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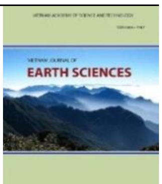

An improved space domain algorithm for determining the 3-D structure of the magnetic basement

Nguyen Thi Thu Hang[1], Erdinc Oksum[2], Le Huy Minh[3], Do Duc Thanh[1]*

[1]*VNU, Hanoi - University of Science, Faculty of Physics, Department of Geophysics*
[2]*Süleyman Demirel University, Engineering Faculty, Department of Geophyisical Engineering, 32260 Isparta, Turkey*
[3]*Institute of Geophysics, VAST*

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ABSTRACT

The paper presents an improved algorithm based on Bhaskara Rao and Ramesh Babu's algorithm to invert magnetic anomalies of three-dimensional basement structures. The magnetic basement is approximated by an ensemble of juxtaposed vertical prisms whose bottom surface coincides with Curie surface with the known depth. The computer program operating with the proposed algorithm is built in Matlab environment. Test applications show that the proposed method can perform computations with fast and stable convergence rate where the results also coincide well with the actual model structure. The effectiveness of the method is demonstrated by inverting magnetic anomalies of the southeast part of Vietnam continental shelf. The calculated magnetic basement relief of the study area provides useful additional information for studies in the aim of dealing with the geological structure of the area.

Keywords: 3D magnetic inversion; magnetic basement; Vietnam's continental shelf.

1. Introduction

Understanding the deep structure of the crust is one of the objects of geophysics, in which the determination of the depth of magnetic sources constitute an important task in studying and interpreting geological and tectonic problems. So far, a series of methods have been introduced for determining the depth and structure of magnetic sources. The classical methods of determining the source depth are the Werner deconvolution (Werner, 1955) and the Euler deconvolution (Thompson, 1982). Later on, Mushayandebvu et al. (2004) introduced the extended Euler equation leading more stable results. Subsequently, the Euler deconvolution was combined with the analytical signal (Keating and Pilkington, 2000) and the field tensor (Beiki, 2010), providing relatively good results. Although the Euler deconvolution is a common method in determining of depth, it also reveals some limitations such as the requirement of the input of the structural index (SI) known as the shape type of the body whereas the prediction of this is difficult in practice. Other methods commonly used to determine the depth of sources are based on spectral analyzes of magnetic anomalies. The method of the energy spectrum of anomalies

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*Corresponding author, Email: doducthanh1956@gmail.com is derived from Parker's formula (Parker, 1973), based on the relationship between the Fourier transform of magnetic data and the total Fourier transform of vector intensities describing the terrain at the discrete points. Pilkington et al. (1994) and Pilkington (2006) demonstrated the effectiveness of this method. Xu (2006) improved the loop in this method to speed up the convergence rate. Recently Zhang et al. (2016) replaced the Fourier transform with the Padé approximation in Parker's method and yielded higher accuracy. The advantages of the spectral method are the short calculation time and the ability to interpret data large in size. However, its disadvantage is that the accuracy of depth determination depends on the average depth.

There are a number of researches for the aim of determining the depth of magnetic sources subjected to different study areas of Vietnam (i.e.: Nguyen et al., 2014a, 2014b; Vo et al., 2005; Do et al., 2009; Do, 2013). However, researches and/or applications of methods for determining the depth of three-dimensional magnetic basement are very few. For instance, Nguyen et al.(2014b) combined the Euler deconvolution and the maximum horizontal gradient method to determine the magnetic basement structure in the Gulf of Tonkin and applied the method of energy density spectrum of anomalies (Nguyen N. T. et al., 2014a) to determine the depth of magnetic basement in Tu Chinh - Vung May area. Do et al. (2009) and Do (2013) also performed the 2D and 3D inversions to determine the depth of magnetic basement in the space domain. The introduced method has fast and stable convergence rate, however the algorithm is limited to the assumption that the basement bottom surface is flat. Nguyen et al. (2018) has presented an improved algorithm to invert magnetic anomalies of two-dimensional basement structures in space domain.

Here in this study, we have improved the algorithm of determining the parameters of magnetized vertical prismatic objects by Rao and Babu (1993) in order to solve the 3D inverse problem of defining the magnetic basement depth within a more reasonable assumption that the basement bottom surface is variable in depth and coincides with Curie surface. The suggested approach is applied to the southeast of Vietnam's continental shelf.

2. Theoretical basis

Figure 1 illustrates a magnetized vertical prism model located in a 3D Cartesian coordinate system defined with an origin O where x and y axis in the horizontal plane are pointing towards north and east, respectively and the z axis in vertical plane is pointing downward. Here, the observation grid is parallel to the x and y axes.

