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Seismic record of tectonic evolution and backarc rifting in the southern Ryukyu island arc system

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Abstract

The southern Ryukyu island arc system is located at a convergent plate margin where the Philippine Sea Plate is subducting under the Eurasia Plate. We have conducted multi-channel seismic reflection surveys to study tectonic evolution and backarc rifting of the southern Ryukyu island arc system using the R/V *Tansei-maru* of the Ocean Research Institute, University of Tokyo, in June 1993 and 1994. We describe systematically a complete cross-section from the East China Sea continental shelf to the Ryukyu trench from the viewpoint of seismic stratigraphy. Seven major seismic units and three stages in the tectonic evolution of the system are identified: (1) during stage 1 from Late Miocene to earliest Pleistocene, pre-rift deposits of the Shimajiri Group accumulated over a wide region from the East China Sea continental shelf to the forearc region; (2) stage 2 is defined by a series of tectonic processes involving crustal doming, erosion, subsidence, and sedimentation, in association with initial rifting of the southern Okinawa Trough during most of Early Pleistocene time; and (3) the backarc rifting is still in progress and syn-rift sedimentation has been under way since the Late Pleistocene (stage 3). A new significant observation lies in the fact that the Pliocene Shimajiri Group is not distributed in most of the present-day southern Okinawa Trough. This implies that the backarc rifting of the southern Okinawa Trough was probably initiated after the deposition of the Shimajiri Group, that is, during the Early Pleistocene. Crustal-scale simple shear allowing an asymmetrical half-graben structure, rather than pure shear, governed the initial rifting of the southern Okinawa Trough. The possibility, however, cannot be excluded that pure shear associated with symmetrical rifting may be predominant in the present-day rifting of the southern Okinawa Trough as a result of northwestward migration of the rifting axis. The average extension rate of the southern Okinawa Trough is estimated to be approximately 1–2 cm/year on the basis of fault geometry observed on the acoustic basement.

Keywords: seismic reflection; tectonic evolution; backarc rifting; Okinawa Trough; simple shear; extension rate

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1. Introduction

The Ryukyu island arc system is located at a convergent plate margin where the Philippine Sea Plate is subducting under the Eurasia Plate, and is characterized by the existence of an active continental backarc basin, the Okinawa Trough. This arc system extends for approximately 1200 km in total length from Kyushu to Taiwan, and involves a typical trench–arc–backarc basin system, i.e. the Ryukyu trench, the Ryukyu arc and the Okinawa Trough backarc basin, all oriented in a general NE–SW direction. According to the calculation of relative plate motion by Seno (1977), the convergence rate between the Philippine Sea Plate and the Eurasia Plate varies from 5 to 7 cm/year along this arc system. From the physiographic and geologic viewpoints, the island arc system can be subdivided into the northern Ryukyu arc, the middle Ryukyu arc and the southern Ryukyu island arc system from northeast to southwest by the Tokara Channel and the Kerama Gap.

The study area is the southern part of the system whose backarc basin, the southern Okinawa Trough, is characterized by high heat flow (Yamano and Kinoshita, 1995) and a water depth exceeding 2000 m. Such a depth is never found in the middle and northern Okinawa Troughs, suggesting that the southern Okinawa Trough is the most active and evolved backarc rift in the entire Ryukyu island arc system. Some seismic reflection and refraction studies (Furukawa et al., 1991; Hirata et al., 1991; Sibuet et al., 1995) indicate that the southern Okinawa Trough is in an incipient rifting stage of the backarc basin accompanied by a slight thinning of the continental crust.

A large number of seismic stratigraphic studies (Aiba and Sekiya, 1979; Lee et al., 1980; Kimura, 1985; Letouzey and Kimura, 1985, 1986; Sibuet et al., 1987; Furukawa et al., 1991) based on single- or multi-channel seismic reflection data have been done to examine the backarc extension and tectonic evolution in the southern Ryukyu island arc system. Lee et al. (1980) and Letouzey and Kimura (1986) proposed evolutionary stages of the Okinawa Trough since the Tertiary, which involve volcanism (or doming), rifting, and drifting in the backarc basin. The multi-channel seismic reflection data which were used to propose a tectonic evolution model of the arc system by Kimura (1985) and Letouzey and Kimura (1986), rely on a single transect of the entire arc system. Moreover, the data were only common depth point (CDP) stacked and the acoustic image appears to have been affected by diffraction, due to the many faults (especially in the extended backarc basin). In addition the data for this area were published as interpreted cross-section only.

The rifting chronology of the Okinawa Trough is still controversial. Some previous works (Herman et al., 1978; Lee et al., 1980; Letouzey and Kimura, 1986; Sibuet et al., 1987) proposed that the rifting started in the Late Miocene, based on geologic and seismic observations. Kimura (1990) and Furukawa et al. (1991) proposed that rifting occurred at about 2 Ma, based on geologic and seismic observations. Miki (1995) proposed a two-phase opening model for the origin of the Okinawa Trough on the basis of palaeomagnetic and geochronologic study: the first phase would be between 10 Ma and 6 Ma, and the second phase at about 1 Ma.

There has been no detailed discussion concerning the rifting style of the Okinawa Trough. Recent seismic refraction data (Hirata et al., 1991) across the southern Okinawa Trough indicate a symmetrical crustal structure, but do not uniquely constrain the rifting style. Nevertheless, based on these same data Hino (1991) proposed symmetrical rifting of the southern Okinawa Trough. Abe (1991) suggested the possibility of symmetrical rifting on the basis of multi-channel seismic (MCS) reflection data, but did not discuss it in detail.

Sibuet et al. (1995) have estimated an amount of extension across the southern Okinawa Trough from refraction and gravity data. If seismic reflection data give any information on the detailed shape of the pre-rift sedimentary sequence, it may be possible to quantify the amount of extension on the basis of fault geometry in the southern Okinawa Trough.

In this paper we show migrated MCS profiles transecting the southern Ryukyu island arc system and reconstruct the tectonic history in the system since the Neogene on the basis of seismic stratigraphic interpretation. Moreover, we propose a backarc rifting model and an exact time of the rifting inception, and evaluate an extension rate for the southern Okinawa Trough.

