Pre-Cenozoic basement structure in the Truong Sa archipelago and sea deep basins

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Abstract

The structure of marine Cenozoic basement is a problem that has greatly concerned marine geologists and geophysicists engaged in geological study and oil-gas exploration. In this paper, the author has applied a methodology involving gravity data interpretation including frequency filtering, horizontal gradient and maximum horizontal gradient, to define clearly the structure and form of faults and uplift zones in basement as well as the seafloor spreading axis and crustal boundary in the Truong Sa archipelago and the East Sea deep basins.

These results allow some initial remarks concerning the structure of the Cenozoic basement in the Truong Sa archipelago and the East Sea deep basins to be made.

Introduction

The Cenozoic basement structure in the Truong Sa archipelago and the East Sea deep basin area have been studied for a long time, but such studies developed most strongly in recent decades when the process of oil-gas exploration became active. Especially, in recent years, when earthquake events have occurred, fault tectonics are increasingly considered by scientists. The structure of fault systems, uplift and depression zones of basement as well as crustal boundaries, which are possible features of the East Vietnam Sea, have been the subjects of previous studies by scientists both inside and outside Vietnam. Interpretation of gravity data, in combination with other recently acquired geological-geophysical datasets, is now possible in order to determine the nature of the structure of the Cenozoic basement.

In the study area, data derived from shipboard and satellite surveys are abundant. Using such gravity field and seismic data along with new methodologies and modern interpretation techniques allows us to determine the fault geometric parameters, fault zone characteristics and uplift and depression zones of basement with greater accuracy.

Overview of previous studies

In the period 1991 - 1995, in National Project KT-03-02, Bui Cong Que, Nguyen Giao et al. constructed geophysical maps, crustal deep cross-sections and geodynamic systems in the Vietnam continental shelf and the East Sea.

In the period of 1996 - 2000, in National Project KHCN-06-04, KHCN-06-12, Bui Cong Que, Pham Nang Vu, Nguyen Giao et al. (collaboration between Hanoi Institute of Oceanography and Vietnam Petroleum Institute) constructed geological-geophysical maps of the East Vietnam Sea and adjacent areas. Based on these data, deep crustal cross-sections, fault systems, geodynamic and geotectonic sketches were established in the Vietnam continental shelf, at a scale of 1:500.000 [2, 6].

The fault systems, tectonic and geodynamic activities in the Vietnam continental shelf and the East Sea have also been studied by Le Duy Bach (1987, 1990), Bui Cong Que (1985, 1990, 1999, 2000), Nguyen Dinh Xuyen (1996, 2004), Cao Dinh Trieu (1999, 2005), Phan Trong Trinh (2000), Nguyen Trong Tin (1997, 2005), Tran Huu Than (2003) and Tran Tuan Dung (2003, 2006) [2, 5, 7, 8].

In the recent years, in National Project KC-09-02, Bui Cong Que et al. (2001 - 2005) have collected and supplemented new datasets, which are satellite and shipboard data, from oil-gas companies I order to to construct a series of geological-geophysical maps (including gravity map). These data sources are very valuable and important for new studies of the geological structure and tectonics in the East Vietnam Sea.

Besides, studies of the geological structure of the East Vietnam Sea have also been carried out by scientists from outside Vietnam. In the 1970's, US geologists presented a study of tectonic structure in the tectonic context of the East Sea (Parke, 1971 - Emery, 1972). Hayes and Taylor (1978 - 1980) have published geophysical maps and structure of the Southeast Asian Sea. In 1989, Kulinic et al (Far-East geological Center, Soviet Union Academy of Science) resented a monograph, "Earth crustal evolution and tectonics in Southeast Asia". The monograph integrated results of studies of geology-geophysics such as tectonics, crustal structure and geodynamics. The structural characteristics of the main deep crustal boundaries, fault system and the tectonic and geodynamic activities involved have been illuminated by the studies of Hayes (1975, 1980), Parke (1985), Wujimin (1994), Lieng Dehua (1993), Rangin (1986,1990), Watkins (1994) and Hinz et al., (1985, 1996). In the years from 1980 - 1990, French scientists such as as P. Tapponnier, A. Briais et al. introduced some tectonic-geodynamic models that involved the movement of the Indian subcontinent and Asian plate [2, 6].

