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IMPROVING ALGORITHM OF DETERMINING THE COORDINATES OF THE VERTICES OF THE POLYGON TO INVERT MAGNETIC ANOMALIES OF TWO-DIMENSIONAL BASEMENT STRUCTURES IN SPACE DOMAIN

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Abstract. In this paper, we present an improved algorithm based on Murthy and Rao's algorithm to invert magnetic anomalies of two-dimensional basement structures. Here, the magnetic basement interface is approximated by a 2N-sided polygon with assumption that the bottom of the basement is the Curie surface. The algorithm is built in Matlab environment. The model testing shows that the proposed method can perform computations with fast and stable convergence rate. The obtained result also coincide well with the actual model depth. The practical applicability of the method is also demonstrated by interpreting three magnetic profiles in the southeast part of the continental shelf of Vietnam.

Keywords: Magnetic inversion, magnetic basement, continental shelf of Vietnam.

INTRODUCTION

One of the important roles of research in structural geology and tectonics is to determine the magnetic basement relief from the magnetic anomalies. Many different magnetic interpretation methods have been used to solve this problem. In this introductory review, we will describe three groups of methods. The first one consists of the automated depth estimation methods. The second one includes the methods based on the spectral content of the magnetic response of the crystalline basement. The third group uses a nonspectral approach to determine the depth to basement.

The first group of methods includes the Euler and Werner deconvolutions. The mathematical basis of the Euler deconvolution was originally presented by Thompson [1] for profile data, and by Reid et al., [2] for gridded data. The Werner deconvolution method was originally introduced by Werner [3]. Several authors have suggested further extension of this method (e.g. Ku and Sharp [4], Hansen and Simmonds [5], and Ostrowski et al., [6]). These methods are used as useful tools in interpreting magnetic data.

The group of spectral approaches includes statistical spectral methods and the inversion methods based on Parker's [7] forward algorithm. The statistical spectral method was first proposed by Spector and Grant [8] and further refined by Treitel et al., [9]. Spector and Grant [8] analyzed the shape of power spectra calculated from magnetic data and showed that the spectral properties of an ensemble of magnetic sources are equivalent to the spectral properties of an average member of the ensemble. The method was designed to estimate average depths of ensembles of sources. Therefore, it cannot estimate a detailed basement relief. The inversion methods are based on Parker's [7] forward method to reduce the computation time. However, the methods require a given mean depth of the interface and a low-pass filter to achieve convergence.

The group of nonspectral approach studied by many researchers was used to estimate the depth to basement (Mickus and Peeples [10], Zeyen and Pous [11], García-Abdeslem, (2008) [12]). Although the methods take more time to calculate, they provide depth determination results with higher precision, compared to the inversion methods based on Parker's [7] forward algorithm.

In Vietnam, some researchers have studied and applied the above methods to determine the depth of magnetic sources (e.g. Nguyen Nhu Trung et al., [13, 14], Vo Thanh Son [15], Do Duc Thanh [16], among others). However, determination of the depth to basement has not been studied much by Vietnamese researchers. Based on spectrum analysis of magnetic anomaly data and Euler deconvolution, Nguyen Nhu Trung et al., [13, 14] determined the basement relief in some areas of Vietnam. The results show that using the spectrum analysis method, the depth to the basement depends strongly on the size of the analyzed area; whereas Euler deconvolution depends strongly on structural index that is difficult to detect. In order to overcome these problems, Do Duc Thanh [16] used the algorithm of Murthy and Rao [17] to invert magnetic anomalies. However, the computer programs are based on assumption that the bottom of the basement is flat.

In this paper, we further developed the algorithm of Murthy and Rao [17] that is used to invert magnetic anomalies of 2D bodies of polygonal cross section to estimate the depth to the basement with assumption that the bottom of the basement is not flat, but it is Curie surface [18], because under this surface the magnetic materials lose their permanence.

