Structural control of the Gagua "Wedge" Zone east of Taiwan Island on the southern Okinawa Trough

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Received June 16, 2003

Abstract Based on compositive analysis and interpretation of the observed and historical data, the geophysical field characters and structural properties of the Gagua "Wedge" Zone of the sea area east of Taiwan Island and the primary tectonic stress direction and its variabilities of backarc spreading in the southern Okinawa Trough are studied. It is concluded from the study results that the Gagua "Wedge" Zone is structurally consistent with the Gagua ridge and two fault basins on both sides of the Gagua ridge, and adjusts the moving direction and distance of the western Philippine Sea plate to make the northwestward motion of the plate on its east side change to the northward subduction of the plate on its west side so that the primary tectonic stress direction of the Okinawa Trough changed from NW-SE to nearly N-S, which provided the stress source for the Okinawa Trough to enter the second spreading stage.

Keywords: east of Taiwan Island, Gagua "Wedge" Zone, Okinawa Trough, structural control.

DOI: 10.1360/03yd0246

The sea area east of Taiwan Island is a unique active arc-continental collision margin in China and even in the world with the NE-nearly EW extending Ryukyu trench-arc-backarc basin system on the east and the nearly N-S extending Manila trough and Luzon arc on the west. The sea area east of Taiwan Island differs from the Ryukyu trench-arc-basin system in structural property, but there is a certain genetic relation between the two (Fig. 1)[1−3].

Since the 1990s, many investigations and researches of marine geophysics and geology have been carried out on the Okinawa Trough and the sea area east of Taiwan Island along with the application of new marine geophysical survey techniques and methods such as multibeam swath survey. In September 1995, R/V M. Ewing carried out multi-channel seismic exploration in the sea area east of Taiwan Island. During May to June 1996, R/V L'Atalante carried out multibeam swath survey, gravity survey, magnetic survey and seismic exploration in the sea area east and south of Taiwan Island and collected a large number of important data. From 1999 to 2000, the First Institute of Oceanography, SOA carried out comprehensive multibeam swath survey and geophysical survey and obtained abundant multibeam swath, gravity, magnetic and single-channel seismic data. Based on composite analysis and interpretation of the data observed by the First Institute of Oceanography, SOA and other his-

