Active Rift System in the Okinawa Trough and Its Northeastern Continuation

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Abstract

Recent submarine, geological and geophysical investigations have revealed that the present central rift system of the Okinawa Trough which is an active extensional axis of the trough has been formed since about 2 Ma. Two stages of the formation processes of the Okinawa Trough can be distinguished. The crustal thinning and thus eastward drifting of the Ryukyu Arc may have occurred during late Miocene to middle Pliocene time (about 6–4 Ma) at the first stage. The extensive subsidence may have occurred at the second stage since late Pliocene time (about 2 Ma). The Okinawa Trough and its northeastern continuation might be identified as a plate boundary of a newly proposed Southwest Japan Micro-plate. Based on the relationship between backarc basin and subducting slab development, one model for the origin of the backarc basin is proposed. The model suggests that the heat related to opening processes of the Okinawa Trough might rise up from the independent portion of the subducting plate.

1. Introduction

The Okinawa Trough is a backarc basin lying to the east of the East China Sea formed by an extension within the continental lithospheric plate behind the Ryukyu trench-arc system. In recent years, submarine, geological and geophysical investigations have been carried out in the Okinawa Trough region (Fig. 1) by various international organizations (e. g., Japanese DELP Research Group on Back-Arc Basins, 1991; Sibuet et al., 1987). Seismic reflection profiles of single and multi-channel systems obtained from almost all organizations were compiled for the present study to clarify geological and sedimentological features of backarc rifting. Dredging and drilling data were also incorporated to determine the stratigraphy in the studied area. Data collected by detail surveys with multi-narrow beam, manned and non-manned submersible, and seismic refraction experiments were also available to study geologic and geophysical features in the Okinawa Trough and Ryukyu Islands (Nanseishoto) areas.

The present paper discusses the origin of rifting in the Okinawa Trough and its northeastern continuation using all of the above mentioned available data.

2. Tectonic framework of the Okinawa Trough

The morpho-tectonic framework in the Okinawa Trough region can be defined based on tectono-morphological similarities from west to east in Figs. 1 and 2. Those are I)

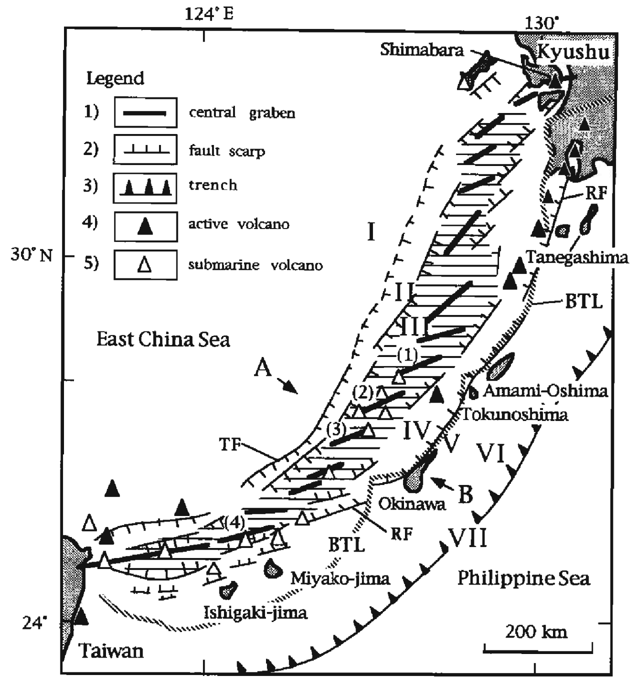

Fig. 1. Regional map showing the location of the study area. The tectonic framework has been modified from Kimura et al. (1988). I: Tunghai Shelf, II: Tunghai, Slope, III: Okinawa Trough, IV: Tokara Belt, V: Ryukyu Ridge, VI: Arc-trench gap VII: Nanseishoto Trench. TF: Tunghai Shelf Fault, RF: Ryukyu Ridge Fault, BTL: Butsuzo Tectonic Line. Active hydrothermal mounds were found in central rifts labeled (1)–(4): (1) Torishima Rift (including Minami Ensei Knoll); (2) Iheya Rift; (3) Aguni Rift (including Izena Hole); (4) Yaeyama Rift. Legend: 1)= central rift. 2)= fault scarp. Broken line shows a buried fault. 3)=trench. Tooth thrust up side. 4)= historically active volcanoes, 5)= probably active volcanoes (mostly submarine).