METHODOLOGY

Inversion of magnetic anomaly of 2D polygonal cross sections. According to Murthy and Rao [17], the position and size of a 2D source can be determined by coordinates of vertices of an N-sided polygon. The coordinates of vertices (x_k, z_k) are denoted by:

$$a_k = x_k \quad \text{and} \quad a_{k+N} = z_k \quad (k=1,N) \qquad (1)$$

The method of interpretation starts by assuming the initial depth ordinates (z) of the polygon. Then the magnetic anomaly generated by this initial model is calculated by Murthy and Rao method [17]. The differences $d\Delta T$ between the observed and calculated anomalies can be used to construct equations for determining partial derivatives da_k (including dx_k, dz_k) through the minimization of the object function.

$$\sum_{i=1}^{N_{obs}}\sum_{k=1}^{N_p}\frac{\partial\Delta T(X_i)}{\partial a_k}\frac{\partial\Delta T(X_i)}{\partial a_j}(1+\delta\lambda)da_k = \sum_{i=1}^{Nobs} d\Delta T(X_i)\frac{\partial\Delta T(X_i)}{\partial a_j} \quad (j=1, N_p, \text{with } N_p = 2N) \qquad (2)$$

Where: X_i is the observation point coordinate i; $\delta = 1$ for $i=j$ and $\delta = 0$ for $i \neq j$; λ is Marquardt's damping factor and $\Delta T(X_i) = f(X_i, a_1, a_2, ... a_{2N})$ is total field magnetic anomaly at the observation point i calculated by Murthy and Rao method [17].

The improved values of the coordinates of the vertices are given by:

$$a_k^n = a_k^{n-1} + da_k \qquad (k=1,N)$$

a_k^n, a_k^{n-1} are respectively a_k at n and n - 1 iterations.

The procedure is iterated several times, until the root mean square error (RMS) between the observed and calculated data is reduced to a small value.

Inversion of magnetic anomaly of the magnetic basement relief. Through inversion of magnetic anomaly of 2D polygonal cross sections using Murthy and Rao method [17], we found that it is possible to extend this algorithm to determine the depth to basement by approximating the vertical cross section of the basement by a 2N-sided polygon, in which:

The vertices from 1^{th} to N^{th} have horizontal and vertical coordinates x_k, z_k ($k = 1–N$) corresponding to the positions of the observation points from 1^{th} to N^{th} and the depth to the top of the basement, respectively.

The remaining vertices from the $(N+1)^{th}$ to the $2N^{th}$ vertices have horizontal and vertical coordinates x_k, z_k ($k = (N + 1) \div 2N$) corresponding to the locations of the observation points in the opposite direction from N to 1 and the depth to the bottom of the basement. Here, the bottom of the basement is defined by the Curie surface [18].

Essentially, determination of magnetic basement depth is determining the vertical coordinates z_k of a 2N-sided polygon having N vertices from the $(N+1)^{th}$ to $2N^{th}$ vertices known (fig. 1). The calculation process consists of the following steps:

Step 1: Calculating the total field magnetic anomaly ΔT from the initial model.

Step 2: Calculating the difference between the calculated anomaly and observed anomaly.

Step 3: Calculating the partial derivatives.

Step 4: Constructing and solving equation (2) for determining da_k.

Step 5: Calculating the anomaly after each iteration and RMS between calculated and observed anomalies.

Step 6: If the RMS is less than the allowable value → exit the program. Otherwise, return to step 1.

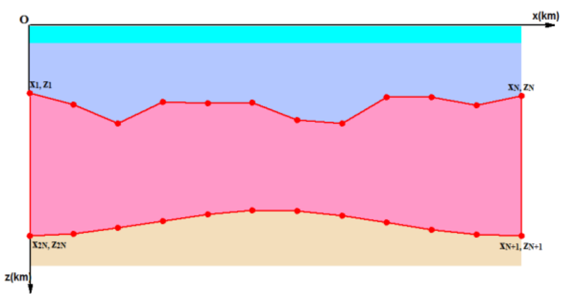

Fig. 1. Approximate a magnetic basement by a 2N-sided polygon

The flow diagram used to estimate the depth to the basement is shown in fig. 2.

