Back-arc rifting in the Okinawa Trough

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Geological and geophysical data reveal that the Okinawa Trough shows incipient continental rifting, and crustal separation started from about 2 Ma. The early extensional movements in the trough are probably of Miocene age. In addition to the Miocene phase, two main periods of extension are recognized: a Pleistocene phase between 1.9 and 0.5 Ma and the present day phase. During the stage short central rifts (Central Grabens) were formed. The opening however, may have occurred only in the southern part of the trough basin having an average half spreading rate of 2 cm yr^{-1} since Early Pleistocene time, producing its present width of several tens of kilometres. These activities were well represented by igneous intrusions, sedimentary facies and sedimentary structures in and around the Okinawa Trough. The width of the zone affected by back-arc extension (defined as Greater Okinawa Trough) is larger than the present Okinawa Trough, whose width is 200–250 km. The present form of the Greater Okinawa Trough started to form at the same time as that of the Okinawa Trough.

Keywords: Okinawa Trough; Back-arc rifting

Introduction

The Okinawa Trough is a back-arc basin of the Ryukyu Arc (*Figure 1*). Konishi and Sudo (1973) suggested that the Okinawa Trough has been spreading since Middle Miocene time based upon geologic evidence from the Ryukyu Islands. However, based upon analyses of single channel airgun reflection profiles, Herman *et al.* (1978) proposed that there is an unconformity between the upper and lower sediments (their Unit A and B) in the southern Okinawa Trough, and that back-arc spreading was initiated sometime after Late Miocene-Early Pliocene time when the Ryukyu Arc was rifted from the continental margin. They suggested that the basin of the Okinawa Trough had opened to almost its present day width before the deposition of the thin upper sediments of Unit A began and that Unit B was probably deposited in the basin before the major period of spreading ceased. Units A and B, however, were not dated. Subsequently, a two ship refraction study was carried out in the southern Okinawa Trough (Lee *et al.*, 1980). The Upper mantle was found to be very shallow in the Okinawa Trough, compared to the surrounding areas of the continental crust. Relatively young basalt was also found beneath the axial area of the trough. Lee *et al.* (1980) concluded that crustal separation has occurred in the southern Okinawa Trough from Pliocene to Recent time. None of these studies has discussed the northern and middle parts of the Okinawa Trough.

This paper presents a compilation of seismic reflection and refraction, dredging, magnetic anomaly and well data covering the entire Okinawa Trough area, all of which appear to support the existence of crustal separation in the Okinawa Trough since Early Pleistocene time.

Data

Submarine topography in and around the Okinawa Trough was contoured (*Figure 1*) using the Ocean Water Depth compilations of the Japanese Hydrographic Department, Marine Safety Agency of Japan and was supplemented by the author's own data.

Most of the seismic reflection profiles used here are single channel data of the Geological Survey of Japan compiled by Kimura *et al.* (1979 and 1980), Kimura (1983) and Honza (1976). Data from the Ocean Research Institute, University of Tokyo (Kagami, 1975), US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), US Naval Oceanographic Office (USNOO), R/V Hunt data (Wageman *et al.*, 1970), Lamont-Doherty Geological observatory of Columbia University and the Hydrographic Department, Maritime Safety Agency of Japan were also reanalysed and compiled. Multichannel seismic reflection profiles by the Japan National Oil Corporation (JNOC) were also used (*Figure 2*). Magnetic data from the Geological Survey of Japan, Kobe University and University of the Ryukyus were used (*Figure 3*). Seismic refraction data were mainly taken from Murauchi *et al.* (1968), Hayes *et al.* (1978), Leyden *et al.* (1978) and Lee *et al.* (1980). Dredge samples from the Ocean Research Institute, University of Tokyo and from the Geological Survey of Japan were also studied and offshore drilling data for oil prospecting carried out by JNOC and petroleum companies are reviewed in part (*Figure 4*).

Submarine topography

The topography of the Okinawa Trough (*Figure 1*) and surrounding vicinities is arranged in belts, from east to