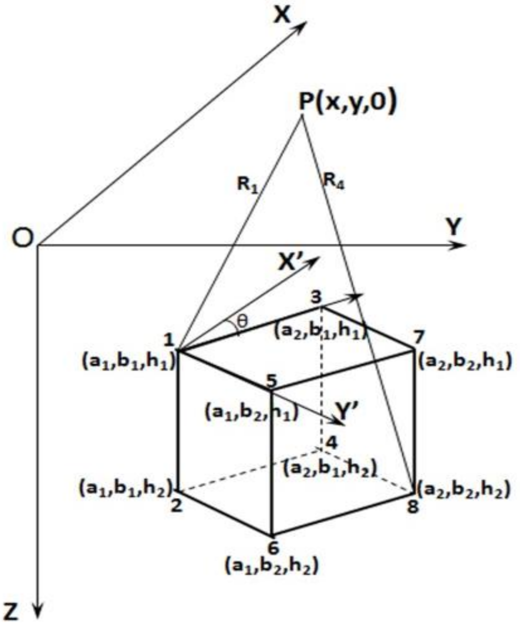

Figure 1. The magnetized vertical prismatic object

The solution of 3D inverse problem due to a prism model in order to determine its spatial parameters (a_1, b_1, h_1, a_2, b_2, h_2, θ) as well as the parameters related to its magnetization (the magnetic susceptibility (χ) and the inclination angle (I) of the magnetization) was previously introduced by Rao and Babu (1993). In that, the initial parameters determined by field observations are progressively adjusted in an iterative process until the object function f is minimized:

$$f=\sum_{i=1}^{M_x}\sum_{j=1}^{M_y}\left[\Delta T_{obs}(i,j)-\Delta T_{cal}(i,j)\right]^2 \tag{1}$$

where $\Delta T_{obs}(i,j)$ and $\Delta T_{cal}(i,j)$ are the observed and calculated anomalies at the $(i,j)^{th}$ observation point respectively.

In this study, the algorithm by Rao and Babu (1993) is improved in order to determine the depth of magnetic basement in 3D domain. Hereunder, the magnetic basement is approximated by an ensemble of juxtaposed vertical prisms, the parameters of magnetization are estimated from field data. Then, the determination of magnetic basement depth is only the calculation of the depth to the top surface $h_1(i,j)$ of the ensemble of prisms. The determination of the depths $h_1(i,j)$ is also carried out by selecting and adjusting the solution convergence in which the increments $dh_{1k}(i,j)$ are the solutions of the following system of equations:

$$\left[\sum_{i=1}^{M_x}\sum_{j=1}^{M_y}\sum_{k}^{N_p}\frac{\partial\Delta T(X_{i,j})}{\partial h_{1k}}\frac{\partial\Delta T(X_{i,j})}{\partial h_{1l}}(1+\delta\lambda)dh_{1k}=\sum_{i=1}^{M_x}\sum_{j=1}^{M_y}d\Delta T(X_{i,j})\frac{\partial\Delta T(X_{i,j})}{\partial h_{1l}}\right] \tag{2}$$

where M_x and M_y are the number of grid points in x and y direction, respectively, and

$l=1, 2, 3, \dots, N_p$ $(N_p=M_x\times M_y)$.

In Eq 2, $X_{i,j}$ is the coordinate of the $(i,j)^{th}$ grid point; $d\Delta T$ is the difference between the observed and the calculated anomalies, λ is Marquardt damping factor, and ΔT is the initial total magnetic anomaly determined by the procedure of Rao and Babu (1993).

After each iteration, the depth is changed as follows:

$$h_{1k}^{n}=h_{1k}^{n-1}+dh_{1k}\,(k=1,N) \tag{3}$$

where h_{1k}^{n}, h_{1k}^{n-1} are h_{1k} in the n^{th} and $(n-1)^{th}$ iterations.

The process is performed iteratively until the mean squared deviation between the observed and calculated values reaches an allowable value. The stepwise routine of the process is summarized as the following:

Step 1: Determine the anomalies by an initial model.

Step 2: Determine the error between the observed and calculated anomalies.

Step 3: Calculate the derivatives according to the variables h_{1k}.

Step 4: Establish the equation (2) and solve this equation to find the values dh_{1k}.

Step 5: Determine the anomalies according to the values $h_{1k}+dh_{1k}$ and calculate the error.

Step 6: If the error is less than the allowable value then terminate, otherwise return to step 3 and again proceed for steps 4 and 5.

The proposed algorithm has been built in a Matlab based code operating according to the progressive steps given above.

3. Synthetic Example

In this section, we present the application of the proposed algorithm on a synthetic data produced by a known three-dimensional model. The parameters of the synthetic model are as follows: The observation field encloses an area of 135 × 135 km in size within a square grid interval of 5 km which constitutes a 28 × 28 grid area for the total number of observation; the inclination angle of the magnetization is $I=4°$ and the susceptibility is $\chi=0.005SI$. The basement surface of the model is shown in Fig. 2a and the bottom surface assumed to coincide with the Curie surface is shown in Fig 2b.

The total magnetic anomaly ΔT determined using the method of Rao and Babu (1993) is considered as the initial (observed) anomaly in this inversion procedure. Herewith, in order to investigate also the effect of noise in solving the inverse problem, random noise of 3% according to the Gaussian distribution is added to the observed data (Fig. 3a). Calculation results after 10th iteration steps are represented in Fig. 3b-d.

