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Determining and detailing the structure model of the Earth's crust in the East Vietnam Sea deep basin and adjacent areas using new seismic, OBS and gravity data

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ABSTRACT

The East Vietnam Sea deep basin and its adjacent areas exhibit a complex geological landscape. In many locations, the marine geological structure remains poorly understood due to insufficient data, the presence of a thick seawater layer, and the geopolitical sensitivities among the countries in the region. This paper employs 3D modeling techniques alongside the analysis of new seismic data, Ocean Bottom Seismometer (OBS) data, gravity measurements, and other relevant information to determine the Cenozoic basement, Moho surfaces, as well as the uplift and depression zones of the Earth's crust. The findings of this study reveal several key insights: (1) In the oceanic crust area, the thickness of Cenozoic sediments is significantly greater, particularly along the sea floor spreading axis, with some locations reaching nearly 3 km; (2) This phenomenon is attributed to the gravity field along the spreading axis, which exhibits lower values compared to the surrounding areas, indicating a greater sediment thickness and lower sedimentary density; (3) The Moho surface in the oceanic crust is relatively flat but exhibits a rising trend along the spreading axis, reaching depths of up to 9 km in certain areas. Beneath the oceanic crust, the granite layer is absent, the basalt layer is very thin, and the upper mantle layer is elevated. These results have been validated using the available seismic and OBS data from the region. The newly constructed model represents a significant advancement beyond previous studies and provides a more detailed and accurate depiction of the Earth's crust structure in the East Vietnam Sea, enhancing both the thickness values and the structural morphology of the fundamental boundary surfaces.

Keywords: Seismic, OBS, gravity data, Cenozoic basement, Moho surface.

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INTRODUCTION

There have been both domestic and international studies on the structure of the Earth's crust in the deep basin of the East Vietnam Sea. These studies have generally outlined the deep geological structure, particularly regarding boundaries and faults. However, the topic is still being debated due to a lack of comprehensive data. Therefore, it is important to include new updated data into the geological model to enhance understanding of the structural geomorphology in this region. Additionally, several key issues need to be addressed, such as deep sea mining, the continent-ocean boundary (COB), the continent-ocean transition zone (COTZ), and the correlation between sub-basins within the deep basin of the East Vietnam Sea.

The geological and geophysical data of the East Vietnam Sea have been utilized for various purposes, including structural geology research, mineral exploration, the design and construction of marine structures, as well as natural hazard prediction and prevention. This study primarily relies on a database encompassing bathymetry, Cenozoic sedimentary data, and gravity anomalies, mostly derived from shipboard measurements conducted in the 1990s and subsequent years through joint collaborations involving Russia, France, Germany, the United States, Japan, and Vietnam. Additionally, the Institute of Marine Geology and Geophysics has undertaken national projects under the marine research program from 1987 to 2023, resulting in the collection, processing, and supplementation of valuable geological and geophysical data. In recent years, researchers have also determined the depth to the Moho surface through various studies interpreting Ocean Bottom Seismic (OBS) data, which serves as a key correlation parameter for modeling the Earth's crust. Furthermore, satellite gravity anomaly data is regularly updated by the University of California, San Diego (United States), with a resolution of 1′ × 1′ (Sandwell and Smith V29.1), along with global bathymetric data at the same resolution (Sandwell and Smith V19.1). Consequently, this geophysical data source offers uniform resolution, extensive coverage, and suitable accuracy, making it effectively applicable for studying the geological structure of the East Vietnam Sea [1–5].

This article utilizes new seismic, OBS, gravity data, and other recent information to enhance, refine, and improve the accuracy of the Earth's crust structure model. This model addresses both thickness values and the structural morphology of the fundamental boundary surfaces in the East Vietnam Sea deep basin and its surrounding areas. The study area is located within the coordinates of 8°00′00″N to 17°00′00″N latitude and 107°00′00″E to 115°00′00″E longitude (Fig. 1).

DATA USED

Gravity data

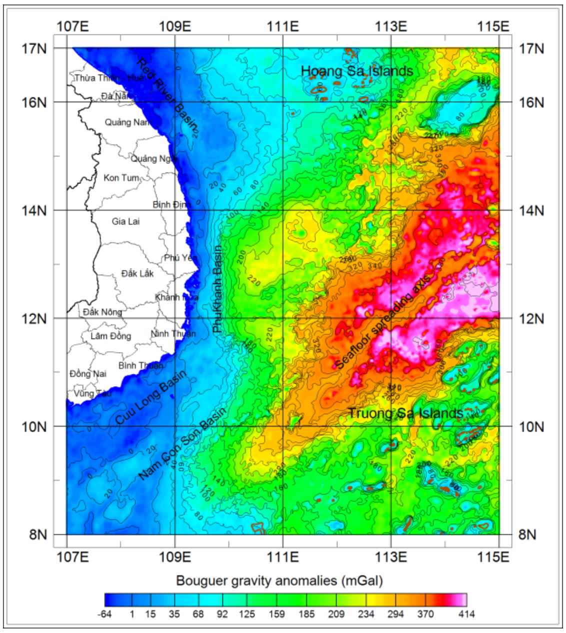

Figure 1. Bouguer gravity anomalies (mGal)