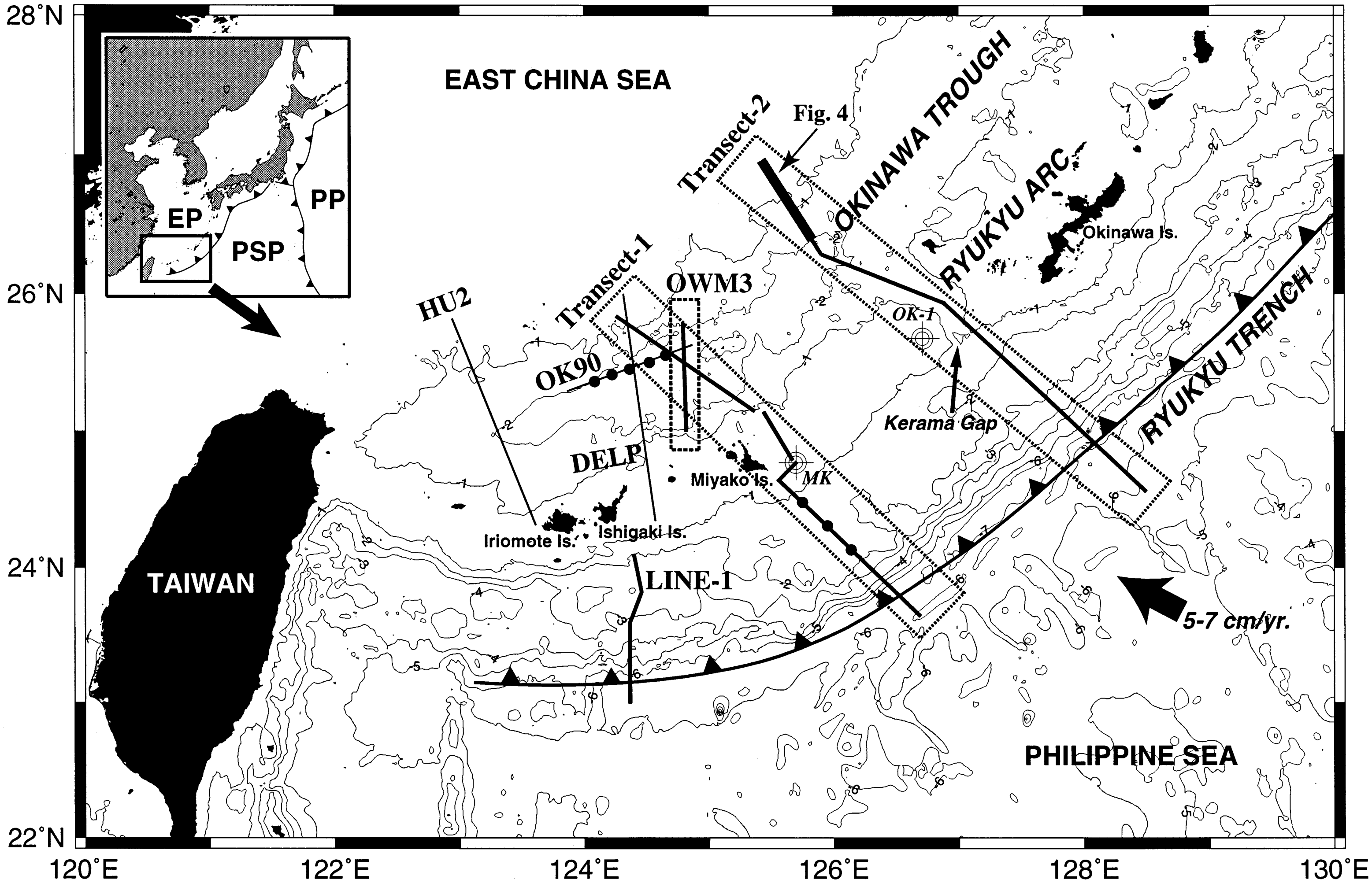


Fig. 1. Bathymetry and physiographic features of the southern Ryukyu island arc system. Positions of multi-channel seismic reflection and OBS refraction survey lines are shown. The MCS reflection lines consist of Transect-1, Transect-2 and Line-1 resulting from KT93-8 and KT94-9 cruises (6-channel), 12-channel OWM3 line provided by the Japan Oceanographic Data Center, 6-channel DELP line resulting from the DELP 1988 cruise (Furukawa et al., 1991). Ryukyu arc segment (48-channel) of Transect-1, which is located off eastern Miyako Island, was provided by the Geological Survey of Japan. HU2 is a single-channel seismic reflection line after Lee et al. (1980). The OBS refraction lines include a line in the forearc region with three OBSs (KT94-9 cruise; Park, 1996) and the OK90 line in the trough region with five OBSs (Sekine, 1994). The dots on the OBS lines indicate the positions of the OBS. Two offshore petroleum exploration well data are shown by double-circled symbols: *MK* (Tsuburaya and Sato, 1985) and *OK-1* (Ishiwada, 1981; Aiba and Sekiya, 1979). Unit and interval of water depth contours are km and 1 km, respectively. *EP* = Eurasia Plate. *PSP* = Philippine Sea Plate. *PP* = Pacific Plate.

2. Data acquisition and processing

We have conducted MCS reflection surveys in the southern Ryukyu island arc system, using the R/V *Tansei-maru* of the Ocean Research Institute (ORI), University of Tokyo, in June 1993 and June 1994. We used an air-gun of 580-in^3 capacity as a controlled sound source and a 6-channel streamer with 50 m group spacing during the MCS surveys. We obtained two MCS transects (Transect-1 and -2) from the Ryukyu trench to the East China Sea continental shelf, crossing the entire trench–arc–backarc basin system, and a MCS profile (Line-1) from offshore Ishigaki Island to the Ryukyu trench. Positions of the MCS lines are indicated in Fig. 1. These MCS data were demultiplexed and processed conventionally by the Phoenix Vector 2-D Seismic Data Processing System of the ORI. The data were sorted, deconvoluted and filtered for enhancement. Velocity correction was applied for normal move-out based upon results of velocity analysis using a constant velocity stack method. After stacking, the data were migrated with a finite difference wave equation migration program to remove diffraction interferences. Gain recovering was finally applied. MCS data of the Ryukyu arc of the entire Transect-1, which is located off eastern Miyako Island, were acquired by a 48-channel streamer and provided by the Geological Survey of Japan. These MCS data were reprocessed by the same procedure as described above.

3. Seismic stratigraphy and interpretation

Transect-1 is considered here to be more representative of the subsurface structure of the southern Ryukyu island arc system than is Transect-2. Additionally we reinterpret a MCS profile (OWM3) acquired by a 12-channel streamer across the southern Okinawa Trough, already published by Katsura et al. (1986).

We used the data of a petroleum exploration well 'MITI MIYAKOJIMA OKI' (MK) (Tsuburaya and Sato, 1985) to constrain the geologic age of the seismic units on the MCS profile. On Transect-1, some P-wave velocity data are used for stratigraphic interpretation and written within each seismic unit on the interpreted profile (Fig. 3). Park (1996) determined P-wave velocities of four seismic units in the forearc region from shot point (SP) 1200 to 2800 with the help of the Ocean Bottom Seismograph (OBS) experiment. The velocities are 1.7–2.0 km/s, 2.3–3.0 km/s, 3.6 km/s, and more than 4.5 km/s, from top to bottom. Park (1996) calculated P-wave velocities of the Shimajiri and Yaeyama Groups from depth-stratal age control of the well MK around SP 3450 and seismic reflection travel time data given by Tsuburaya and Sato (1985). The velocities of the Shimajiri and Yaeyama Groups are approximately 2.7 and 3.5 km/s, respectively. An OBS experiment line OK90 (Sekine, 1994) is intersecting around SP 5950 and the experiment provides P-wave velocity information for three seismic units in the trough region. The velocities are 1.7 km/s, 2.8–3.6 km/s, and more than 4.9 km/s, from top to bottom.

Seismic units and their seismic characteristics along the MCS profiles are summarized in Table 1. The seismic units have mutual unconformable relationships. Correlation of the submarine seismic stratigraphy obtained during the present study with onshore geology is given in Table 2. It is noticeable that unit C is recognized on the submarine seismic stratigraphy but not on the Ryukyu Islands.

3.1. Synthesis of seismic stratigraphy

We could identify a total of seven major seismic units which are denoted by A, B, C, D, E, F, and G, based on acoustic characteristics and P-wave velocity data of the units, and on the petroleum exploration well (MK) data. We have described external form, internal reflection configuration, and seismic facies of each unit on Transect-1 and OWM3 profile, according to Mitchum et al. (1977).

Unit A, consisting of Holocene deposits, generally shows a basin fill or slope front fill external form, parallel or hummocky internal reflection configuration, and discontinuous, transparent seismic facies. Unit B of the Ryukyu Group, which is confined to the arc region, shows a sheet drape external form, sub-parallel internal reflection configuration, and discontinuous, transparent seismic facies. Unit C, whose distribution is confined to the backarc basin, shows a basin fill or channel fill external form, sub-parallel internal reflection configuration, and discontinuous, transparent seismic facies. Unit D (upper part of the Shimajiri

Table 1
Characteristics of seismic units and facies along Transect-1 and OWM3 profile, according to Mitchum et al. (1977)

Seismic unit	External form	Internal reflection configuration	Seismic facies
A	sheet or basin fill or slope front fill	parallel or hummocky or parallel with some hummocky	continuous or discontinuous, transparent
B	sheet drape	sub-parallel	discontinuous, transparent
C	basin fill or channel fill	sub-parallel	continuous or discontinuous, transparent
D	bank or channel fill or sheet drape	parallel or wavy or sub-parallel or progradational or hummocky	continuous or discontinuous, transparent
E	sheet drape or lens	hummocky or parallel	discontinuous, transparent
F	sheet drape or wedge or channel fill or lens	parallel or hummocky	discontinuous, semi-transparent or transparent or chaotic
G		hummocky	chaotic

Table 2
Correlation of submarine seismic stratigraphy deduced from the present study with onshore geology in the southern Ryukyu island arc system

Age (Ma)	*Epoch*		*Onshore Geology*	*Seismic Stratigraphy (Present Study)*
	Holocene		Alluvium	Unit A
0.01	Pleistocene	Late	Ryukyu Group	Unit B
0.7		Early		Unit C
1.6	Pliocene		Shimajiri Group	Unit D
				Unit E
5.3	Miocene	Late		
11.2		Middle		
16.6		Early	Yaeyama Group	Unit F
23.7	Oligocene			?
36.6	Eocene		Nosoko Formation	Unit F
			Miyara Formation	
57.8	Paleocene			
66.4	pre-Cenozoic		Fusaki Formation *or* Tomuru Formation	Unit G : Acoustic Basement

The onshore geology was modified after Kizaki (1986) and Ujiie and Nishimura (1992). Wave stripes between each unit represent lack of sedimentation. See text for summary of the lithology of each unit.

