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Report on DELP 1988 Cruises in the Okinawa Trough Part 7. Geologic Investigation of the Central Rift in the Middle to Southern Okinawa Trough

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Abstract

It has been suggested that the spreading of the sea-floor is expected only in a limited area along the central rift in the southern part of the Okinawa Trough if it occurs. Therefore, the active extensional features and the mode of occurrence of igneous rocks in the central rift were studied in detail by means of the analysis of 3.5 KHz sonic, profiling records and rock samples dredged up during the DELP 1988 Cruises along the middle to southern Okinawa Trough. In addition to these data, research findings from various other organizations were supplementally used. The result revealed that in trending E-W to ENE-WSE five segments (grabens) of the central rift are distributed in echelon along the trough axis, which has been active since early Pleistocene time. The length of the central grabens is 50-100 km and the width is 10-20 km. The present central graben formation is represented by the topographic, central valley first shaped in late Pleistocene time. Transform faults connecting segments of the central graben were not found. Calc—alkaline and tholeiitic rocks showing typical island arc nature were dredged from the Yaeyama Central Graben, which is the deepest in the Okinawa Trough. The rocks are younger than 1 Ma., and the oxygen fugasity of the rock rather indicates initial stage of a rifting environment shown in mid-oceanic ridges. A black smoker indicating an active rifting environment was discovered at the eastern end of the Aguni Central Graben

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in 1989. The geologic evidence of the central grabens strongly supports the finding that the middle to southern Okinawa Trough does not yet reach to sea-floor spreading but represents the back-arc rifting stage. The evidence is consistent with other geophysical one such as seismic refraction and magnetic measurements during the Cruises. Moreover, the whole Okinawa Trough is identified as being in a back-arc rifting stage in the continental crust, judging from previous data in addition to the present results.

1. Introduction

Recent geologic and geophysical studies show that the middle to northern Okinawa Trough has a continental nature which has not yet spread (i.e. JAPANESE DELP RESEARCH GROUP ON BACK-ARC BASIN, 1986; IWASAKI *et al.*, 1990). On the contrary, LEE *et al.* (1980) pointed that the general structure of the Okinawa Trough is continental, with a thick crust. The center of the trough itself, however, has a relatively thin crust, with the velocity of the lower crust approaching that which is typical of the ocean basins. Intrusion and extrusion of igneous rocks are along short spreading centers, connected by transform faults; it is sufficiently organized to produce areas of oceanic-type crust that can be identified by seismic refraction measurements. The strongest supplemental evidence supporting identification of the oceanic-type crust was relatively fresh basalt recovered from the Yaeyama Central Graben.

SIBUET *et al.* (1987) also suggested that the major parts of the southern Okinawa Trough is underlain by a thinned continental crust and that except for the system of echelon rift of the southern Okinawa Trough, the back-arc basin oceanic domain is limited to a width of some tens of kilometers or less in the axial portion of the Trough. Chemical compositions of collected rocks from the Central Graben, however, were not shown.

Consequently, the central rift of the middle to southern Okinawa Trough would be the crucial area to determine whether the Okinawa Trough is spreading or not. In order to solve the problem, we focussed to clarify the distribution of the central rift, the active extensional features of the central rift, the nature of igneous rocks relating rifting in the middle to southern Okinawa Trough during the DELP 1988 Cruises carried out from the 3–31th of July, 1988 (Figs. 1 and 2). We also made an effort to detect transform faults connecting segments of the central rift.

The geographic relations between the volcanic front and igneous bodies along the central grabens were also studied. SIBUET *et al.* (1989) suggested the volcanic activity in the southern Okinawa Trough is the

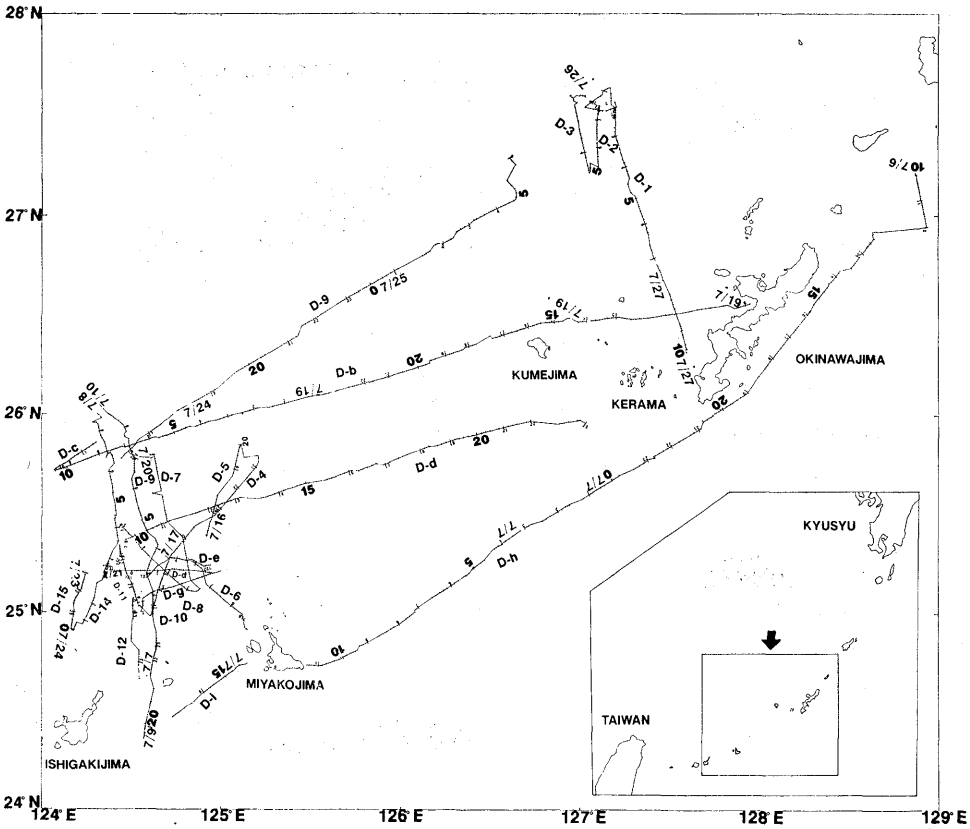

Fig. 1. Survey lines of 3.5 KHz profiling records carried out by DELP 1988 Cruises.

phenomenon in the extension of the northern Tokara volcanic arc because they thought that the volcanic arc is a fundamental line of weakness which determines where initial back arc spreading occurs as described by MOLNAR and ATWATER (1978).

2. Used data

The 3.5 KHz subbottom profiling records and samples dredged on the DELP 1988 Cruises were used, and they were supplemented by original data obtained on the 1984 POP 1 Cruise of the R/V *Jean Charcot* of IFREMER in France, the KH-87-2 Cruise, Ocean Research Institute, University of Tokyo and the 1988 *SONNE* 55 Research Cruise of West Germany. Data published by the HYDROGRAPHIC DEPARTMENT MARITIME SAFETY AGENCY (1987) were also available. Igneous rocks dredged during the DELP 1988 Cruises are petrologically described in the another paper by ISHIKAWA *et al.* (in this issue). Seismic reflection profiling records of

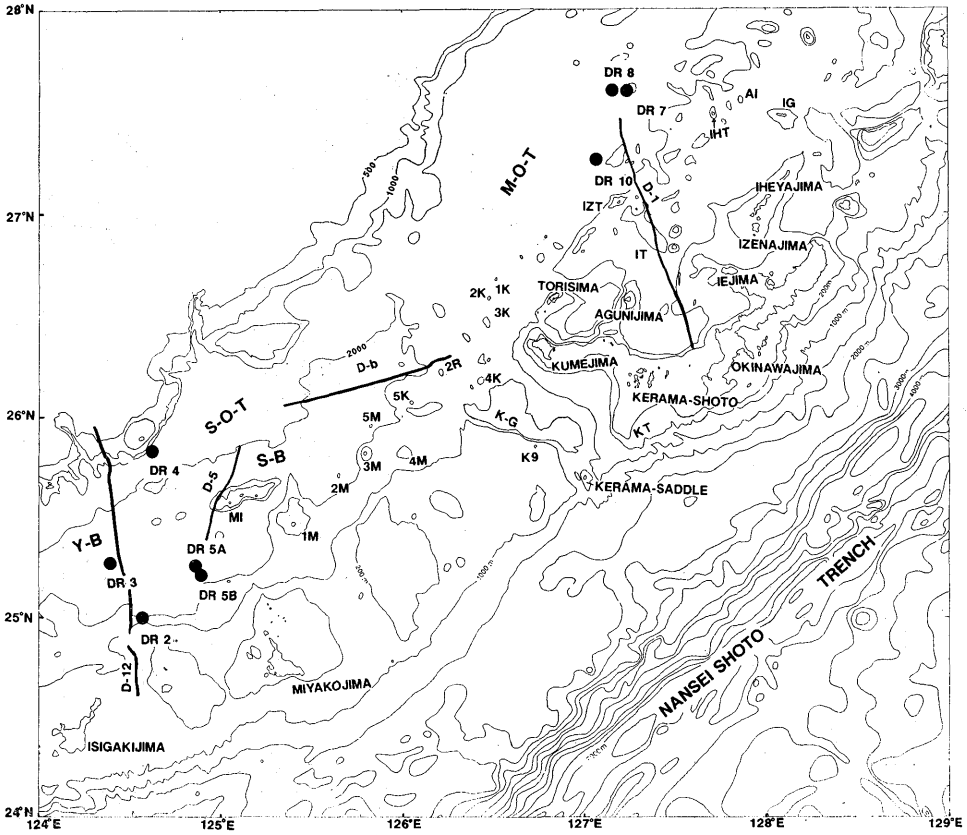

Fig. 2. Locations of dredge station and survey track of 3.5 KHz profiling records (D-1—D-12) as shown in Figs. 10, 11, 14 and 15. Contour interval of the submarine topography is 500 m, made by MAGBAT program using data of Hydrographic Dept. Maritime Safety Agency of Japan. Topographic names were mainly take from KATO *et al.* (1982), KATSURA *et al.* (1986), OSHIMA *et al.* (1988), KIMURA (1983a) and KIMURA *et al.* (1986). S-O-T: Southern Okinawa Trough, IG: Igyo Sone, AI: Aino Sone, IHT: Iheya Tai, M-O-T: Middle Okinawa Trough, IZT: Izena Tai, IT: Ie Tai, RY: Ryukyu Sone, 1K: Daiiti-Kume Knoll, 2K: Daini- Kume Knoll, 3K: Daisan-Kume Knoll, 4K: Daiyon-Kume Knoll, 5K: Daigo-Kume Knoll, 2R: Daini-Ryukyu Sone, 1M: Daiiti-Miyako Knoll, 2M: Daini-Miyako Knoll, 3M: Daisan-Miyako Knoll, 4M: Daiyon-Miyako Knoll, 5M: Daigo-Miyako Knoll, S-B: Sakishima Basin, Y-B: Yaeyama Basin, K-G: Kerama Gap, KT: Kerama Tai, K9: Kita-Daiku Tai, MI: Miyako Seamount.

single and multi channel systems on the DELP 1988 Cruises and published such kind of data were valid for the basis of understanding the deep structure and the geologic framework in the study area. The MAGBAT program of the Marine Geophysics Basic Tool System (NAKANISHI *et al.*, 1987) was used for data arrangement.