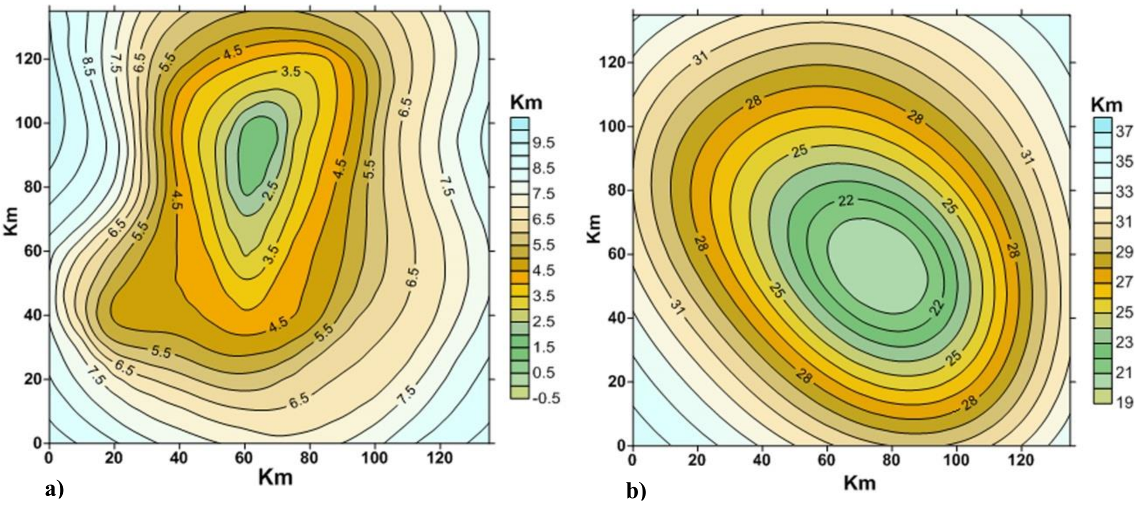

Figure 2. The model of magnetic basement; a) Top of the basement; b) Bottom of the basement (Curie surface)

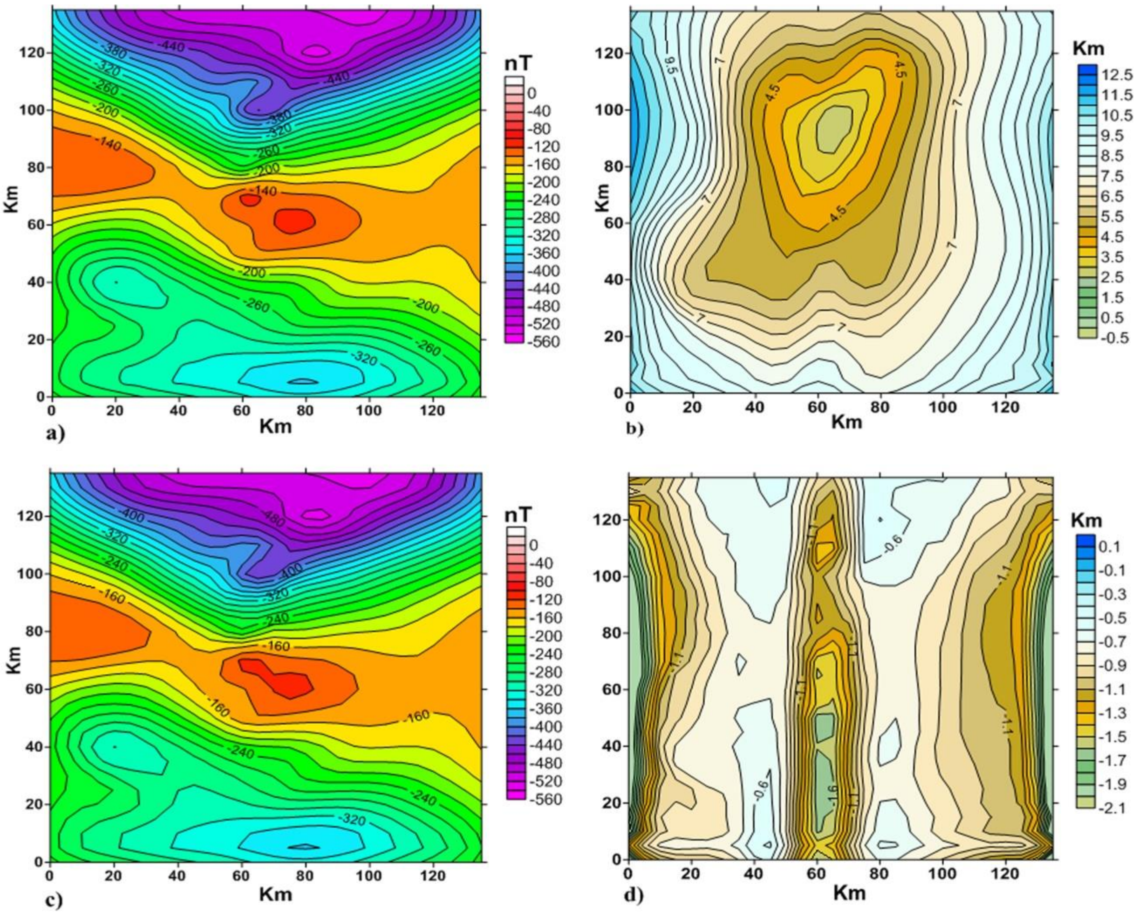

Figure 3. The calculation results with the magnetization inclination of 4° (I=4°)

a) The theoretical anomaly with noise; b) The calculated depth at last iteration; c) The calculated anomaly at last iteration; d) The error between model and calculated depth

According to the results, although the calculated anomalies (Fig. 3c) are quite coincident with the theoretical anomalies given in Fig. 3a., the calculated depth of the magnetic basement is significantly different by its greater values than those of the model (Fig. 3b). The error in depth between the model and calculated range mainly from 0.7 to 0.9 km, however, it increases up to 1.7 km towards the edges of the study area.