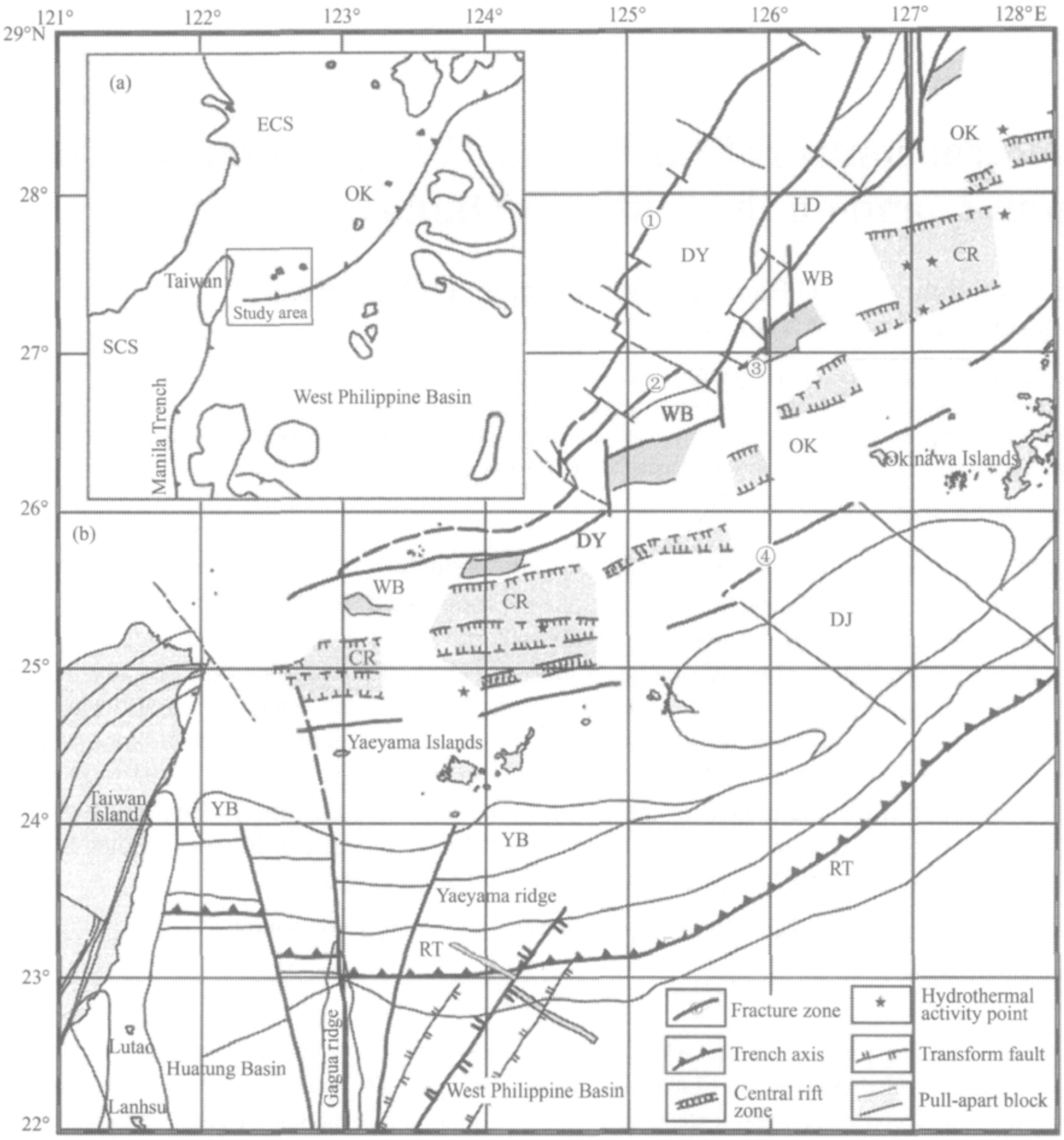

Fig. 1. Geological structural map of study area. (a) Tectonic map of study area; (b) regional structural map of study area and its adjacent region. ① Keelung-Xihu fracture zone; ② East China Sea shelf margin fracture zone; ③ East China Sea slope fracture zone; ④ eastern fracture zone; ECS, East China Sea; SCS, South China Sea; DY, shelf margin fold zone of ECS; OK, Okinawa Trough; LD, shelf edge depressions of ECS; WB, western pull-apart basins of OK; CR, central rift zone of OK; YB, Yaeyama Basin; RT, Ryukyu Trench.

torical data, the geophysical field characteristics and structural properties of the Gagua "Wedge" Zone of the sea area east of Taiwan Island and the primary tectonic stress direction and its variabilities of backarc spreading in the southern Okinawa Trough are studied.

1 Formulation of problem

Many domestic and foreign scholars have long believed that the tectonic stress generated by the subduction of the Philippine Sea plate is the main dynamic source for the formation of the Okinawa Trough. The latest results indicate that the central rift zone identified at the axis of the southern Okinawa Trough is composed of many different-scale en echelon valleys, which generally have a NEE to nearly EW trend and are characterized by intense earthquake, volcanic and tectonic activities as well as high heat flow and strong hydrothermal activities. Along with further attenuation and tension of the axial crust, seafloor spreading and formation of new oceanic crust might occur in some areas. The direction of seafloor spreading and primary tectonic stress is nearly N-S, and makes a certain angle with the direction of tectonic stress generated by the subduction of the Philippine Sea plate[4].

It is shown from Fig. 2 that the main basement faults controlling the structural pattern in the sea area east of Taiwan Island are the nearly N-S fault extending along the Gagua ridge, the NNW fault west of the Gagua ridge and the NNE fault east of the Gagua ridge. These faults separate the Gagua ridge and the fault basins on its two sides from the surrounding plate tectonic units. The plate tectonic units on two sides of the structural zone differ in seafloor topography and geophysical characteristics, especially in magnetic anomaly. With the western Philippine Sea plate moving northwestward, the eastern oceanic curst subsides, the western oceanic curst uplifts relatively along this structural zone, and the moving direction and velocity of the western Philippine Sea plate is adjusted as well. The moving direction of the western Philippine Sea plate changes from NW to N-NNW clockwise after the adjustment, which spatially corresponds to the NEE-EW trend of the southern Okinawa Trough.

2 Kinematical characteristics of the Gagua “Wedge” Zone

The Gagua ridge is located in the sea area east of Taiwan Island, is a linear aseismic ridge, about 350 km long in N-S extent, 30 km in width, 3－4 km above seafloor and its burial depth of oceanic crust is about 1－2 km. The bathymetric data measured with multibeam system have revealed that the peaks and troughs on the Gagua ridge range generally from NNW to SSE, which is suggested to be related to the activities of N-S slip fault occurring along the Gagua ridge.