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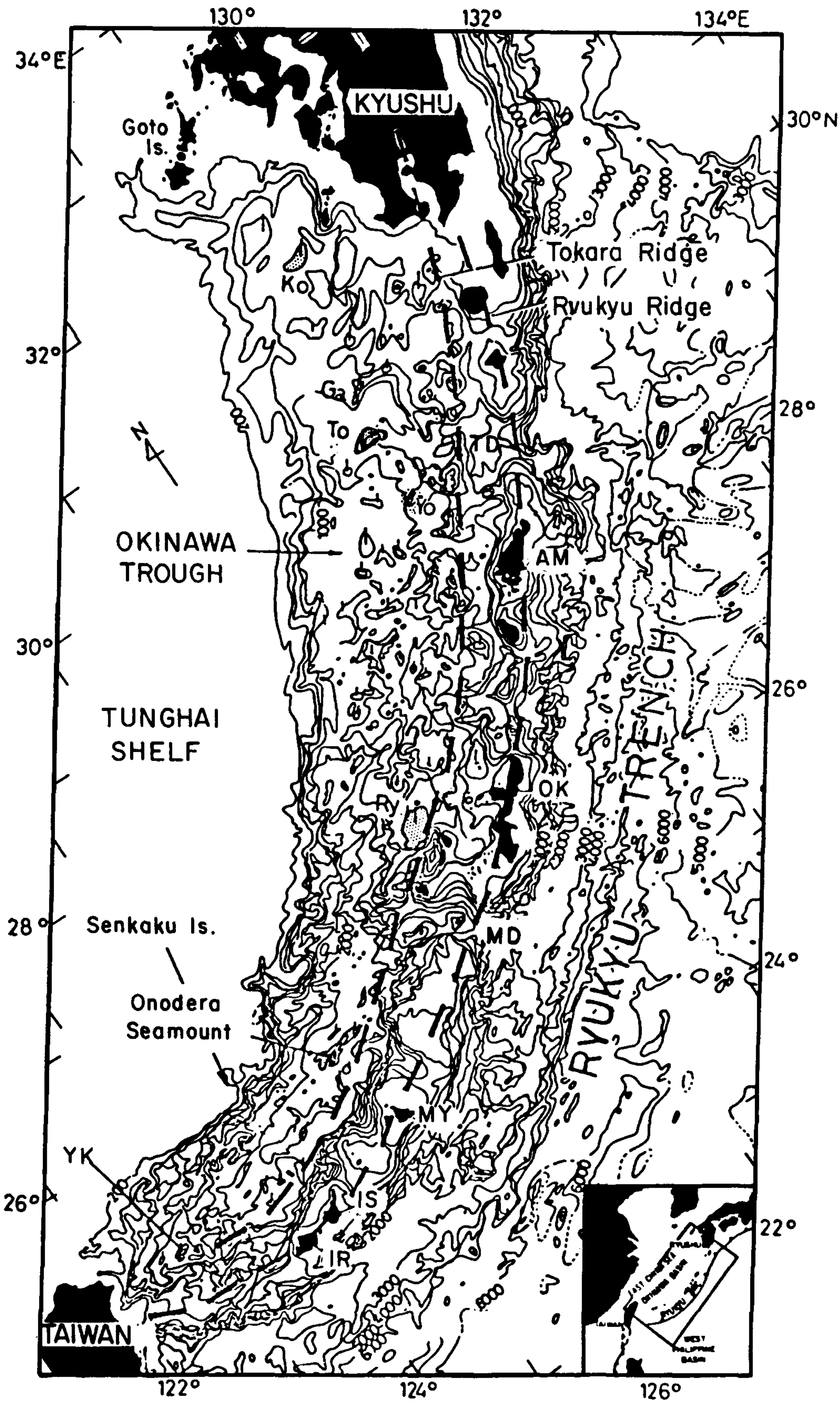

Figure 1 Submarine topography in and around the Okinawa Trough based upon the map by Kimura (1983b). The contour interval is 200 m to 2000 m water depth; 1000 m for deeper areas. Ko, Koshiki Knoll; To, Tokara hill; Ga, Gama-sone; Yo, Yokogan-sone Bank; Am, Amami-oshima; Ok, Okinawa-jima; Ry, Ryukyu-sone Bank; My, Miyako-jima; Is, Ishigaki-jima; Ir, Iriomote-jima; Yk, Yonaguni Knoll; Td, Tokara depression; Md, Miyako depression (Kerama gap)