Tunghai Shelf, II) Tunghai Slope (western rifted margin of the Okinawa Trough), III) Okinawa Trough, IV) Tokara Belt (eastern rifted margin of the Okinawa Trough), V) Ryukyu Ridge, VI) Arc-trench gap and VII) Nanseishoto Trench (former Ryukyu Trench).

The width of the present Okinawa Trough is about 100–150 km. The topography of the Tunghai Slope and Tokara Belt is rough, and both features are regarded as marginal, tensile rifted margins of the Okinawa Trough (Fig. 2). The Ryukyu Ridge Fault and the Tunghai Shelf Fault were generated during the early Pleistocene as mentioned later. The Okinawa Trough is estimated to have been filled with deposits since the late Miocene and the thickness of the sediments reaches to 6 km in places. The Okinawa Trough is developing generally parallel to the Ryukyu Ridge. Central grabens or rifts develop along the axial part of the Okinawa Trough in an echelon pattern (Fig. 1).

Existence of the central graben was first described in the middle Okinawa Trough area by Kimura et al. (1975). Central grabens in the southern part of the Okinawa

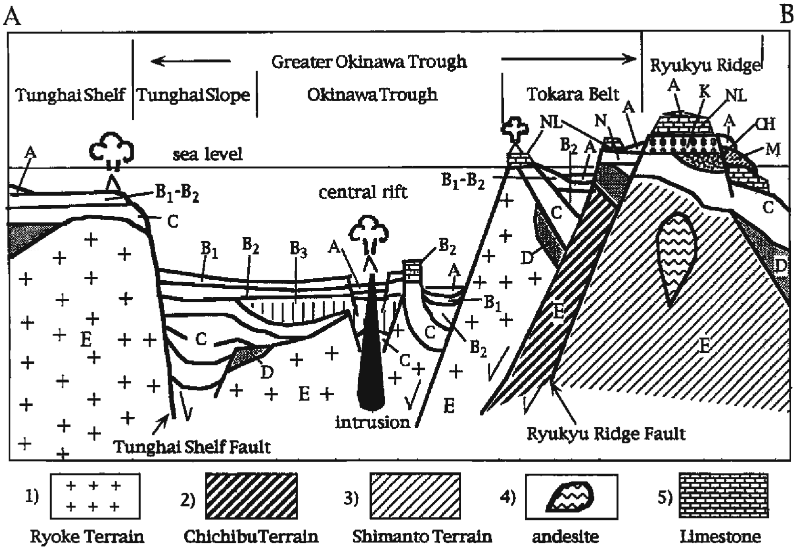

Fig. 2. Schematic, geologic cross section of the middle Okinawa Trough along A-B in Fig. 1 (no scale). Morpho-tectonic divisions are given. It shows the central graben of the rift. Layers A-D are Tertiary sediments. Layer E shows Paleozoic and Mesozoic formations. Active volcanic activities occur along the major faults including the central rift. CH: Chinen sandstone, N: Nakoshi sandstone, NL: Naha Limestone, M: Minatogawa Limestone, K: Kunigami Gravel. Legend: 1= Ryoke Terrain, 2= Chichibu Terrain, 3= Shimanto Terrain, 4= Paleogene and Miocene intrusive rocks (andesitic, and granitic rocks), 5= Limestone. Revised after Kimura (1990).

Trough were found by Herman et al. (1978). In places, the central grabens of the northern Okinawa Trough show common half graben features. Seismicity shows that the central graben is active and focal mechanism solutions (Eguchi, 1982; Eguchi and Uyeda, 1983; Yamamoto and Tokunaga, 1981) show that the tensional axis is oriented in a north-south direction. Intrusive bodies exist beneath the central grabens to form basal highs in many cases. In other words, the central graben is defined as the most recent fissure originating in response to uprising of magmas. Many active hydrothermal spots, including a black smoker, were found in the Izena Hole, eastern end of the Aguni Central Graben (Aguni Rift) in the middle Okinawa Trough (Fig. 1-(2)) (Nakamura et al, 1990, Kimura et al., 1989, 1991).