2.1 Geophysical characteristics of the Gagua “Wedge” Zone

As shown in Fig. 2, several basement faults controlling the structural pattern of study areas can be revealed by the seafloor topographic map, free-air gravity anomalies, magnetic anomalies and composite geophysical profiles crossing the Gagua ridge. Among them, NNW slip-fault F1 separates the Huatung Basin from the fault basin west of the Gagua ridge, and NNE slip-fault F3 separates the West Philippine Basin from the fault basin east of the Gagua ridge, and nearly N-S slip-fault F2 is distributed along the axis of the Gagua ridge. The wedge zone is composed mainly of the Gagua ridge and two fault basins on two sides of the Gagua ridge, so is called the Gagua “Wedge” Zone.

The Gagua “Wedge” Zone differs from the plate tectonic units such as the Huatung Basin and the West Philippine Basin in free-air gravity anomaly, magnetic anomaly, number and extending direction of magnetic strip, and the difference in magnetic anomaly is more distinct. Fig. 3 shows that the direction of magnetic strip of the Huatung Basin is 268°－270°, extending in the E-W direction, and magnetic strips Nos. 15－19 can be identified from north to south. The magnetic strips of the West Philippine Basin extend in the NW-SE direction and are dislocated by a few transform faults, which is consistent with the axial spreading direction of the West Philippine Basin. Among them, magnetic strips Nos. 13 and 15－18 can be identified, and there is an angle of 30°－40° between the magnetic strip extending directions of the Huatung Basin and the West Philippine Basin. The magnetic anomalies of the Gagua “Wedge” Zone between the Huatung Basin and the West Philippine Basin are chaotic and the magnetic strips cannot be identified. Similarly, the free-air gravity anomalies of the Huatung Basin are similar to those of the West Philippine Basin in anomaly value and isoline shape, but the Gagua ridge has obvious north-southly ascending anomalies with positive anomaly values decreasing toward its two sides. The decreasing range and gradients of the free-air gravity anomalies are larger on the east side than on the west side. The ascending anom-