3. Results

3-1. Stratigraphy

Sediment in the study area (Fig. 3) is divided into two layers designated as Layers A and B in descending order on the 3.5 KHz and other seismic reflection profiles (Figs. 4 and 5). They show conformable relation although the lower layer often shows steep, inclined bedding.

Layer A: This is an uppermost layer correlating with the Holocene

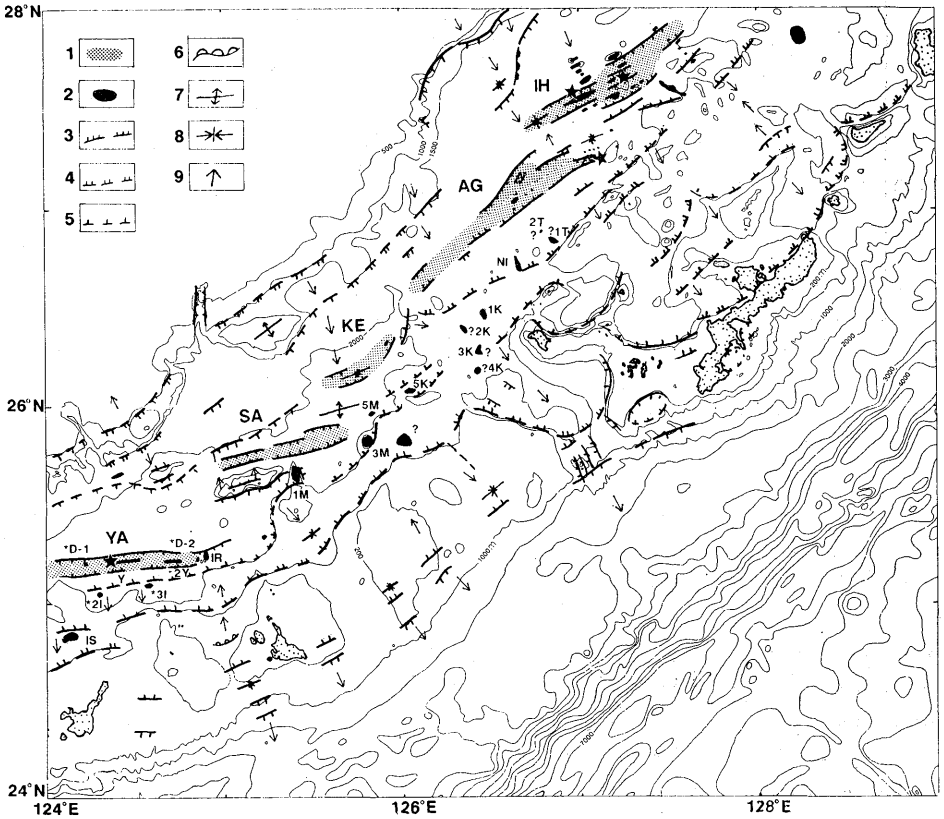

Fig. 3. Quaternary geo-structural map of the middle to southern Okinawa Trough and its vicinity. Large asterisks indicate active hydrothermal areas. IH: Iheya Central Graben, AG: Aguni Central Graben, KE: Kerama Central Graben, SA: Sakishima Central Graben (tentatively named), YA: Yaeyama Central Graben, Y: Yaeyama Central Knoll, 2Y: Daini-Yaeyama Central Knoll. D-1: DELP88-1 Knoll, D-2: DELP88-2 Knoll. Small asterisks show topography tentatively named. 1M: Daiiti-Miyako Knoll, 3M: Daisan-Miyako Knoll, IR: Irabu Knoll, IS: Ishigaki Knoll. 2I: Daini-Ishigaki Knoll, 3I: Daisan-Ishigaki Knoll. Legend 1: Central deep, 2: Quaternary igneous body, 3: Fault. Tooth shows a down throwing side, 4: Buried fault, 5: Estimated fault, 6: Escarpment, 7: Anticline, 8: Syncline, 9: Apparent dipping direction on the survey line.

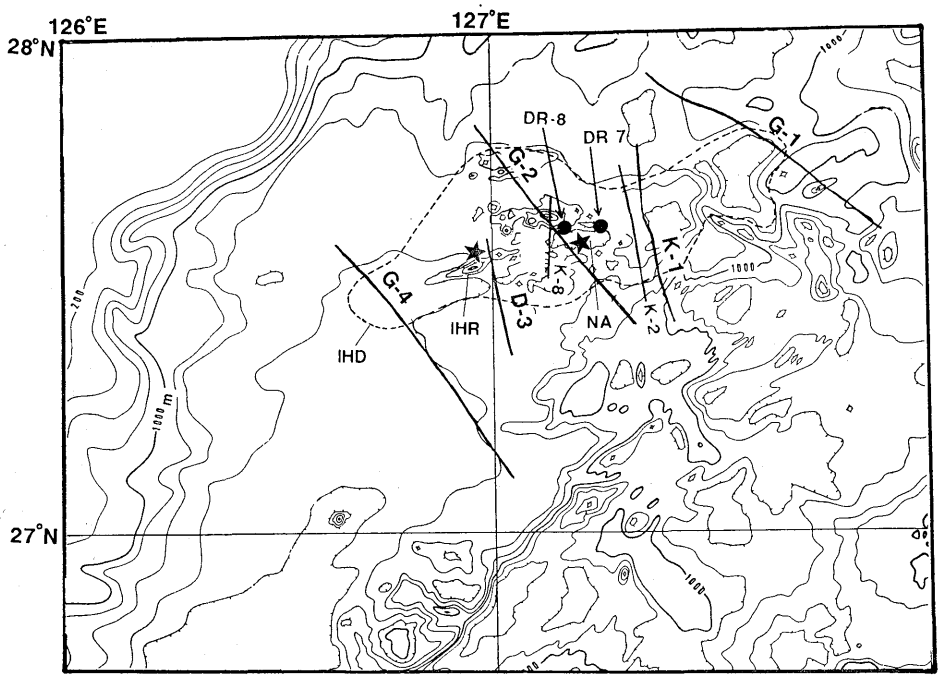

Fig. 4. Survey lines of 3.5 KHz in the vicinity of the Iheya Central Graben, shown in Figs. 5 and 6. Topography of the base map is after SIBUET *et al.* (1987). Solid circles represent dredge-sampled sites. Asterisks show active hydrothermal areas. G: Geological survey of Japan, K: (KH-87-2 Cruise), D: DELP 1988 Cruises. IHD: Iheya Deep, IHR: Iheya Central Ridge, NA: Natsushima Small Basin.

sediment. It shows acoustically transparent pattern but it has fine stratification on the expanded profiles. Layer A is rather thickly distributed along the central grabens and is very thin, the ordinary sea-floor being less than a few meters. The maximum thickness of Layer A is about 30 m in the Iheya and Yaeyama Central Grabens (Fig. 3). The basic origin of Layer A is estimated to be a hemipelagic in the ordinary seafloor, as shown by the cored sediment of massive gray silty clay. On the other hand, the thicker sediment in the central valley is considered to be turbidite in basic origin. Some turbidite layers showing a graded bedding were obtained by piston coring carried on in the central grabens during the DELP 1988 Cruises. The sedimentation rate estimated from non destructive gamma ray spectrometric analysis is 1–2 mm/yr (1.5 mm/yr in average) (TSUGARU *et al.*, 1991). The accumulation rate of sediment in other place in the middle Okinawa Trough axis was calculated as 2–5 mm/yr (3.6 mm/yr in average) in the same way by using samples with a box corer carried out by SONNE Cruise (TANAHARA *et al.*, 1989).

Layer B: This is correlatable layer showing stratified patterns on

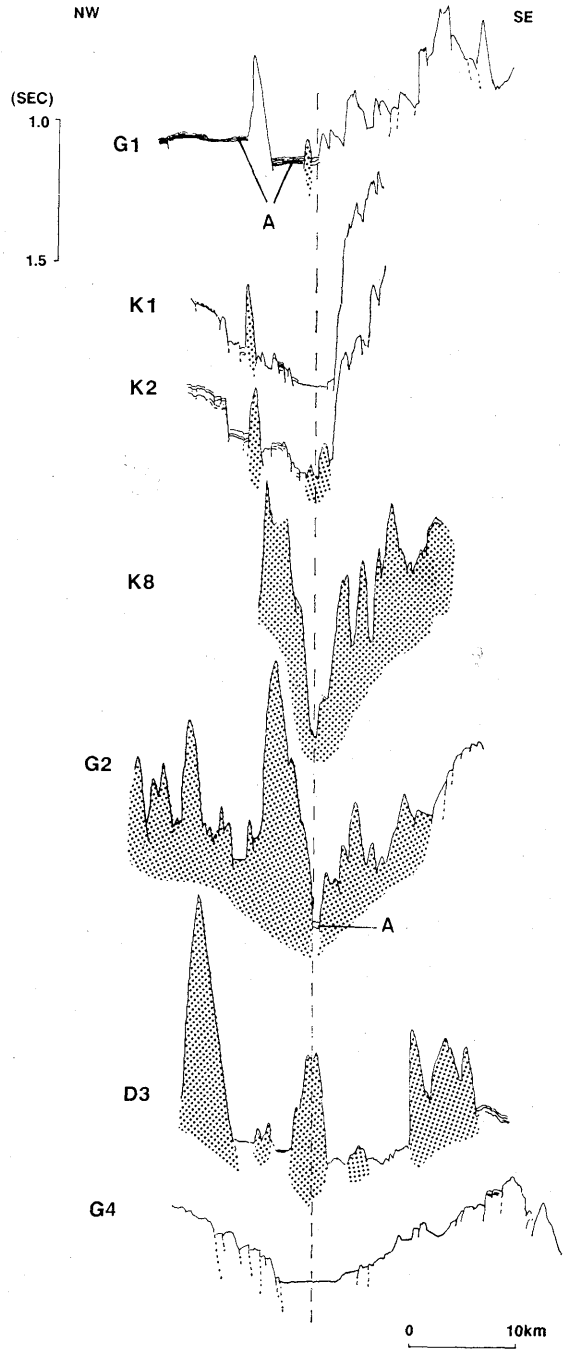

Fig. 5. Cross sections analyzed with 3.5 KHz profiling records in the Iheya Central Graben. (K-1 and K-8: KH-87-2 Cruise, G-1—G-4: Geological Survey of Japan (HONZA, 1976), D-3: DELP 1988 Cruises). Locations are shown in Fig. 4. A: Layer A, Shaded parts show igneous bodies judged from magnetic anomaly analysis (SIBUET *et al.*, 1987).

the 3.5 KHz profiling records. The acoustic pattern shows that the major ingredient of the upper half should be turbidite. Layer B is widely distributed throughout the Okinawa Trough, becoming thicker towards the axis of the Trough. The layer is more than 3,000 m thick in the center of the Southern Okinawa Trough based upon multi-channel reflection profiles (AIBA and SEKIYA, 1979; KIMURA, 1985; DELP 1988 Cruises data). If the accumulation rate has been constant at 1.5 mm/yr, the beginning of the deposition of Layer B, took place about 2 million years ago. The stratigraphic correlation between submarine and subaerial geology shows that Layer B began to form early to late Pleistocene time.