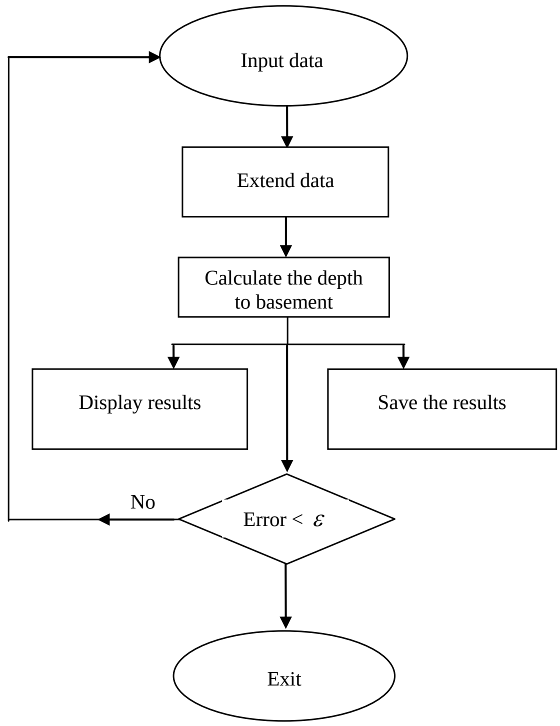

Fig. 2. Flow diagram of computer program for magnetic basement depth estimation

TEST CALCULATION ON MODELS

To investigate the applicability of the program, the calculation was performed on a particular two-dimensional model. The magnetic model was investigated with an inclination of $I = 1^o$ and residual susceptibility $X = 0.005CGS$. The 660 km observation route is assumed to cover the change in depth of the basement and azimuth angle $\alpha = 90^o$. The undersides H_2 of the basements are coincident with Curie surface with known depth.

Here, the calculated result is the depth to the top of the basement at each observation point determined at the last iteration when solving the inverse problem for the anomaly without noise and anomaly with noise 3%. The results of determining the depth to the top of the basement are shown in fig. 3a and fig. 4a. The convergences are shown in fig. 3b and fig. 4b.

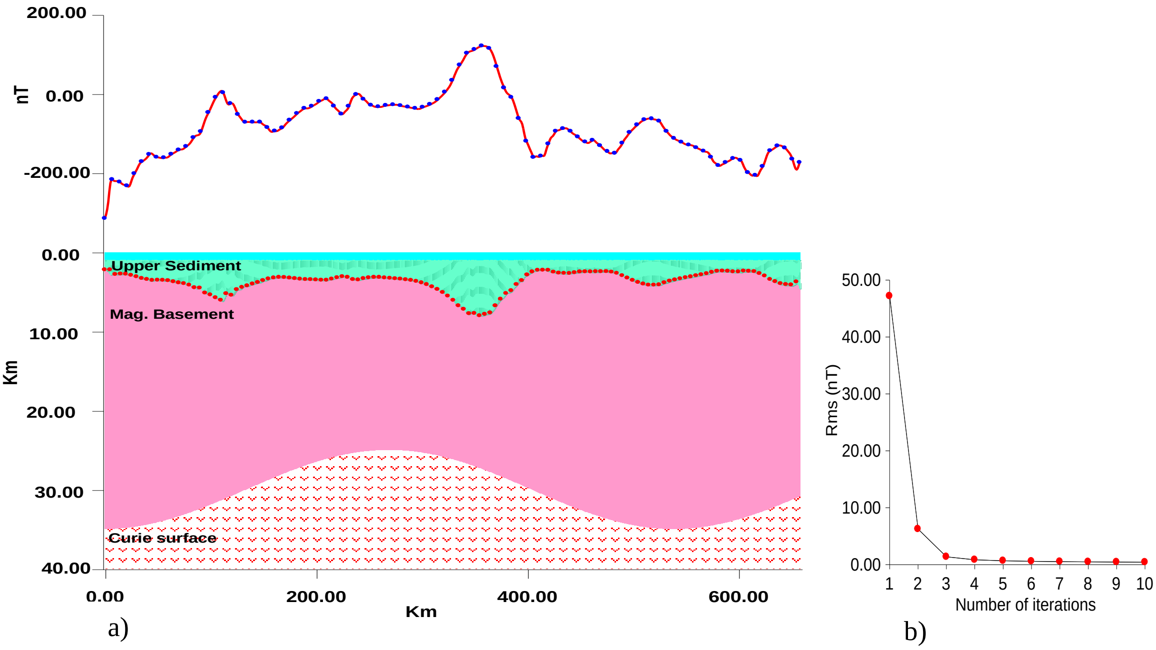

Fig. 3. a) Determination of the depth of the magnetic basement from anomaly without noise

