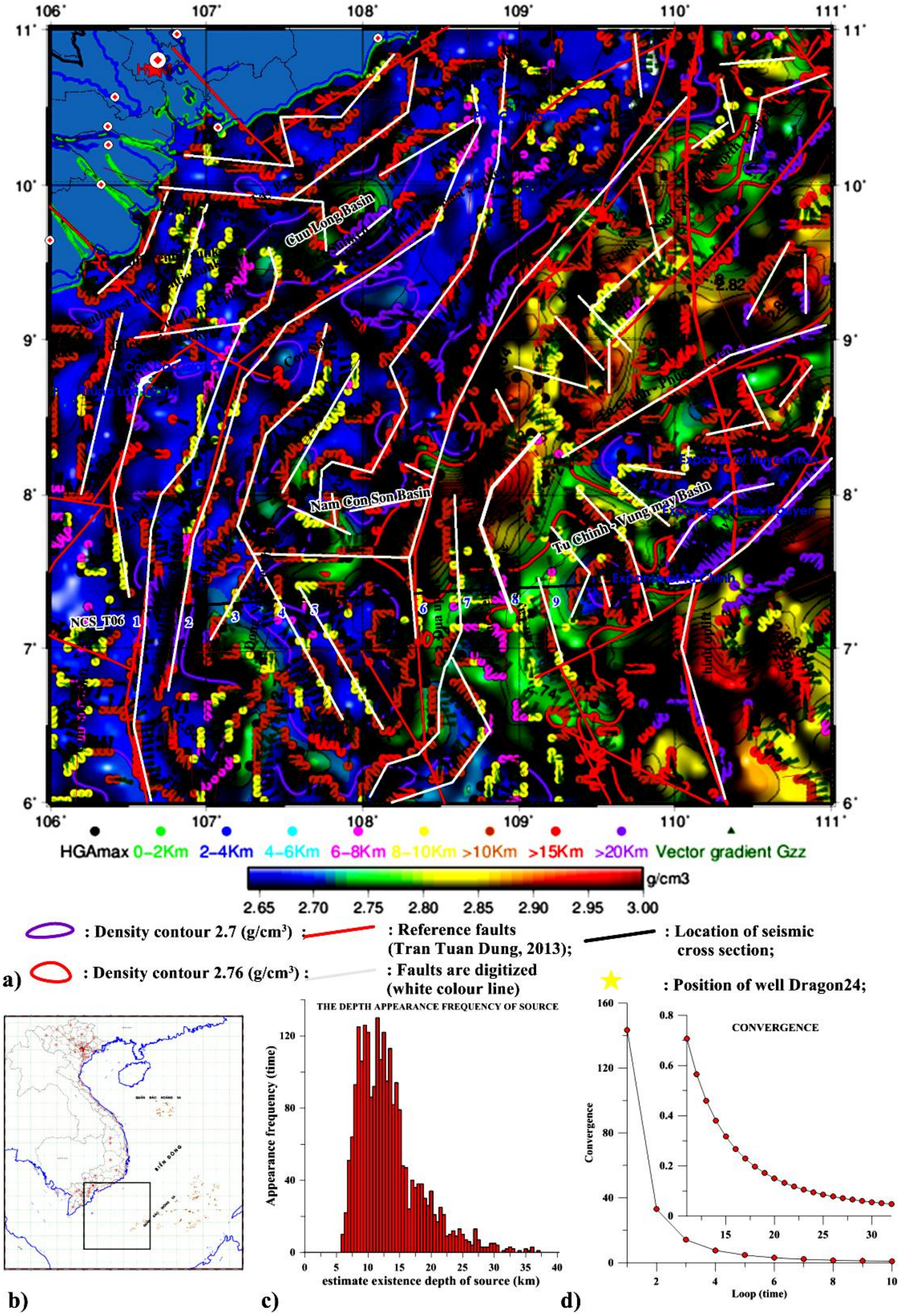

Fig. 2. The Pre-Cenozoic basement structure on the Southeast continental shelf of Vietnam