Gravity data

The gravity data in the East Vietnam Sea is mainly collected from joint shipboard surveys between Vietnam and foreign countries such as Russia, America, France,

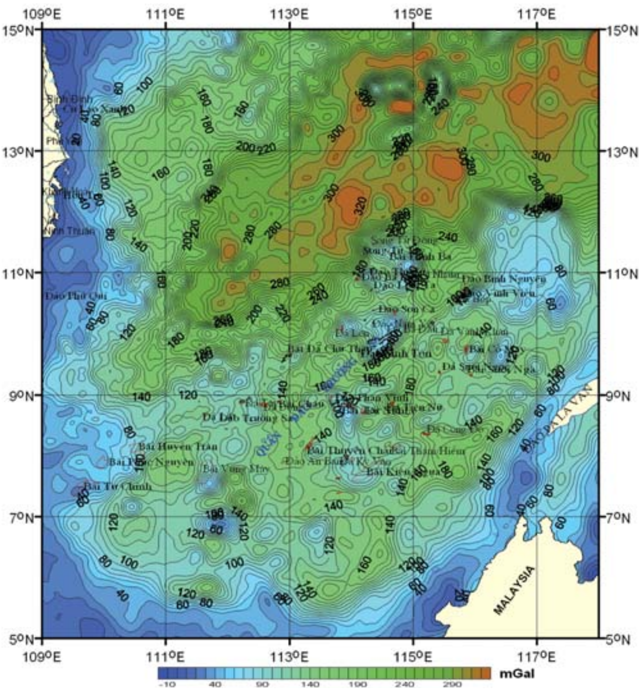

Fig.1. Bouguer gravity anomalies in the Truong Sa archipelago and the East Sea deep basins

Germany and Japan… Also the author has used the gravity data from National Research Projects which are carried out by the Hanoi Institute of Oceanography and the Vietnam Petroleum Institute and others; such as project 48B-III-2 (1986 - 1990), KT-03-02 (1991 - 1995), KHCN-06-04 (1996 - 1998), KHCN-06-12 (1999 - 2000), and KC-09-02 (2001 - 2005). These projects have revealed new and useful results. A gravity anomaly map at a scale of 1:500.000 has been constructed for the whole study area [2, 6] (Fig.1).

On this gravity map (Fig. 1) it can be seen that the gravity anomalies are quite high. The range of the various gravity anomalies is within -10 to +300mGals. Theset can be simply depicted as follows:

In the Western part of the study area, the gravity anomalies are quite small and with varied range from -10 to + 50 mGals. There are also some small gravity anomalies that appear scattered in the central and South-Eastern part. Here, the gravity anomalies are characteristic of gravity anomalies of continental crust alternating with sedimentary basins. The main trends of the gravity anomalies are meridional and sub-meridional.

In the central and Southern part of the area, it can be seen very clearly that gravity anomalies vary stably from +100 to +200mGals. These anomalies have a blocky shape and developed on transitional crust between continental and oceanic crust. They clearly manifest the blocky geological structures in the archipelago area.

In the Northern part, the gravity anomalies are high, up to +300mGals. These are gravity anomalies of the oceanic crust. Here, gravity anomalies have a banded form and developed in a Southwest - Northeast direction (Fig.1). Also, the major faults and sea-floor spreading axis are clearly indicated on the gravity map by gravity gradient bands in a Southwest - Northeast direction, some of hundreds of kilometer length.

Determination of Cenozoic basement structure

In this study, the faults and uplift zone on the seafloor surface are not discussed. It is concentrates on determination of the Cenozoic basement structure and faults at different, greater depths.

Frequency filtering of gravity field

In general, the high frequency component of the gravity field with short wavelength relates to geological bodies at small depth. On the contrary, the low frequency component of the gravity field, with long wavelength, reflects geological structures at greater depth. In this study, the frequency filtering method is applied to separate the gravity effect of Cenozoic sedimentary layers from the total gravity field. After that, residual gravity fields can be used to determine the density boundaries, uplift zones and fault characteristics in basement or at greater depth.

To select a suitable wavelength λ for the process of frequency filtering of the gravity field, the following steps were used:

- *Step 1:* Constructing the model of Cenozoic basins based on seismic data (for area for which seismic data is available)

- *Step 2:* Calculating gravity effect to determine the residual gravity field caused by the Cenozoic sedimentary layers.