All of the seismic refraction data show a clear resemblance on the crustal structure of the Okinawa Trough from north to south. The depth of the Moho discontinuity varies 25-16 km from north to south (Iwasaki et al., 1987, Hirata, et al., 1991). They indicate that there is no oceanic crust in the entire Okinawa Trough. Based on the detailed velocity structure in the southern Okinawa Trough by Hirata et al. (1991), the thickness of the 4.5-6.0 km/s and 6.2-6.4 km/s layers remarkably decreases beneath the trough. This suggests that crustal stretching occurred after the formation of the 4.5-6.0 km/s layer. The 1.8-1.9 km/s layer is correlatable with early Pliocene to early Pleistocene sediment of the upper Shimajiri Group and Quaternary sediments. The

3.0–3.5 km/s layer is correlatable with late Miocene to early Pliocene strata of the lower Shimajiri Group on the basins of seismic reflection records and drilling data (Marutani and Sato, 1985). The 3.6–3.9 km/s layer should be the Yaeyama Group of early Miocene time based upon the stratigraphic sequence.

3. Geologic evidence of southeast-ward migration of the Ryukyu Arc

Based on onshore geological surveys in Nansei (Ryukyu) Islands, Konishi (1965) correlated the metamorphic rocks in Ishigaki-jima Island (South Ryukyu Arc) with those of the Sanbagawa Belt in Southwest Japan. Kizaki (1978), however, suggested that the metamorphic rocks were correlatable with those of the Sangun Belt in the Inner Zone of Southwest Japan on the basis of age dating of metamorphism. Marutani and Sato (1985) estimated that a paleo-land composed of gneiss or granitic rocks existed in the south of Miyako-jima Island. Adding our submarine geologic data to them, the Inner Zone of pre-Late Miocene geotectonic terrains in Southwest Japan may continue to southern Ryukyu Islands and to central Taiwan (Ho, 1986). On the contrary, the Outer Zone may continue from Southwest Japan through the middle and northern Ryukyu Islands to the continental slope off the southern Ryukyu Islands and to eastern Taiwan. Accordingly, the Butsuzo Tectonic Line (BTL), that is, a northeastern boundary of the Shimanto Terrain in the Outer Zone may occur in the continental slope south off Miyako-jima and Ishigaki-jima Islands in the southern Ryukyu Arc (Fig. 1).

The distributional trend of the BTL represented in Fig. 1 shows a convex curve toward the Philippine Sea, and horizontal distance from the position of the Butsuzo Tectonic Line in Kyushu mainland to the top of the convex in the offshore area off Ishigaki-jima is about 150 km. It suggests that the convex pattern of the tectonic line is closely related to the backarc opening of the Okinawa Trough and the BTL shifts toward the east.

Many regional hiatuses after the Paleozoic are recognized in the Ryukyu Arc and the Okinawa Trough region, although data are scarce in the Okinawa Trough yet. A significant hiatus suggesting the first stage of crustal movement may have occurred in the Paleocene, based on the occurrence of granitic intrusion dated at 61 Ma on Tokunoshima Island. The second stage of the crustal movement may have occurred in Oligocene to the early Miocene. Before that, Eocene Green Tuff activity has occurred in Ishigaki-jima Island and granitic intrusive activities around 30 Ma has been recognized in the Ryukyu Arc (Kizaki, 1978).

The third stage of the crustal movement may have occurred in the middle Miocene to late Miocene and its pre-activity is thought to be granitic intrusive activities of 20 Ma in Yaeyama Islands. As the result of the repeated movement, the crust may have been extensively eroded and stretched. Subsequently, the crust became thinner and thick sequences of eroded sediments were deposited in the paleo-Nanseishoto Trench.

Thus, regional upheavals may have occurred intermittently in the backarc areas from the Paleogene to late Miocene. The upheavals may have been caused by up-welling of voluminous magmas in the back-arc region, as indicated by intrusions of granitic