Many edge points of source are supplemented and detected by the ED function (colour dots). While, the maximal points of HGA function (black dots) do not appear (fig. 2a). The combination of determining the position by the maximum values of the ED function with the direction of the gradient vector of the 2nd order vertical derivative G_{zz} has clearly shown location and direction of dip of the major faults in the study area such as Song Hau fault (2), Song Dong Nai (4, 5), Mang Cau (6),... Mang Cau fault runs almost parallel to Song Hau fault, but it is on the side of the East of Nam Con Son basin, starting at 6.5° latitude running along the western slope of the Dua uplift and on the east side of the central trench of Nam Con Son basin, and running along the north branch of the central trench and ending at the south of Phu Khanh basin. The Song Hau fault is determined as a series of maximal points of ED function, it runs from 6° latitude along the west bank of the Song Hau uplift zone to the west bank of the Con Son uplift and ends at the south of Phu Quy island. In the southern part of this fault, the gradient vector of the G_{zz} function has the East-West decisive direction, in the north of the fault, it has the Northwest-Southeast (NW-SE) decisive direction. Not only the fault locations are determined but also their depth are also predicted, mainly from 5 km to 15 km, there are many points over 15 km and even over 30 km (fig. 2c). Comparing the location of the maximal points of ED function with the boundary of the major density blocks in the study area, it is easy to see that they have a relationship and their locations match, although the two approaches are different.

Structural blocks. The curvature gravity gradient tensor method was used in combination with upward continuation to determine the major structural block boundary of Pre-Cenozoic basement layer on the Southeast continental shelf of Vietnam.

Here, to investigate the form change of the structural blocks in depth, the other upward continuations at higher levels including *h* = [10, 20, 25, 30, 35, 40 km] were performed. At each *h* level, the values of λ_1, λ_2, det function are determined. The contour line that has 0 value of the detΓ function at each h level delineates the anomaly source boundary with a corresponding depth. Based on the test calculation on the numerical models and the practical application on Song Hong basin [12], it is shown that: Contour line 0 of λ_1 function delineates the boundary of blocks that has the positive excess density (the number marked by the black color), it corresponds to the uplift of Pre-Cenozoic basement structure. The contour line 0 of λ_2 function delineates the boundary of blocks that has the negative excess density (the number marked by red color), it corresponds to the trench of the Pre-Cenozoic basement. Therefore, with many upward continuation levels, we can get a set of contours. The result in fig. 3 represents the contour lines 0 of the $\det\Gamma$ function at multiple higher levels and each level is delineated by a different color.

Based on the results, it can be easily seen that the contour lines 0 of det$\Gamma = \lambda_1\lambda_2$ function from low to high delineate the structural form whose scale is from small (level 10 km, blue line) to larger and more stable (level 40 km, red line). Comparing the results obtained with the main structural diagrams in the study area, it can be clearly seen that the shape of Cuu Long basin is formed by the sources (has number from 1 to 8). In which Bac Lieu differential depression (number 12), Ca Coi differential depression (number 1), Cuu Long main depression (number 6, 7) are the main subsidence part of the basin and occupy most of this basin; Cuu Long uplift (number 8), the northwestern slope (number 4,5), the form of the Bach Ho East depression (number 6.1), the Bach Ho West depression (number 7.1) and the Southwest differential depression (number 8.1) are clearly visible at 10 km level. On Cuu Long basin, we also encounter two sources (number 2 and 3), they are the depressions that are part of the land and part of the sea. The depression 2 appears in the area of Vung Tau city and the depression 3 appears in the area of Binh Thuan province. These are structural blocks in the study area but they are not shown on many diagrams before. If we look at 20 km level (blue), sources 2 and source 4 will merge, sources 3 and source 5 will also merge and create a continuation of northwestern slope. However, they are separated at levels above 40 km. This shows that a fault exists between sources 2 and source 4, sources 3 and source 5 at 40 km level , this may be Thuan Hai-Minh Hai fault, it is still controversial. Another problem that we mention here is that at a higher level for this area (60 km level, we do not represent here), we see the continuation between the blocks (1, 6, 7) on Cuu Long basin and the continuation between the blocks (23, 27, 28, 29) on Nam Con Son basin (fig. 3). This shows that two large sunken structural strands exits in the entire structure on the Southeast continental shelf. These depressions may penetrate the Earth's crust layer. If we represent the function λ_1, we will obtain 3 uplift strips including strip 15 (Con Dao uplift strip), strip 11 (uplift strip of deep trench of East Sea), strip 36 (Tu Chinh uplift strip) that connect with the strip 30 (Da Lat uplift strip), creating a large uplift strip on the side of the southeast of the study area.