The Layer B associating with Layer A is severely offset by many step faults along the central grabens. The surface geologic structure is compiled in Fig. 3. Many faults developed on the continental shelf and slope areas except central grabens. They, however, are mostly covered with Quaternary sediments (Layers A or B). The active rifting features are concentrated in the central axial parts of the Trough.

3-2. Central Rift

Five segments of the active central rift were identified along the axis of the middle to souther Okinawa Trough. The grabens are about 10 km in width and 50-100 km in length. Their directions change from the E-W trend to the ENE-WSW trend veering towards the north. and align in echelon along the axis of the Trough. They show the active extensional features of the Okinawa Trough, and all of them produce topographic central valleys and or rift valleys.

1) Iheya Central Graben

This graben almost coincides with the topographically named Iheya Deep (KIMURA *et al.*, 1986) (Fig. 4). Diving surveys by means of the submersible "SHINKAI 2000" have been carried out in the Graben in 1984 and in 1986-1990 (UYEDA *et al.*, 1985; KIMURA *et al.*, 1987, 1988, 1989). The deepest water depth of the Graben reaches to more than 2,000 m. Survey tracks covering it are shown in Fig. 4. The Graben is a narrow depression generated by complicated normal faulting (Fig. 5). There are many volcanic knolls in and around the depression. There is an axial valley (rift valley) called the Wakashio Small Basin in the middle of the Graben (Fig. 4). The valley extends from east to west, and its maximum water depth reaches to 1,770 m. The thickness of sediment (Layer A) is about 30 m. There are two knolls in it; Natsushima 84-2 Knoll on the east side and Natsushima 86-1 Knoll on the west side. On the other hand, the western extension of the valley is a transformed basaltic, volcanic small ridge named Iheya Central Ridge (KIMURA *et al.*, 1986) (Figs. 4, 5 and 6).

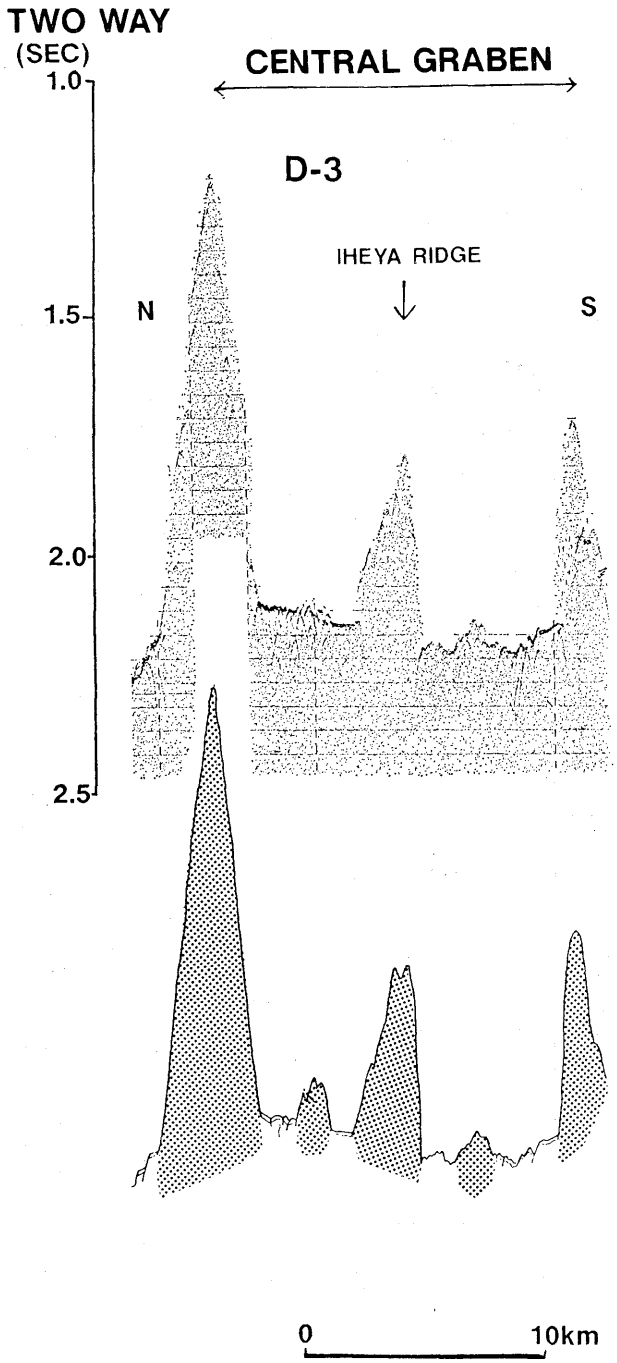

Fig. 6. 3.5 KHz profiling record (D-3) and analyzed profile of the western part of the Iheya Central Graben. Shaded parts show igneous bodies judged from magnetic anomaly analysis (SIBUET *et al.*, 1987).

Table 1. Locations of dredged samples in the middle to southern Okinawa Trough on DELP 1988 Cruises.

Dredge station	Date (1988)	Time (on & off)	Position		Depth (m)	Samples
			Latitude (N)	Longitude (E)		
R2	July, 22	7:30 8:09	24°59.32′ 24°59.21′	124°33.83′ 124°33.78′	1,240 950	Three pieces of pumice blocks (max. size: 12×9×8cm). Large amount of soft sediment (total weight: 20kg). (Southern wall of the southern Okinawa Trough)
DR3	July, 21	17:52 18:51	25°16.84′ 25°15.31′	124°25.75′ 124°22.22′	2,130 2,325	Less amount of scoria (max. size: 1×1×1cm, total weight: 20kg). (Yaeyama Central Knoll)
DR4	July, 20	18:59 19:59	25°49.4′ 25°50.5′	124°37.1′ 124°36.9′	1,420 975	Several pieces of sandstone blocks (max. size: 20×15×10cm and abundant size: 15×10×7cm). Total weight of rock samples: 30kg. Large amount of soft sediment. (Northern wall of the Southern Okinawa Trough)
DR5A	July, 23	7:19 7:57	25°14.28′ 25°14.28′	124°53.62′ 124°52.71′	2,210 2,215	Empty. (East Yaeyama Central Knoll)
DR5B	July, 23	8:52 10:00	25°13.68′ 25°13.80′	124°54.67′ 124°53.18′	2,205 2,050	Fresh basalt (olivine basalt) lava blocks (size of three blocks: 12×8×3cm, five blocks: 11×5×3cm, twenty blocks: 5×4×2cm, Total weight: 10kg). Platy lava with flow structure. (East Yaeyama Central Knoll)
DR7	July, 26	11:30 12:36	27°35.63′ 27°36.93′	127°13.48′ 127°15.31′	1,760 1,530	Dacite lava blocks (max. size: 24×17×11cm). Woody pumice blocks (max. size: 14×10×10cm). Several pieces of host rocks forming the hydrothermal mound. Four blocks with dark green and yellow hydrothermal deposition (max. size: 10×9×5cm), and three blocks with iron oxide (max. size: 11×8×7cm). Total weight of rock samples: 5kg. (Northeastern wall of the Iheya Deep)
DR8	July, 26	9:18 10:02	27°35.50′ 27°36.14′	127°09.25′ 127°08.98′	1,630 1,400	Andesite lava blocks (max. size: 40×35×22cm). Weathered andesite blocks (max. size: 20×15×10cm). Woody pumice blocks (max. size: 19×14×11cm). Total weight of rock samples: 100kg. (Northwestern wall of the Iheya Deep)
DR10	July, 25	13:42 15:28	27°15.77′ 27°16.17′	127°03.29′ 127°04.35′	1,660 1,490	Acidic tuff and tuffbreccia blocks (max. size: 35×25×20cm) and tuffaceous sandstone blocks (max. size: 30×19×17cm), with thin ferro-manganese coating. One sulfide block with pyrite (size: 12×9×4cm). Small amount of soft sediment. Total weight of rock samples: 60kg. (Northern wall of the Izena Hole)

Table 2. Description of hydrothermally altered samples in the middle to southern Okinawa Trough on DELP 1988 Cruises.

Dredge station and sample		Minerals
DR4	Greenish gray sandstone	Quartz, plagioclase, muscovite, biotite, calcite, chlorite, smectite, magnetite
DR7-1	Dark green soft precipitates	Nontronite
-2	Yellowish brown precipitates	Amorphous material
-3-1	Dark brown part	Birnessite
-3-2	Yellow part	Rhodochrosite, birnessite, amorphous material
-4	Pumice stained with black	Volcanic glass, alkali-feldspar
-5*	Fresh gray dacite	Alkali-feldspar, plagioclase, augite, hypersthene, magnetite, tridymite
DR8-1	Black Mn crust (10mm thick)	Todorokite, quartz, alkali-feldspar
-2-1*	Fresh dacite gray-black flow banding	Alkali feldspar, hypersthene, augite, hornblende, plagioclase, magnetite, cristobalite
-2-2	Fresh black glassy dacite	Alkali-feldspar, cristobalite
-3	Fresh glassy dacite	Alkali-feldspar, cristobalite
DR10-1*	Gray silicified rock	Quartz, pyrite
-1	Sulfied veinlets	Quartz, sphalerite, galena, pyrite
-1	White clayey veinlets	Chlorite/smectite, quartz, pyrite
-2*	Alterd dacite (?) (light gray part)	Quartz, Mg-chlorite (IIb), analcite
-2	Altard dacite (?) (green gray part)	Quartz, sericite (1M), albite, calcite, Fe-Mg-chlorite (Ib: $\beta=90°$)
-2	Altered dacite (?) (outer white part)	Quarte, sericite (1M), chlorite
-2	Dark brown crust	Todorokite, amorphous material, quartz
-3*	White altered tuff	Quartz, sericite (1M), analcite, chlorite
-3	Dark brown crust	Amorphous material, quartz
-4*	Dark gray silicified dacite	Quartz, sericite, K-feldspar
-5*	Dark compact dacite lava	Plagioclase, hypersthene, magnetite

* Microscopic observation

Acidic augite andesite was dredged from the northeastern wall of the Wakashio Small Basin during the DELP 1988 Cruises (Tables 1 and 2). The DR7-5 sample (Table 2) is fresh gray dacite and contains phenocrysts of alkali feldspar, minor plagioclase, hypersthene, augite, and magnetite in a glassy groundmass. Cristobalite occurs in numerous small gas cavities. Sample DR8-2-1 is a porous, altered hypersthene dacite with gray and black flow bands that contain phenocryst of alkali feldspar, hypersthene and minor augite, hornblende, plagioclase and magnetite in

a glassy groundmass. Cristobalite occurs in small gas cavities.