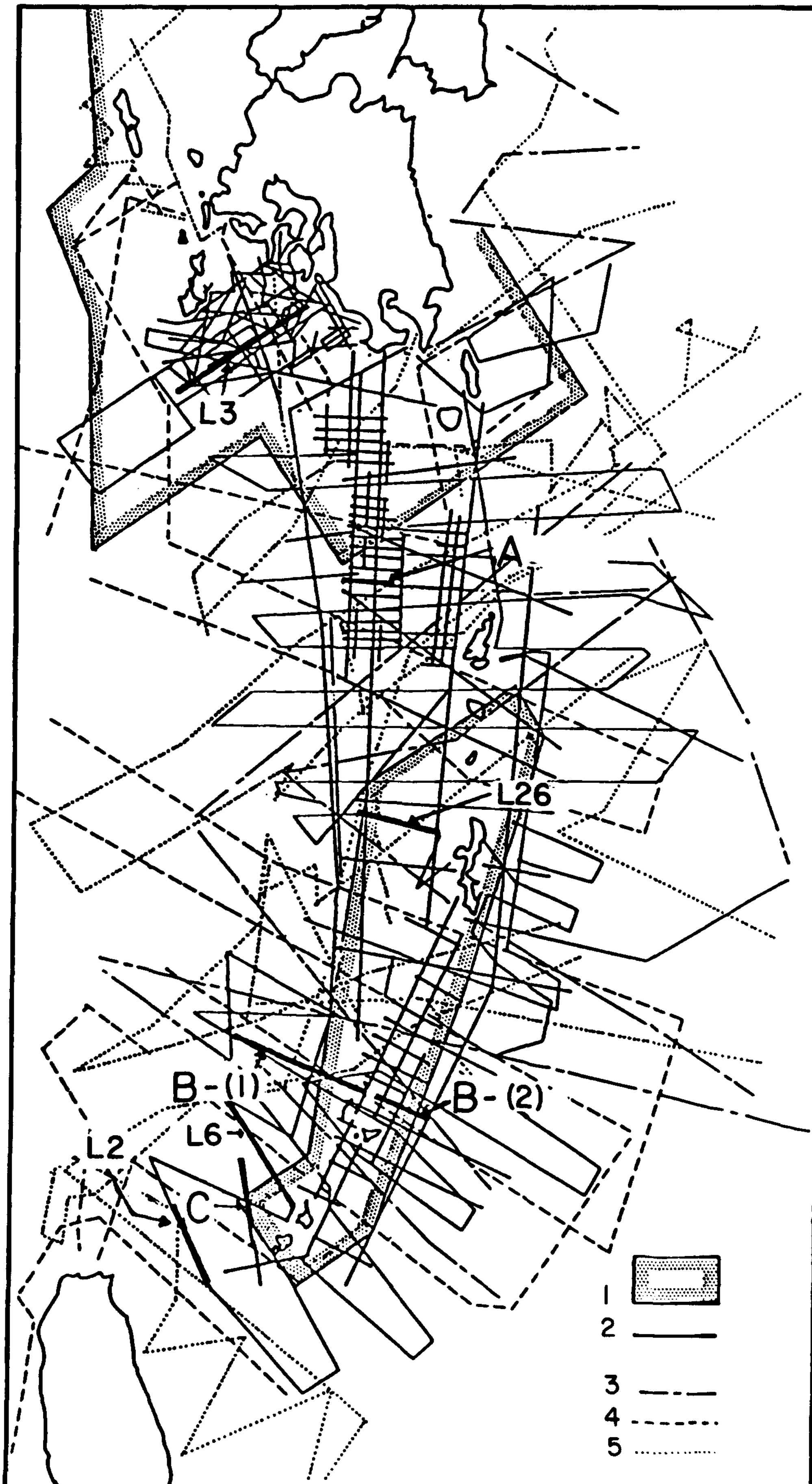

Figure 2 Track lines of seismic reflection profiles used in this study. (1) Area of dense survey lines carried out of the Geological Survey of Japan and the Hydrographic Department, Maritime Safety Agency of Japan; (2) seismic reflection survey lines by Geological Survey of Japan and JNOC; (3) Ocean Research Institute, University of Tokyo; (4) USNOO; and (5) Lamont-Doherty Geological Observatory of Columbia University. Thick lines show locations of seismic reflection profiles presented in the present paper, *Figures 5, 6, 7, 8, 11, 12* and *14*