- *Step 3:* Carrying out the filtering of the gravity field at different wavelength λ (from 20 - 150km). Comparing residual gravity fields at these wavelengths λ with residual gravity field at *step 2*, one by one. The comparative result with the smallest error will is used to select wavelength λ.

From the results of the three steps above, a filter with wavelength λ = was selected to separate the gravity effect that is likely caused by the Cenozoic sedimentary layer. With the wavelength selected, the low frequency gravity anomaly is calculated for the whole area by the following formula [6]:

$$\Delta g_{LPF}(x,y) = \frac{1}{(2\Pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Delta g(\lambda_x,\lambda_y)p(\lambda_{cutoff})\exp\left[i(\lambda_x x+\lambda_y y)\right]d\lambda_x d\lambda_y$$

With Gauss filter:

$$p(\lambda_{cutoff}) = 1, |\lambda| \le \lambda_{cutoff} \qquad p(\lambda_{cutoff}) = 0, |\lambda| > \lambda_{cutoff}$$

After separating the gravity effect of the Cenozoic sedimentary layer from the total gravity field, the remaining gravity anomalies are used to define the horizontal gradient and maximum horizontal gradient (magnitude and vector) for the Cenozoic basement and greater depths in the Truong Sa archipelago and the East Sea deep basins [3], [6], [7].

Horizontal gradient and maximum horizontal gradient of gravity anomalies

In this paper, the Bouguer gravity anomalies and residual gravity anomalies filtered at wavelength λ = 50, 100km are used to calculate the horizontal gradient and the maximum horizontal gravity gradient, respectively.

Calculating steps are as follows:

- *Step 1:* Calculating magnitudes of the horizontal gradient at the above-mentioned filtering levels by selected formula along *x* and *y* direction of data grid [6]:

$$H[\Delta g]_{i,j} = \sqrt{\left(\frac{d\Delta g(x,y)}{dx}\right)^2 + \left(\frac{d\Delta g(x,y)}{dy}\right)^2}$$

Δg(*x*,*y*) is gravity anomaly at each grid intersection. $H[\Delta g]_{i,j}$ is the horizontal gradient at each grid intersection. In fact, the horizontal gradient often reflects faults, edges of vertical bodies or igneous intrusive blocks.

- *Step 2:* Calculating magnitudes of maximum gravity horizontal gradient [1].

The maximum horizontal gradient is calculated by using magnitudes of the horizontal gradient at *step 1* above. The locations of the maximum horizontal gradient on the data grid are defined by comparing $H[\Delta g]_{i,j}$ at each grid intersection with its eight nearest neighbors in four directions. The comparison follows the below-mentioned inequalities [1], [6]:

$$H[\Delta g]_{i-1,j} < H[\Delta g]_{i,j} > H[\Delta g]_{i+1,j}$$
$$H[\Delta g]_{i,j-1} < H[\Delta g]_{i,j} > H[\Delta g]_{i,j+1}$$
$$H[\Delta g]_{i+1,j-1} < H[\Delta g]_{i,j} > H[\Delta g]_{i-1,j+1}$$
$$H[\Delta g]_{i-1,j-1} < H[\Delta g]_{i,j} > H[\Delta g]_{i+1,j+1}$$

Here, a counter N is increased by one for each satisfied inequality. At any intersection of data grid, the maximum number of satisfied inequalities is N = 4 and minimum is N = 0. Some previous studies have shown that locations and magnitudes of the maximum horizontal gradient are fully defined when N ≥ 2 [1, 4, 6].

In this study, when N ≥ 2 then locations and magnitudes of the maximum horizontal gradient $H[\Delta g]_{i,j}$ are defined by a second-order polynomial as follows:

$$X_{Max} = \frac{bd}{2a}; \qquad G_{Max} = aX_{Max}^2 + bX_{Max} + H[\Delta g]_{i,j}$$

Here, *d* is the distance between grid intersections, *a*, *b* are developed coefficient of the polynomial, which are calculated from the grid of gravity anomalies [1].