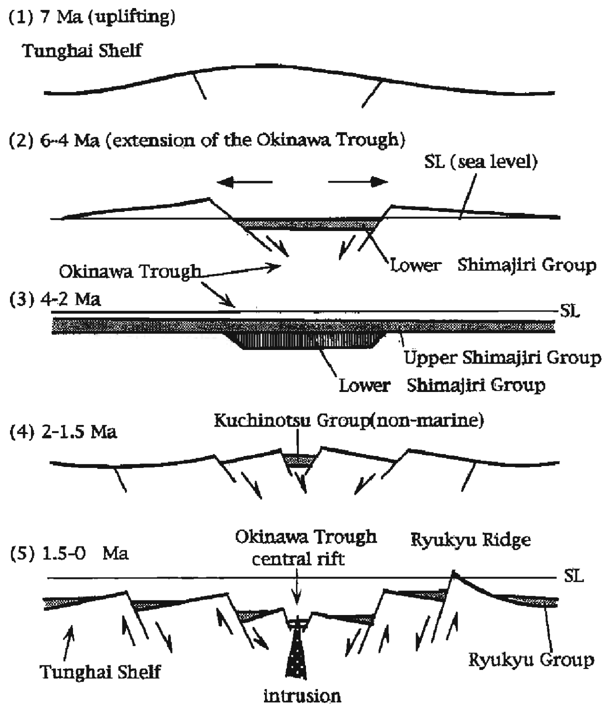

Fig. 3. Geologic development of the middle Okinawa Trough.

rocks and by acidic to intermediate volcanisms. Uplift of the central axis cf the dome occurred in the Miocene (Fig. 3-(1)), then making the apparent crustal thickness thinner and shifting the pre-Miocene geologic terrain toward the southeast (Fig. 3-(2)).

During the time, the so-called Green Tuff activity of Neogene volcanism occurred in the back-arc region. Maximum activity occurred in the middle Miocene. At this time, it is thought that the crust was stretched and thinned. As a result, the shallow crust was rifted, but the plate has not been completely rifted off yet. While the general trend of bedding and structural trend of the terrains in Kyushu were changed sometime during the middle Miocene to the middle Pliocene, and consequently, pre-Late Miocene terrains were shifted trench-ward. The timing of the bending of the Shimanto Terrain is thought to be later than that of the extension of the Japan Sea and be compatible with that of the Okinawa Trough, characterized by the Green-Tuff activity.

As mentioned above, the lateral shift of about 150 km of the Butsuzo Tectonic Line (BTL) occurred toward the trench in the middle to southern Ryukyu Arc. This may have been caused by subduction of the trench wall from around 12 Ma to the present. Lateral movement is also suggested by the shifting of the stratigraphic position of the C/D unconformity (unconformity between Layers C and D) (Fig. 2) in the arc-trench gap. That is, the unconformity exists very near the Ryukyu Trench. The rate of shift of BTL toward the trench is estimated at about 1 cm/yr in the middle to southern Ryukyu Arc, based upon the distance of the lateral shifting of about 150 km since the middle Miocene.

The major cause of the lateral movement of the outer terrains in the Ryukyu Arc and that of the bending of the pre-late Miocene outer terrains in Kyushu and Taiwan are thought to be primarily of common origin by the opening movement of the Okinawa Trough since the middle Miocene. Thereafter, the subducting Philippine Sea plate may have been well coupled with the continental plate at the Ryukyu Trench while the Eurasian Plate was extended and rifted to make a backarc basin during the late Pliocene to early Pleistocene.

Uplifting in the back-arc region may have continued at the same time and may have extended toward the arc-trench gap, because the regional angular unconformity that was formed sometime during Middle to Late Miocene times is observed there. After formation of the unconformity, the arc-trench gap area subsided. The unconformity is now found 4 km below sea level as shown by Kimura (1988). An average subsidence rate of about 0.7 mm/yr is calculated.

4. Rifting of the Okinawa Trough

(1) First stage

The crustal section suggests that stretching may have occurred after the formation of the 4.5–6.0 and 6.2–6.4 km/s layers, whereas, the 3.0–3.5 km/s layer seems to be a syn-tectonic sedimentary layer formed during a major extensional movement of the Okinawa Trough. Paleomagnetic evidence shows that the southern part of the Ryukyu Arc has rotated clockwise 19° with respect to Eurasia during the past 10–4 Ma (Miki et al, 1990; Miki, 1991). Miki et al. (1993) attributed this rotation to the backarc opening of the southern part of the Okinawa Trough, which occurred by means of the "wedge" mode later than 10 Ma. On the other hand, Tanegashima Island, located in the northern Ryukyu Arc, rotated counter-clockwise about 30° with respect to Eurasia and Southwest Japan after the late Miocene, probably during the last 6 Ma (Kodama et al., 1991; Kamata and Kodama, 1994).