The gravity data for the East Vietnam Sea deep basin and its adjacent areas has primarily been collected through joint shipboard surveys conducted by Vietnam in collaboration with foreign countries, including Russia, the USA, France, and Germany, along with satellite-derived marine gravity measurements. The accuracy and resolution of altimetry-derived marine gravity anomalies are influenced by various factors, such as sea surface conditions and proximity to land. Significant contributions to the dataset include results from Russian-Vietnamese expeditions aboard the R/V Professor Gagarinsky (1990–1992), R/V Professor Polshkov (2007–2008), and R/V Professor Larentyev (2019), as well as data from the international marine gravity database, which serves as a primary source for shipboard data. Additionally, a substantial collection of gravity data is archived at the International Gravimetric Bureau (BGI) in France. In this paper, the authors employ the methods and results proposed by Tran Tuan Dung et al., (2018), along with a newly updated gravity dataset, to enhance the accuracy of marine gravity anomalies [5–7] (Fig. 1).

The Bouguer gravity anomaly exhibits significant variation, with amplitudes reaching up to several hundred mGal (Fig. 1). In this study, the Bouguer correction of the gravity data using an crust's mean density of 2.67 g/cm^3 and sea water density of 1.03 g/cm^3. The intensity of the anomaly tends to increase gradually from the continental shelf to the deep basin of the East Vietnam Sea. The range of variation in the anomalous field spans from -64 to 414 mGal, with the maximum value located in the deep basin and the minimum on the continental shelf. The negative anomalies, characterized by small amplitudes of several tens of mGal on the continental shelf, are believed to be closely associated with sedimentary basins. In the deep basin, an anomalous strip extends in a northeast-southwest direction, likely resulting from seafloor spreading.

Seismic data, bathymetry and Cenozoic sediment

In this study, seismic data were collected from marine surveys conducted by Vietnam in cooperation with international partners. In recent years, these collaborative marine survey projects have significantly enriched the geological and geophysical dataset, particularly regarding seismic exploration, providing enhanced detail and accuracy. This study utilizes interpreted results from several previous projects, including AW-HS, PK-3, PGS-8, PGS-9, WA-74, NOPEC-93, VOR-93, SEAS-95, SEAS-TC, TC-93, TC-95, TC-98, TC-03, TC-06, VGP-09-08, PV, STC-6, CPV-05, CPV-07, PKBE-07, CSL07-0808, JMSU05-07, as well as Ocean Bottom Seismometer (OBS) profiles [8–11]. These valuable seismic data sources are combined with gravity data to identify the Cenozoic basement and Moho surfaces (Fig. 2). Detailed studies have been applied using seismic reflection and OBS sections that passed through the East Vietnam Sea deep basin [4, 11].

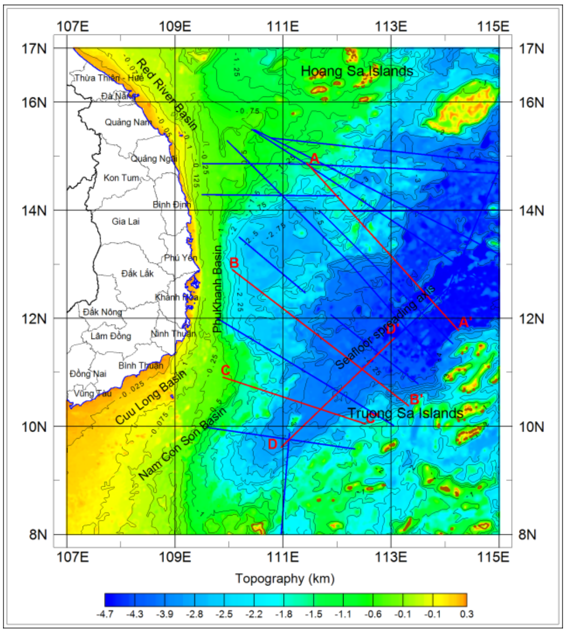

Figure 2. Topography, seismic and OBS (AA')profiles [4]

The seafloor topography in the study area is generally complex and diverse, reflecting the characteristics of marginal seas. The seafloor topography transitions from the continental shelf (up to the depth of 500 m), to the continental slope (up to the depth of 3,000 m), and finally to the deep basin in the central area (over the depth of 4,000 m). The outer boundary of the continental slope in the East Vietnam Sea marks the transition from continental crust to oceanic crust. The central area is surrounded by abyssal plains interspersed with ancient continental remnants (Truong Sa and Hoang Sa Islands), and deep-water troughs that represent ancient subduction zones [11].