In order to enhance the computation results, the initial magnetic anomaly was reduced to the pole (Fig. 4a) as the pre-processing of the data using the algorithm of Keating and Zerbo (1996) and then the inversion process has been repeated. The obtained results after 7 iterations is shown in Fig. 4b-d. Hereunder, it can be seen that the contour lines of calculated anomalies (Fig. 4c) and those of theoretical anomalies (Fig. 4a) are nearly identical and the calculated basement depth (Fig. 4b) accord relatively well with those of the model depth. In this case, the error in depth between the actual and calculated vary from 0.15 to 0.75 km, mainly in the center of the study area whereas greater values up to 1 km are concentrated only at the edges of the observation plane (Fig. 4d). The convergence rate (Fig. 5) obtained during the iterative decreases rapidly and steadily after each iteration step. After 7 iterations, the mean squared error decreases from 124nT to 0.3nT which proves that the calculation results in case of noise still ensure the necessary accuracy.

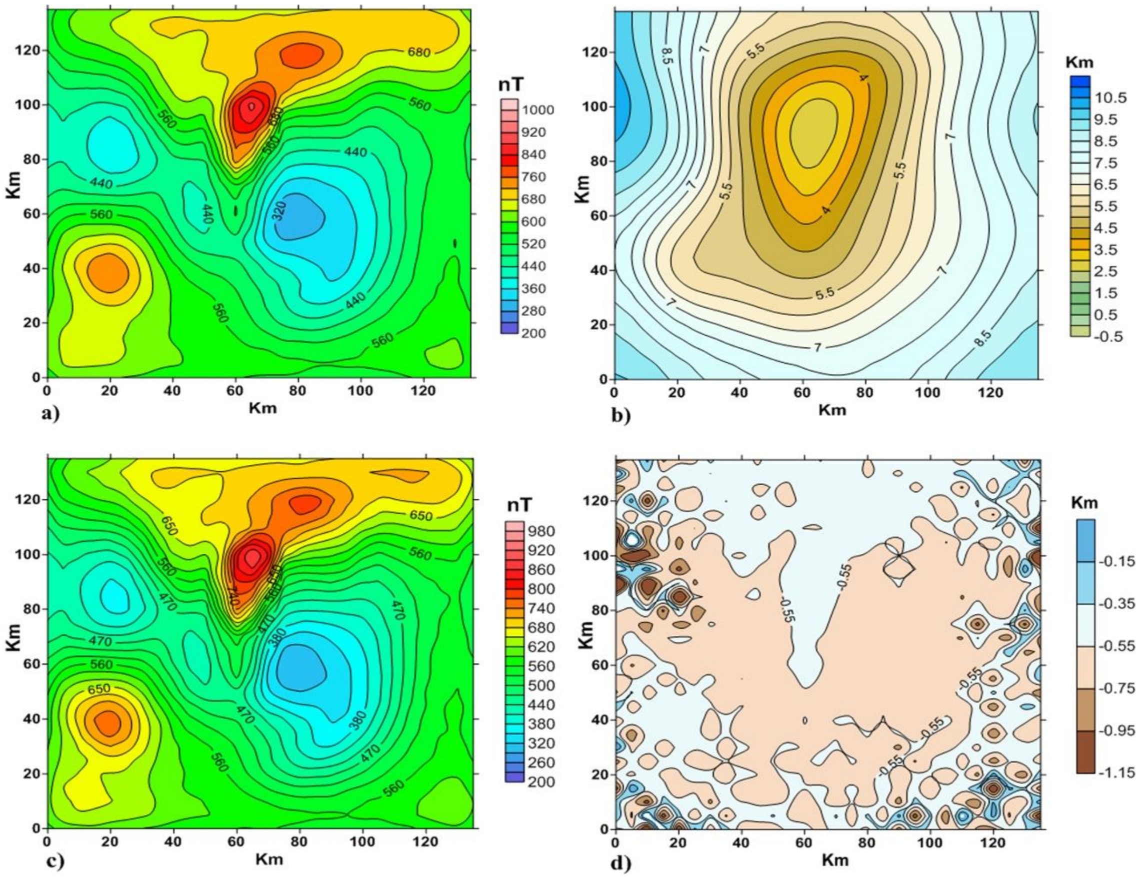

Figure 4. The calculation results with anomaly reduced to the pole

a) The theoretical anomaly with noise; b) The calculated depth at last iteration; c) The calculated anomaly at last iteration d) The error between model and calculated depths