Group) generally shows a sheet drape external form, progradational internal reflection configuration, and discontinuous seismic facies. Unit E (lower part of the Shimajiri Group) generally shows a sheet drape or lens-shaped external form, parallel or hummocky internal reflection configuration, and discontinuous seismic facies. Unit F, correlative of the Nosoko and the Miyara Formations, shows a sheet drape or lens-shaped external form, hummocky internal reflection configuration, and discontinuous seismic facies. Finally, unit G of the pre-Cenozoic acoustic basement shows hummocky internal reflection configuration and chaotic seismic facies.

The lithology of each unit is based on Tsuburaya and Sato (1985) and Ujiie and Nishimura (1992), and is summarized as follows. The Ryukyu Group is mainly composed of reefal limestone and sandstone. The lower part of the Shimajiri Group is composed of an alternation of sandstone and siltstone, whereas the upper part of the Shimajiri Group is composed mainly of siltstone. The Yaeyama Group is characterized by paralic sediments with sandstone-rich facies and contains some coal-measures. The Nosoko Formation consists of greenish altered volcanics including pillow lavas and pyroclastic sediments, whereas the Miyara Formation consists of reefal limestone. The Fusaki Formation is dominated by a chaotic complex of a variety of allochthonous blocks in a muddy matrix. The Tomuru Formation of high-pressure metamorphic rocks is mainly composed of mafic and pelitic schists accompanied by felsic and psammitic schists.

3.2. General observation on the profiles Transect-1 and OWM3

Transect-1 and its interpretation are represented in Figs. 2 and 3, respectively. Unit A around SP 5400 is thickest, and its seismic character suggests that it contains Holocene turbidites which seem to have been supplied from the continental shelf and the Ryukyu arc. Unit B can be recognized in the Ryukyu arc only, and unit C is restricted to the trough region only, from SP 4800 to 6750. Unit C is thickest around SP 5400, and unconformably overlies units D, F and G, covering and burying them. Unit D of the Ryukyu arc shows a pronounced parallel progradational foreset with a northwest–southeast direction of bedding plane around SP 3600 to 4000. This kind of foreset can also be recognized in the continental slope region of the trough from SP 6800 to 7000, even though it is not so pronounced, compared with those of the Ryukyu arc, possibly because of subsequent tectonic deformation. The bedding plane direction of the foreset allows us to infer that sediments of unit D are originated from the northwestern continental shelf area. Unit E is defined at the continental slope region of the trough and in the Ryukyu arc. Unit F can be identified along most of this profile. In particular, it is noticeable that the lens-shaped unit F overlies unit G around SP 1600, 5950, 6050 and 6500. Trenchward extension of unit G, which represents the acoustic basement, is not obvious. In the Ryukyu trench from SP 400 to 650, we can identify a clear image of the oceanic crust with chaotic seismic facies, which signifies that the Philippine Sea Plate is subducting under the Eurasia Plate.

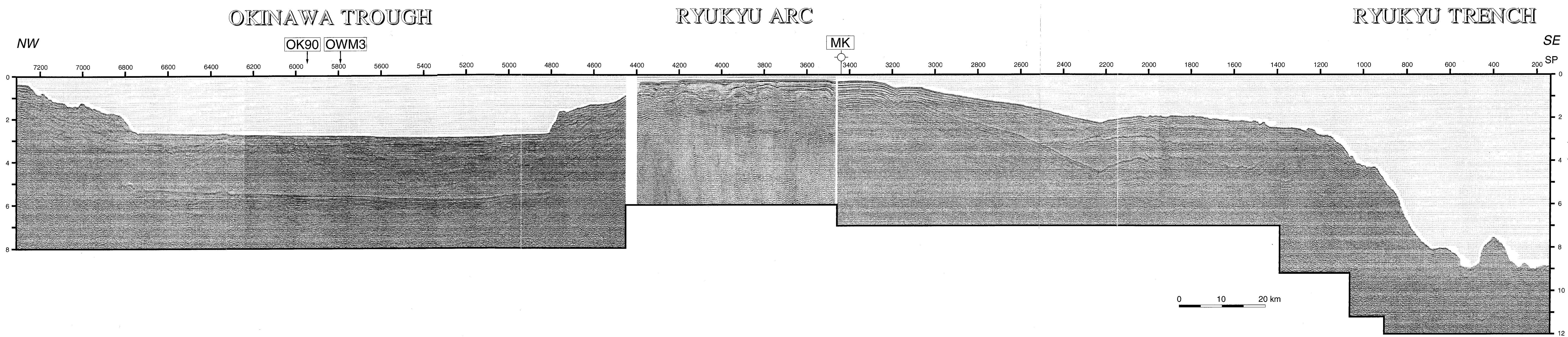
The OWM3 profile and its interpretation are represented in Fig. 4. The vertical scale of this profile is not two-way travel time but depth in km. In addition, the free-air gravity anomaly along the OWM3 profile is indicated in the lower part of Fig. 4. Digital data of the gravity anomaly were taken from Hydrographic Department, Maritime Safety Agency of Japan (1987). Unit A has a maximum thickness exceeding 2 km around CDP 2600. The northern part of unit C pinches out around CDP 2600 and overlaps unit G of the acoustic basement, resulting in a clear unconformity. Unit D is confined to the arcward region of the trough around CDP 3300 as in Transect-1. Unit F can be identified around CDP 200, 600, 1300, and 3300 as a lens-shaped unit. Unit G of the acoustic basement shows very irregular surface configuration, probably because of erosion.

4. Tectonic evolution since the Neogene

We have systematically described a complete cross-section from the East China Sea continental shelf to the Ryukyu trench from the viewpoint of seismic stratigraphy. A total of seven major seismic units can be recognized in the southern Ryukyu island arc system. These seismic units represent different acoustic characteristics which enable us to reconstruct the geologic history associated with the tectonic evolution of the southern Ryukyu island arc system. The petroleum exploration well MK provides seismic units with a chronology from Early Miocene times to Present. A tectonic evolution model of the southern Ryukyu island arc system since the Neogene is illustrated in Fig. 5. This model is based on the new significant observation that the Shimajiri Group is not distributed in most of the present-day southern Okinawa Trough.

4.1. Stage 1 (Late Miocene to earliest Pleistocene): pre-rift sedimentation

On the MCS profiles presented above, we could identify units D and E, which are equivalent to the upper and lower parts of the Shimajiri Group, respectively, over a wide region including the continental slope region of the trough, arc, and forearc, with the exception of most of the trough region. Distribution of the Shimajiri Group in the East China Sea continental shelf has been reported by Aiba and Sekiya (1979) and Ishiwada (1981). Fig. 6 shows the distribution map of the Cenozoic strata newly compiled on the basis of both the present study and of Kizaki (1986). Compared with the work of Kizaki (1986), the distribution of the Shimajiri Group in the southern Okinawa Trough is very limited. From the distribution map, it can be estimated that the deposits of the Shimajiri Group originated from the Chinese mainland. Some works proposed that the deposits of the Shimajiri Group were supplied from Ryukyu–Oldland located around the Ryukyu arc, based on heavy mineral (Sato and Suzuki, 1977)