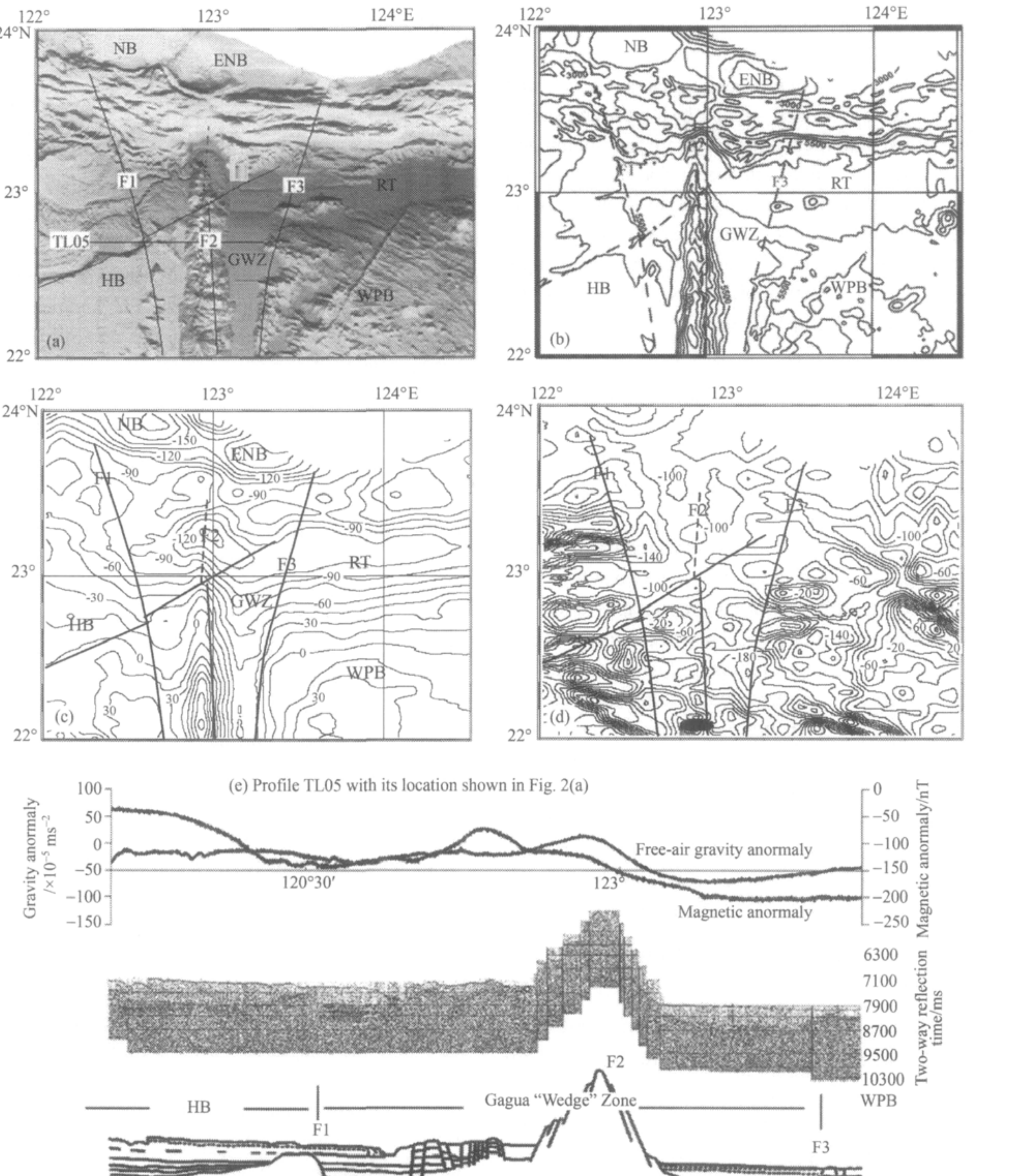

Fig. 2. Geophysical characteristics of the Gagua "Wedge" Zone. (a) Shaded relief map; (b) topographic map; (c) free-air gravity anomaly map; (d) magnetic anomaly map; (e) composite geophysical profiles; Fault F1 lies west of the Gagua ridge; Fault F2 extends along the Gagua ridge; Fault F3 lies east of the Gagua ridge; NB, Nanao Basin; ENB, East Nanao Basin; RT, Ryukyu Trench; HB, Huatung Basin; GWZ, Gagua "Wedge" Zone; WPB, West Philippine Basin.

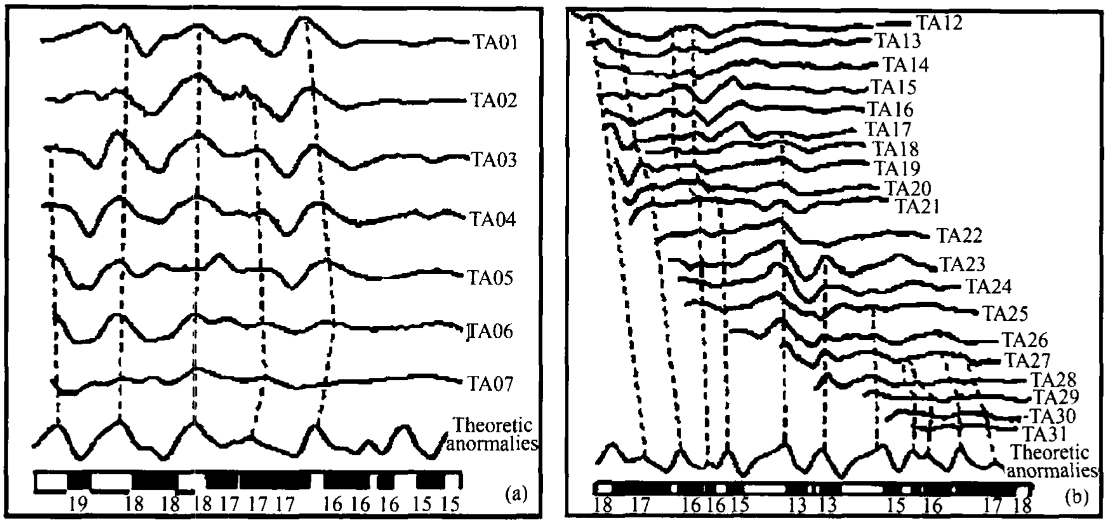

Fig. 3. Characteristics of magnetic strips on two sides of the Gagua "Wedge" Zone. (a) Nearly east-west magnetic strips Nos. 15—19 on the west side of the Gagua "Wedge" Zone; (b) nearly NW-SE magnetic strips Nos. 13 and 15—18 on the east side of the Gagua "Wedge" Zone.

aly zone of the Gagua ridge runs northward to connect with the negative anomaly zone of the Ryukyu Trench, but the anomaly characteristics of the ascending anomaly zone are obviously different from those on its two sides.

2.2 Crust properties of the Gagua "Wedge" Zone

So far, the knowledge of the plate tectonic property and the structural location of the Gagua ridge are not clear yet, and the opinions on its origin vary greatly. Sibuet et al. suggested that the Gagua ridge was a plate margin transform fault caused by the interaction of adjacent plate tectonic units, formed between the Ryukyu subduction zone and the Manila subduction zone in a geologic history period (about 13 Ma, middle Miocene), and this transform fault was then uplifted due to the northwestward collision and junction of the Luzon island arc[5], but it remains to be further explored how to form such a large-scale and long extension transform fault between two plate subduction zones with opposite subduction direction.