2) Aguni Central Graben

This reveals classic graben structures, and topographically exhibits a narrow depression. There exist several central knolls such as Aguni Knoll (KATO *et al.*, 1989a) in the vicinity of 27°N (Figs. 7 and 8). The graben continues to the previously described "Kume Graben" (KIMURA, 1989) to the west. The present paper newly defines the series of grabens as: "Aguni Central Graben", including the Kume Grabens. The Izena Hole, where the black smoker was discovered (NAKAMURA, 1989), is located at the northeastern extension of the Graben (Fig. 9).

3) Kerama Central Graben

Classic graben and half graben structures appear south to the Aguni Graben (Fig. 10). The northern half of the Graben had been described by KIMURA *et al.* (1986). Layer B shows synclinal features in the northern part of the Graben. Dislocations by faulting become larger toward the southwestern part. A central valley is also developing.

4) Sakishima Central Graben

The Sakishima Central Graben partly described by KIMURA *et al.* (1986) is located to the south of the Kerama Central Graben and trends on in a ENE-WSW direction. The graben has a steeper wall in the

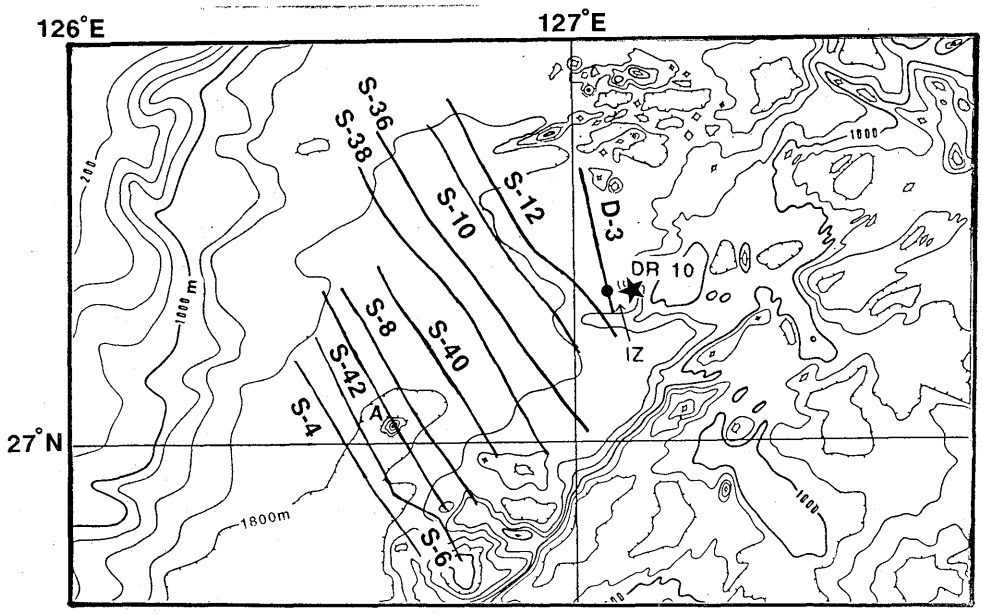

Fig. 7. Locations of cross sections represented in Figs. 8 and 9 in the Aguni Central Graben (D: DELP 1988 Cruises, S: *Sonne* 55 Cruise) IZ: Izena Hole, A: Aguni Knoll. Solid circle shows site dredge-sampled. Asterisk shows active hydrothermal area.

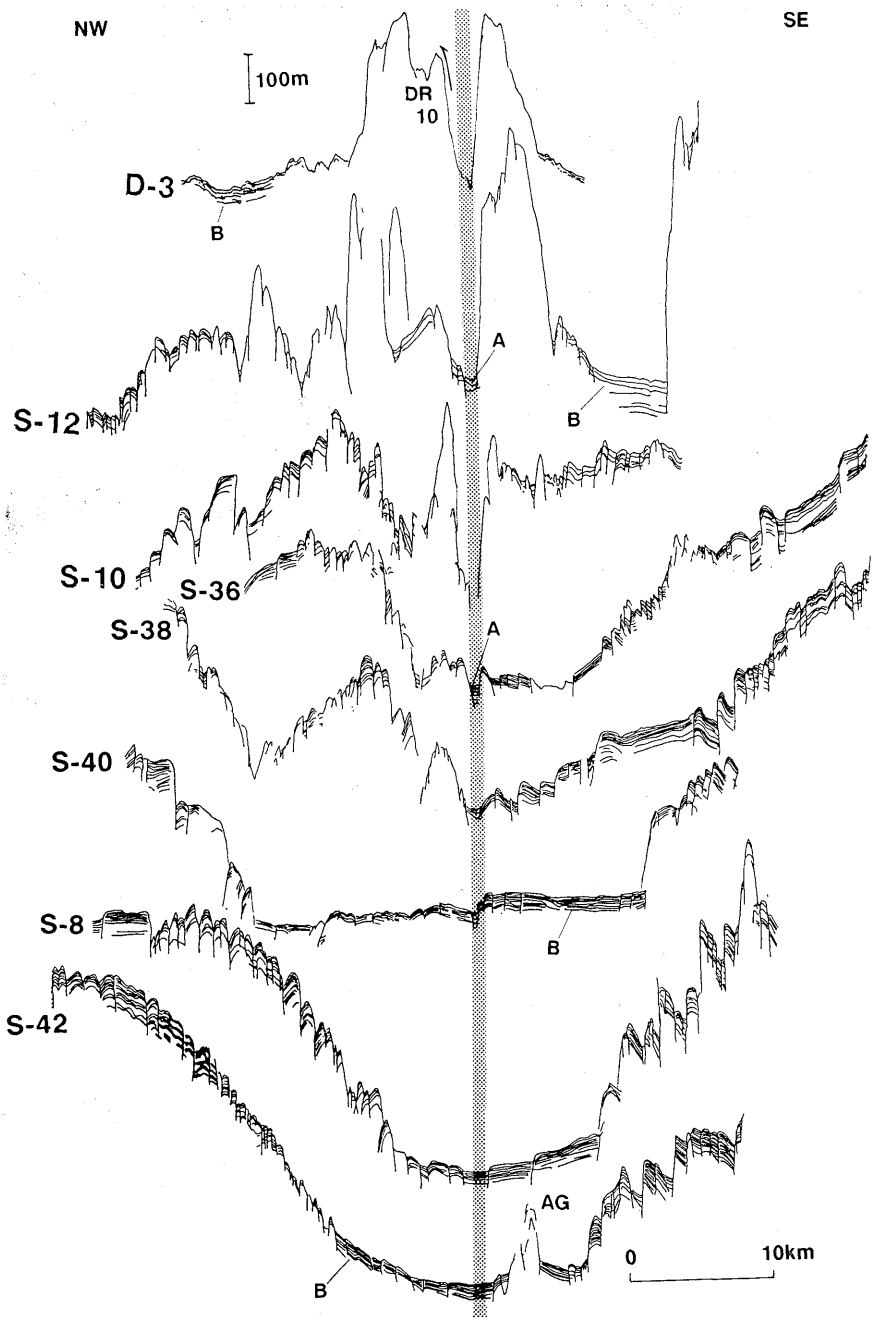

Fig. 8. Aanlyzed cross sections of 3.5 KHz profiling records in the Aguni Central Graben and the Izena Hole. Locations are shown in Fig. 7. A: Layer A, B: Layer B. Shaded line represent a rift axis.

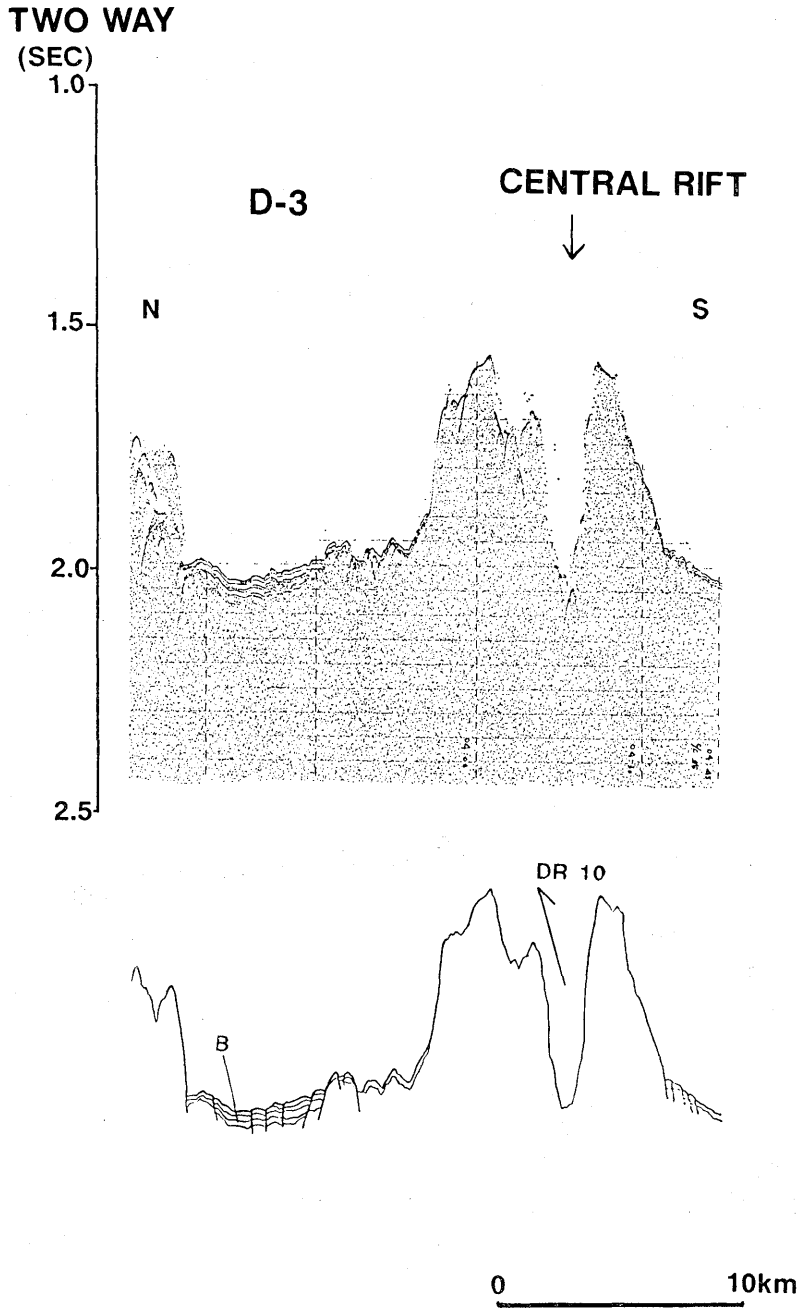

Fig. 9. 3.5 KHz profiling record and analyzed profile of the Izena Hole (D-3). Location is shown in Fig. 7.