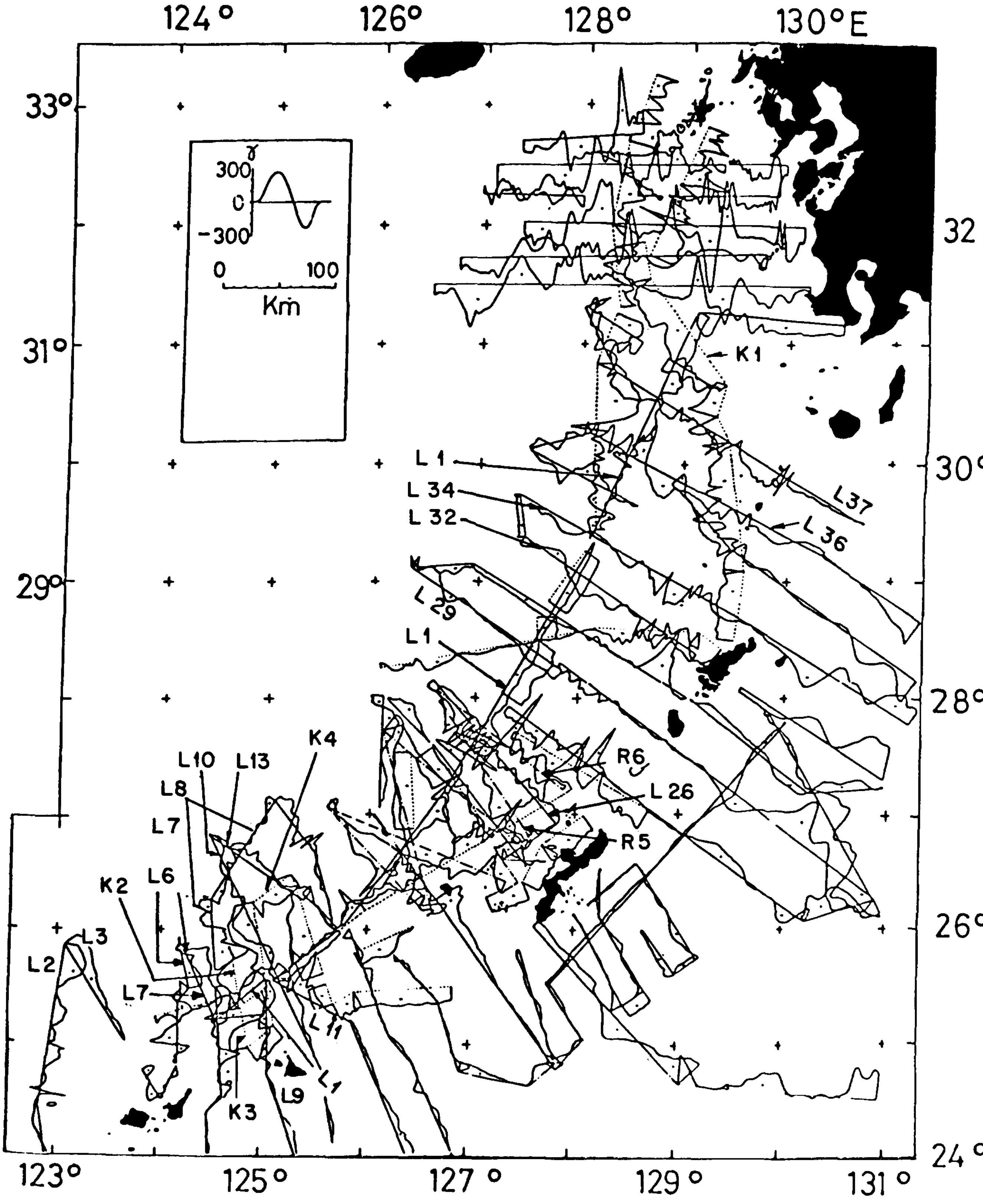

Figure 3 Map displaying magnetic anomaly profiles across the Okinawa Trough based upon data by the Geological Survey of Japan, Kobe University and University of the Ryukyus. Letters are magnetic profiles presented in *Figures 16* and *17*

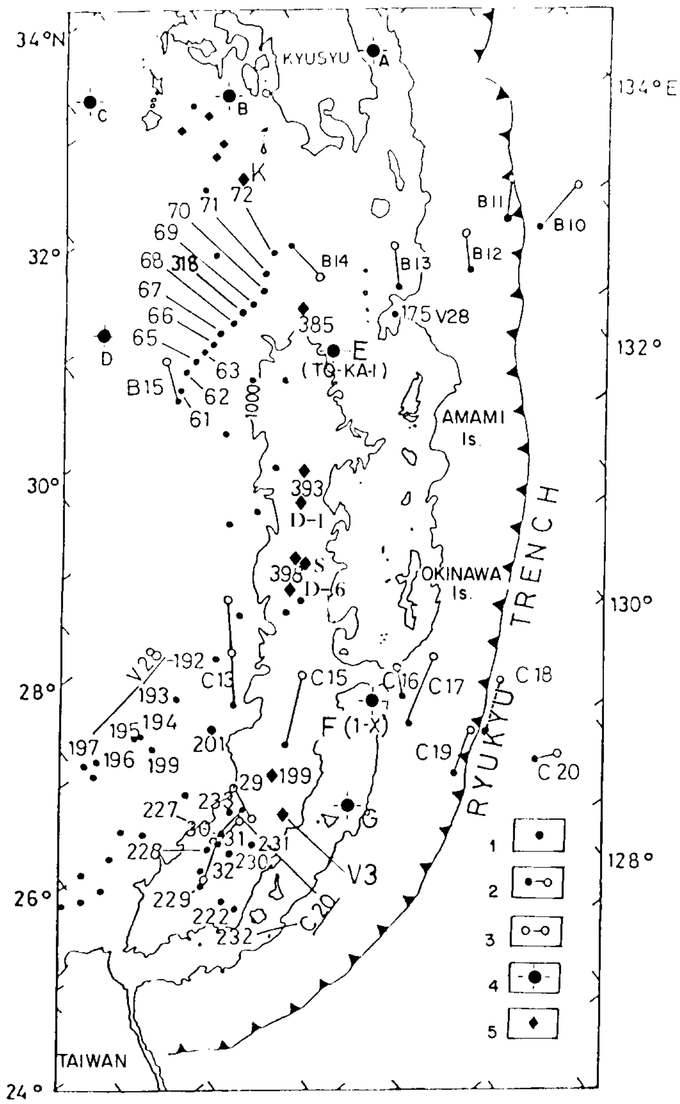

Figure 4 Location map of sonobuoy, drilling and dredging stations by various organizations. (1) Sonobuoy stations (Hayes *et al.*, 1978). (2) Two-ship refraction stations (Hayes *et al.*, 1978; Lee *et al.*, 1980). (3) Unreversed refraction lines. (4) Offshore drillings. (5) Dredge stations with basement rocks obtained (Honza, 1976). St. S represents dived site by the submarsible 'SHINKAI 2000' of Japan Marine Science and Technology Center