It is shown from Fig. 2(c) that the Gagua "Wedge" Zone shows a juxtaposed arrangement of gravity anomalies, that is, the gravity anomaly values in the Gagua ridge area are higher and decrease toward its two sides. The high positive anomalies indicate that the Gagua ridge is made up of high-density matter. Some of the rock samples taken from the seafloor have signs of scratch or erosion[6], indicating that the Gagua "Wedge" Zone was formed in an extruding environment at its early stage. It is shown from study results that basements of the Gagua "Wedge" Zone and the Huatung Basin are oceanic upheaval crust of the west margin of the western Philippine Sea plate. With the northwestward moving and extruding of the Philippine Sea plate, the basement in the weak zone of the Gagua "Wedge" Zone was subducted on the east side and uplifted on the west side to result in 400—500 m difference in water depth on two sides of the Gagua ridge, and the extruding rising of the upper crust and the sedimentary formation also led to a rapid uplift of the Gagua ridge.

2.3 Adjustment of the moving direction of plate east of Taiwan

It is shown from the recent plate motion data that the Philippine Sea plate moves northwestward (310°) at a velocity of 7 cm/a and subducts under the Eurasian plate along the Ryukyu Trench. Based on the multibeam swath data, free-air gravity data and magnetic data collected in the latest investigations, it is very obvious that the western Philippine Sea plate moves northward and subducts under the Ryukyu arc along the western Ryukyu Trench, which shows the typical characteristics of the ocean-continent plate subduction zone and the differences in moving direction and velocity in different places of the plate.

The Gagua "Wedge" Zone and the plate tectonic units on its two sides have different characteristics. The magnetic strips of the West Philippine Basin run in a NW-SE direction and magnetic strips Nos. 13 and 15—18 and the central spreading ridge running in NNW direction can be identified. During the moving process of the Philippine Sea plate, the central spreading ridge moves northwestward and subducts under the Ryukyu Trench. However, the magnetic strips of the Huatung Basin run in nearly EW direction, magnetic strips Nos. 16—19 south of the spreading ridge can be identified from north to south, and the spreading ridge and the magnetic strips on its north side have rapidly subducted under the Ryukyu arc so that the age of oceanic crust basement there is a little older than that in the West Philippine Basin. Because of intense structural activities and horizontal differential movements of plates on its two sides, the magnetic strips in the Gagua "Wedge" Zone and the fault-basins on its two sides are fragmentized and cannot be identified.

The adjustments of the moving direction and velocity of the western Philippine Sea plate by the Gagua "Wedge" Zone are characterized by the following: the moving direction of the plate changes from NW in the sea area east of the Gagua ridge to N-NNW in the Huatung Basin. In addition, differential movement of the plate tectonic units is present on two sides of the Gagua ridge, which shows that the Ryukyu Trench and some forearc basins such as the East Nanao Basin, the Nanao Basin and the Hoping Basin display en echelon northwestward patterns (Fig. 4)[7], which is consistent with the assumption that the magnetic strips and the northward moving velocity of the Huatung Basin are different from those of the West Philippine Basin.

3 Structural characteristics and formation evolution of the northern-middle and southern Okinawa Trough

Previous researches made by domestic scholars concentrated mainly on seafloor topography, geomorphology, geophysical characteristics, crust properties, formation mechanism and structural evolution of the Okinawa Trough[8]. Although researches on crust