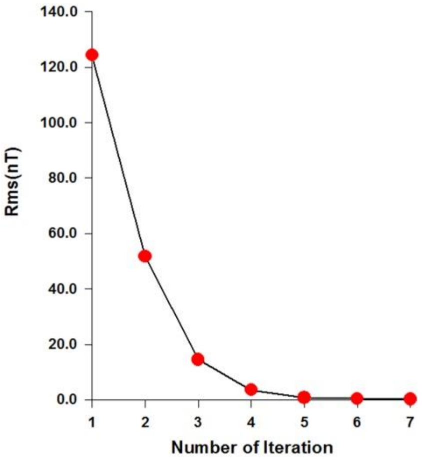

Figure 5. The convergence rate

4. Determination the depth of magnetic basement in the southeast of Vietnam's continental shelf

In order to confirm the applicability of this proposed method in the case of real data, we have applied this method to determine the magnetic basement depth in the southeast of Vietnam's continental shelf (Fig. 6).

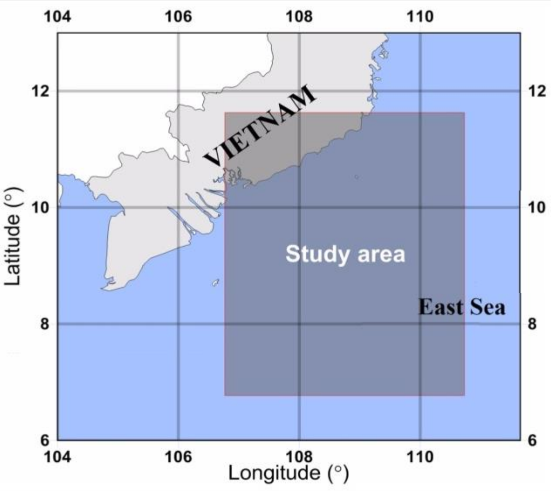

Figure 6. Location map of the study area

The southeast continental shelf of Vietnam is recognized as one of the most prominent areas due to its great petroleum potential, comprising two large sedimentary basins, namely the Cuu Long basin, the Nam Con Son basin and a sub-basin as a part of the East Vietnam Sea deep basin. According to the geological frame of the study area (Mai et al., 2011), the geological formation consists mainly of Pliocene-Quaternary sediment. The detailed stratigraphic units are categorized as follows: lower Pliocene N^{12}; upper Pliocene N^2; lower Pleistocene ($Q1^1$), lower part of middle Pleistocene ($Q1^{2a}$), upper part of middle Pleistocene ($Q1^{2b}$), lower part of upper Pleistocene ($Q1^{3a}$), upper part of upper Pleistocene-lower and middle Holocene ($Q1^{3b}$ –$Q2^{1-2}$) and upper Holocene. The Pliocene - Quaternary sedimentary basins have their own evolution. This feature is expressed in subsidence rate, sedimentary environment, inheritance from ancient structural plan and combination of different sedimentary-effusive, sedimentary formations. Especially in this area and on the Central continental shelf, there is the occurrence of turbidite facies along with the formation of low stand wedges from early Pliocene which continued to develop throughout Pliocene-Quaternary on the eastern edge of Phu Khanh and Nam Con Son basins. On the southeast continental shelf, the fine-grained sediments predominate; in addition to terrigenous materials, there are volcanic ash and sand dunes. The depth of Pliocene basement and Quaternary basement, and their thickness varies complicatedly in different areas of the continental shelf.

The magnetic anomaly map of the study area (Fig. 7a) is established by the Geological Survey of Japan and the Coordinating Committee for Offshore Prospecting in Southeast Asia in 1994, on a scale of 1:4,000,000. The Curie point depth surface of the study area (Fig. 7d) is taken from the results by Tanaka A. et al. (1999). Field information about the magnetization properties of the sediments and the basement of the study area are achieved from the previous report by Do et al. (2009) and also from tables of rock susceptibilities provided by the Northeast Geophysical Society (NGA). Accordingly, the magnetic susceptibility of the sedimentary layer changes from 0.002 to

0.0045cgs and the remnant magnetization varies between 0.002 and 0.004 emu/cm^3. Also the magnetic susceptibility of the basement is about 0.005cgs and the remnant magnetization varies from 0.005 to 0.02 emu/cm^3.

In order to improve the accuracy of calculation of magnetic basement depth, we have used the magnetic anomaly map, which was reduced to the pole by Le et al. (2003) (Fig. 7b). Next, the effects of shallow sources in this data have been eliminated by performing an upward continuation to 20 km. Fig. 7c shows the magnetic anomaly map after the continuation process. The data used were interpolated within a square grid interval of 10 km leading 45 × 55 data nodes in the observation plane. The calculation results are represented in Fig. 8.

Some general remarks on the results are as in the following;

The magnetic basement depth in the southeast of Vietnam's continental shelf varies considerably. The depth is shallower in the nearshore area and increases in the offshore area, in which there are two small uplifts, from 1.5 to 2 km, almost parallel to the coastline in the northeast-southwest direction. The deepest part of the magnetic basement is about 10 km to 15 km in the southeast of the study area. In addition, in this area, the rate of variation of magnetic basement depth is relatively high. In general, in the study area, the direction of changes in the basement depth is mainly northwest-southeast.