- *Step 3:* Determining directions of the maximum horizontal gradient vector

Direction of the maximum horizontal gradient vector is determined by a formula as follows:

$$\alpha = arctg\left[\frac{\frac{d\Delta g(x,y)}{dy}}{\frac{d\Delta g(x,y)}{dx}}\right]$$

The maximum horizontal gradient manifests clearly the rock density boundaries, of course, from a certain point of view, it can be said that they are faults. The maximum horizontal gradient vector has a very special significance in defining spatial structure of the faults. The faults are often displayed by bands of the maximum horizontal gradient vectors in the same direction. The rock blocks, which have the higher density compared with that of the surroundings, are shown by the maximum horizontal gradient vectors that trend outward from the center of the blocks [1, 4, 6]. Analyzing and linking the locations and magnitudes of the maximum horizontal gradient by suitable methods will give a general picture of fault distribution, uplift zones in the Cenozoic basement and at greater depth concerning their spatial locations and developed directions.

Results

The horizontal gradient magnitudes as well as locations and directions of the maximum horizontal gradient vectors of the Bouguer gravity anomalies and of the gravity field filtered at wavelength λ = 50 and 100km are calculated and are represented on the Figs. 2, 3, 4, respectively.

On the Fig.2, the distributions of the horizontal gradient magnitudes, locations and directions of the maximum horizontal gradient vector of the Bouguer gravity anomalies are shown. These distributions, caused by near-seafloor geological structures, are very complicated and multiform. The Fig.2 gives us a general view about local geological structure, uplift and depression blocks, also possible basalt blocks and fault systems. However, it is very difficult to link these structures together.

Fig.3 also shows the distributions of the horizontal gradient magnitudes, locations and directions of the maximum horizontal gradient vector of the gravity field filtered at wavelength λ = 50km (it is reckoned as the distribution in Cenozoic basement). With respect to the study of faults based on gravity data, then the above-mentioned distributions are the distributions of the faults system and rock density boundaries as well. The fault systems are displayed by bands of maximum horizontal gradient vectors. Although the distribution of the maximum horizontal gradient vectors are still quite complicated, Fig.3 clearly indicates the main faults as well as density boundaries, uplift and depression blocks and geological structures in the area (Fig.3).

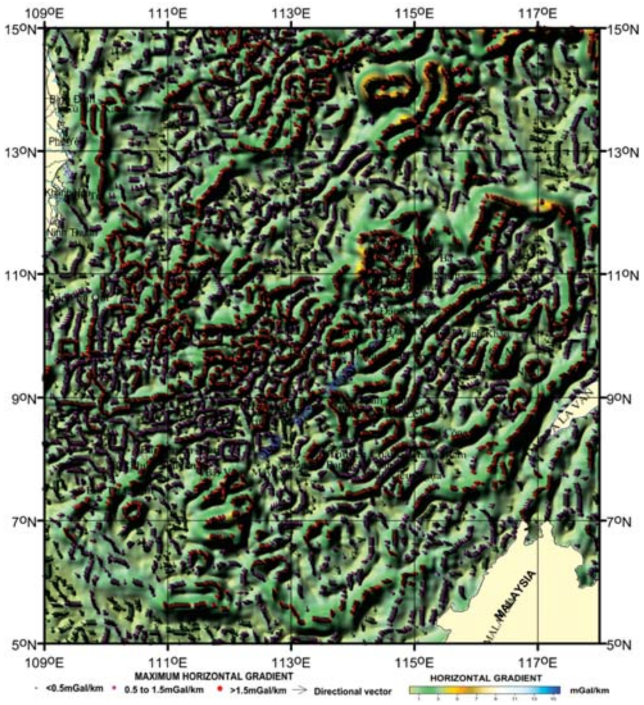

__Fig.2.__ Horizontal gradient magnitudes and maximum horizontal gradient vector of Bouguer gravity anomalies

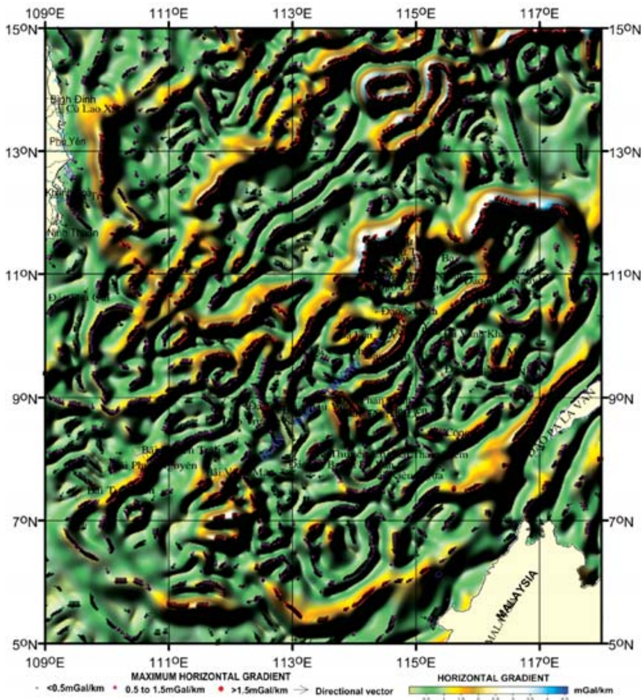

__Fig.3.__ Horizontal gradient magnitudes and maximum horizontal gradient vector of gravity anomalies (filtered at wavelength λ = 50km)