Bathymetric data in the East Vietnam Sea deep basin and its adjacent areas have primarily been collected through joint shipboard surveys conducted by Vietnam in collaboration with foreign countries, as well as through numerous national projects undertaken by the Institute of Marine Geology and Geophysics and other organizations. The altimeter-derived marine gravity and bathymetric grid, featuring a 1' x 1' interval, was produced by Sandwell et al., (2020) [6, 7] (Fig. 2).

Cenozoic sediments are referenced from previous studies, revealing that the continental shelf is covered by a sediment layer of considerable thickness, reaching over 13 km in some areas, unconformably overlying rocks of various ages. The thickness of the sediment layer is greatest in regions where Cenozoic basins are formed, particularly in sediments from the Neogene and Quaternary periods. However, the depth and thickness of Cenozoic sediments in the East Vietnam Sea deep basin and surrounding areas remain controversial and require further clarification [4].

METHODS APPLIED

Correlation and regression method

The objective of this method is to examine the relationship between two quantities: the depth of the Cenozoic sedimentary basement (variable *Y*) and the Bouguer gravity anomaly (variable *X*) using correlation and regression analysis. This analysis will determine the strength of the relationship between variables *Y* and *X*, assessing whether they are connected and to what degree. The closeness of this relationship is represented by the correlation coefficient. Once it is established that a correlation exists, regression analysis is performed to identify the linear or non-linear relationship mathematically, allowing us to predict one quantity based on the other [4, 12].

In this case, the source of the seismic data (referred to as quasi-standard data) is typically limited to a narrow range, while the gravity data is more widely distributed. Consequently, the regression equation enables the determination of the Cenozoic basement depth across a broader area, extending beyond the limitations of the quasi-standard data.

The correlation coefficient R is used to assess the relationship between *Y* and *X*. A relationship is considered stronger when the R value approaches ±1 ($-1 \le R \le 1$).

The correlation coefficient is calculated using the following formula [12]:

$$R = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2 \sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}$$

in where: $\overline{X}$ average value of variable *X*; $\overline{Y}$ average value of variable *Y*; X_i and Y_i represent the *i*-th values of the Cenozoic sedimentary basement depth and the Bouguer gravity anomaly field, respectively

Correlation assessment criteria:

$|R|$> 8: Strong correlation; $|R|$= 0.4–0.8: Moderate correlation; $|R|$ < 0.4: Weak correlation.

$0 < R \le 1$: Positive correlation (*X*↑, *Y*↑);

$-1 \le R \le 0$: Negative correlation (*X*↑, *Y*↓)

The linear regression equation is determined as follows:

$$Y = aX + b$$

The coefficients *a* and *b* are determined through the least squares method.

Studies indicate that filtering the gravity field can help identify parameters which are more closely related to underlying geological structures [12–14]. In order to eliminate interference from geological bodies near the surface, the Bouguer gravity anomaly is low-pass filtered at a wavelength of λ = 5 km [4].

3D gravity anomaly modeling method

The method of determining geological structure through 3D gravity anomaly modeling has been of interest and application to geophysicists for many decades. One significant application of this method is to identify fundamental structural features in the Earth's crust. Numerous researchers worldwide have developed various 3D forward-reverse algorithms to model and delineate density boundaries within the crust. Notable contributions include Parker (1973) [15], Bhaskara and Ramesh (1991) [16], and Oldenburg (1974) [17]. Based on the Parker-Oldenburg algorithm, a variation of the 3D gravity anomaly model was proposed, which has been implemented in Geosoft software to perform calculations of 3D gravity model in the frequency domain [18].

Deep boundary surfaces within the Earth's crust are determined using GM-SYS 3D. The algorithm is described as follows [18]:

$$F\{\Delta g\}(x) = -2\pi G\rho e^{-kz_0} \sum_{n=1}^{\infty} \frac{k^{n-1}}{n!} F\{h^n(x)\}$$

in where: $F\{\}$ is the Fourier transform; G is the gravitational constant; Δg is the Bouguer gravity anomaly; ρ is the density contrast across the boundary; k is the wavenumber; z_0 is the mean depth; and $h(x)$ is the depth of the boundary.

The model of the Earth's crustal structure is assumed to consist of the following layers:

Continental Crust and Transitional Crust: This structure includes a seawater layer, Cenozoic sediments, a granite basement layer, and a basalt layer.