The error between observed and calculated anomalies in the study area is very small, mainly around 0.05nT. In order to reduce the error due to the marginal effect in the computation, the expansion of the computation area is carried out in both x and y directions (30 km in each direction). However, this error cannot be completely reduced. In the southeast of the study area, the Curie surface is deep, the basement thickness is greatest; therefore, the marginal effect is strongest. This explains why the error between observed and calculated anomalies in this area is greater than that in the surrounding areas. However, it is only about 1nT in absolute value. The relativity is about 1%. In the processing and analysis of actual data, this error is perfectly acceptable.

The curve of the convergence rate is very steep. The mean squared error decreases rapidly (from 228.34 nT to 1.06 nT in the 10th iteration) and approaches the asymptote from the 6th iteration. This proves that this method has a fast and stable convergence rate.

In order to see the correlation with the deep geological structural boundaries, cross sections of the Curie surface depth and the estimated magnetic basement are compared with the result of the study (Bui et al., 2007) based on gravity data (Fig. 9). The depth to deep structural boundaries is presented in Fig. 10. According to this, the bottom of Cenozoic sediment and the upper surface of the magnetic basement have relatively similar morphology, i.e. uplifted or lowered together. However, the bottom of Cenozoic sediment and the upper surface of the magnetic basement are not coincident. In most of the observation profile, the Cenozoic bottom is shallower than the upper surface of the magnetic basement. Only a short part of Cenozoic bottom has the greater depth than the surface of the magnetic basement.

It is obvious that the accuracy of determining the magnetic basement depth as well as determining the depth of Cenozoic sediment bottom depends on the accuracy of the data used. The morphological similarity of the obtained magnetic basement depth and the depth of the Cenozoic sediment bottom indicates that the depth information can complement each other in the study on regional deep structure.

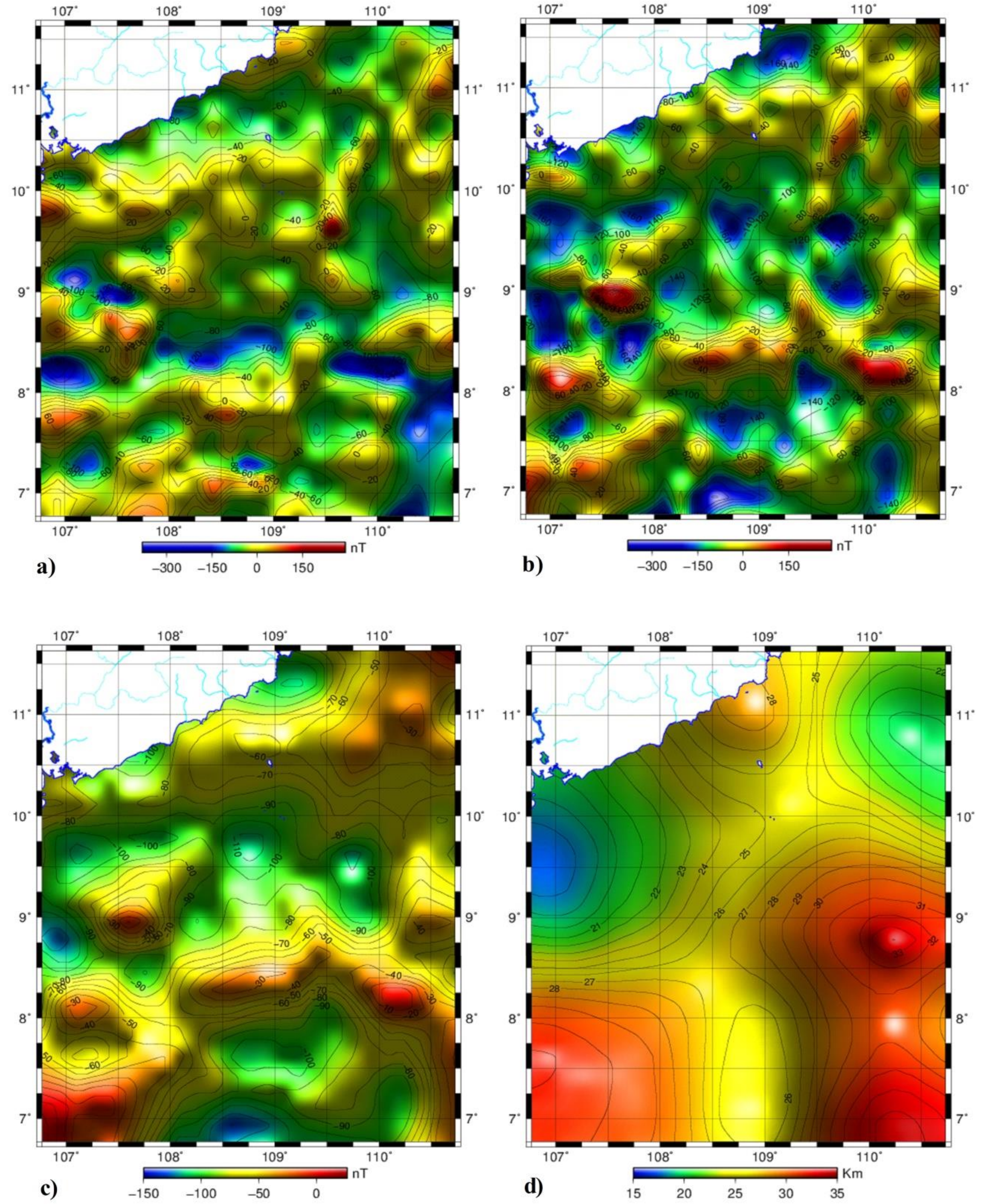

Figure 7. The anomalies and Curie surface of the southeast of Vietnam's continental shelf