west consisting of the Ryukyu Trench, Trench-Arc Gap, Ryukyu Ridge, Tokara Ridge, Okinawa Trough and the margin of the Tunghai Continental Shelf.

Although two parallel ridges of the outer inactive volcanic arc (Ryukyu Ridge) and the inner volcanic arc (Tokara Ridge) can be recognized in the northern and middle Ryukyu Arc, these features are less well expressed in the southern part of the Ryukyu Arc (*Figure 1*). Water depth of the axial part of the Okinawa Trough increases from 500 m in the north to about 2300 m in the south. In the northern and southern part of the Okinawa Trough the floor of the Trough is smooth (see *Figures 5, 7* and *8*), but it is very rough in the middle part (*Figure 6*). In the middle and the southern Okinawa Troughs there occur narrow WSW-ENE trending en échelon depressional basins but these features are not obvious in the northern part.

Structural framework

The structural map (*Figure 9*) shows the distribution of the main faults and tectonic provinces, all are believed to be related to the Okinawa Trough formation as deduced from seismic reflection, dredging and drilling data. The width of the zone affected by back-arc extension (defined as the Greater Okinawa Trough) is greater than the present Okinawa Trough (130 km) whose width is 200–250 km (*Figure 9*).

The topography of the Tunghai Slope and Tokara Ridge is rough and both features are regarded as marginal, tensile rifted zones of the Okinawa Trough. The Ryukyu Ridge Fault and Tunghai Shelf Fault have been active during the deposition of Early Pleistocene sediments (Layer C, *Table 1*). The Okinawa Trough is regarded as the area filled with deposits from Layer C upwards, two to three kilometres in thickness. The Greater Okinawa Trough and the Okinawa Trough have developed generally parallel to the Ryukyu Ridge. Central Grabens or rifts exist in the axial part of the Okinawa Trough in an en échelon pattern. The existence of the Central Graben of the Okinawa Trough was first noted by Kimura *et al.* (1975) in the middle area. Central Grabens in the southern part of the Okinawa Trough were found by Herman *et al.* (1978). In places the Central Grabens of the northern Okinawa Trough are half graben features. In many cases, intrusive bodies exist beneath the Central Grabens to make basal highs. In other words, the Central Graben is defined as the most recent fissure originating in response to uprisings of magma. Seismicity shows that the Central Graben is active and focal mechanism solutions show that the tensional axis is oriented in a north–south direction (Eguchi, 1982; Eguchi and Uyeda, 1983; Yamamoto and Tokunaga, 1981).

Stratigraphy

The stratigraphy in and around the Okinawa Trough (*Table 1*) is arranged as follows. *Layer E:* Acoustic basement consisting of pre-Miocene formations and igneous bodies of various ages. *Layer D:* Early to Middle Miocene sediments. The layer displays a stratified pattern in the multi-channel seismic reflection profiles but is opaque in the single channel seismic reflection profiles. In the area of the so-called 'Green Tuff' activities, characterized by Neogene volcanism in Japan (Matsumoto, 1979) and containing huge volumes of volcanic material, Layer D displays a massive acoustic basement pattern in both single and multi-channel profiles. It is correlated with the Yaeyama Group and Sasebo Group which contain thick sandstone and coal beds. *Layer C:* Stratified transparent layer. It shows a well stratified pattern in multi-channel records. Layer C is correlated with Late Miocene to Early Pleistocene sediments, called the Shimajiri Group in the Ryukyu Islands. The Shimajiri Group is mainly composed of shallow facies mudstone rich in foraminifera. *Layer B:* Well stratified transparent layer correlated with sediments from 2 Ma to Late Pleistocene time. *Layer A:* Transparent layer correlated with Holocene sediments.