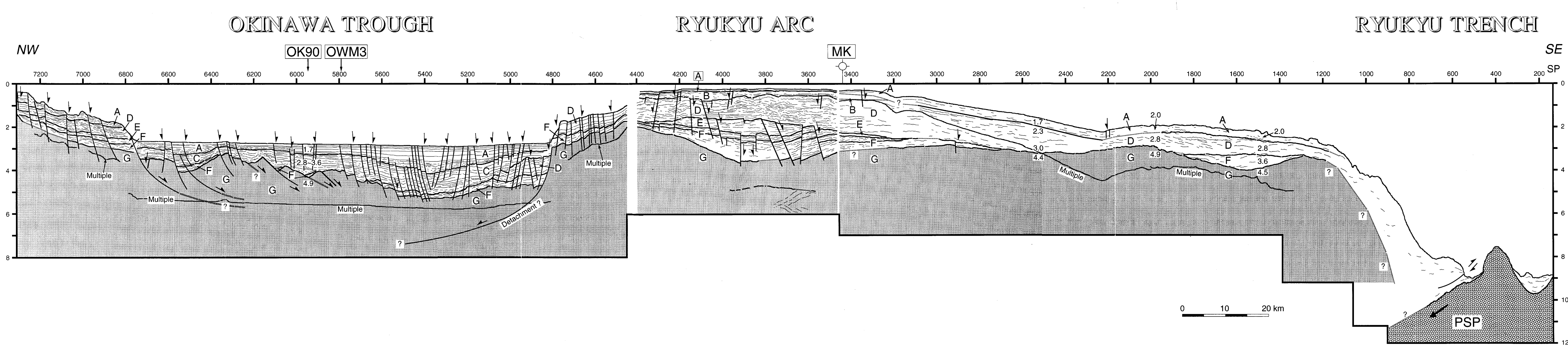


Fig. 2 (top). Seismic profile of Transect-1. Vertical exaggeration is about 10 : 1.

Fig. 3 (bottom). Interpretation of seismic profile (Fig. 2) of Transect-1. Numbers within each seismic unit in the interpretation indicate P-wave velocity determined from OBS refraction experiment. Vertical exaggeration is about 10 : 1.

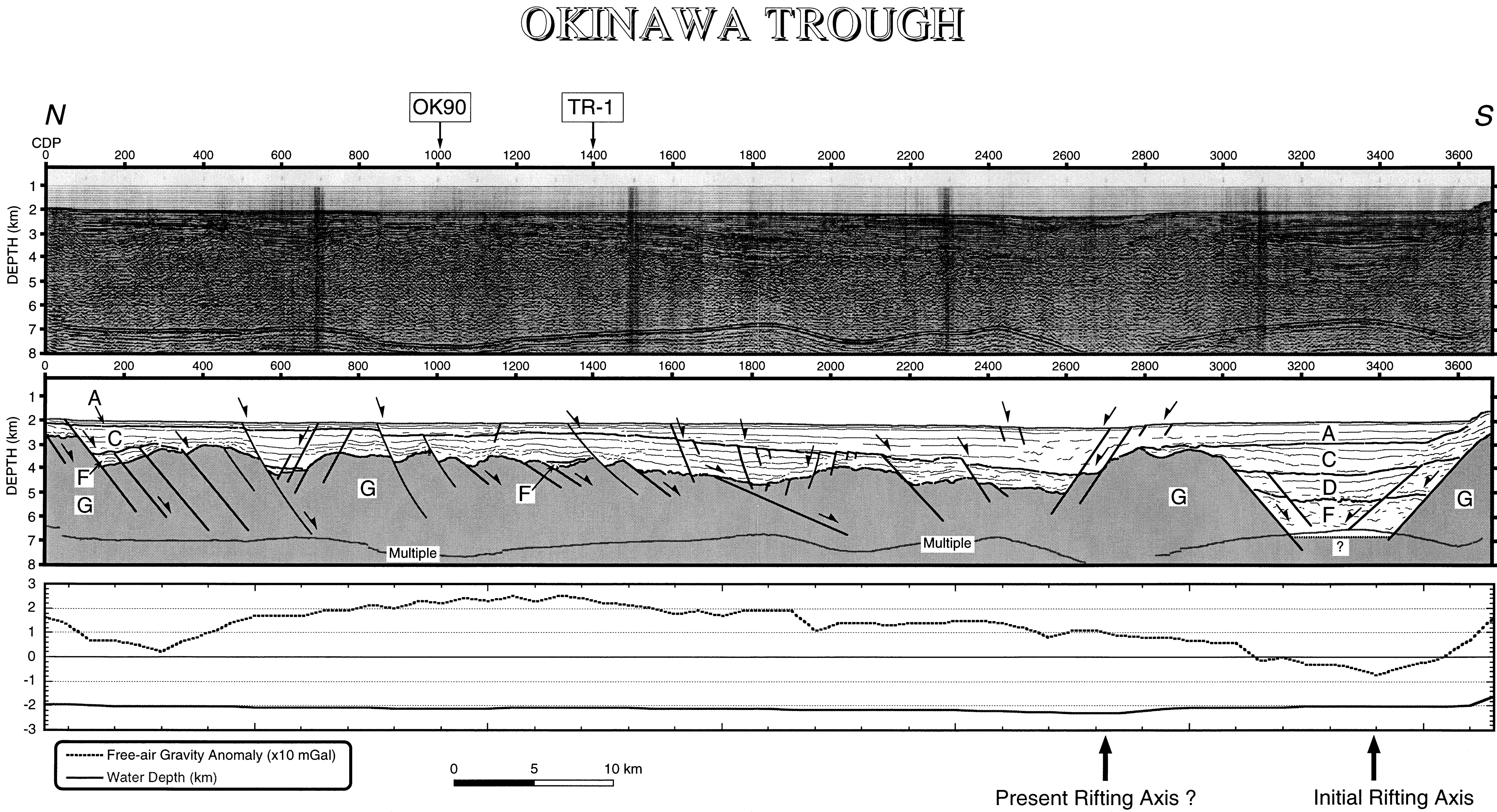


Fig. 4. Seismic profile of the OWM3 line and interpretation. Also represented are free-air gravity anomaly and water depth along the line. Vertical exaggeration is about 10 : 1.