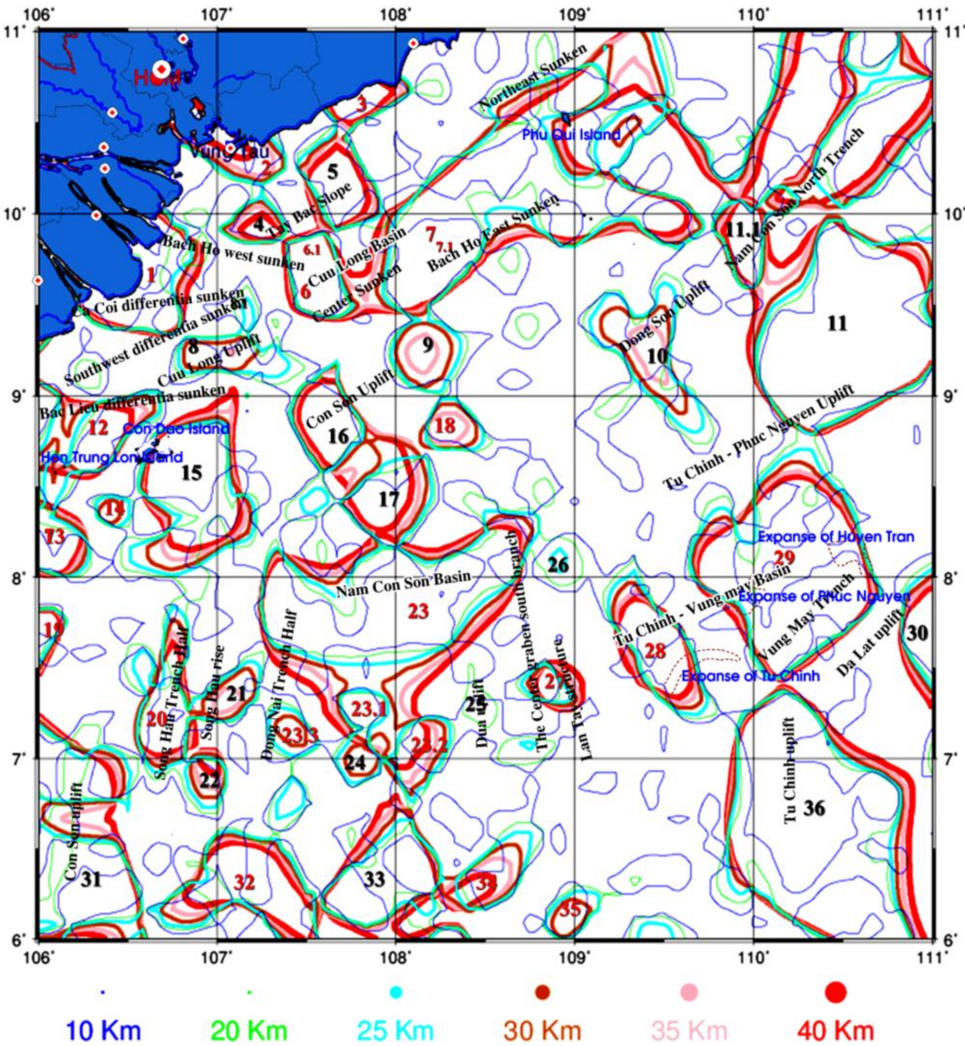

Fig. 3. The main structural blocks inside of the Pre-Cenozoic basement at elevation levels

Nam Con Son basin (block 23 is center) and many blocks on the side of the southwest of basin (sources) are determined as Song Hau half trench (number 20), Song Hau rise (number 21, 22), Dong Nai half trench (number 23.3),... Song Hau trench (20) has almost longitudinal direction with the expansion in the south and the narrowing to the north. The adjacent are of Nam Con Son basin (number 28) has Tu Chinh-Vung May basin (number 29), Da Lat uplift (number 30), Tu Chinh-Phuc Nguyen uplift (number 11),... In addition, many of the local anomalous sources are identified at low levels.