Observed anomaly — *Calculated anomaly*
Sea water — *Calculated depth*

b) Convergence

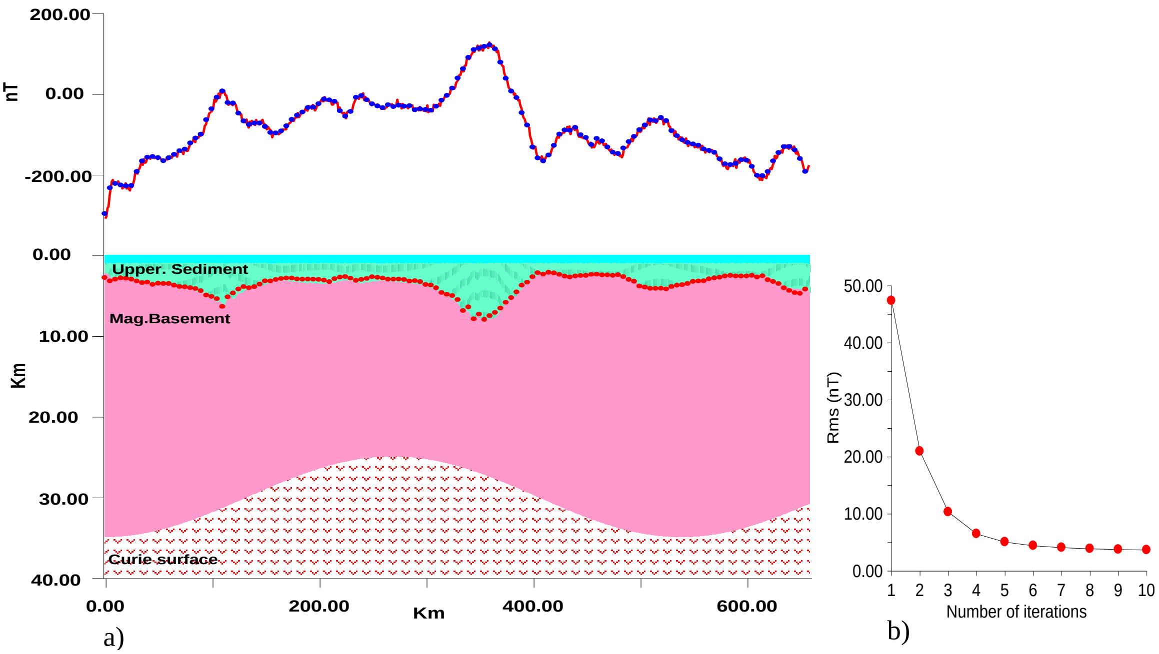

Fig. 4. a) Determination of the depth of the magnetic basement from anomaly with noise 3%

Observed anomaly — *Calculated anomaly*
Sea water — *Calculated depth*

b) Convergence

Based on the calculation results of this model, the following remarks can be made:

For the anomaly without noise (fig. 3a, 3b): After only 10 iterations, the average squared error between the observed and calculated anomalies falls sharply from 47.2 nT to 0.4 nT. This shows that the method has a fast convergence. Decreasing convergence curve demonstrates the stability of the method. At the last iteration, calculated anomaly (blue dots) almost coincides with observed anomaly (red line). The computed depth is represented by red dots that almost coincide with the depth of the basement pattern.

For the anomaly with noise 3% (fig. 4a, 4b): Calculated anomaly (blue dots) remains very close to observed anomaly (red dots). The computed depth (red dots) is also close to the model depth. The convergence is not as fast as in the case of no interference but still stable. After 10 iterations the average squared error decreases from 47.4 nT to 3.7 nT. It indicates that the calculation results even in case of the noise still ensure the needed accuracy.

CALCULATION RESULTS BASED ON ACTUAL DATA

From the results obtained on the numerical models, the obvious advantages of the improved method for determining the depth of the basement can be seen. In order to confirm the applicability of this method in the interpretation of actual data collected in practice, we have tested this method to determine the depth of the basement from three profiles of Southeast Vietnam continental shelf.

The Southeast continental shelf is one of the large oil and gas potential areas on the continental shelf of Vietnam, comprising two large sedimentary basins, the Cuu Long basin, Nam Con Son basin and part of the Deep East Sea. According to the geological documents [19], the geological formation consists mainly of Pliocene - Quaternary sediments. Detailed stratigraphic units are Lower Pliocene N^{12}; Upper Pliocene N^2; Lower Pleistocene ($Q1^1$), Middle Pleistocene ($Q1^{2a}$), Upper Pleistocene ($Q1^{2b}$), Upper Pleistocene ($Q1^{3a}$), Upper Pleistocene ($Q1^{3b}$ - $Q2^{1-2}$) and Upper Holocene ($Q2^3$). Pliocene - Quaternary sedimentary basins has their own evolved identity. This feature is shown in the rate of sedimentation, sedimentary environment, inheritance of ancient architecture chart and combination of sedimentary formations, sedimentation - different eruptions. Particularly in this area and on the Central continental shelf there is the presence of turbulent turbidite sediment along with the formation of sediments from the early Pliocene which continued to develop throughout Pliocene - Quaternary on the eastern margin of the Phu Khanh and Nam Con Son basins. The eastern continental shelf has fine-grained sediments; extraterrestrial materials also contain volcanic ash and sand dunes develop. The depths of the Pliocene bottom, Quaternary bottom and their thickness change very differently in different parts of the continental shelf.