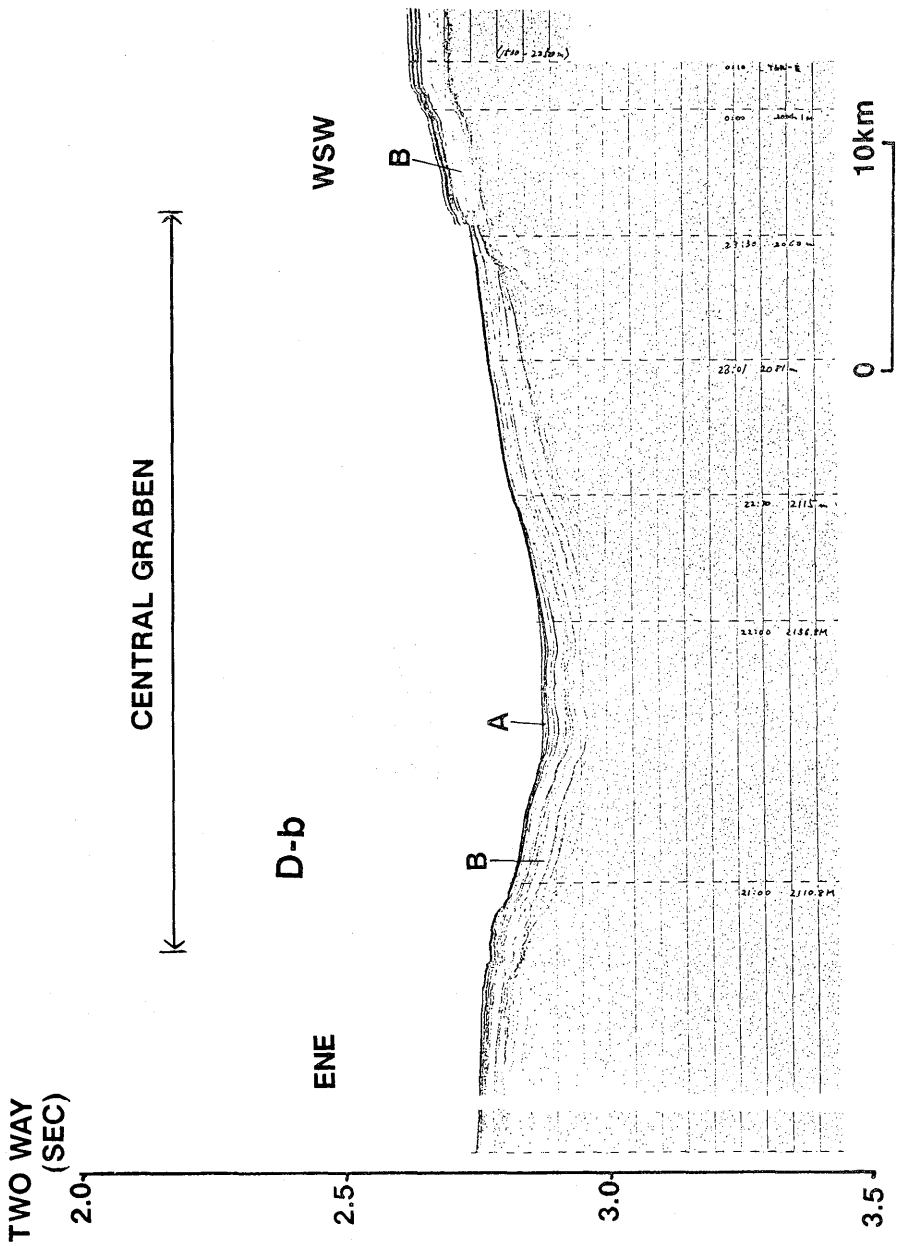

Fig. 10. 3.5 KHz profiling record (D–b) crossing the Kerama Central Graben represents classic graben structure at the surface. Location of the cross section is shown in Fig. 2. A: Layer A, B: Layer B.

south than it does in the north (Fig. 11). Layer A develops thicker in the axial valley.

5) Yaeyama Central Graben

The steep-walled Yaeyama Central Graben trending almost in an east-west direction is located south of Miyako Seamount (Figs. 12 and 13). It was called Yaeyama Graben (KATSURA *et al.* 1986) or Yaeyama Submarine Graben (OSHIMA *et al.* 1988). Many normal faults are developed along both walls, and the width of the Graben is 10–20 km. A fairly

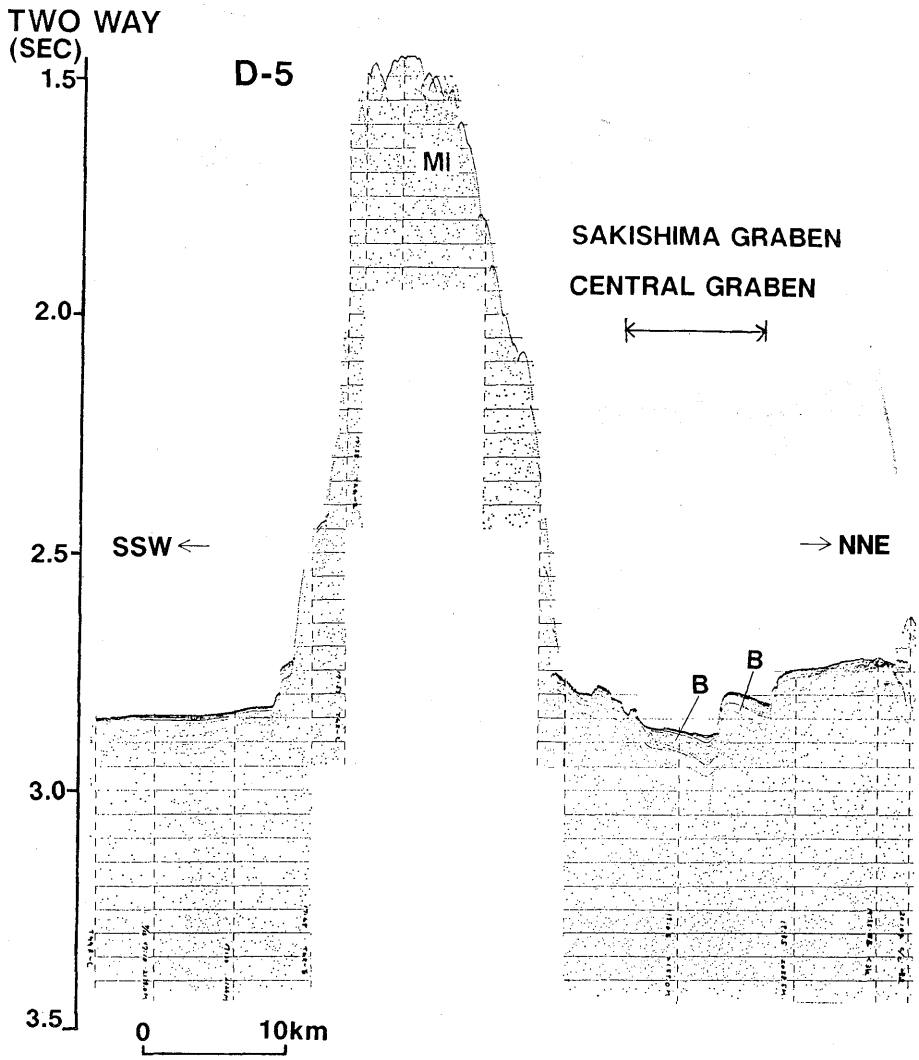

Fig. 11. 3.5 KHz profiling record (D-5) in the Sakishima Central Graben. Location is shown in Fig. 2. B: Layer B.

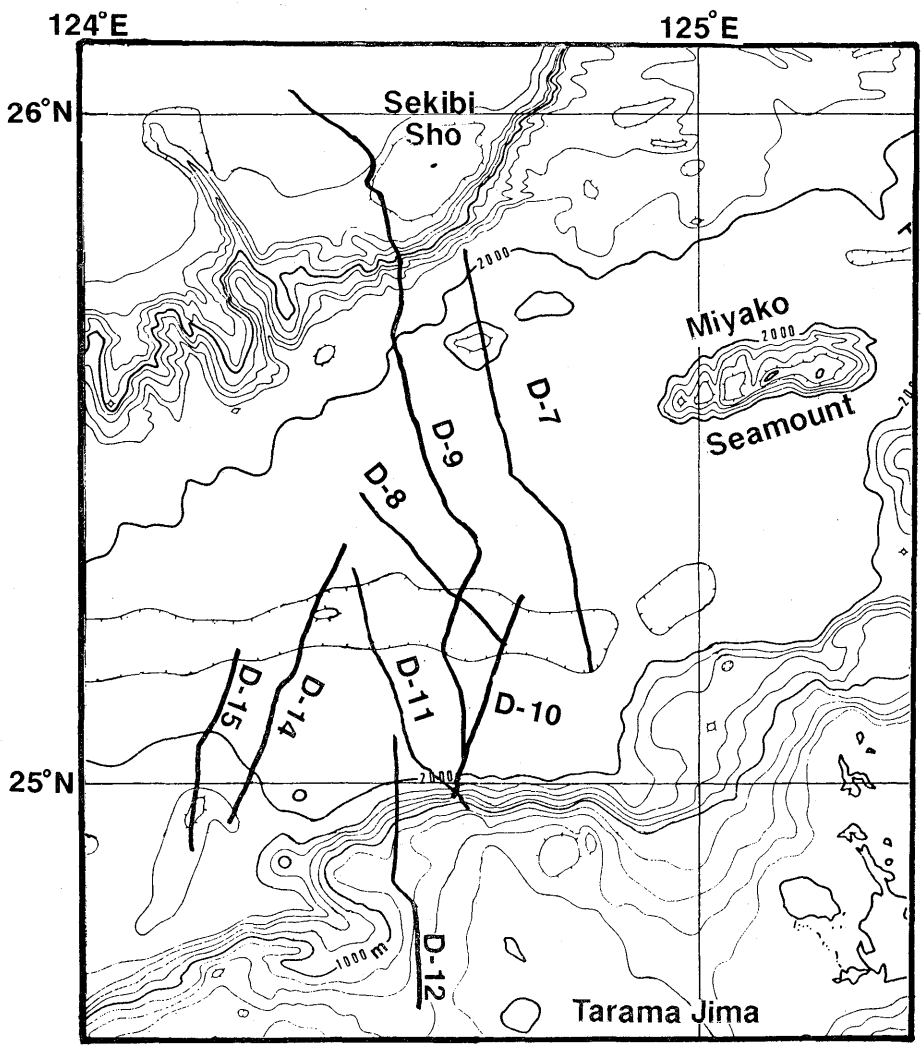

Fig. 12. Location of cross sections of 3.5 KHz profiling records in the Yaeyama Central Graben carried out by DELP 1988 Cruises. Cross sections are shown in Fig. 13.