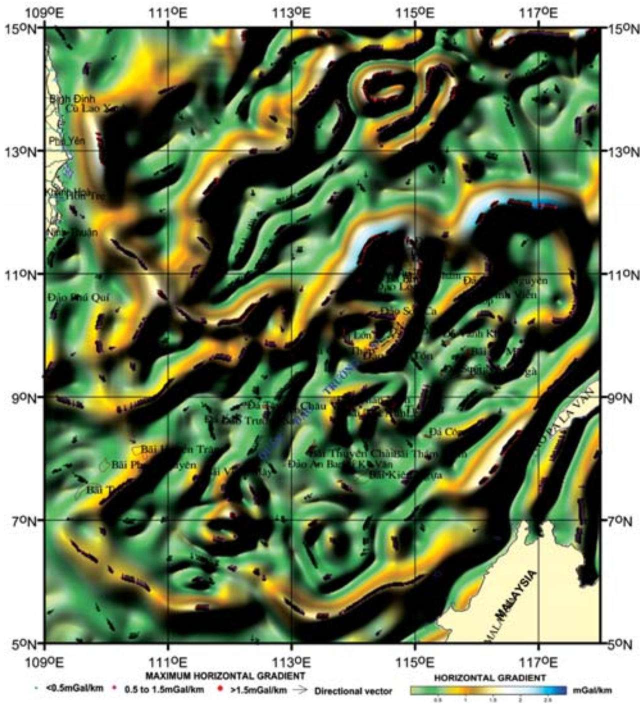

Fig.4. *Horizontal gradient magnitudes and maximum horizontal gradient vector of gravity anomalies (filtered at wavelength λ = 100km)*

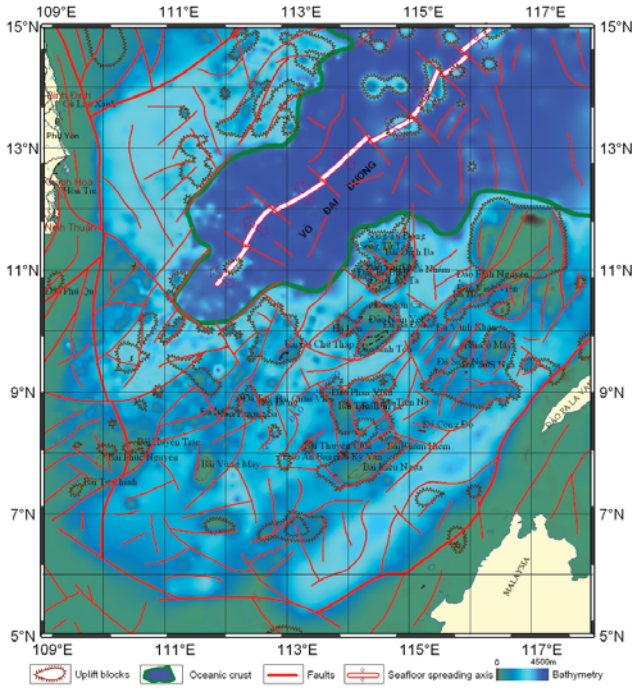

Fig.5. *Structure of Pre-Cenozoic basement in the Truong Sa archipelago and in the East Sea deep basin area*

On the Fig.4 are shown the horizontal gradient magnitudes, locations and directions of the maximum horizontal gradient vector of the gravity field filtered at wavelength λ = 100km. With this wavelength, we only the deep faults, regional structural blocks, crustal boundaries and sea-floor spreading axis are seen. The faults and structures at smaller depths have almost vanished. In Cu Lao Xanh a deep fault appears that runs along the Southern part of the Hoang Sa archipelago and meets the South Hai Nam fault in its Eastern part. In Fig. 4 also can be seen very clearly the change in direction of the 109^0 meridional fault after going through the Tuy Hoa shear zone. The main fault systems, which separate individually the sedimentary basins, are also represented very clearly in the Fig.4.