The materials used to test the application of the methodology include the following:

The abnormal data from ΔT was obtained from the map of anomaly from the Geological Survey of Japan and the Committee for Mining Cooperation Offshore in Southeast Asia established in 1996 on a scale of 1:4,000,000 (CCOP). The survey area is in the southeast of the continental shelf of Vietnam with longitude from 106.5^o–111^oE and the latitude from $6{,}5^o$–12^oN in the geographic coordinate system (fig. 5).

Documentation of seabed depth: exploited from the website: http://topex.ucsd.edu/cgi-bin/get_data.cgi.

Curie depth data for Southeast Vietnam continental shelf: Using Curie point depth calculated by A. Tanaka et al., [18] (fig. 6).

Based on the results obtained in the works of Do Chien Thang et al., 2009 (Report on the results of interpretation of magnetic and gravity survey data in the area of the outer limits of Vietnam continental shelf**,** *Project CSL08 Component: Magnetic and gravity survey data interpretation,* Vietnam Academy of Science and Technology - Institute of Marine Geology and Geophysics), and the index table of magnetic susceptibility of rocks provided by the Northeast Geophysical Society (NGA), we choose:

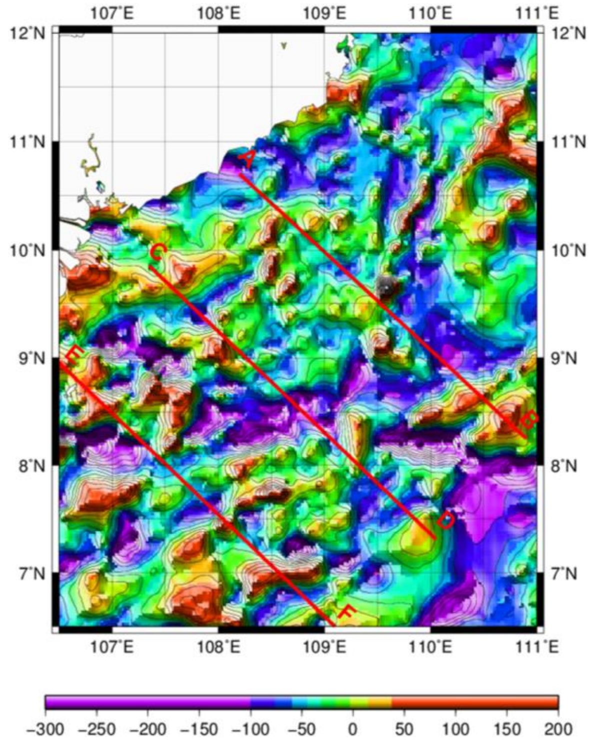

Fig. 5. Magnetic anomaly map ΔT in the southeast part of the continental shelf of Vietnam (Scale 1:4,000,000) (CCOP 1996)

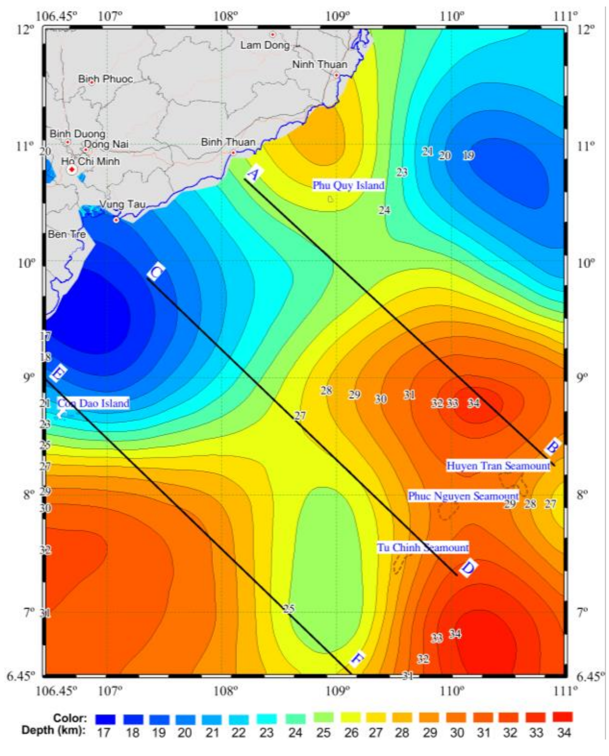

Fig. 6. Curie surface of the southeast part of the continental shelf of Vietnam [18]