thick, acoustically transparent layer (Layer A) is recognized in the Graben. Layer A inside the Central Graben, is offset by faults but slightly although it is severely offset on the walls of the Graben. Five knolls were recognized in the Graben. The Yaeyama Central Knoll (KATSURA *et al.*, 1986) is the biggest one. Two of the knoll including the Yaeyama Central Knoll had been known from previous studies (HERMAN *et al.*, 1978, KATSURA *et al.*, 1986, SIBUET *et al.*, 1987). Three knolls were found on the DELP 1988 Cruises, and they are tentatively named DELP88-1

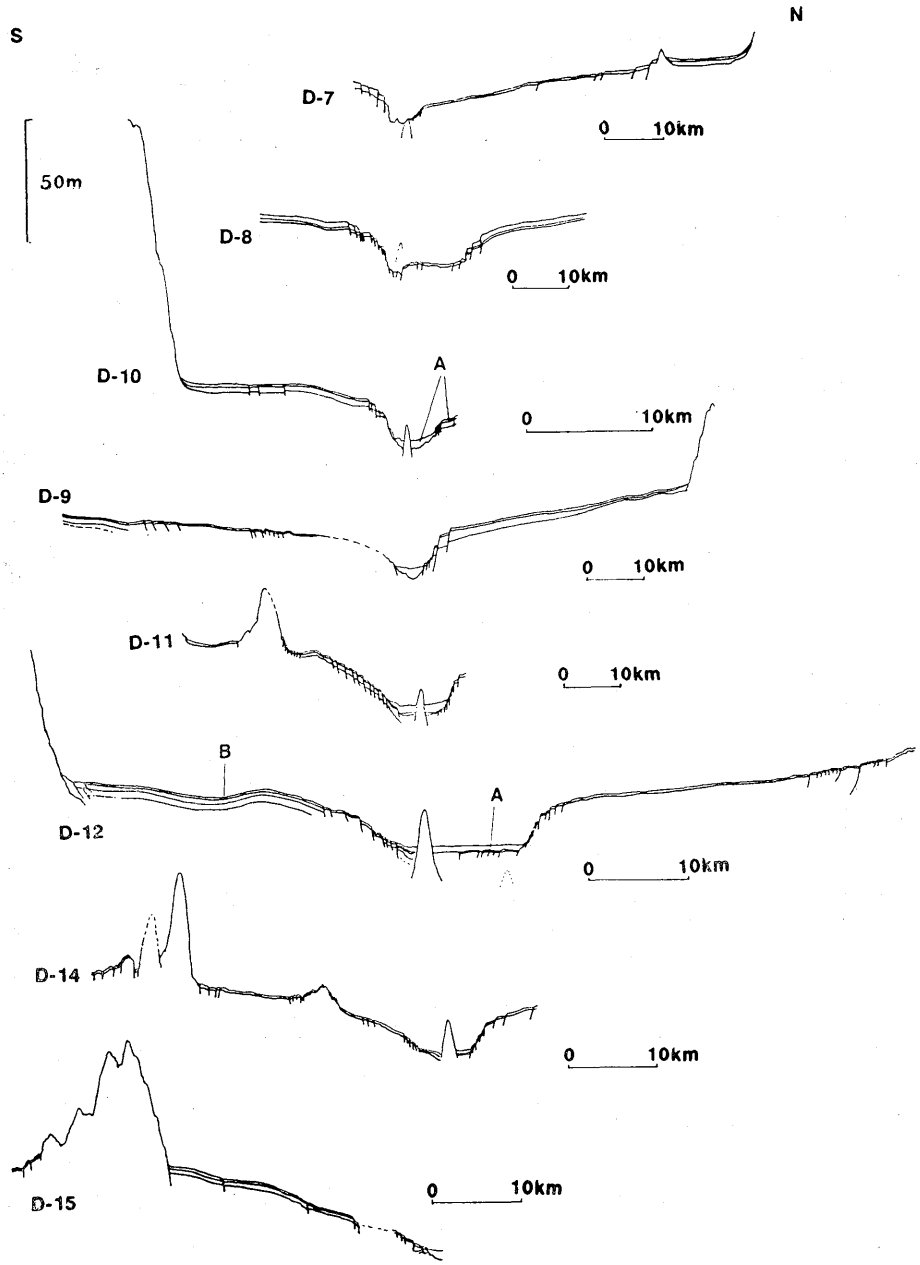

Fig. 13. Cross sections of the Yaeyama Central Graben, analized from 3.5 KHz profiling records. Location is shown in Fig. 12. A: Layer A, B: Layer B.

Knoll, DELP88-2 Knoll and Daini-Yaeyama Knoll (Fig. 3). The piercement structure reported by HERMAN *et al.* (1978) in the Graben floor is at almost the same site as DR5 (Irabu Knoll, KIMURA, 1983b) studied on the DELP 1988 Cruises, from which relatively fresh basalt was dredge-sampled. Its chemical composition, however, was not represented. Island arc type of tholeiite was recovered from the Yaeyama Central Knoll (25°14.068′N; 124°24.405′E) during the 1984 POP 1 Cruise. Dacite and basalt showing island-arc affinity (OSHIMA *et al.*, 1988) had been obtained from the same Knoll by HYDROGRAPHIC DEPARTMENT MARITIME SAFETY AGENCY (1987). In the DELP 1988 Cruises, scoria was recovered from a part of the Knoll (DR3, Table 1). We recovered fresh basalt from the Irabu Knoll. (DR5B; field name as East Yaeyama Central Knoll in Table 1) The rock is olivine two-pyroxene basalt. Those rocks are calc-alkali and tholeiitic rocks showing an island arc type based upon petrological and chemical analytical studies ISHIKAWA *et al.*, this issue). All volcanic rocks collected from the Yaeyama Central Graben on the DELP 1988 Cruises and on the other recent cruises show island arc affinity.

3-3. Hydrothermal activity

1) Iheya Central Graben

In 1986, active hydrothermal mounds were discovered on the Natsushima 86-1 Knoll prior to other similar findings in back-arc basins around the world (KIMURA *et al.*, 1988). Hydrothermal biota and ores were found at the northern flank of the Iheya Central Ridge in 1988 (HALBACH *et al.*, 1989) (Fig. 3). During the DELP 1988 Cruises, three kinds of hydrothermal deposits were recovered from St. DR7, which is located on the northeastern slope of the Wakashio Small Basin in the Iyeya Graben. On the basis of analysis by the X-ray diffraction (XRD) method (Table 2), they are composed of dark green nontronite, yellowish brown amorphous matter (probably iron hydroxide) and rhodochrosite with birnessite (7 Å manganate). A black manganese-crust on dacite of DR8-1 consists of todorokite (10 Å manganate) and birnessite (7 Å manganate) (Table 2).

2) Izena Hole

Silicified acidic tuff and gray tuff were obtained from the northeastern wall of the Izena Hole (DR10) on DELP 1988 Cruises. Porous aphyric andesite and altered lapilli tuff were also obtained. The dredge site is very near the place where the black smoker was discovered.

An active hydrothermal vent system and a black smoker were found in the Izena Hole in 1988 and 1989 (HALBACH *et al.* 1989; NAKAMURA *et al.*, 1988; 1989; KATO *et al.*, 1989b; KIMURA *et al.*, 1989). Sulfide minerals occur as veinlets in the silicified dacite, based upon the X-ray diffraction

(XRD) method and the petrologic analysis of DR10-1A in the northeastern wall of the Izena Hole on the 1988 DELP Cruises. The country rock consists of an aggregate of minute quartz, due to strong silicification. Sphalerite and galena are the major constituent sulfide minerals. Quartz, pyrite and white clay (interstratified chlorite/smectite) also occur in veinlets. Silicified dacite consists of quartz and pyrite. Several kinds of hydrothermally altered dacite and dacitic tuff were recovered. Alteration minerals are quartz, chlorite (polytype: 1M) (polytype: IIb or Ib $\beta=90°$), sericite, analcite, calcite and albite. Fluid inclusions were observed in sphalerite from DR10-1. Most of the inclusions are secondary in origin and are mostly smaller than 5 μm. Only one inclusion was suitable for geothermometry, and a homogenization temperature of 250°C was obtained.

Sulfide mineralization found at DR10 is similar to that of the highly altered, sphalerite-bearing Keiko (siliceous ore) of the Kuroko type deposits. Hydrothermal minerals (quartz-chlorite-sericite) and the temperature of mineralization (250°C) are comparable with the typical mineralization environment of the Kuroko type deposits in Northeast Japan. There is a possibility that the sample recovered from the Izena Hole is equivalent to the lower part of the Kuroko ore. This suggests that the distribution of the ore is fairly wide.

The complilation of 3.5 kHz profiling records revealed that the Izena Hole is located at the eastern end of the Aguni Central Graben, where the Izena Hole forms a cauldron structure. The constituent layer of this hole is interbedded by tuff, pumice and muddy sediment (NAKAMURA *et al.*, 1987). It is likely that the hole was formed by the fault-motion accompanying rifting. Hydrothermal hot water gushes from some kinds of cracks. The formation ages of the hydrothermal mound are based on preliminary results and are calculated by radioactivity measurements and show that the mounds had been formed within the last 100 years (KIMURA *et al.*, 1989).

3) Yaeyama Central Graben

KATSURA *et al.* (1986) reported that a flickering phenomenon of seawater occurs over the biological colony on the Yaeyama Central Knoll in the Yaeyama Central Graben at depths of 2,000 m. We could not recover any hydrothermally altered samples in this area.