On reflection seismic profiles of the Okinawa Trough, a deep sedimentary trough in the Tunghai Slope to the western Okinawa Trough (Marutani and Sato, 1985; Letouzey and Kimura, 1986) and late Miocene to early Pliocene strata (lower Shimajiri Group) show specific sedimentary features reported from the central axis of the trough, suggesting that the basement has been extended. It strongly supports the first extension of the Okinawa Trough occurring during the late Miocene to early Pliocene.

In conclusion, the Okinawa Trough may have extended sometime during 6–4 Ma in the first step. Subsequently, the trough was filled up by sediments (upper Shimajiri Group) and the depocenter of the trough was not coincident with the northern-half of the present Okinawa Trough, but with its southern part.

(2) Second stage

The large quantity of available data not only revealed the features of a central rift in the Okinawa Trough, they also confirmed several pieces of evidence of volcanic activity in the central rift valley in the middle Okinawa Trough (Kimura et al., 1986). An extremely high heat flow value of 1600 mW/m^2 was observed in the valley (Yamano et al., 1986). K-Ar ages of volcanic rocks represent activity younger than 0.5 Ma (Kimura et al., 1986). The probably youngest central ridge composed of high alumina basalt is located in the axial, central rift in the middle Okinawa Trough. On one of the central knolls in the rift valley, active hydrothermal mounds were found ("SHINKAI 2000" Research Group on the Okinawa Trough, 1986), of which the basement rocks were determined as dacitic. The western central ridge inside the central rifts in the middle Okinawa Tough are composed of young basalt. Such combination of basalt and dacite in the axial zone shows bi-modal volcanism which is characterized in the extensional fields. A feature of the central rifts in the southern Okinawa Trough is classic graben offsetting the most recent sediments. In addition, the marginal crustal blocks of rifts are back-tilted with respect to each rift axis. The width of the central graben is about 10–20 km. Andesite and tholeiite were recovered from the ridges in the central graben in the southern Okinawa Trough. These ridges showed positive magnetic anomaly (Kimura et al., 1986; Sibuet et al., 1987). Correlation with sedimentary basins between the Okinawa Trough and Kyushu regions showed that the initiation of the subsidence in the central axial part of the Okinawa trough was about 2 Ma (Kimura, 1985; 1990).

As a result, the present grabens generating the Okinawa Trough may have been formed by extensive fault movements along the trough with lithospheric rifting perhaps occurring from about 2 Ma. The central rift, that is a depocenter of the Okinawa Trough, occurred in the east to the trough center of the first stage.

5. Northeastern continuation of the Okinawa Trough

The axial depression of the Okinawa Trough which is 10–20 km in width, may connect to the Beppu-Shimabara Graben in central Kyushu from the northeast of the trough (Kimura, 1983). There are many active faults and volcanoes in the Beppu-Shimabara Graben. As recently as 1991, Unzen Volcano in the graben erupted, producing a huge lava flow.

East of the Beppu-Shimabara Graben is a series of major topographic depressions, such as the Seto Inland (Setonaikai) and Lake Biwa. The starting time of formation of the axial depression in the Okinawa Trough and that of the Southwest Japan inland region are almost the same (Kimura, 1983). Therefore, their formation process should relate to backarc extension. It is possible that the Seto Inland Sea and Lake Biwa are backarc depression in origin. Geological data, however, show some differences between the Okinawa Trough and Seto Inland Sea-Lake Biwa region. The Seto Inland Sea area has a thicker crust and lower heat flow than the Okinawa Trough region (Sumi, 1975; Uyeda, 1989). The trough axis shows a tensile stress field, while the Seto Inland Sea and Lake Biwa region shows a compressional stress field. These differences may be that of the crustal structure before formation of any backarc depression and of the situation of the heat flow beneath the lithospheric plate.