ANALYSIS AND EVALUATION

Density distribution. The calculation results of determininge the density distribution by solving the 3D inverse problem on the basis of the anomaly layer removal were shown in fig. 2a. It is the fisrt result about density distribution of the Pre-Cenozoic basement in the study area. To test the reliability of the results, this paper referenced and analyzed the density distribution of a well that has location on the edge of the Cuu Long basin, its name is Dragon 24 (yellow star spot in fig. 2a, its bottom depth touches the bottom of Cenozoic sediment.

From the discrete density values in the well (fig. 4b, yellow dots), approximating the density distribution in the well by a 5th order polynomial: $Y = -0.1905*Z^5 + 2*Z^4 - 7{,}6162*Z^3 + 12{,}4254*Z^2 - 7{,}1575*Z + 1{,}9942$ (Z is the depth in km, Y is the density value in g/cm^3) because with this order of polynomial, the root mean squared (RMS) between the actual data and the approximate curve data (fig. 4b, black line) is smallest (fig. 4a). With this density distribution, we can see that at the depth less than 3000 m, the density varies from 2.2–2.4 g/cm^3. The density value increases sharply in the last 400 m (the depth over 3000 m) and is approximately 2.7 g/cm^3 (red colour limit line) at the end of the well. Thus, the obtained results about the density distribution of the Pre-Cenozoic basement by solving the 3D inverse problem are consistent with the actual value in the well.

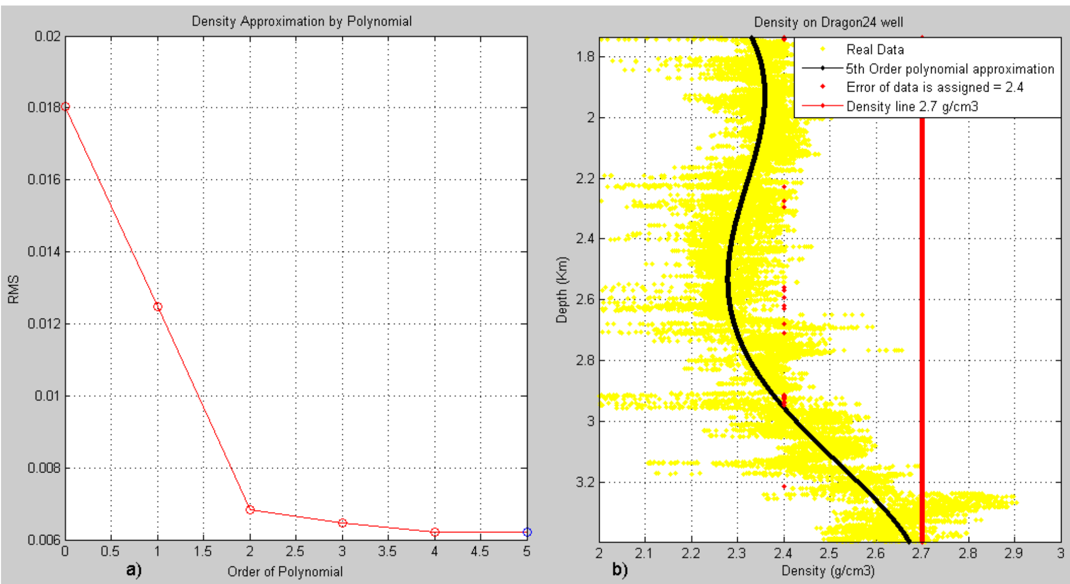

Fig. 4. The density distribution in the well Dragon 24

Fault system. Seismic cross sections are always considered as the standard reference document for the results of the analysis and processing of gravity data. To demonstrate the effectiveness of determining position and depth of the source boundary on the basis of applying the directional analytical signal derivative method and Euler deconvolution method combined with the upward continuation method, the results of the fault depth and location are compared with the fault depth and position on a seismic cross section that is processed by [9] and described in fig. 5b.