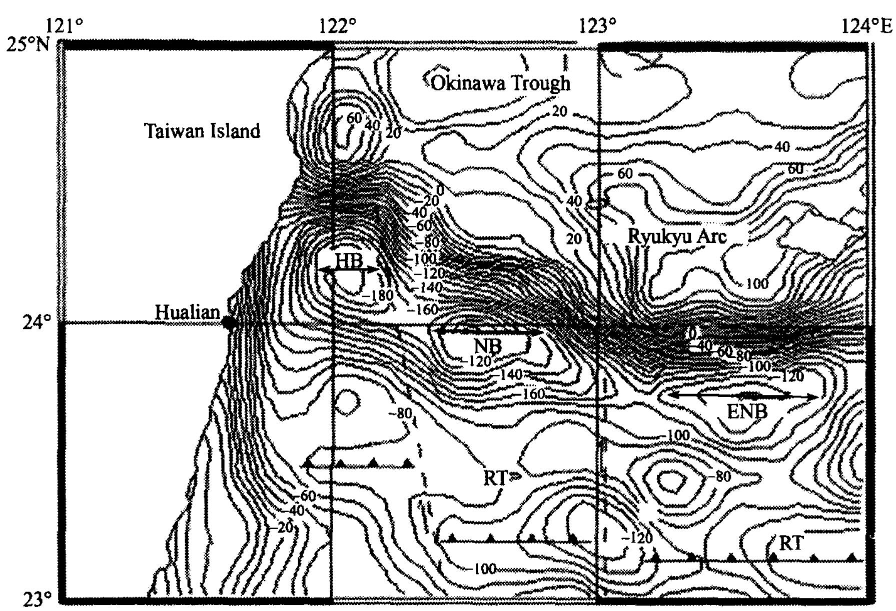

Fig. 4. En echelon pattern of structural unit in the southern Ryukyu trench-arc-backarc basin system (Isolines denote free-air gravity anomalies, adapted from Hsu, S. K. et al., 1996). HB, Hoping Basin; NB, Nanao Basin; ENB, East Nanao Basin; RT, Ryukyu Trench.

properties and tension mechanism of the Okinawa Trough are controversial, most scholars agree with the opinion that the Okinawa Trough underwent twice backarc spreading, and begin to study the difference of structural development between the southern part and the northern-middle part of the Okinawa Trough[4]. Since 1998, both domestic and foreign scholars have monitored earthquakes, seafloor volcano, heat flow value and hydrothermal activities in the southern Okinawa Trough, and gradually studied the activity of the structural evolution in the southern Okinawa Trough and the space-time response of the evolution of the Taiwan arc-continent collision system[9−12].

3.1 Recent active fractures in the northern-middle Okinawa Trough

Figure 5 is a shaded bottom relief map of the middle Okinawa Trough made on the basis of multibeam swath survey data, clearly displaying the characteristics of the seafloor micro-topography, and the NE-NEE trending lineations in Fig. 5 show the active faults exposed at the seafloor or seamount chain generated by intense volcanism according to the comparison with other geophysical data, which indicates that the main structural trend of axial rift system in the northern-middle Okinawa Trough is NE-NEE and obliquely crosses with the extra lateral structural trend of the Okinawa Trough.

3.2 Structural trend and its variabilities of the southern Okinawa Trough

Figure 6 is a general structural map of the southern Okinawa Trough made on the basis of multibeam swath data and other geological and geophysical data. Several rifts can be identified along the axis of the southern Okinawa Trough, show en echelon pattern running in nearly E-W direction and their shape, scale and development level are not completely the same in different places of the axis of the southern Okinawa Trough. The typical rifts are shown as active graben valleys with strong modern fault activities in high-resolution seismic profiles, and the undeformed deposits can be seen to overlie the deformed stratum (or basement) on the flank of the graben valley.

There are two rifts in the southern Okinawa Trough, and the rifts show en echelon pattern. The east rift deviates northward from the trough axis, the west rift deviates southward from the trough axis, and the total

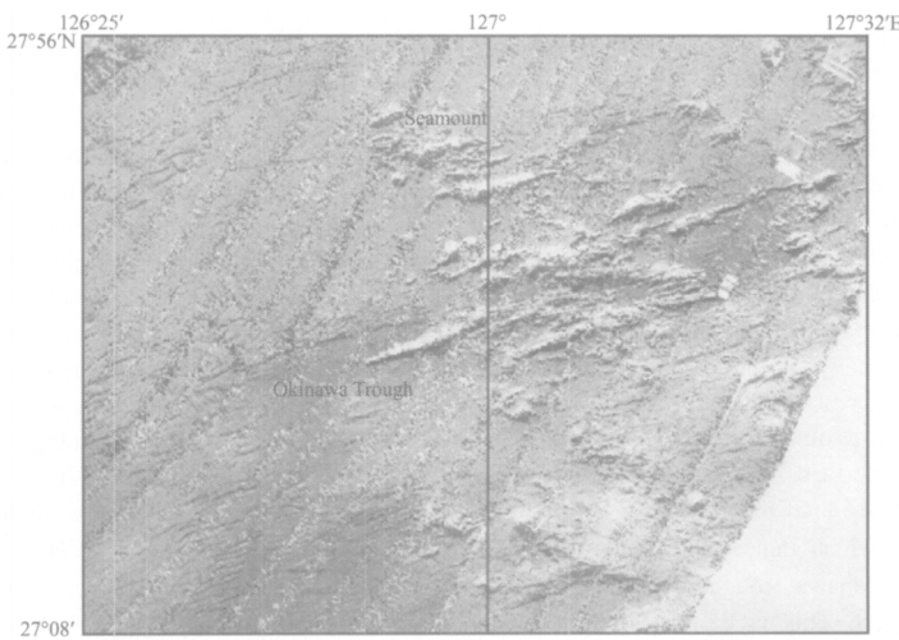

Fig. 5. Recent active fracture in the middle Okinawa Trough. The NE-NEE trending lineations show the active faults exposed at the sea floor or seamount chain generated by intense volcanism.