In the Okinawa Trough, pre-Tertiary rocks of *Layer E*, which belong to the Inner Zone of Southwest Japan (Tanaka, 1977) have been dredged and drilled (St. K, 385, 199 and E in *Figure 4*). Late Cretaceous granitic

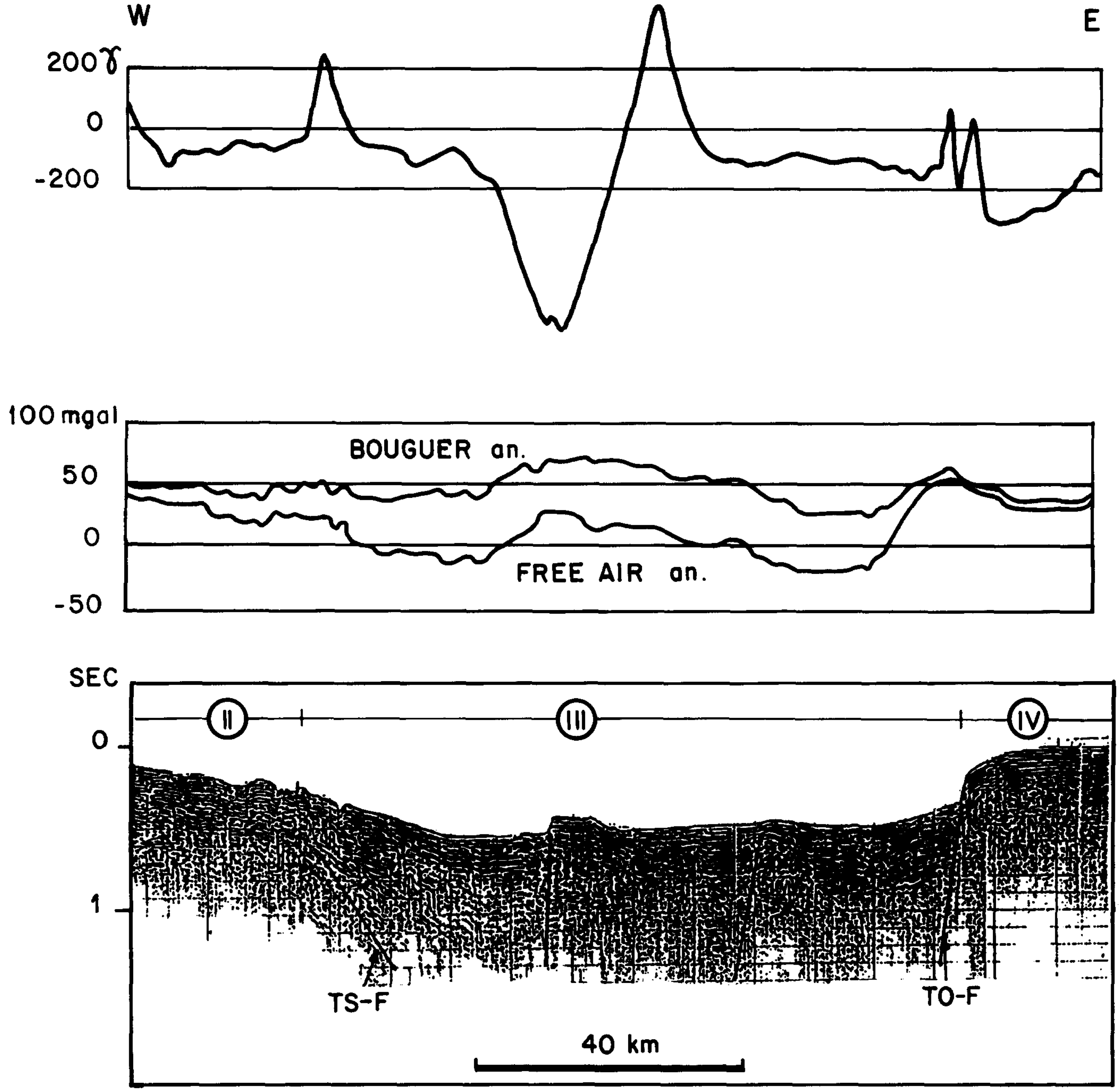

Figure 5 Seismic reflection, gravity and magnetic anomaly profiles (L3) crossing the northern part of the Okinawa Trough. Location is shown in *Figure 2*. Tectonomorphologic division (II, III, IV) and faults (TS-F, TO-F) are given in *Figure 10*. The arrow shows the Central Graben. Magnetic anomalies (γ) and gravity anomalies (mgal) (Joshima, 1978 and Joshima *et al.*, 1978). 'Sec' represents two way travel time

rocks were sampled by the oil well TO-KA-1 (*Figures 4* and *11*). These rocks are directly covered by a 2900 m thick Pliocene (= Quaternary) layer, including Late Miocene lava flows (6 Ma) and sediments (Nash, 1979a, 1979b). Pre-Tertiary sandstones, covered with the Shimajiri Group have also been dredged from Onodera Seamount in the southern part of the trough (St. 199, see *Figures 4* and *13*).

Layer C (Shimajiri Group) and its upper formations are rather easy to distinguish in seismic profiling records because its base is a pronounced unconformity. Layer C can be traced ranging from the Ryukyu Ridge via the Tokara Ridge. Based upon all test drillings (A and G in *Figure 4*) carried out in the Okinawa Trough and the Ryukyu Ridge areas, the 1000–2000 m thick Shimajiri Group and its basal unconformity was recognized.