Oceanic Crust: This structure comprises a seawater layer, Cenozoic sediments, and a basalt layer (with the granite layer absent).

In the 3D model, the densities of the rock layers are defined as follows: Seawater layer: D = 1.03 g/cm^3; Cenozoic sediment layer: D = 1.80–2.45 g/cm^3; Granite basement layer: D = 2.65–2.80 g/cm^3; Basalt layer: D = 2.80–2.95 g/cm^3; Upper mantle layer: D = 3.3–3.33 g/cm^3. This density data is used as input for a 3D computational model to determine the Cenozoic basement surface and the Moho surface [4, 18, 19].

Construction of 2½D geological-geophysical structural sections

In order to achieve a detailed understanding of the geological structure, a 2½D gravity anomaly model was applied to several specific sections that align with the seismic reflection profiles. In the 2½D model, the densities of the rock layers were chosen to be consistent with those in the 3D model described earlier. GM-SYS software, an interactive gravity modeling system developed by Northwest Geophysical Associates (NGA), is used for this purpose. This forward modeling software both estimates gravity changes and provides interactive modeling of 2½D geological cross-sections that run perpendicular to the structure's strike, allowing for gravity calculations and visualizations. For modeled features with a limited strike length, 2½-dimensional corrections can be implemented based on an algorithm of Rasmussen and Pedersen (1979) [18, 20].

In the computational model, when fitting the calculated values to the observed values of gravity, we can use either Freeair gravity or Bouguer gravity. Therefore, here, when using Bouguer anomaly values in the model, the mean crustal density of 2.67 g/cm^3 and the seawater density of 1.03 g/cm^3 must be specified before entering the data, which will set the rock density of the background to the Bouguer reduced density. The computational model will self-correct converting the density of the seawater block to a density contrasting with the Bouguer corrected density. Typical densities for different rock types can be found in Dobrin and Savit (1988) or many other references [21, 22].

The results of the modeling calculations are presented in geological-geophysical structural cross-sections and are thoroughly compared with previously published structural models. The agreement between calculated anomalies and observed anomalies serves as a criterion for model calibration. The method's efficiency is measured by its ability to converge to a specified error threshold after a defined number of iterations. The mean error method is performed to evaluate the alignment between observed and calculated anomalies, as outlined in GM-SYS.

RESULT AND DISCUSSION

Cenozoic basement

In this study, the regression correlation method is specifically applied in deep basin and locations with limited or no seismic data. The correlations is evaluated across 10,370 points representing the depth to the Cenozoic basement surface (derived from reflection seismic and OBS profiles) alongside the corresponding gravity field values (obtained from low-pass filtered Bouguer gravity anomalies at a wavelength of λ = 5 km). At this filtering level (λ = 5 km), the correlation coefficient between the two datasets is maximized at R = -0.8373, indicating a strong negative linear correlation.

The linear regression equation is determined as follows:

$$Z = -0.01513 * \Delta g + 10.091$$

In this equation, Z is the depth of the Cenozoic sedimentary basement; and Δg is the Bouguer gravity anomaly. This equation specifically reflects the relationship between the depth of the Cenozoic basement surface and gravity anomalies in the East Vietnam Sea deep basin, particularly where seismic data is sparse or absent. In other words, in regions with available seismic data, those data should be prioritized; where data is lacking, the linear regression equation should be employed.

Using the depth of the Cenozoic basement surface derived from this regression correlation method, in conjunction with data from previous studies [9, 14], 2.5 km × 2.5 km grid of Cenozoic sedimentary thickness has been established across the entire the East Vietnam Sea deep basin and its surroundings (Fig. 3). This grid data will serve as an input for the 3D gravity anomaly model described in the following section.

The results indicate that sediment thickness reaches maximum in areas where Cenozoic basin are present. The continental shelf is characterized by a thick sediment layer, with some regions exceeding 13 km in thickness. Sedimentary density varies between 1.8 and 2.45 g/cm³. Notably, the sedimentary density is lower in the central part of the East Vietnam Sea basin along the spreading axis than in other areas.

In the Phu Khanh basin, the sediment thickness is approximately 1 km at the edges but rises to nearly 12 km at the basin's center. The Cuu Long basin exhibits clear differentiation, with maximum sediment thickness of 8–9 km in the central region, gradually decreasing towards the edges. In the Nam Con Son basin, sediment thickness varies significantly, reaching 7–13 km at the center. Conversely, in the Hoang Sa and Truong Sa Islands, the sediment thickness ranges from 0.5 km to several kilometers.

In the East Vietnam Sea deep basin, sediment thickness is relatively thin, ranging from 1–3 km; along the ocean floor spreading axis, the Cenozoic basement surface is notably depressed, with the sediment thickness reaching up to 3 km (Fig. 3).