Magnetic susceptibility: 0.005 CGS;

The residual magnetization of the basement: changes in the range of 0.005–0.02 emu/cm^3;

The values of the magnetized inclination, magnetized declination and azimuthal angle I, D, and α of each profile are presented in Table 1 (IGRF-12(2015)).

Table 1. Parameters of three profiles

Parameters	Magnetic inclination (^{o})	Magnetic declination(^{o})	Azimuthal angle (^{o})
Profile AB	6	-0.5	45
Profile CD	4	-0.3	45
Profile EF	2	-0.2	45

The results of calculating the basement depth of the profiles AB, CD, EF are shown infig. 7–9 respectively.

Interpretation for profile AB:

The cross section runs from west (coordinates: λ = 108.2^{o}E, φ = 10.7^{o}N) to east (coordinates: λ = 110.9^{o}E, φ = 8.25^{o}N) with a length of approximately 400 km. The value of ΔT on the cross section varies from -124.58 nT to 87.66 nT.

The depth of the basement changes drastically. The depth of the basement surface (from the sea) varies within about 2.0–13 km. On the first section (L = 0–300 km), the surface is raised and lowered, the depth of the basement surface is not much, only within about 2.0–5.8 km. On the second section, the surface of the basement changes sharply and reaches a maximum depth of about 13.0 km. Along the profile further away from the thickness of the basement, the bottom of the basement increases.

On the cross section, from the seafloor boundary to the basement surface, the thickness of the sediment layer varies sharply with the minimum thickness of about 2 km and the maximum of about 10 km.

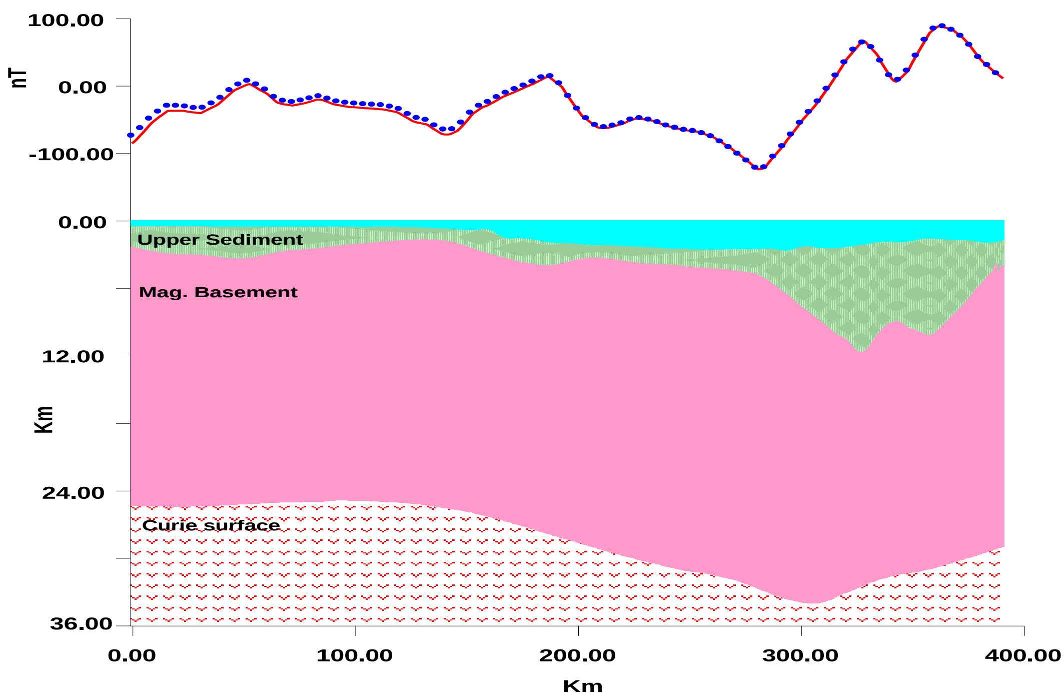

Fig. 7. Determination of the depth of the magnetic basement of profile AB

Observed anomaly ● *Calculated anomaly* *Sea water*

Interpretation for profile CD:

The cross section of the line runs from west (coordinates: λ = 107.35°E, φ = 9.85°N) to east (coordinates: λ = 110.05°E, φ = 7.313°N) with a length of approximately 400 km. The value of ΔT on the cross section changes from -121.13 nT to 22.875 nT.