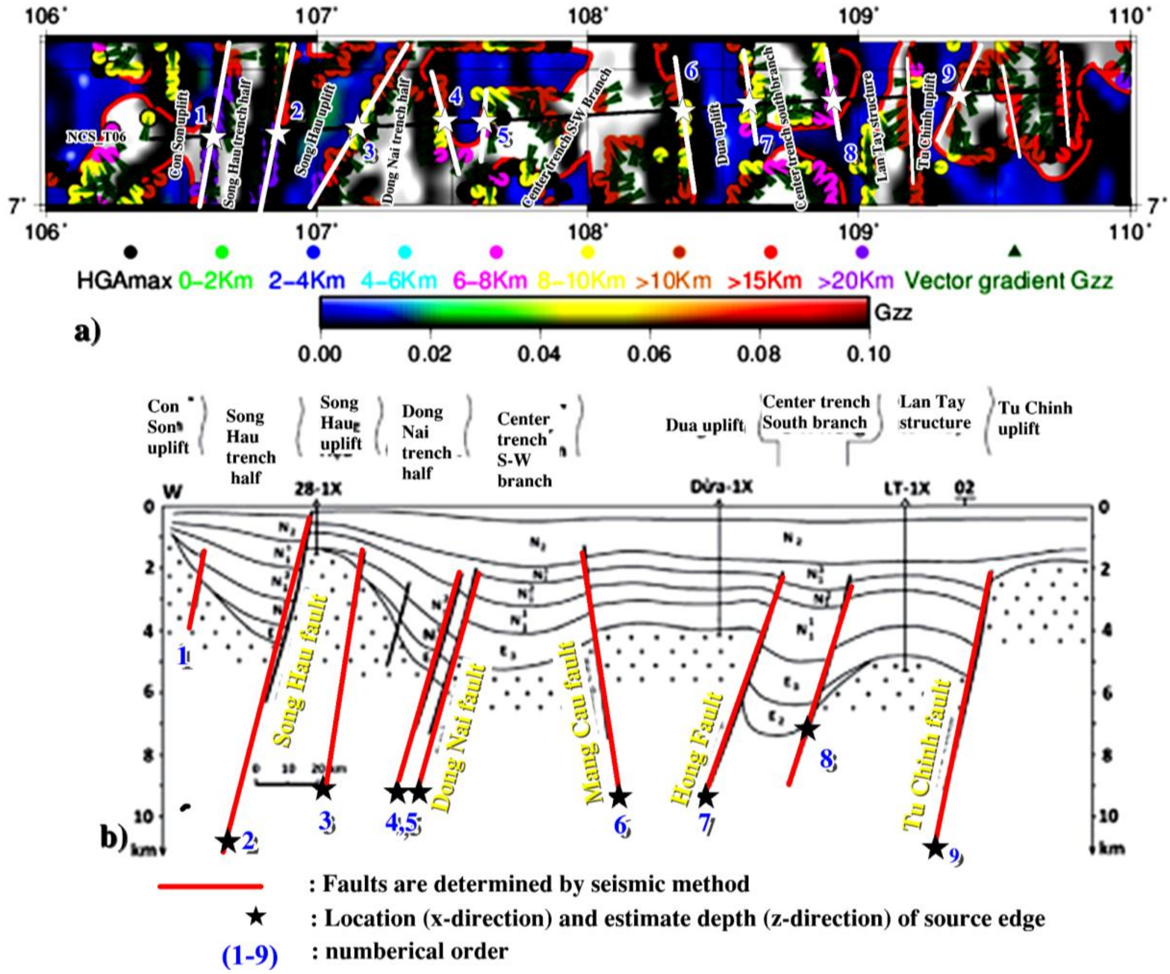

Fig. 5. a) The structure in the zone has the seismic cross section NCS_T06, b) 2D seismic cross section has been interpreted [9]

About position. We can see that alongside the seismic line in the study area (fig. 5a) the black line represents the seismic line location, the white stars are the fault locations on the observed plane and the black stars are correspondingly the fault depth locations in fig. 5b. The major faults in the study area were clearly determined in terms of both location and slope direction: Song Hau fault, Dong Nai fault, Mang Cau fault,...