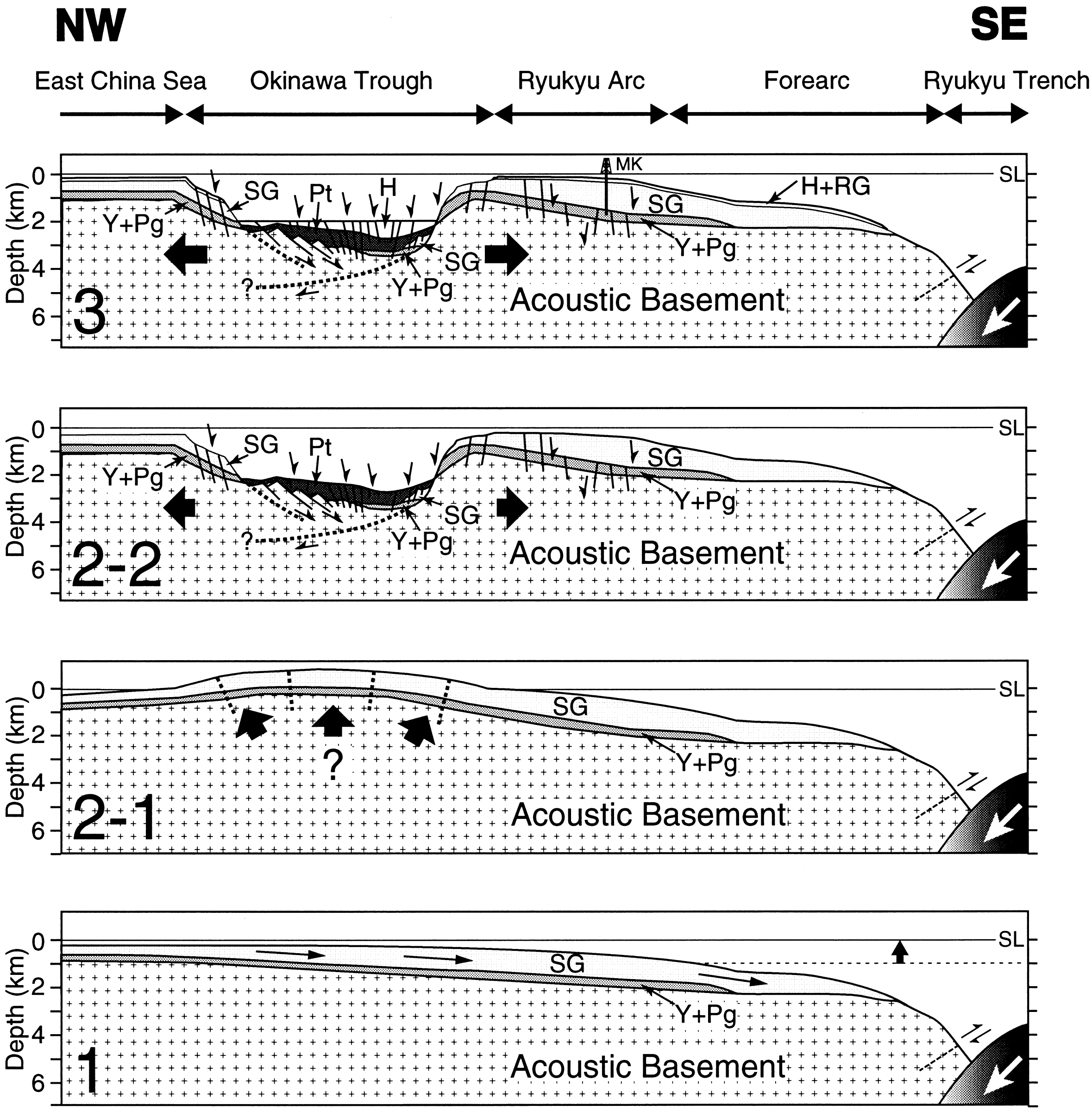


Fig. 5. Tectonic evolutionary stages in the southern Ryukyu island arc system since the Neogene. (1) Stage 1 (Late Miocene to earliest Pleistocene): pre-rift sedimentation. (2-1 and 2-2) Stage 2 (Early Pleistocene): initial backarc rifting. (3) Stage 3 (Late Pleistocene to Holocene): the backarc rifting still in progress. The geologic age of acoustic basement is pre-Cenozoic as shown in Table 2. *Pg* = Palaeogene deposits. *Y* = Yaeyama Group. *SG* = Shimajiri Group. *Pt* = Early Pleistocene deposits. *RG* = Ryukyu Group. *H* = Holocene sediments. *SL* = sea level.

and pollen analyses (Nishida and Itokazu, 1976). However, no clear evidence supporting the existence of the Ryukyu–Oldland has been reported. Additionally, it is noticeable that a pronounced parallel progradational foreset structure is identified within the Shimajiri Group in the Ryukyu arc and continental slope region of the trough on Transect-1. The foreset structure clearly shows a parallel accumulation pattern from the East China Sea continental shelf toward the forearc region, suggesting that the

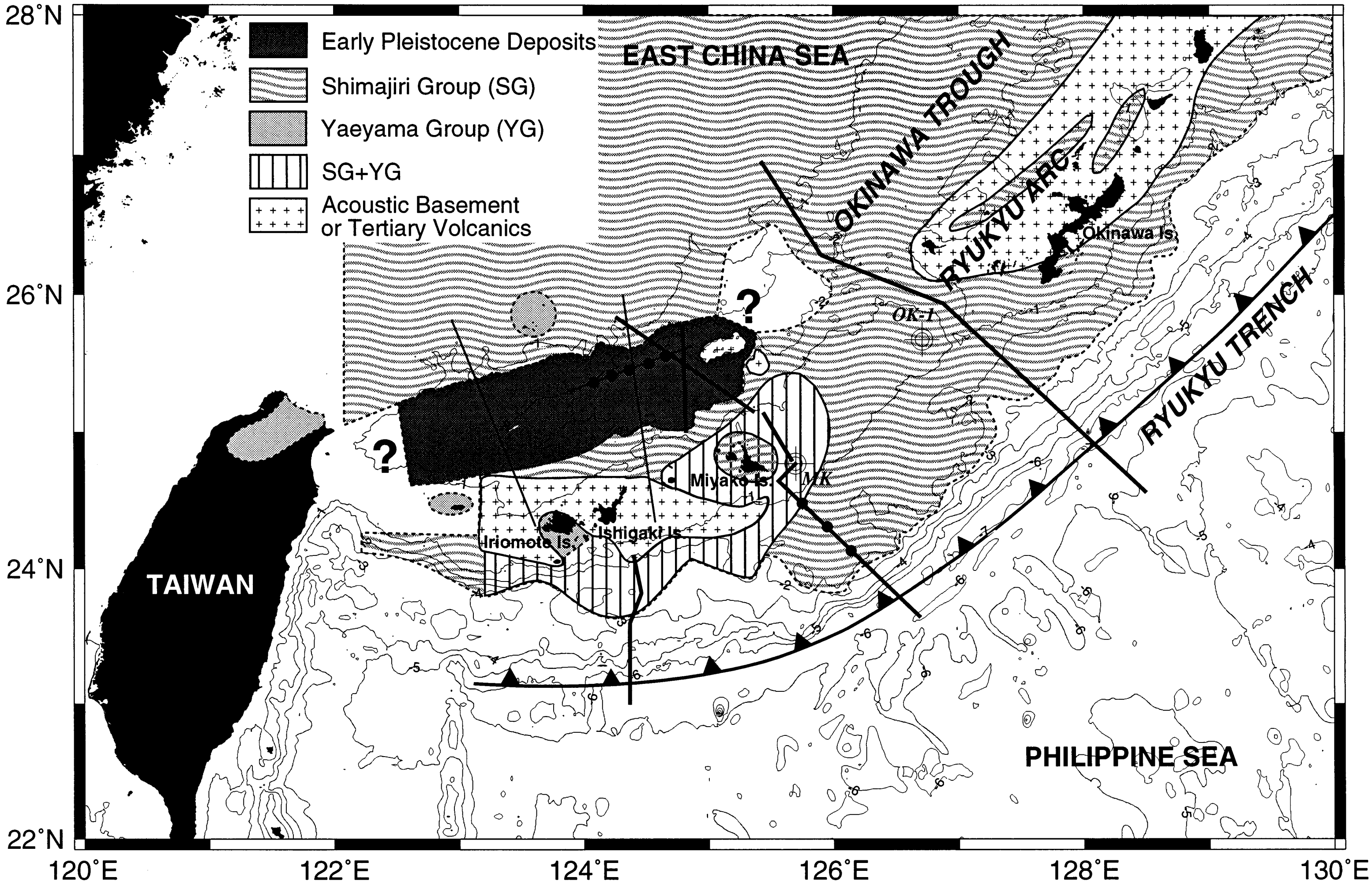


Fig. 6. Distribution map of the Cenozoic strata based on the interpretation of MCS profiles. Comparion of this map with that of Kizaki (1986) shows that the Shimajiri Group, the Yaeyama Group and the Mesozoic acoustic basement are replaced by the Early Pleistocene deposit (unit 3) in most of the southern Okinawa Trough.

sediments of the Shimajiri Group were supplied from the Chinese mainland. A Pliocene sea level rise is well known from the global cycles of relative change of sea level (Vail et al., 1977), and we interpret the Shimajiri Group as a transgressive sequence composed of clastic sediments. The lower part of the Shimajiri Group is composed of an alternation of sandstone and siltstone, whereas the upper part of the Shimajiri Group is composed mainly of siltstone rich in foraminifera (Ujiie and Nishimura, 1992). This may suggest a facies change concordant with relative sea level rise.

4.2. Stage 2 (2-1 and 2-2: Early Pleistocene): initial backarc rifting

As could be recognized on the Transect-1 and OWM3 profiles, the lens-shaped unit F in the trough is intercalated between unit C containing Early Pleistocene deposits and unit G, with unconformities above and below. Compared with unit F in the arc and forearc, unit F in the trough indicates a relatively thinner thickness and an isolated accumulation aspect. Such a lens-shaped seismic unit is interpreted as an erosional remnant after crustal movement. Another lens-shaped seismic unit, D, is intercalated between units C and F in the arcward trough region from SP 4800 to 5100, with unconformities above and below. This unit D pinches out northwestward, probably because of subsidence.

The seismic stratigraphy of the trough region is very different from that of the East China Sea continental shelf and slope regions, the arcward slope region, and the arc area. The stratigraphic differences can be explained by a series of tectonic processes involving backarc crustal doming, erosion, subsidence, and sedimentation associated with initial rifting predominating in the Okinawa Trough during this stage:

(1) Crustal doming occurred between the East China Sea continental shelf and the arc. The doming led to subaerial exposure of the strata below unit D.

(2) The strata below unit D suffered from subaerial erosion, resulting in an unconformity. Even a part of unit G may have been eroded regionally. Some of the strata which survived the erosion remained as units D and F.