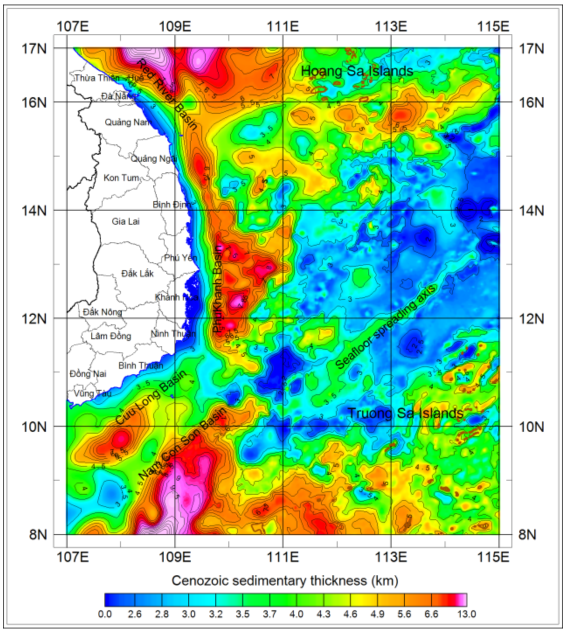

Figure 3. Cenozoic sedimentary thickness (km)

Moho surface

Input layers collectively support the determination of the Moho surface within the 3D model as follows (Fig. 4):

Complete Bouguer gravity anomaly (Fig. 1)

Seafloor topography (Fig. 2).

Cenozoic sediment: thickness, density (Fig. 3).

Initial Assumed Moho surface: A reference plane is set at a depth of 20 km (this depth can be adjusted as needed). Constraint depth points of Moho surface are incorporated on this plane based on seismic OBS data (Fig. 2, Fig. 4).

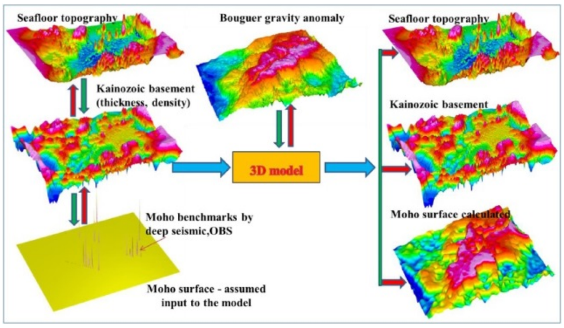

Figure 4. Illustration for the process of building and calculating a 3D model of the Earth's crust

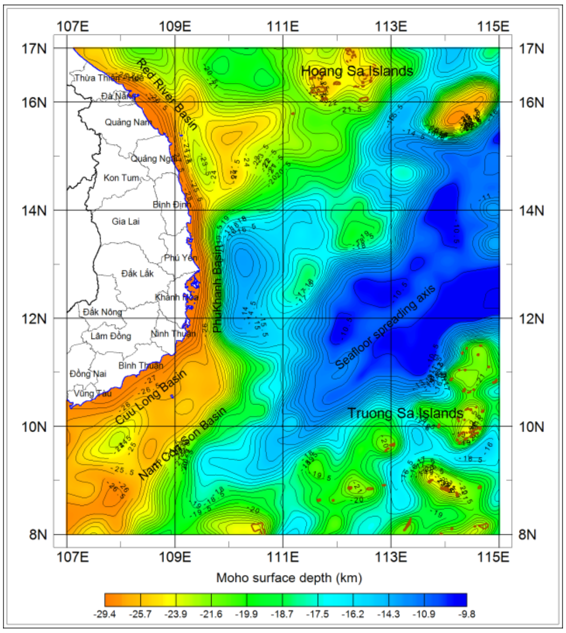

Figure 5. Depth of moho surface

The calculation process for the 3D model is repeated multiple times, with the number of iterations set to 5. During this process, the initial Moho surface is calibrated based on the gravity anomalies and other input parameters of the model. The calculation steps will automatically terminate once the model's error converges to an acceptable value. Throughout the calculations, constraint depth points of Moho surface remain fixed at their specific values, ensuring the integrity of these reference points. The final result is the creation of a new Moho surface structure that preserves the reference points (Fig. 5).

Moho's structural features can be summarized in general as follows:

From the detailed calculation results, it is observed that the depth of the Moho surface varies between 9.8 km and 29.4 km. On the continental shelf, Moho depths generally increase as they approach continents.