3-4. Volcanic Front

Small knolls such as the Daiiti-Kume Knoll, Daini-Kume Knoll, Daiiti-Miyako Knoll (KATO *et al.*, 1982, UEDA, 1986) and Ishigaki Knoll (KIMURA, 1983b) are standing as a line of Quaternary volcanoes in the survey area (Fig. 3). The Ishigaki Knoll consists of fresh dacite (OSHIDA *et al.*, 1988),

and its flank is covered with Layer B. Violent submarine explosions which occurred near the Knoll in 1924 (KATO, 1980). Igneous pierce structures were recognized beneath the southern marginal floor of the southern Okinawa Trough, accompanied by distinct magnetic anomaly in the Quaternary volcanic zone. They should represent the southern extension of the northern Tokara volcanic front, although the Okinawa-Torishima Volcano is the southern terminal of the Tokara volcanic front exposed above sea level in the Ryukyu Arc. On the other hand, volcanic knolls along the segments of the central rift are distributed behind the volcanic front in the middle to southern Okinawa Trough region.

3-5. Structural framework

The geologic, structural framework of the Okinawa Trough and its vicinity are shown on 3.5 KHz profiling records (Figs. 14 and 15). The geo-structural map is presented in Fig. 16. Data from the Geological Survey of Japan and the Hydrographic Office of Japan were valid for supplementing to those of DELP 1988 Cruises. The structural framework of the middle to southern Okinawa Trough region was identified as marginal plateaus, rifted margins and the central basins including the central Graben (Fig. 16). This classification is essentially consistent with the structural framework of the northern to middle Okinawa Trough (KIMURA, 1985).

1) Tunghai Shelf Belt

The Tunghai Shelf Belt has been determined to be the western marginal plateau of the Okinawa Trough. There are many faults near the edge of the eastern Tunghai Shelf. Many of them are covered with Quaternary sediments including Layers B and A. Therefore, these faults are considered to be almost inactive.

2) Tunghai Slope Belt

The Tunghai Slope Belt includes a continental slope and a western margin of the Okinawa Trough (Figs. 15 and 16). It is regarded as the western rifted margin of the Okinawa Trough. Sandstone composed of quartz, plagioclase, muscovite, biotite, and magnetite was dredged from the continental slope south of Sekibi Sho (DR4 in Fig. 2; Table 2) during the DELP 1988 Cruises. Minor amounts of chlorite and smectite are observed in the sandstone. The sandstone may be correlated with that of the late Miocene to early Pleistocene Shimajiri Group based upon the stratigraphic correlation between some seismic reflecting records and dredged samples. Siltstone correlating with the Shimajiri Group had been obtained from the Tunghai Slope near the sandstone dredge site by other organizations (KIMURA *et al.*, 1980; KIMURA, 1983a). Consequently, the slope is thought to be essentially fault scarp an offsetting of sediment-

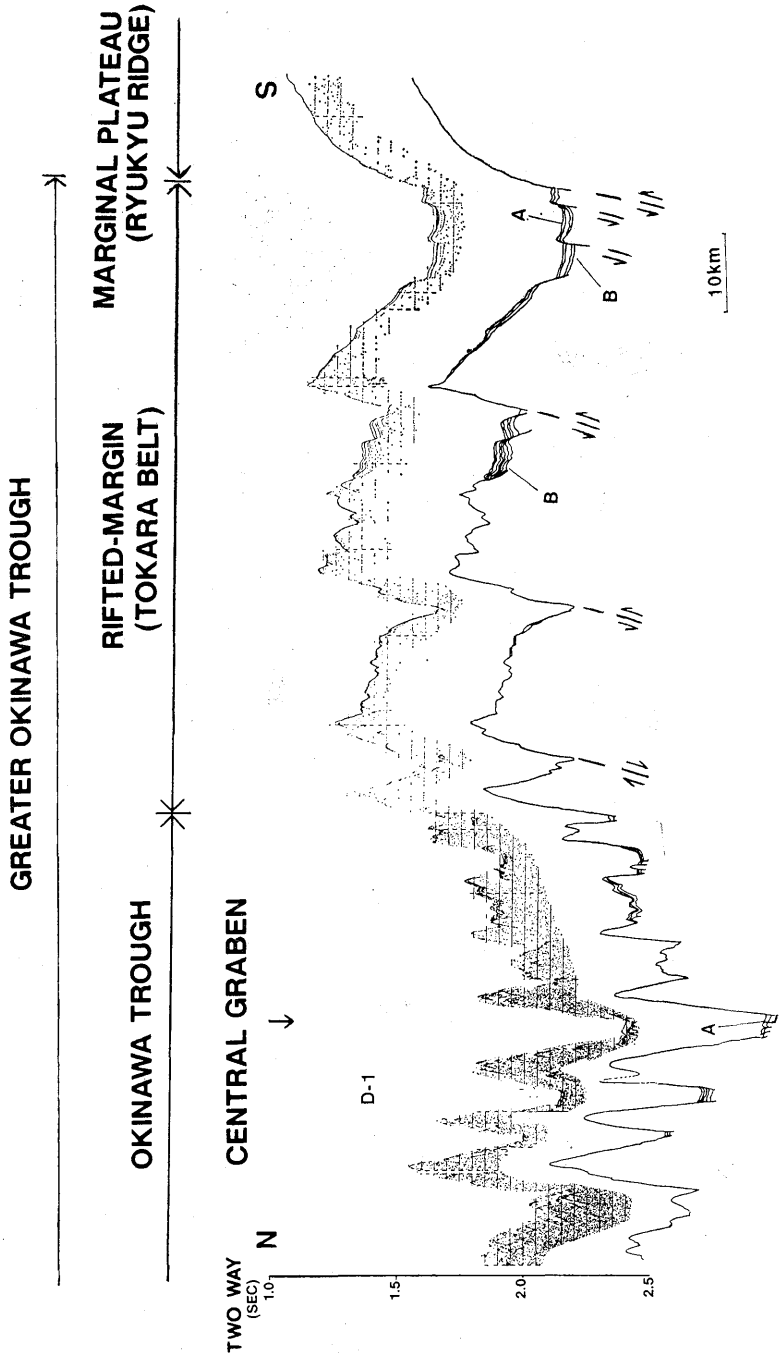

Fig. 14. Cross section of the middle Okinawa Trough represented by 3.5 KHz profiling records (D-1). A: Layer A, B: Layer B. Location is shown in Fig. 2.

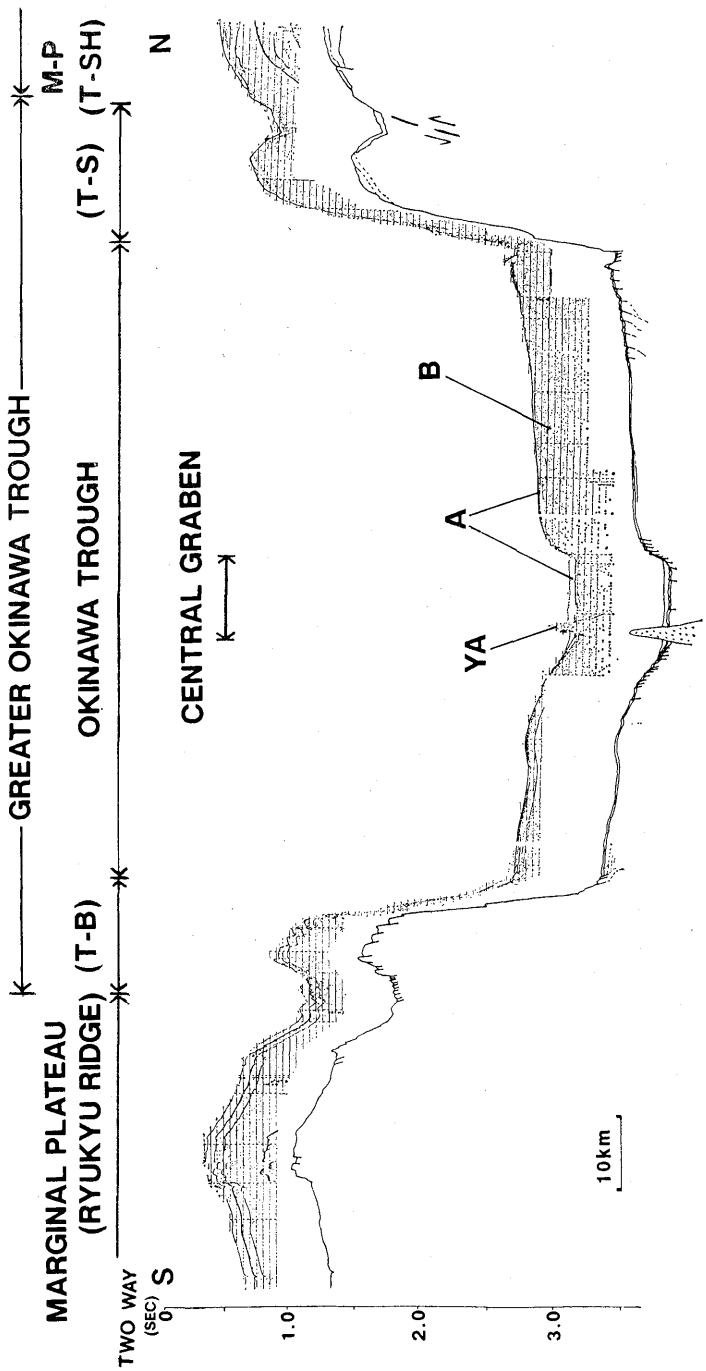

Fig. 15. Cross section of the southern Okinawa Trough represented by 3.5 KHz profiling records (D-12). Location is shown in Figs. 1 and 2. A: Layer A, B: Layer B. YA: Yaeyama Central Knoll, T-B: Tokara Belt, M-P: Marginal plateau, T-S: Tunghai Slope Belt, T-SH: Tunghai Shelf Belt.