(3) Abrupt subsidence, which was triggered by crustal extension, occurred in the Okinawa Trough.

(4) Unit C of the Early Pleistocene deposits (denoted by ‘Pt’) accumulated into the Okinawa Trough as syn-rift sediments, infilling small basins formed by crustal doming and subsidence.

The model of evolutionary stages of the Okinawa Trough proposed by Lee et al. (1980) and Letouzey and Kimura (1986) is somewhat consistent with our model.

Our idea on the crustal doming and subsequent erosion processes is fundamentally based upon the seismic stratigraphic interpretation that most of the Shimajiri Group was removed by erosion and thus does not exist now in most of the southern Okinawa Trough as we have shown in Fig. 6. Some previous works (Aiba and Sekiya, 1979; Kizaki, 1986; Furukawa et al., 1991; Ujiie and Nishimura, 1992) inferred that the Shimajiri Group was distributed over the greatest part of the southern Okinawa Trough. For example, from interpretation of DELP 1988 stacked MCS profiles across the southern Okinawa Trough, Furukawa et al. (1991) proposed that the lowest seismic sequence, which is not masked by multiple reflection of the seafloor, consists of the Shimajiri Group. However, the interpretation of our new migrated MCS profiles suggests that what has been called the Shimajiri Group actually corresponds to the acoustic basement (unit G) of the southern Okinawa Trough. As shown on Transect-1, the acoustic basement of the southern Okinawa Trough has a P-wave velocity (V_p) exceeding 4.9 km/s, whereas the V_p of the Shimajiri Group is approximately 2.7 km/s in the arc, suggesting that the acoustic basement (unit G) is distinct from the Shimajiri Group. Katsura et al. (1986) indicated that the stacking velocity of unit G was more than 4.6 km/s on the OWM3 profile. They interpreted unit G as Miocene or older deposits. Comparing the V_p (3.5 km/s) of the Early Miocene Yaeyama Group with that ($\geq$4.9 km/s) of unit G, it can be inferred that unit G is older than Neogene time at least. This fact can be verified from a statistical study of P-wave velocities for various rocks in Japan by Hattori and Sugimoto (1975).

One may presume that unit C in the trough region is equivalent to unit D (Shimajiri Group) in the arc, suggesting that the Shimajiri Group is distributed continuously from the arc to the trough region. Indeed, the V_p ($\geq$2.8 km/s) of unit C in the trough region is similar to that (2.8 km/s) of unit D in the arc and forearc region. But three observations suggest that unit C is different from unit D. Firstly, the pronounced parallel progradational foreset structure clearly observed within unit D of the arc and the continental slope region cannot be found within unit C of the southern Okinawa Trough. Secondly, from the viewpoint of faulting characteristics such as pattern and offset, the faults cutting the acoustic basement (unit G) are different from those cutting unit C. Not only do many of the faults which cut unit G fail to cut unit C, but also the fault offsets in unit G are much larger than those in unit C. From this it would appear that unit C was deposited after unit G was deformed to form the proto Okinawa Trough. However, if this were so, then deposits of unit C would not have been able to spread to the arc because they would have been trapped by the proto-Okinawa Trough. This contradicts the equivalence of units C and D, because this equivalence implies a deposition which is spatially continuous from continental shelf to arc. Thirdly, from the overall seismic character and sedimentary structure, unit C is different from unit D. For instance, the lower and upper parts of unit C represent onlaps against the underlying acoustic basement around CDP 1900 and 2600 on the OWM3 profile, resulting in a clear unconformity. However, such a stratigraphic relationship cannot be found in unit D.

As the backarc rifting proceeded, the region of the southern Okinawa Trough abruptly subsided, creating southeast- and northwest-facing listric normal faults consisting of synthetic and antithetic faults which were accompanied by a possible detachment fault. The acoustic basement of the Okinawa Trough might be affected by sliding or rotation, and eventually the basement was separated into several tilted fault blocks. The tilted basement can be identified around SP 5700, 6000, 6100, 6500 of Transect-1 and CDP 100, 600, 1000, 1500, 2200 of the OWM3 profile. Most of the tilted basement can be found in the continental shelfward trough, and show southeastward tilting. We can find the subsided structure of unit D around SP 4800 of Transect-1 and CDP 3600 of the OWM3 profile.

From the East China Sea continental shelf and the arc sides, the Early Pleistocene unit C accumulated into the Okinawa Trough as syn-rift sediments, infilling small basins formed by the tilted basement blocks. In particular, large rivers of the Chinese mainland likely played an important role as sediment sources during Early Pleistocene times when river mouths prograded near the Okinawa Trough by sea level lowering during the Early Pleistocene glacial periods. There may have been possible lateral sediment input from Taiwan, suggesting along-trough sediment transport into the Okinawa Trough. However, we consider that the infilling sediment was predominantly supplied from the East China Sea continental shelf to the Okinawa Trough in terms of the southward sedimentation pattern shown within unit C of the OWM3 profile.

This backarc rifting also resulted in the half-graben shape of the acoustic basement (unit G) from SP 4800 to 6800 on Transect-1, associated with sliding and rotation of the tilted fault blocks. The present shape of the trough might have been primarily formed during this stage.

4.3. Stage 3 (Late Pleistocene to Holocene): backarc rifting still in progress

The Ryukyu Group (denoted by RG) and the Holocene deposits (denoted by H) have accumulated with unconformable relationship in the arc region. Holocene thick turbidites of unit A have accumulated in the trough region, and are regarded as syn-rift sedimentary units. There are many faults cutting units A and B in the trough region so that most of units show discontinuous seismic facies, suggesting that the backarc rifting is still in progress.

5. Backarc rifting of the southern Okinawa Trough

A large number of previous works (Lee et al., 1980; Kimura, 1985, 1990; Letouzey and Kimura, 1985, 1986; Sibuet et al., 1987; Furukawa et al., 1991; Hirata et al., 1991; Miki, 1995; Sibuet et al., 1995) have discussed continental backarc rifting of the Okinawa Trough. The seismic stratigraphic interpretation on Transect-1 and the OWM3 profile crossing the trough, which are associated with the well data (MK), some P-wave velocity data, and free-air gravity data, will contribute to bring a more precise chronology of the rifting activity, rifting style, and extension rate of the southern Okinawa Trough.

5.1. When did the rifting start?

A number of previous works (Herman et al., 1978; Lee et al., 1980; Letouzey and Kimura, 1986; Sibuet et al., 1987; Kimura, 1990; Abe, 1991; Furukawa et al., 1991; Miki, 1995) have discussed the age of rifting inception of the southern Okinawa Trough, but it is still controversial.

Our tectonic evolution model suggests that the rifting of the southern Okinawa Trough was probably initiated after the deposition of the Shimajiri Group during Early Pleistocene times (Stage 2). This age may be comparable with phase II of the two-phase opening model of Miki (1995) for the Okinawa Trough. Some previous works (Letouzey and Kimura, 1985; Kimura, 1990; Furukawa et al., 1991) proposed that rifting of the Okinawa Trough occurred at about 2 Ma, and it is approximately similar to our present result. But, in relation to formation processes of the Okinawa Trough, the previous works are fundamentally different from our proposal. The most critical difference is that the previous works proposed that the Shimajiri Group was distributed as a syn-rift deposit in the southern Okinawa Trough, whereas, according to our analysis, the rifting occurred *after* the deposition of the Shimajiri Group in the southern Okinawa Trough.

5.2. Rifting style

The two extreme models of the lithospheric stretching process are a pure-shear model involving uniform and symmetrical stretching across the lithosphere (McKenzie, 1978), and a simple-shear model in which asymmetrical fault wedges in the upper crust are connected laterally by a detachment surface to offset stretching and thinning of the underlying lithosphere (Wernicke, 1985). Pure- and simple-shear models have been discussed in relation to strain geometry in rifts (Wernicke, 1985). Arguments for rifting style are very important to constrain shear stress fields governing backarc rifting.