In the East Vietnam Sea deep basin, which consists of oceanic crust, the Moho surface tends to be comparatively higher than the surrounding areas, particularly in the eastern central region, where depths range from 9.8 km to 11 km. In this area, the granite layer is absent, and the basalt layer is significantly thin (refer to the OBS cross-section in Fig. 6). In the Hoang Sa and Truong Sa Islands, the Moho surface exhibits significant variations in depth, with uplifted blocks interspersed throughout, averaging a depth of 20 km to 25.5 km. On the Central and Southern continental shelf, the Moho isobath generally increase from 22.5 km offshore to 30 km onshore.

Within the Cenozoic basins, the Moho surface often appears higher than the surrounding area, suggesting that these basins are developed on attenuated continental crust or are associated with uplift in the mantle beneath (Fig. 5).

Geological-geophysical structural cross-sections

Several standard geological-geophysical structural cross-sections were constructed based on geological, seismic, and OBS data (Fig. 2).

OBS (A-A') Cross-Section (Fig. 6): This section extends 459.6 km. The 2½D model constructed from the OBS data includes the following layers: The seawater layer with a density of D = 1.03 g/cm^3. The Cenozoic sediment layer whose thickness varies from 1 to 9 km, with a density ranging from D = 1.80 to 2.20 g/cm^3. The granite layer, present in the continental crust but absent in the oceanic crust, where the Moho surface is relatively high. The average density of the granite layer is D = 2.80 g/cm^3. The basalt layer with an average density of approximately D = 2.95 g/cm^3. The upper mantle layer characterized by a variable density of D = 3.30 to 3.35 g/cm^3.

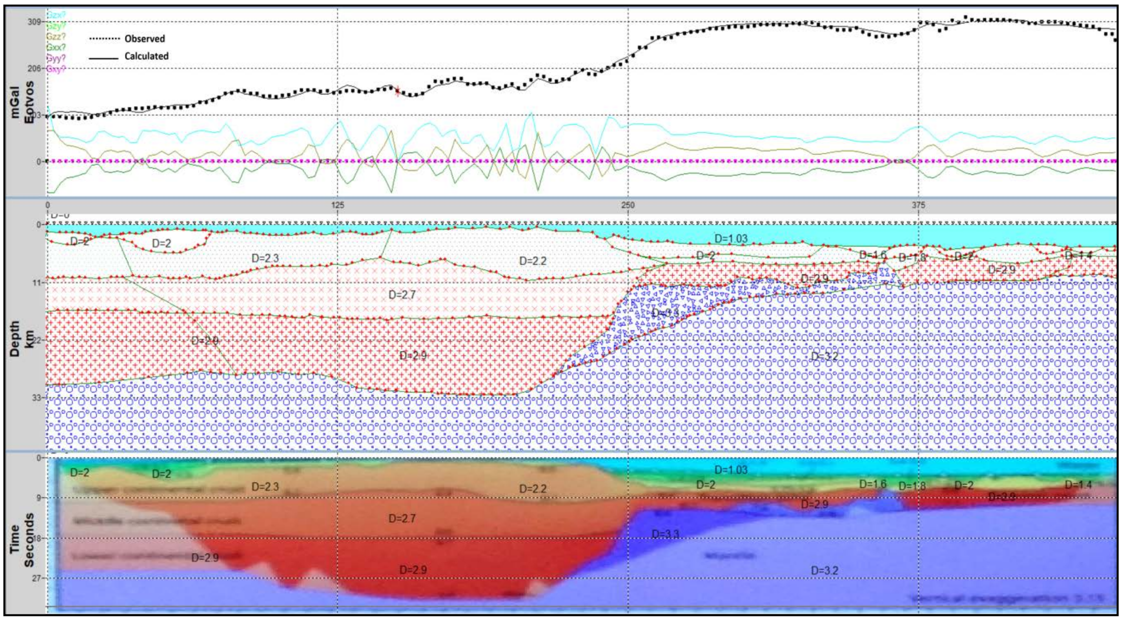

Figure 6. Geological-geophysical structural cross-sections along with OBS proflie A-A’