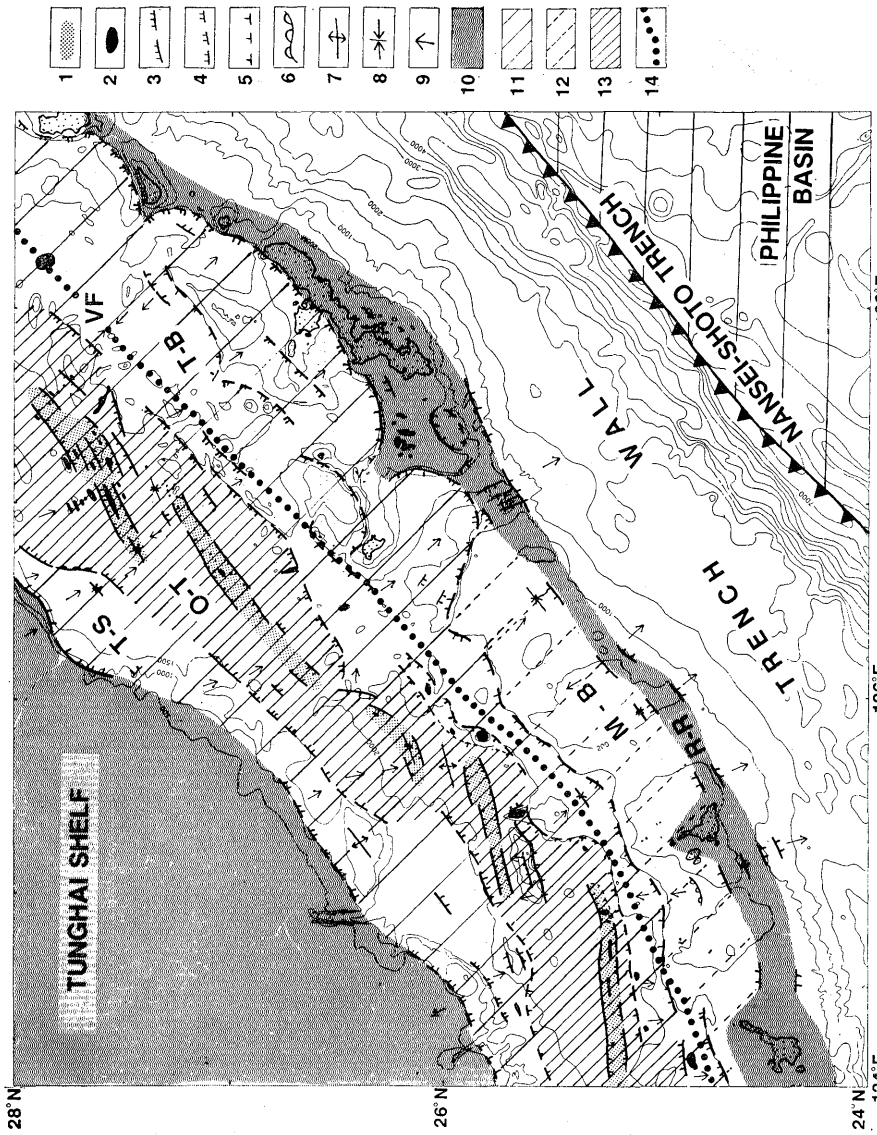

Fig. 16. Structural framework of the middle to southern Okinawa Trough area. T-S: Tunghai Slope Belt, O-T: Okinawa Trough Belt, T-B: Tokara Belt, R-R: Ryukyu Ridge Belt, M-B: Miyako Belt. Legend 1: Central depression, 2: Quaternary igneous body, 3: Active fault, 4: Buried fault, 5: Estimated fault, 6: Escarpment, 7: Anticline, 8: Syncline, 9: Direction of the apparent inclination of the sea-floor on the survey line, 10: Ryukyu Ridge Belt, 11: Tokara Belt, 12: Immature Tokara Belt (?) on the Ryukyu Ridge (Miyako Belt), 13: Okinawa Trough Belt, 14: Quaternary volcanic front.

ary rocks of the Shimajiri Group.

3) Okinawa Trough Belt

The Okinawa Trough Belt is a back-arc basin. It is a big graben bounded by the Tunghai Slope Belt to the west and by the Tokara Ridge Belt to the east. The central grabens develop along the axis of the Trough. Active faults are concentrated along the central axial region. Pre-Tertiary rocks such as Cretaceous sediments and granitic rocks are often exposed on knolls located along both side of the central grabens, as in the Miyako Seamount. Those rocks are overlain by the Shimajiri Group in general. Pleistocene Ryukyu Limestone were recovered from the top of such knolls (KIMURA, 1990).

There exist slight differences in the central rift among the northern, middle and southern Okinawa Trough. For instance, the middle to southern Okinawa Trough has a topographic represented central valley in the central graben, but the northern Okinawa Trough does not often show this. There are many volcanic knolls and ridges in the middle Okinawa Trough. In the southern part, thick Pleistocene sediments accumulate and are offset by step faults to make classic grabens.

4) Tokara Belt

The Tokara Belt is an active volcanic front belt, and is regarded as the eastern, rifted margin of the Okinawa Trough. Major faults developing parallel to the Island Arc seem to be inactive, because they are covered with Layers B and A in general. The Quaternary volcanic front is located in the belt in the southern Okinawa Trough region although the Belt does not show clear topographic expressions in the south.

5) Ryukyu Ridge Belt

This Belt is an outer, inactive volcanic arc and is regarded as being in the eastern marginal plateau of the Okinawa Trough. The western boundary of the Ridge is Ryukyu Ridge Fault (KIMURA, 1985). A newer fault is developing on the southern Ryukyu Ridge parallel to the Okinawa Trough. The western half of the southern Ridge (M-B in Fig. 16) is bounded by the fault.

The whole area including the Okinawa Trough and its marginal rifts such as the Tunghai Slope and the Tokara Belt represent a giant graben structure. This giant graben is called the Greater Okinawa Trough (KIMURA, 1985). This includes the active volcanic arc of Tokara Belt. This is an Okinawa Trough in a broad sense. The eastern marginal fault, Ryukyu Ridge Fault, is in contact with the Ryukyu Ridge to the west.

4. Discussion

Recent studies reveal that the Okinawa Trough has formed since

about 2 Ma in early Pleistocene time, based upon such evidence that the constituting faults of the Okinawa Trough is offsetting the late Miocene to early Pleistocene Shimajiri Group and the Trough has been buried by sediments since early Pleistocene time (Layer B) (KIMURA, 1990). Layer B is divided into two parts as lower and upper. On profiles of multi-channel records, Layer B is inclined to the central axis of the trough to become thinner to the center and is severely faulted in a wide range along the center (KIMURA, 1985). On the other hand, upper Layer B is thicker in the central part of the Trough and the faulted zone is limited very near the axis. There are no transform faults connecting the segments of axial grabens. The fact suggests that a crustal thinning is centered in the axis of the Okinawa Trough during the deposition of Layer B (early Pleistocene—middle Pleistocene time). The central graben may have formed at the same time. The graben is considered to be less extended during the deposition of the upper Layer B (middle to late Pleistocene time) because it is deposited thick in the central part of the Trough and shows typical patterns as seen in deep-sea turbidite.

Later, the extension tectonics again advanced in Late Pleistocene time. The pulse of crustal movement formed the present central grabens (central valley) in the Okinawa Trough.

SIBUET *et al.* (1987) suggested that volcanic activities in the middle to southern Okinawa Trough correspond to the southern extension of the volcanic front of the northern Tokara volcanic arc. This survey, however, showed that most volcanic activities associated with central grabens occur behind the Quaternary volcanic front.

Samples dredged from the central grabens show chemical composition of calc-alkaline and or tholeiitic rocks of Island Arc type and their K-Ar ages indicate that they are younger than 1 Ma in the study area (ISHIKAWA *et al.*, this issue). This result is consistent with the geophysical data suggesting that crustal rocks of the Okinawa Trough exhibit a continental affinity based upon detailed seismic refraction measurements (SEISMIC REFRACTION SURVEY GROUP OF DELP 1988 CRUISES, 1988; HIRATA and KINOSHITA, 1990). The magnetic anomaly shows characteristic features in the continental crustal region, and it shows a good correspondence to Pleistocene intrusive rocks and topography (FURUKAWA *et al.*, 1989). However, the oxygen fugacity of basalt and andesite collected from the middle to southern Okinawa Trough during DELP 1988 Cruises indicates a rather reducing condition of crystallization, the same as in most mid-oceanic ridge basalt (ISHIKAWA *et al.*, this issue), suggesting the initial stage of the rifting environment of the back-arc Okinawa Trough. It suggests that volcanic activity simultaneously occurred in

the Yaeyama Graben and the Iheya Deep under the rifting condition similar to that of ridge formation.

The crust beneath the northern to southern Okinawa Trough shows a continental affinity (IWASAKI *et al.*, 1990; NAGUMO *et al.*, 1986; SEISMIC REFRACTION GROUP OF DELP 1988 CRUISES, 1988; HIRATA and KINOSHITA, 1989), and all volcanic rocks obtained in the whole Okinawa Trough show an island arc nature. The evidence shows the existence of a continental crust beneath the whole Okinawa Trough, suggesting that the whole Okinawa Trough has not yet reached the stage of spreading.

5. Summary and conclusions

1) Five segments of active central rift were identified in the middle to southern Okinawa Trough, which are distributed in echelon along the axis of the Trough. They represent topographically central valleys or rift valleys.
2) Transform faults connecting those segments were not found.
3) The Izena Hole where the hydrothermal activity was found is located at the eastern end of the Aguni Central Graben.
4) Three knolls (DELP88-1, DELP88-2 and Daini-Yaeyama Knolls) were newly found in the Yaeyama Central Graben.
5) Daiiti-Kume Knoll and Ishigaki Knoll are identified with volcanoes belonging to the Quaternary volcanic front continued from the northern Tokara volcanic belt. Igneous bodies along the Central Grabens are distributed in behind the volcanic front.
6) Major faults developing along the Island Arc are almost buried by Layer A and Layer B and thus they have been mostly inactive in Recent time.
7) The middle to southern Okinawa Trouth shows a back-arc rifting stage. Moreover, the whole Okinawa Trough is identified to be in a continental rifting stage judging from previous data in addition to the present results.

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7. 中—南部沖縄トラフ中央地溝の地質学的研究

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沖縄トラフでもし海底拡大が行なわれているとすれば，それは南部の中央地溝付近に限定されるだろうとの指摘がされている．そこで，中—南部沖縄トラフ域で行なわれた DELP 1988 年度航海の際得られた，3.5 KHz 音波探査資料およびドレッジ試料を中心に他の試・資料を補い，トラフ中央地溝の活動的伸張構造およびリフティングに関連する火成岩の産状等を詳しく調べた．その結果，同トラフの中軸に沿って，前期更新世以降活動している東—西から東北東—西南西方向の長さ 50-100 km の 5 つのグラーベンが雁行状に発達し，それらがすべて地形的に中軸谷を形成していることが明らかになった．それらグラーベンは火山フロントより後背に形成され，現在沖縄トラフの伸張運動はこれらのグラーベンを中心として行われている．しかし，これらのグラーベンをつなぐトランスフォーム断層の存在は認められない．沖縄トラフ最深部の八重山中央地溝内より採取された岩石は，100 万年より若い島弧に典型的な calc-alkali rock と theleiitic rock であった．しかし，それらの oxygen fugacity は，大洋中央海嶺域で認められるように還元的な環境を示し．背弧のリフティングとの密接な関係が示唆された．活動的なリフトで認められるブラック・スモーカーが粟国中央地溝の東端で 1989 年に発見された．以上により，沖縄トラフ中—南部は背弧におけるリフティングが行なわれている段階であり，海底拡大に至っていないとみなされる．これは同時に行われた屈折法地震探査や地磁気探査等の地球物理学的な調査結果とも矛盾しない．また，従来の調査結果と合わせると，沖縄トラフ全域が大陸地殻内でのリフティングの段階とみなせる