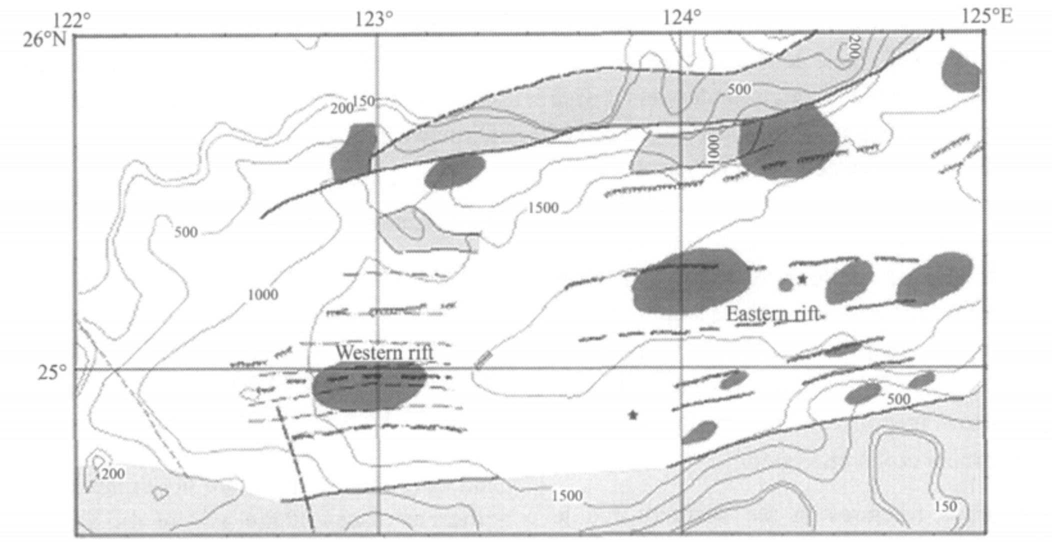

Fig. 6. General structural map of the southern Okinawa Trough.

N-S deviation is about 3 km.

3.3 Difference between the structural evolutions of the northern-middle and southern Okinawa Trough

As a young back-arc basin, the Okinawa Trough probably underwent two back-arc pull-apart and tectonic deformation stages.

Before the late Miocene epoch, the northern-middle Okinawa Trough was a rise area made up of Cretaceous granite and even older rocks. In the late Miocene epoch, this rise area began to rip and the initial Okinawa Trough emerged along with granite diapir zone caused by magma activities. At the end of Miocene, the initial Okinawa Trough was pulled apart approximately in the NNE-NE direction to separate the Ryukyu arc from the East China Sea shelf margin. Thus, the early Okinawa Trough formed. With further pulling-apart of the crust of the early Okinawa Trough, a semi-graben fault basin of the East China Sea shelf margin depression formed. The sedimentary thickness in the East China Sea shelf margin depression zone is over 10—12 km, which indicates that the continent crust of the early Okinawa Trough was greatly thinned by the pulling-apart. This is the first pulling-apart process of the Okinawa Trough, and the pulling-apart direction is NW-SE. According to the distribution characteristics of the Miocene series, the pulling-apart process proceeded from north to south and only occurred in the northern-middle Okinawa Trough (north of 26°N), and the southern Okinawa Trough was in an uplift and denudation stage.

It is inferred from the age of rocks, the number of magnetic strips and other geophysical data that the pulling-apart direction of the Okinawa Trough changed gradually from NW-SE to nearly N-S in the period from the end of Pliocene to the early Pleistocene epoch, and the Okinawa Trough entered the second pulling-apart and spreading stage. The pulling-apart began from the southern Okinawa Trough and extended northward to the middle trough. With the further thinning and tension fracture of crust at the axis of the Okinawa Trough, several central rift zones with en echelon pattern were formed along the trough axis and the structural activities were greatly intensified. The local seafloor spreading occurred in the southern and middle Okinawa Trough, the spreading direction was nearly N-S, and some new oceanic crusts generated in the southern and middle Okinawa Trough. The pulling-apart and spreading is characterized by the obvious change of the pulling-apart direction and the rift extending direction obliquely crossing general trend of the Okinawa Trough. In addition, the structural activities and crust properties of the axial rift of the Okinawa Trough had qualitative changes.