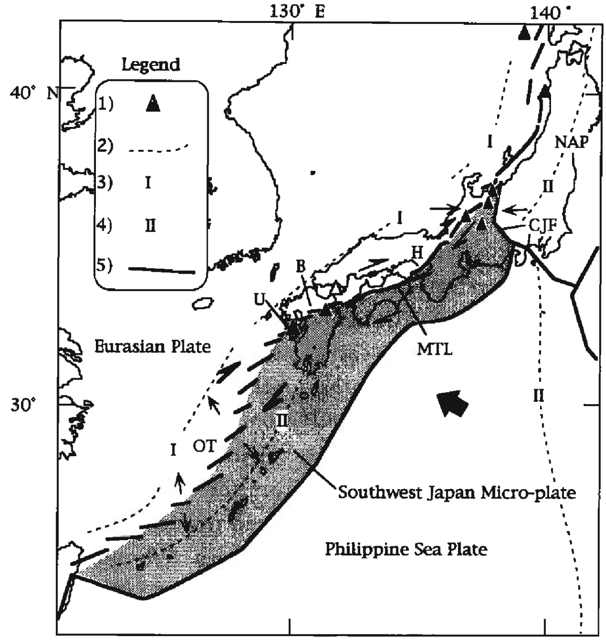

Fig. 4. Proposed plate tectonic map, showing newly proposed plate boundary (Southwest Japan Micro-plate). NAP: North American Plate, OT: Central rifts in the Okinawa Trough. U: Unzen volcano, B: Beppu-Shimabara Graben, MTL: Median Tectonic Line. H: Hanshin District, CJF: Central Japan Fault (Kimura, 1981). The thick, solid arrow represents the direction of plate motion of the Philippine Sea Plate relative to the Ryukyu Arc, from Matsubara and Seno (1980). Legend: 1)=major Quaternary volcano along Japan Arc Fault, 2)=Quaternary volcanic chain, 3)=Quaternary backarc volcanic chain, 4)=volcanic front, 5)=active fault.

There are many active faults along the sedimentary depressions above mentioned: There is the active Median Tectonic Line (MTL) bordering Seto Inland Sea (Seto-naikai) to the east of the Okinawa Trough. Further northeast, a series of active faults are found such as the Nojima Fault, Arima-Takatsuki Faults, the western marginal faults in Lake Biwa, Hatogayu Fault and Atotsugawa Fault. There exist active volcanoes such as Haku-san and Yakeyama inside central Japan (Ono et al., 1981). Such volcanoes as Ontake and Yakedake also seem to occur along those weak lines (Fig. 4). Farther northeast, there are many active faults in the margin of the eastern Japan Sea (Research Group for Active Faults of Japan, 1991).

The Unzen Volcano and volcanoes of central Japan exist in backarc region stand along the above mentioned active backarc rift system (Fig. 4). Therefore, the series of active faults and backarc volcanoes are identifiable as the northeastern continuation of the central rift of the Okinawa Trough, that is, an intraplate boundary in the Eurasian Plate (Kimura, 1993). Whole series of these rifts and volcanoes are tentatively named "Japan Arc Rift Series" or "Japan Arc Fault" and are regarded as a intraplate boundary.

Based on this idea, a new framework of plate division in Japan Arc is proposed in

Fig. 4. Namely, the platelet between the Nankai Trough to Nanseishoto (Ryukyu) Trench and the Japan Arc Fault is identified as a micro-plate tentatively named "Southwest Japan Micro-plate". The nature of the central rifts of the Okinawa Trough is different from their north-eastern extension. The former is a tension crack and the latter is a shear fault with a sense of dextral lateral movement. The Southwest Japan Micro-plate is affected by east-west or southeast-northwest compression. The open echelon cracks in the axial zone of the Okinawa Trough may be generated by the southwestern movement of the micro-plate as a Reidel shear shown in Fig. 4.

The micro-plate should move westward induced by the oblique subducting movement of the Philippine Sea Plate. The Hyogoken-nanbu Earthquake in 1995 (M=7.2) occurred along the Japan Arc Fault in the Hanshin District (Fig. 4), which shows right lateral displacement. Such dextral, lateral movement of the Japan Arc Fault might have generated en echelon the Reidel shear as central rifts in the Okinawa Trough.

6. Opening mode of occurrence of backarc basins

Until now, the heat source for backarc rifting has been thought to be closely related to the subducting slab. According to recent mineralogical studies, dehydration of some minerals in hydrate peridotite at depths of about 100 km and 150 km plays an important role in magma genesis in subduction zones (Tatsumi, 1989). This dehydration suggests a possible origin of volcanic arc magmatism. However, the central rift volcanism in the northern Okinawa Trough occurs in an area where no subducting slab lies beneath it. Therefore, I conjecture that genesis of the heat source in the central rifts of the Okinawa Trough does not relate to subducting slabs.