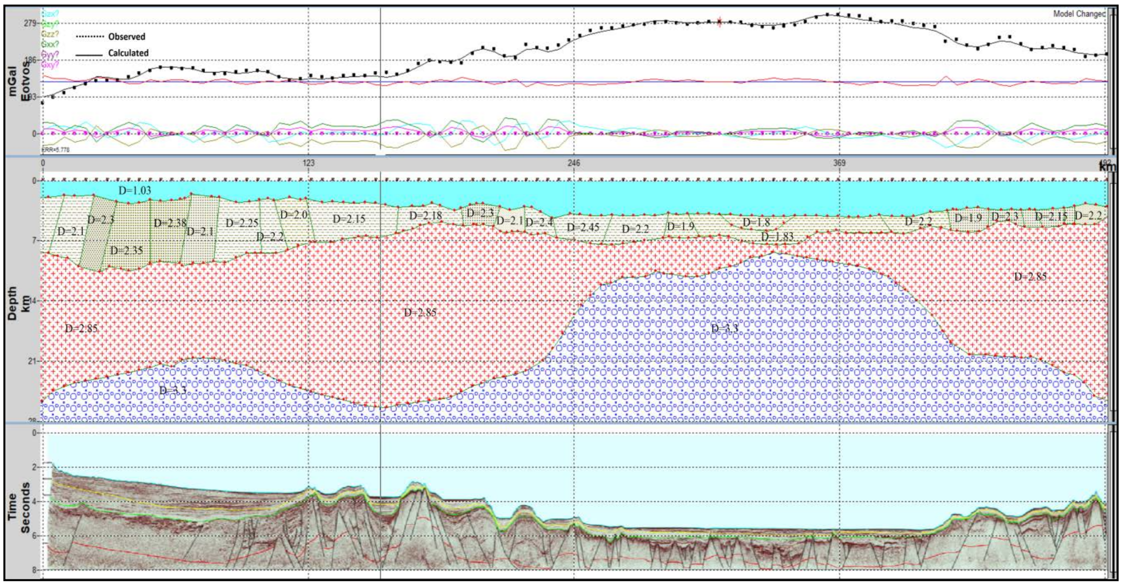

Figure 7. Geological-geophysical structural cross-sections along proflie B-B’

B-B’ Cross-Section (Fig. 7): This section extends 493 km, with Bouguer gravity anomaly values ranging from +77.7 mGal to +301.4 mGal. The seawater layer has a density of D = 1.03 g/cm³. The sedimentary layer, which extends from the seabed to the Cenozoic surface, consists of small blocks with densities ranging from D = 1.8 to 2.4 g/cm³. This sedimentary layer is thinner in the central area of the East Vietnam Sea, where it intersects deep basin with a relatively flat terrain. Its thickness varies from 1.5 km to over 11 km, with the maximum thickness exceeding 11 km located in the Phu Khanh basin. The basalt layer has an average density of approximately D = 2.9 g/cm³. The final layer is the upper mantle, with an average density of D = 3.33 g/cm³. The Moho surface exhibits significant changes, gradually rising from the continent to the East Vietnam Sea deep basin.

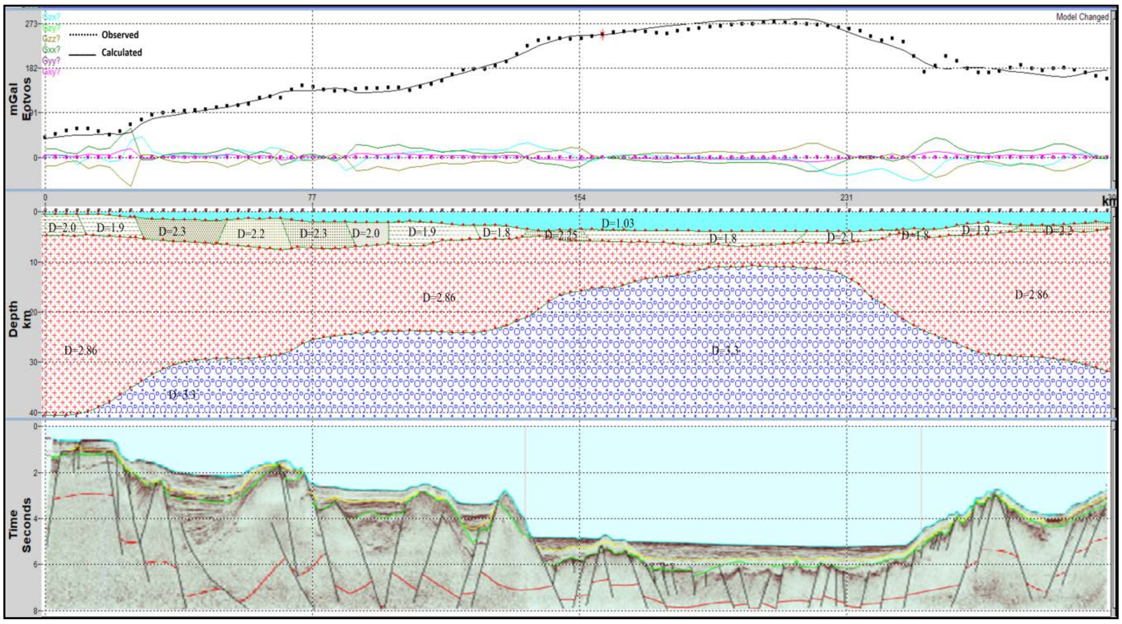

Figure 8. Geological-geophysical structural cross-sections along proflie C-C’