This study has analyzed and linked the results obtained, along with the bathymetry, seismic data and other geology-geographical data, to construct the fault systems, uplift and depression structures in the Cenozoic basement, the sea-floor spreading axis and crustal boundaries in the Truong Sa archipelago and the East Sea deep basins (Fig.5). The structural characteristics of the Cenozoic basement are depicted as in Fig.5.

The East Sea Western faults system (109^o meridional fault) is clearly manifested by the maximum horizontal gradient bands that have magnitudes >1.5mGal/km with meridian-directional extension in the Western part of the study area. At Cu Lao Xanh area (Binh Dinh) appear a series of faults with branched shape, which run to South Hai Nam Island. At Khanh Hoa, it can be seen that the 109^0 meridional fault is shifted eastward by the Tuy Hoa shear zone. The greater the depth, the more clearly the Tuy Hoa shear zone is manifested by the maximum horizontal gradient bands (Fig.4). The shear zone extends toward the East Sea deep basin in a Southeast - Northwest direction and bends at the place that is possible the boundary between the continental and oceanic crusts. From the results ontained, it is possible to speculate that the Tuy Hoa shear zone is the likely Southwestern boundary of the continental and oceanic crusts (Fig.5). The above results prove the cohesive relationship of geological structure between the Truong Sa archipelago area and the Cuu Long, Nam Con Son, Tu Chinh - Vung May Basins.

After passing through the Tuy Hoa shear zone, the 109^o meridional fault seems to be divided into two branches: The first branch runs southwards along the boundaries of the Cuu Long and Nam Con Son Basins then goes to the Ma Lai - Tho Chu Basin. The second branch runs southwards along the 110^o meridional and its direction changes to sub-parallel direction at 6^o and extends continuously to 114^0 meridian to connect with a reversed fault in the Borneo basin.

On the Fig.5, it can be seen very clearly that the sedimentary basins such as the Cuu Long, Nam Con Son, Tu Chinh - Vung May are bounded by large faults. Especially, the Tu Chinh - Vung May Basins are separated by regional faults that extend from the North to South of the area. Therefore, it may be concluded that the Tu Chinh - Vung May are two distinct basins, and they are not a united structure.

At the central part of the East Sea appear the maximum gradient bands with high magnitudes. It could be affirmed that these are signs of a seafloor spreading axis, a crustal boundary (continental and oceanic crusts) and uplift zones. In the Truong Sa archipelago area, there are lots of closed maximum horizontal gradient bands. These are possible uplift blocks or intrusive blocks in the Cenozoi basement, which are often of higher density than that of the surroundings.

The fault systems in the Truong Sa archipelago can be divided into two main groups. The larger fault group is developed in a Southwest - Northeasterly direction and the smaller fault group is developed in a southeast-northwesterly direction.

In the East Sea basin area are transverse faults perpendicular to the seafloor spreading axis. Besides, there are several small fault systems that are developed in a sub-meridional direction.

Remarks and conclusions

The methodology of horizontal gradient and maximum horizontal gradient of gravity anomaly is efficient and reliable in determining structure and form of faults as well as crustal density boundaries. The frequency filtering method can be used to separate the gravity effects which are caused by geological bodies at different depths, with higher accuracy and reality than those of other methods.

The results achieved have revealed that the main structures in the area are generally controlled by deep faults. Also, the sedimentary basins such as Phu Khanh, Cuu Long, Nam Con Son, Tu Chinh - Vung May and Truong Sa are controlled by deep regional faulting.

Especially, the results of this study have shown that the Tu Chinh - Vung May basins seem to be two individual sedimentary basins. Moreover, it is possible to conclude that the Tuy Hoa shear zone is the probable Southwest boundary of the continental and oceanic crusts. These results have proved the cohesive relationship of the geological structure between the Truong Sa archipelago area and the Cuu Long, Nam Con Son, Tu Chinh - Vung May Basins.

Based on the newest datasets, along with modern methodology, this study has produced a new and objective picture of the structure and form of the faults, uplift zone in basement as well as the seafloor spreading axis and crustal boundaries in the Truong Sa archipelago and in the East Sea deep basins.

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