Layer B can be divided into sub-layers B_1 and B_2, in ascending order by differences in dip and mode of deformation of the layers in the trough. Layer B_1 (*Table 1*) is regarded as ponded sediments in the Okinawa Trough that were derived from eroded materials during the formation of the marked unconformity between Layer C and B in the surrounding regions of the Okinawa Trough. It is clear that the Layer B sediments in the trough are younger than the main Shimajiri Group based on relative stratigraphic position as seen in the profiling records. The Shimajiri Group should include the Olduvai Event because the uppermost Shimajiri Group in Miyako-jima island includes zone N.22 in age (Planktonic foraminiferal zonation of Blow, 1969) (Natori, 1976; Ujiié and Oki, 1974). Correlation of Pleistocene chronology from the exposures on the land areas around Okinawa Trough

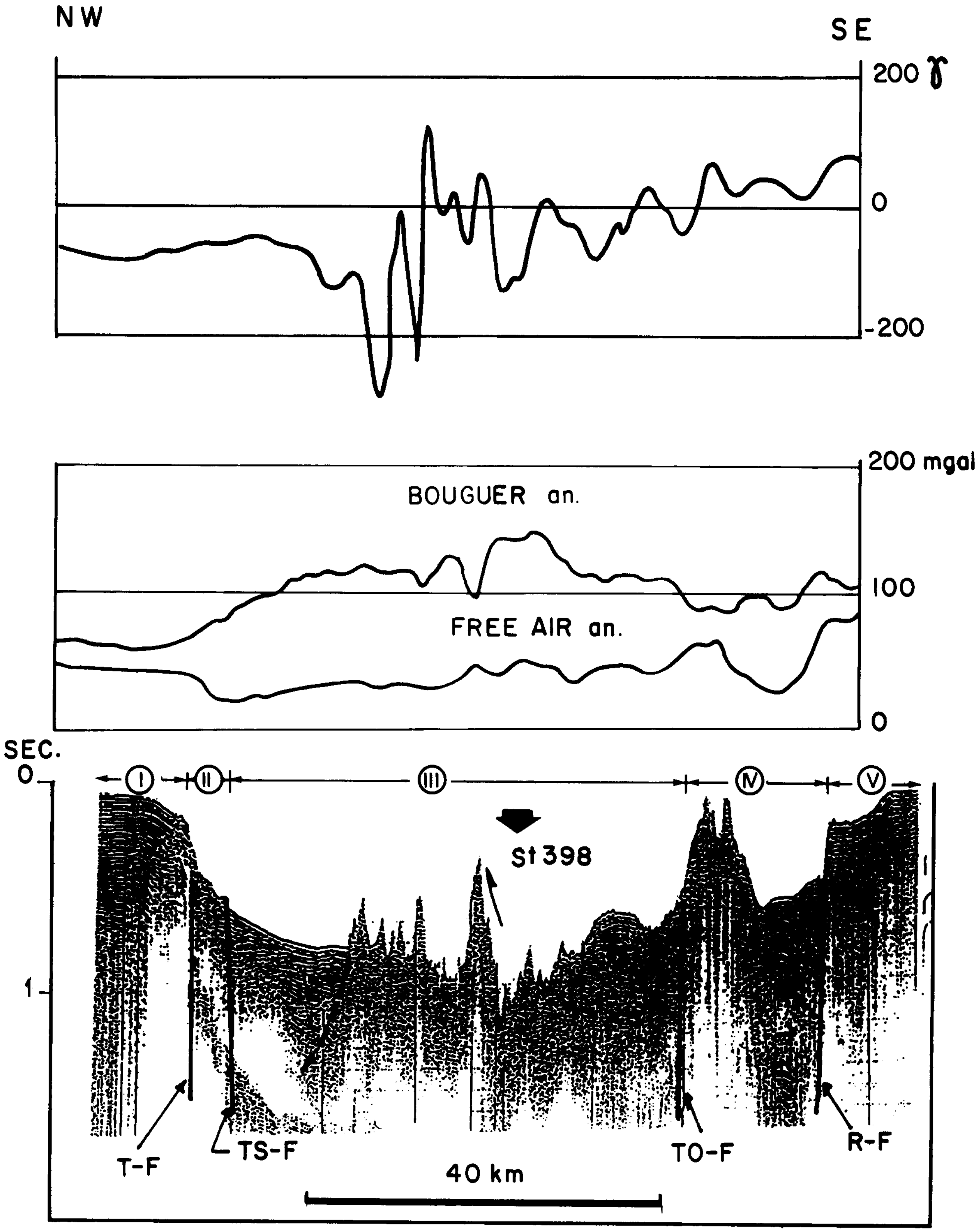

Figure 6 Seismic reflection, gravity and magnetic anomaly profiles (L26) in the middle Okinawa Trough. Location is shown in *Figure 2*. (γ) magnetic and (mgal) gravity anomalies (Miyazaki *et al.*, 1976 and Murakami, 1976). Tectonomorphologic division (I to V) and faults (T-F, TS-F, TO-F, R-F) are given in *Figure 10*. The arrow shows the Central Graben (rift in this case). St. 398 shows the dredging station, with the dredged direction. Broken lines represent the boundary between Quaternary sediments and its basement or igneous rocks.