4 Formation evolution of the Gagua “Wedge” Zone and its structural control over the southern Okinawa Trough

As mentioned above, the Gagua “Wedge” Zone makes the plate tectonic units on its two sides have different moving directions and velocity. The western Philippine Sea plate east of fault F3 shows a NW linear alternating ridge and trough pattern, has fault-block structural features formed by the cutting of NNE trending transform faults, and subducts northwestward under the Ryukyu Trench. The direction of the magnetic anomalies in the Huatung Basin west of fault F1 is nearly EW. Further west, the main structural line of the Taiwan Island runs in nearly N-S direction and is consistent with that of the Luzon island arc, which indicates that the Gagua “Wedge” Zone has close relations with the space-time evolution of the Taiwan collision orogenic belt and the western Philippine Sea plate.

In the middle Miocene (about 6.5 Ma), the arc-continent collision of the northern Luzon island arc and the South China Sea passive continent margin in the eastern Taiwan Island started the Taiwan collision orogenic history. Because the collision and subduction were oblique, the northern Luzon island arc rotated clockwise to form the coastal mountain chain extending northward. During this stage the Gagua ridge had undergone neither of uplift and tectonic deformation and had the same basement crust and upper sedimentary structure as the fault basins on its two sides. Seismic profiles (Fig. 2(e)) show that the fault basins on two sides of the Gagua ridge have a similar sedimentary structure, and their sedimentary thickness might be over 1.2 km.

In early Pliocene epoch, the northward movement of the northern Luzon island arc and the Taiwan arc-continent collision still continued. With the Philippine Sea plate continuously moving in the NW direction, the differential movement of the northwestward plate on the east and the north-northwestward plate on the west and the tectonic stress resulting from the movement were adjusted and absorbed by the weak structural zone located at the original Gagua ridge. It is inferred from the moving directions of the side plates that the tectonic stress generated in the Gagua “Wedge” Zone is of compresso-shear type. The early Gagua “Wedge” Zone was subjected to highly compressional deformation to cause the uplifting of the Gagua ridge and the reduction of upper crust and to make the Huatung Basin rotate anticlockwise about 25—35°.

By the end of Pleistocene, the northern Luzon island arc largely moved northward, and the northward migration amount of the involved plates increased gradually from east to west due to the right-lateral strike slip adjustment of several faults of the Gagua “Wedge” Zone, which can be verified by the measured data shown in Fig. 4. The northward differential movement of the plates and the subduction of the plate under the Ryukyu arc made the primary tectonic stress direction of the Okinawa Trough change gradually from NW-SE to nearly N-S.

Therefore, the formation evolution of the Gagua “Wedge” Zone played an important role in controlling the Okinawa Trough to enter the second spreading stage. It is shown from Fig. 2(a) and (c) that the northward subduction of the Gagua ridge causes an intense tectonic deformation of the Ryukyu Trench and its fore-arc zone.

5 Conclusions

(1) The Gagua “Wedge” Zone is a N-S structural zone controlled by a series of compresso-shear basement fractures and has complex and special geophysical characteristics and is structurally consistent with the Gagua ridge and two fault basins on both sides of the Gagua ridge.

(2) The Gagua “Wedge” Zone is located at the junction of the Philippine Sea plate moving northwestward and the northern Luzon island arc system moving northward. Their differential movement controlled the formation and evolution of the Gagua “Wedge” Zone.

(3) The Gagua “Wedge” Zone adjusts the moving direction and distance of the western Philippine Sea

plate to make the northwestward motion of the plate on the east change to the northward subduction of the plate on the west and result in the primary tectonic stress direction of the Okinawa Trough changing from NW-SE to near N-S, which provided the stress source for the Okinawa Trough to enter the second spreading stage.

(4) The Okinawa Trough underwent two back-arc pull-apart and spread stages. The first pull-apart occurred at the end of Miocene epoch with a NW-SE pull-apart direction, processed from north to south and occurred only in the northern-middle Okinawa Trough (north of 26°N). The second pull-apart and spreading stage occurred from the end of Pliocene to the early Pleistocene epoch, its pull-apart direction changed gradually from NW-SE to near N-S, the pull-apart and spreading began from the southern Okinawa Trough and extended northward to the middle Okinawa Trough along with local seafloor spreading.

Because the tectonic evolution of the Okinawa Trough and the sea area east of Taiwan Island is complicated and the methods and the equipment used for geophysical survey are limited, it is very difficult to have an overall understanding of their crust property, formation mechanism and evolution characteristics. For a clear understanding, the further development of survey technique and continued accumulation of new data are needed. These studies have definite significance for understanding the interaction of the Eurasia plate and the Philippine Sea plate in the sea area east of Taiwan Island and its influence on the formation evolution of the eastern continental margin of China.

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