The depth of the basement changes drastically. The depth of the basement surface (from the sea) varies in the range of 1.738–9.377 km. On the first section (0–150 km), the surface is raised and lowered again, the depth of the basement surface varies from 3.113 km to 7.332 km. On the second segment (150–290 km), the surface of the basement changes sharply and is raised to a minimum height of about 1.738 km. At the other end of the section, the surface of the basement is slightly different from the previous two sections, the depth of the basement is in the range of 4.757–9.377 km. Along the profile further away, the depth of the basement increases.

On the cross section, from the seafloor boundary to the basement surface, the thickness of the sediment layer varies greatly due to the rise and fall of the basement surface. The smallest sediment thickness is about 2 km, the largest one is about 8 km. However, the thickness of the sedimentary layer gradually decreases as it enters the depths of the East Sea.

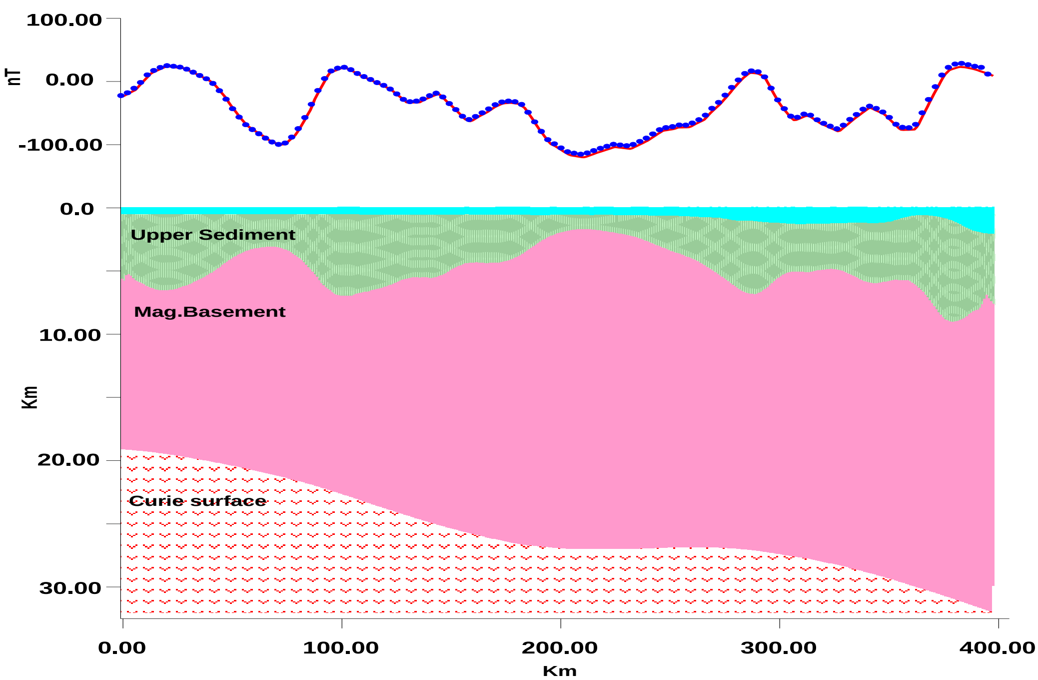

Fig. 8. Determination of the depth of the magnetic basement of profile CD

Observed anomaly ● *Calculated anomaly* *Sea water*

Interpretation for profile EF:

The cross section of the line extends from west (coordinates: λ = 106.5°E, φ = 9.0°N) to east (coordinates: λ = 109.15°E, φ = 6.5°N) with a length of approximately 400 km. The value of ΔTa on the cross section varies from -102 nT to 92.5 nT.