a) The magnetic anomaly map ΔT (CCOP, 1996); b) The magnetic anomaly reduced to the pole; c) The magnetic anomaly reduced to the pole and upwarded to 20 km; d) The depth of Curie surface

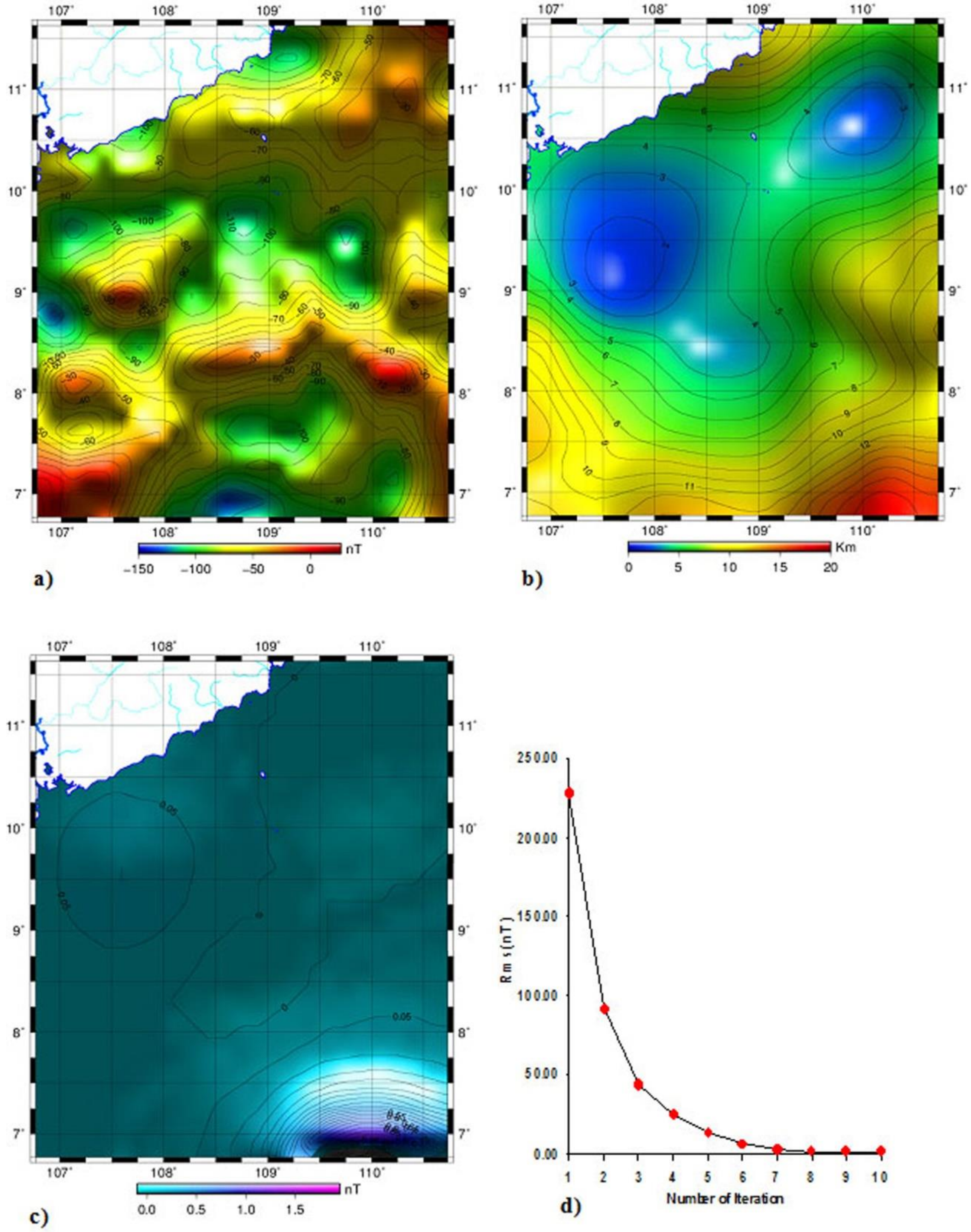

Figure 8. The calculation resunts at the last iteration

a) The calculated magnetic anomaly; b) The calculated magnetic basement depth; c) The error between observed and calculated anomalies; d) The convergence rate