It is necessary to notice overall shapes and motions of the tilted basement blocks of the acoustic basement to examine the rifting style of the southern Okinawa Trough. On the acoustic basement of Transect-1, a probable detachment fault, which verges toward the East China Sea continental shelf at the arcward flank of the southern Okinawa Trough, is recognized beneath tilted and rotated basement blocks, finally resulting in a typical half-graben structure (Figs. 2 and 3). Similar tilted blocks can be also clearly identified in the continental shelfward Okinawa Trough around SP 7000 on Transect-2 (Figs. 7 and 8). Other similar tilted blocks with $V_p = 4.9$ km/s, overlain by Quaternary to Pliocene sediments of $V_p = 2.0$ km/s, were identified in the continental shelfward Okinawa Trough along profile HU2 (Lee et al., 1980), between Iriomote Island and the continental shelf across the trough (Fig. 1). A large number of syn-rift normal faults cutting units A and C on Transect-1 are tilted toward the rifting axis which seems to be located around SP 5350. The OWM3 profile with free-air gravity anomaly indicates a fault system similar to that of Transect-1. As for the uppermost boundary configuration of acoustic basement recognized in the OWM3 profile, it is remarkable that the thickest part of the sedimentary cover overlying basement unit G exists in the arcward Okinawa Trough around CDP 3400.

In addition we can observe some negative gravity anomaly around CDP 3400, which is not found in the continental shelfward Okinawa Trough. Such a gravity anomaly pattern seems to reflect an asymmetrical structure or arrangement of the acoustic basement in the southern Okinawa Trough and to indicate that the rifting axis was located at the arcward Okinawa Trough province rather than the continental shelfward Okinawa Trough. Accordingly, we consider that the rifting of the southern Okinawa Trough was asymmetrical during at least the initial stage. However, we cannot ignore a remarkable topographic feature of the seafloor around CDP 2700 where the water depth exceeds 2200 m. The region corresponds to the Yaeyama Graben which is one of the en-echelon central grabens developed in the southern Okinawa Trough. Katsura et al. (1986) found a conspicuous knoll consisting of igneous rocks including pyroxene andesite, at the Yaeyama Graben. Such a maximum in bathymetry and an active igneous activity in the Yaeyama Graben suggest that the present-day rifting axis is located around the graben and the rifting of the southern Okinawa

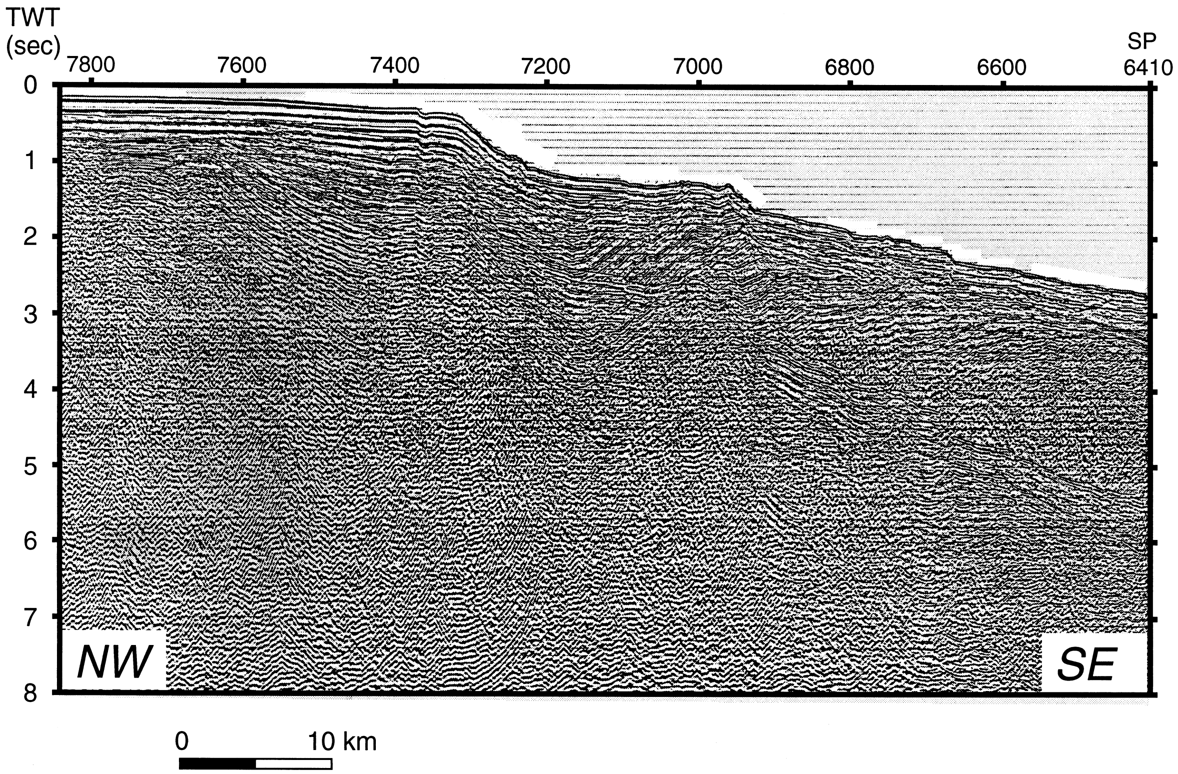


Fig. 7. Seismic profile of the East China Sea continental shelfward Okinawa Trough of Transect-2. Vertical exaggeration is about 10 : 1.

Trough is still active, and there is even a possibility of symmetrical rifting. The discrepancy between the present-day rifting axis from the seafloor configuration around the Yaeyama Graben and the initial rifting axis from topographic features of the acoustic unit around the CDP 3400 permits us to propose migration or jumping of the rifting axis. We suggest that the initial rifting axis indicated by the acoustic basement shape and gravity anomaly pattern, might migrate or is now migrating northwestward toward the Yaeyama Graben. Evidence for migration of the concentrated rifting zone, which is related to asymmetrical rifting, can be identified within other rifting backarc basins in the world (Hawkins, 1994; Martínez et al., 1995; Baker et al., 1996; Wright et al., 1996). For instance, Martínez et al. (1995) indicated that rifting zone has migrated laterally in the northern Mariana Trough formed by asymmetrical rifting which is still active, based on magnetic and sidescan acoustic imagery data.

Consequently, we conclude that simple shear allowing asymmetrical half-graben structure, rather than pure shear, has been governing the initial rifting of the southern Okinawa Trough. However, we cannot exclude the possibility that pure shear associated with symmetrical rifting may be predominant in the present-day rifting of the southern Okinawa Trough as a result of northwestward migration of the rifting axis.

5.3. Estimation of the extension rate

Extension (or extension factor) can be defined as the change in length in a given direction caused by the deformation, divided by the original length (Twiss and Moores, 1992). The amount of extension in the southern Okinawa Trough can be estimated from fault geometry. In order to do so, we have to assume that the fault strikes are uniform across the region and that the change in length of the region is the sum of the horizontal extensions on each individual fault.