About depth. Fig. 5b is a seismic cross-section that was illustrated, the fault locations on the Cenozoic sedimentary basement were shown very clearly. However, do they have ability to penetrate into the Pre-Cenozoic basement or even penetrate through the Earth's crust? This cannot be represented in fig. 5b. With the obtained results (fig. 2 and fig. 3), it has been shown that not only the locations of the faults on the cross section NCS_T06 (fig. 5a) were indicated fully and clearly but also their existence depth was also predicted (this depth is represented by the black star in fig. 5b; for example Song Hau fault can penetrate deep more than 15 km, the Mang Cau fault can penetrate deep about the 8–10 km, Tu Chinh fault can penetrate deep more than 10 km.

With Song Hau fault, if we only consider and exam it on NCS_T06 cross section, it is only known on the surface of the Pre-Cenozoic basement and penetrates into the Pre-Cenozoic basement with very modest depth (only 6 km, fig. 5b). On the basis of the integrated analysis (fig. 2 and fig. 3), Song Hau fault can begin at latitude 6^o alongside the west bank of the Song Hau uplift, connect with the western bank of the Con Son uplift and end at the south of Phu Quy island. Alongside this fault, we can find many different depth points from 6 km to 8 km in the north and over 15 km in the south of this fault (This is also indicated by existence of block-20 boundary in fig. 3). Therefore, we can see the effectiveness of the results of the integrated analysis that are calculated based on modern methods. Hence, we can know more about the existence and activities of Song Hau fault in particular and the faults inside of the Pre-Cenozoic basement in general.

CONCLUSION

Based on the results obtained on the Southeast continental shelf of Vietnam, we have some following conclusions:

In the horizontal direction (by area), the density value of the Pre-Cenozoic basement on the Southeast continental shelf of Vietnam varies from 2.64 to 3.0 g/cm^3. The density distribution reflects the form of the sedimentary basins in the study area. The density contour σ = 2.7 g/cm^3 is almost the circumference of the Cuu Long basin, while on Nam Con Son basin, it is the density contour σ = 2.76 g/cm^3. The density of the Pre-Cenozoic basement has the maximum value at the basin center: With Cuu Long basin, the maximum value is σ_{max} = 2.76 g/cm^3 and with Nam Con Son basin, the maximum value is σ_{max}= 3.0 g/cm^3.

The main structural blocks inside of the Pre-Cenozoic basement on the Southeast continental shelf of Vietnam are indicated in detail at levels 10, 20 and 30 km. At the 60 km level, 2 large depressions and 3 large uplift zones exist. Two depressions are determined almost parallel to each other, they run in the southwest-northeast direction. The contour line 0 of the λ_2 function delineates the main sunken source boundary, it is the form of Cuu Long basin and Nam Con Son basin.

In the study area, the marginal position of the anomalous source that is determined by the maximal values of the ED function has better resolution than that is determined by the maximal values of the HGA function (the maximum horizontal gradient method) and it has quite close interconnection to the major density boundary in the area. The results show that the deep faults exist in a wide range, from 6 km to 30 km, even over 30 km, in which faults with depth of 8–10 km are in the majority (fig. 2c), it is larger than the depth of the Cenozoic sediment basement at the corresponding site. These are the faults inside the Pre-Cenozoic basement.

A combination of gravity data modern analysis and processing methodologies with the other geophysical document as reference material allows us to have additional information about the inner structure of the Pre-Cenozoic basement. This result is different from the results that only show the characteristics of the top of the Pre-Cenozoic basement (or Cenozoic sediment basement).

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