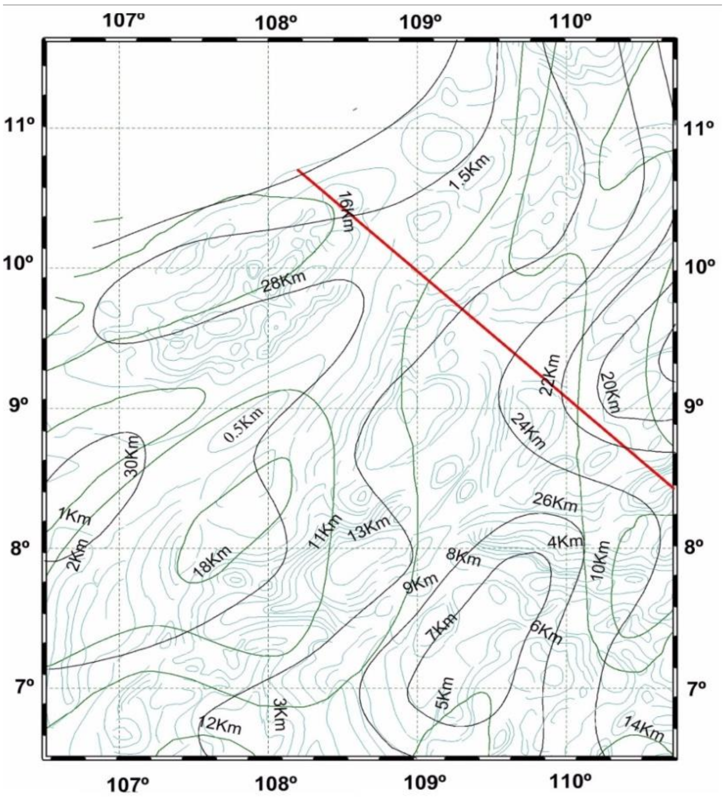

Figure 9. Diagram of deep structure in the southeast of Vietnam's continental shelf (Bui et al., 2007)

~ Cenozoic contour ; ~ Conrad contour; ~ Moho contour ; — Comparative section

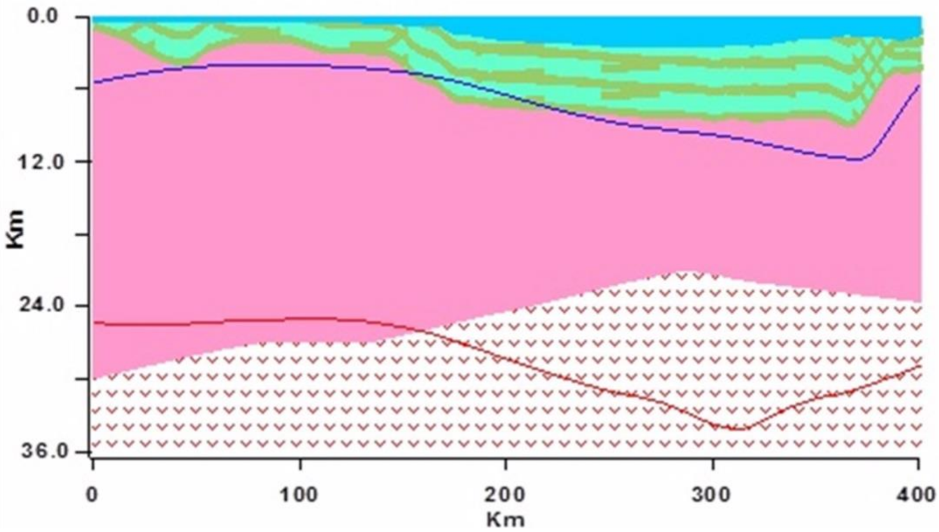

Figure 10. Deep geological section according to gravity data (Bui et al., 2007) and the depths of magnetic basement and Curie surface

■ Seawater; ▨ Cenozoic; ■ Granite and basalt; ⌄ Moho

~ Magnetic basement depth (according to the 3D result of determining magnetic basement depth)

~ Curie surface depth (according to the result of Tanaka et al., 1999)

5. Conclusions

Based on the results of improving the algorithm of Rao and Babu to determine the magnetic basement depth in the numerical model and application in analyzing magnetic data in the southeast of Vietnam's continental shelf, the following conclusions can be drawn:

(i) By improving the algorithm of Rao and Babu to define the parameters of the prismatic anomaly-causing object, the determination of depth to the top surface of the magnetic basement is entirely feasible. When the computer program built according to the improved algorithm is applied to the reduced-to-the-pole anomalies, it gives relatively high accuracy results even in case of noise.

(ii) The application results in the southeast of Vietnam's continental shelf show that the magnetic basement depth in this area varies quite significantly. There are the uplifts of the magnetic basement (from 1.5km to 2km) along the northeast-southwest direction. In general, the variation in magnetic basement depth in the area follows the northwest-southeast direction and tends to descend towards the deep basin of the ocean. Gradient variation also increases sharply in this area.

(iii) The computer program based on the improved algorithm to determine the magnetic basement depth at each observation point is fully automatic and performs fast and stable convergence rate due to the adjustment after each selection. Thus, the code is entirely feasible in determining the magnetic basement depth in the space domain.

In practice, the solution of the 3D inverse problem in the southeast of Vietnam's continental shelf with the area of 490km x 450km and the distance of 10km between the observation points shows that with 10 iterations, the calculation time on the computer is only 45 minutes.

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