In the same way, marine geologic and seismological data reveal that subducting slabs do not develop well beneath most active backarc basins of the western Pacific margin, such as the Mariana Trough and the North Fiji Basin. In contrast, subducting slabs fully underlie inactive backarc basins such as the Okhotsk and Japan Seas. Both show evidence that the mantle plume comes up from deeper part than the subducting slab to open the backarc basin, which then becomes inactive when the path of the plume is blocked by the subducting slab (Fig. 5). Based on this view, mantle plumes beneath the backarc basins may not be related to subducting slabs, as in classic models, but may rather be generated in areas independent of the subducting slabs, such as at the core-mantle boundary. On the other hand, the heat source of a volcanic front clearly relates the volcanic front to the subducting slab.

Therefore, I propose a new model for the opening of backarc basins wherein the mantle plume comes up from the mantle deeper than the subducting plate (Fig. 5), finally breaking the lithospheric plate. The model can explain well the nature of the Japan Arc Fault system. For example, in the past, the rift system in central Japan and the eastern margin of the Japan Sea suggested that there existed a mantle plume beneath the plate on the verge of penetrating the lithospheric plate. However, the subducting plate cuts off the uprising plume. If the relict of a plume could be found beneath the rift zone, this hypothesis would be proved.

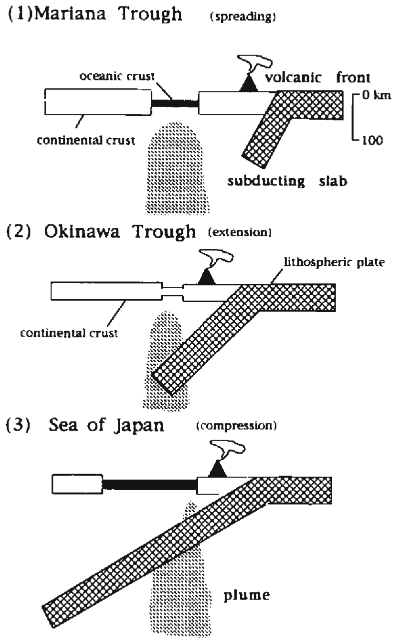

Fig. 5. Proposed model of back arc opening process. (1) and (2) are active in opening movement, and (3) is dormant. Hatched column represents hot, mantle plume. Black plate includes oceanic crust.

That is, the Okinawa Trough backarc basin and the Seto Inland Sea developed in a region where the subducting slab does not develop well. On the contrary, there is no opening trough and inland seas within the central Japan where there is a well developed subducting slab. This is the reason why the mantle plume is blocked by the subducting slab in northern central Japan.

7. Summary and conclusion

1) Recent submarine, geological and geophysical investigations have revealed that the morpho-tectonic division in the East China Sea and Okinawa Trough areas is defined as I) Tunghai Shelf, II) Tunghai Slope (western rifted margin of the Okinawa Trough), III) Okinawa Trough, IV) Tokara Belt (eastern rifted margin of the Okinawa Trough), V) Ryukyu Ridge, VI) Arc-trench gap and VII) Nanseishoto Trench (former Ryukyu Trench) from west to east.
2) The Okinawa Trough has a central rift system which is regarded as an active extensional axis.
4) Two stages of the formation process of the Okinawa Trough can be distinguished. The crustal thinning and thus eastward drifting of the Ryukyu Arc may have occurred during the late Miocene to middle Pliocene (about 6–4 Ma) at the first stage. Extensive subsidence may have occurred at the second stage from the late Pliocene (about 2 Ma).

The present central rift zone of the Okinawa Trough might have been formed from about 2 Ma.

5) The heat source relating to extension processes of the Okinawa Trough might be generated in a portion of independent to the subducting plate, probably in the deeper part than that on the subducting slab, such as the core-mantle boundary.

6) The northeastern continuation to the Okinawa Trough may connect to the Beppu-Shimabara Graben, Median Tectonic Line and active fault zone in Hanshin to active faults and volcanoes inside central Japan. This series of active faults is newly proposed to be a plate boundary of the Southwest Japan Micro-plate.

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