The depth of the basement changes quite sharply. The depth of the basement surface (from the sea) varies within about 2.673–8.659 km. On the first section (0–223 km), the surface of the basement is lowered (about 8.659 km) and then raised up, the depth of the basement hovers at about 2.673 km. Then, on the second section, the basement tends to go up to a depth of about 2.673 km and then go down to a depth of about 7.106 km. This is where the depth of the basement changes most strongly.

The sediment layer thickness changes as much as the magnetic basement because the seafloor is relatively flat but the basement surface is sudden. The smallest sediment thickness is about 3 km, the largest one is about 8 km and it also tends to decrease when entering the deep sunken area of the East Sea.

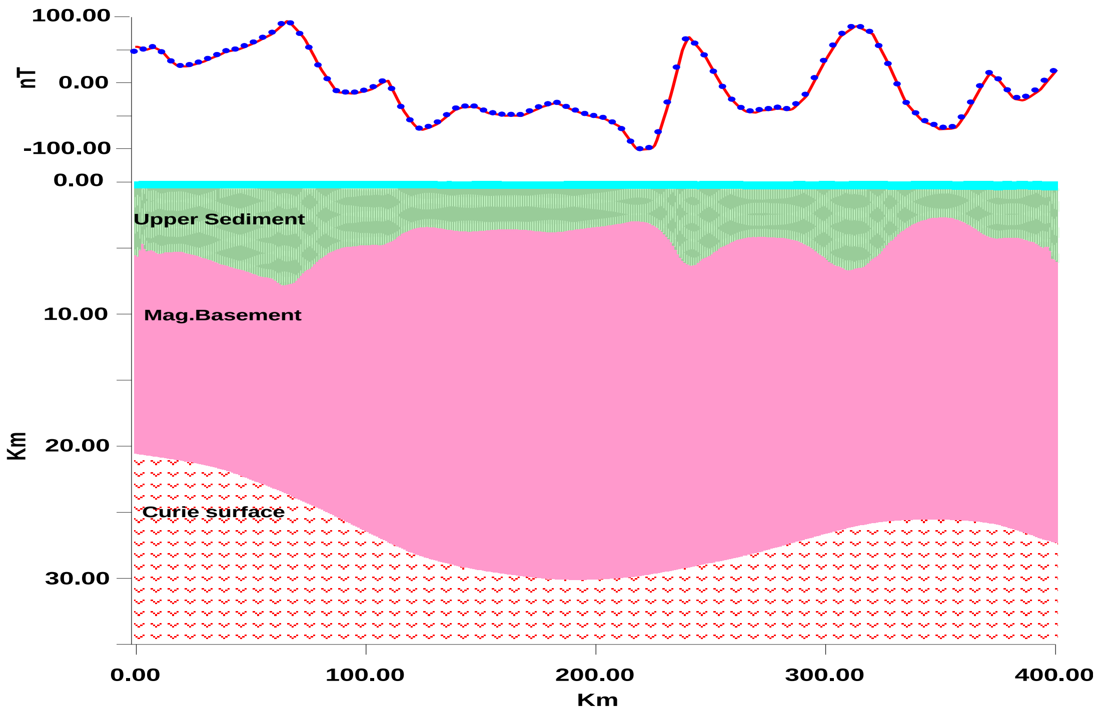

Fig. 9. Determination of the depth of the magnetic basement of profile EF

Observed anomaly *Calculated anomaly* *Sea water*

From the obtained results, some general comments can be made on the structure of the basement from this area:

Within the continental shelf of the Southeast of Vietnam, the depth to the surface of the basement varies considerably, ranging from 2–3 km to 10 km over the seabed.

In the horizontal direction, the change in band structure and the opposite of the observed magnetic field are closely related to the change in the substrate depth of the magnetic basement.

CONCLUSION

We improved Murthy and Rao's algorithm and developed a computer program to estimate the depth to the basement. By applying the improved algorithm on synthetic and real data, we draw the following conclusions:

Determining the depth to the basement by developing an inverse algorithm to determine the shape of the causative bodies is perfectly possible.

The efficacy of the algorithm is that it is fully automatic in the sense that it improves the depth based on the differences between the observed and calculated magnetic anomalies until the calculated anomalies mimic the observed ones.

The applicability and validity of this improved algorithm is also demonstrated on both synthetic and real data. For the synthetic data case, the obtained results coincide well with the actual model depth, even for the model including noise. Application on actual data shows that the structure basement of the study area is relatively consistent with the terrain of the oceanic crust. It is the magnetic basement that tends to be raised and thinned as it reaches the deepest part of the ocean.

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