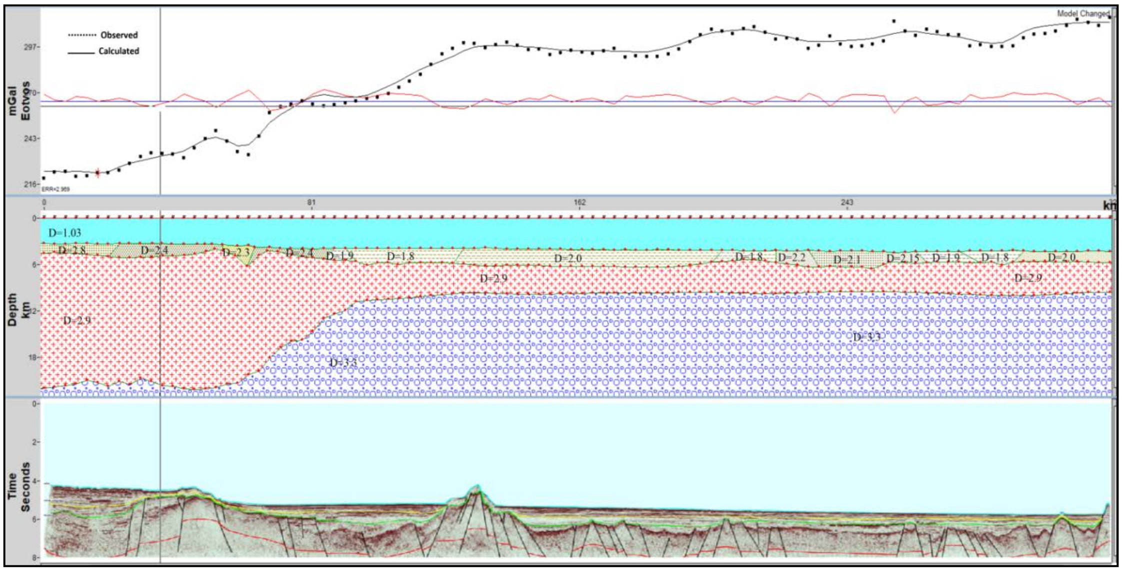

Figure 9. Geological-geophysical structural cross-sections along proflie D-D’

C-C’ Cross-Section (Fig. 8) extends 306 km, with Bouguer gravity anomaly values ranging from +32 to +275 mGal. This section includes a layer of seawater with a density of D = 1.03 g/cm³. The sediment layer is relatively thin, with densities varying from D = 1.9 to 2.33 g/cm³. The upper mantle layer has an average density of approximately D = 3.33 g/cm³. The depth of the Moho surface decreases significantly on both ends, reaching its highest point in the central of the cross-section. The peak of the Moho surface is located approximately 10 km below the sea level.

D-D' Cross-Section (Fig. 9) extends 322 km, with Bouguer gravity anomaly values ranging from +219 to +314 mGal. This section includes a seawater layer with a density of D = 1.03 g/cm³. The sediment layer is relatively thin, measuring between 1 and 2.5 km in thickness and exhibiting a density range of D = 1.81 to 2.44 g/cm³. The basalt layer varies in thickness from 4 km to 17 km, with a density between D = 2.8 and 2.9 g/cm³. The Moho surface exhibits significant changes in this area, marking the transition between the continental and oceanic crusts. In the oceanic crust region (deep basin), the Moho surface rises approximately 10 km below the sea level.

CONCLUSION

New sources of data on seismic reflection, OBS, bathymetry, and Bouguer gravity anomalies have been analyzed using regression correlation and 3D gravity anomaly modeling method. As a result, the key structural surfaces in the Earth's crust, including the Cenozoic basement and the Moho surface, have been identified and detailed for the entire the East Vietnam Sea deep basin and its surrounding areas.

The crustal structural model developed in this study presents several new important findings: (1) The thickness of Cenozoic sediments within the oceanic crust is notably greater, particularly along the oceanic spreading axis, where it reaches nearly 3 km in some locations; (2) The gravity field values along the spreading axis are lower than those of the surrounding areas. This is attributed to the increased sediment thickness in this region, which has a lower density compared to adjacent areas; (3) The Moho surface in the oceanic crust is relatively flat and tends to be elevated compared to surrounding regions, reaching depths of nearly 10 km in certain areas. Within the oceanic crust, the granite layer is absent, the basalt layer is very thin, and the upper mantle is elevated.

The newly constructed crustal structure model enhances and complements from previous studies. These findings contribute to a more comprehensive understanding of the modern crustal structure in the East Vietnam Sea, particularly regarding depth, and the structural morphology of fundamental boundary surfaces.

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