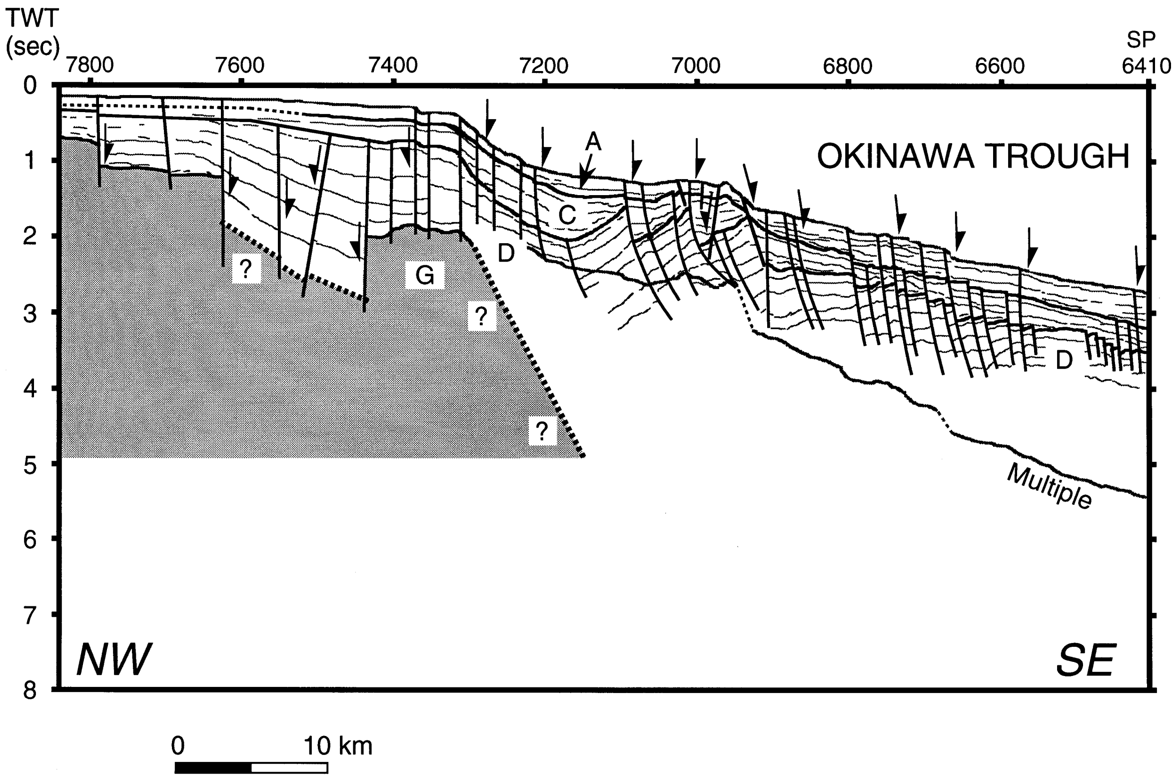


Fig. 8. Interpretation of seismic profile (Fig. 7) of the East China Sea continental shelfward Okinawa Trough of Transect-2. Note tilted basement blocks around SP 7000. Vertical exaggeration is about 10 : 1.

We estimated the amount of extension of the southern Okinawa Trough from SP 4450 to 7300 on Transect-1 on the basis of fault geometry (Figs. 5, 6 and 9). This approach is the only way to quantify the extension by means of seismic reflection data in the southern Okinawa Trough. Original surface of the acoustic basement (unit G) is simplified for calculation. Extended total length and overall extension are approximately 11 and 0.08 km, respectively. Assuming that the extension started at about 1 Ma, i.e. after deposition of the Shimajiri Group, the average extension rate is approximately 1.1 cm/year. We also estimated the amount of extension on the entire OWM3 profile on the basis of fault geometry (Fig. 9). Extended total length and overall extension are approximately 20 km and 0.28, respectively. Assuming that the extension started at about 1 Ma, average extension rate is approximately 2 cm/year. It is remarkable that, in the southern Okinawa Trough, the overall extension rate of the N–S direction (OWM3 profile) is much larger than that of the NW–SE direction (Transect-1). Sibuet et al. (1995) estimated an amount of extension of 80 km across the southern Okinawa Trough. Their estimation was done on the profile DELP (Fig. 1) which is close to the OWM3 profile. The amount of 80 km is four times as large as that on the OWM3 profile (20 km).

After all, we conclude that the average extension rate of the southern Okinawa Trough is approximately 1–2 cm/year. This rate is very similar to that resulted from GPS measurements at the Okinawa–Sakishima Islands conducted by Imanishi et al. (1996) (1-3 cm/year). The extension rate (1–2 cm/year) of the southern Okinawa Trough is comparable with that of other western Pacific backarc basins, for instance, the northern Mariana Trough of ~2 cm/year (Yamazaki et al., 1993) or the South China Sea basin of 2–3 cm/year (Nakasa, 1995).

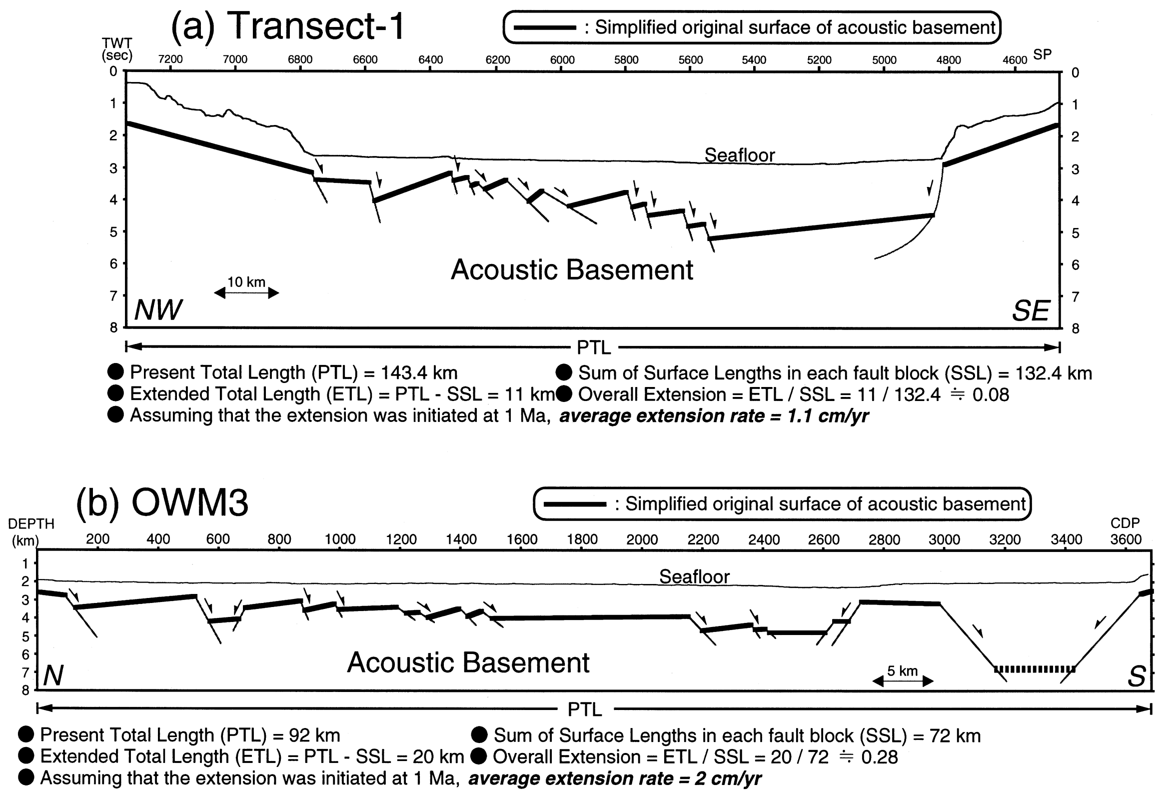


Fig. 9. Calculation of the extension amount and rate in the southern Okinawa Trough on the basis of fault geometry observed in the acoustic basement of profile Transect-1 (a) and OWM3 (b). Surface configuration of the acoustic basement was simplified for estimation.

6. Conclusions

New multi-channel seismic reflection data in the southern Ryukyu island arc system have enabled us to reconstruct the tectonic evolution of the system since the Neogene, and to constrain the rifting style and extension rate of the southern Okinawa Trough backarc basin.

(1) The stratigraphy of the sedimentary cover from the East China Sea continental shelf to the Ryukyu trench has been clarified on the basis of seismic stratigraphic interpretation. We have identified seven major seismic units and three stages in the tectonic evolution of the system. During stage 1 from the Late Miocene to earliest Pleistocene, pre-rift deposits of the Shimajiri Group accumulated over a wide region from the East China Sea continental shelf to the forearc region. Stage 2 is defined by a series of tectonic processes involving crustal doming, erosion, subsidence, and sedimentation, in association with initial rifting of the southern Okinawa Trough during most of Early Pleistocene time. The backarc rifting is still in progress and syn-rift sedimentation has been underway since the Late Pleistocene (Stage 3). Our new tectonic evolution model is based on the significant observation that the Shimajiri Group is not practically distributed in most of the present-day southern Okinawa Trough.

(2) Based on this reconstruction, we propose that the backarc rifting of the southern Okinawa Trough was probably initiated after the deposition of the Shimajiri Group, that is during Early Pleistocene times.

(3) Simple shear allowing an asymmetrical half-graben structure rather than pure shear, governed the initial rifting of the southern Okinawa Trough. The possibility, however, cannot be excluded that pure shear associated with symmetrical rifting may be predominant in the present-day rifting of the southern Okinawa Trough as a result of northwestward migration of the rifting axis.

(4) The average extension rate of the southern Okinawa Trough is estimated to be approximately 1–2 cm/year on the basis of fault geometry observed on the acoustic basement.

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