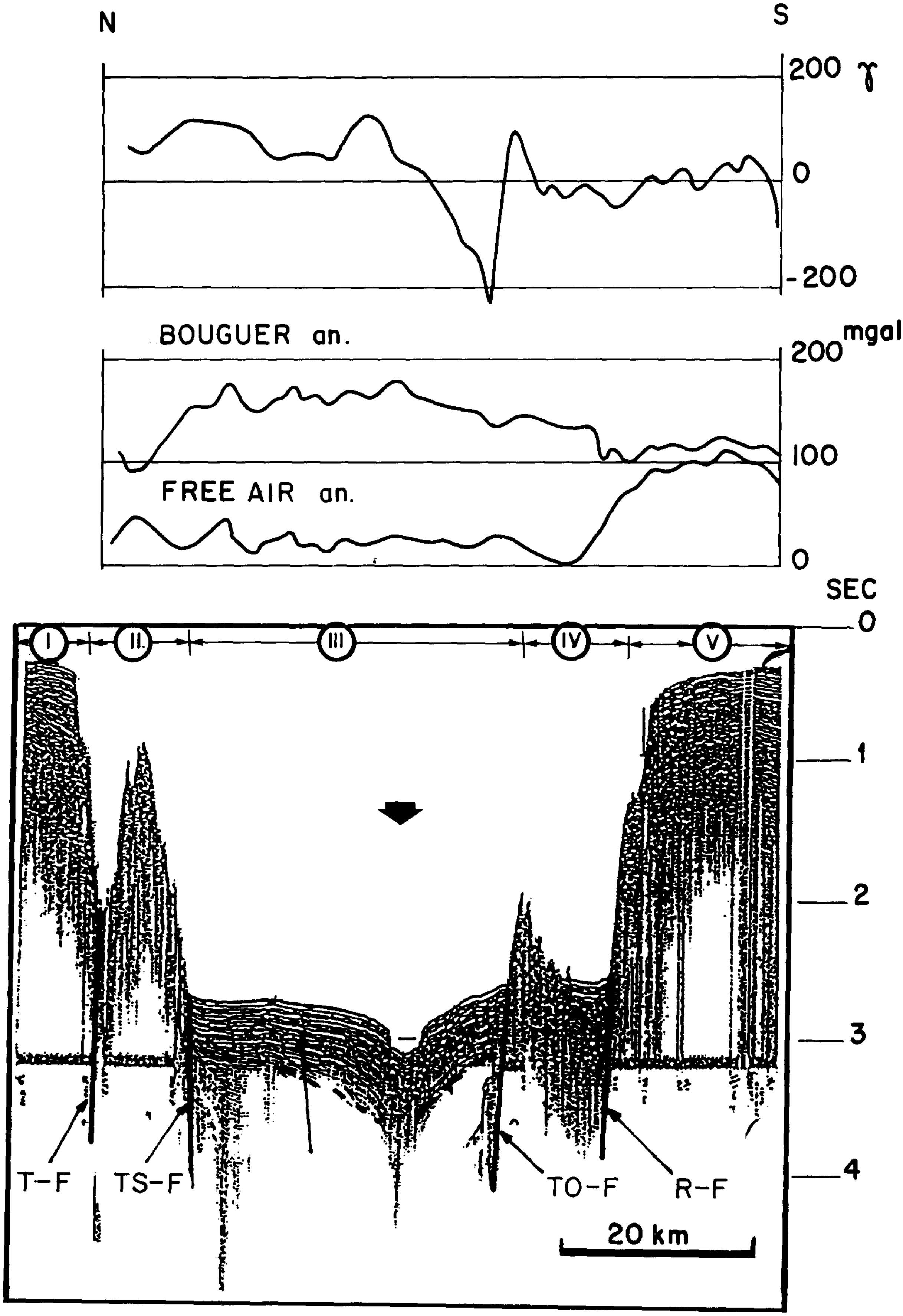

Figure 7 Seismic reflection, gravity and magnetic anomaly profiles (L6) in the southern Okinawa Trough. Location is shown in *Figure 2*. (γ) magnetic and (mgal) gravity anomalies (Ishihara and Murakami, 1976). The arrow shows the Central Graben. Tectonomorphologic division (I to V) and faults (T-F, TS-F, TO-F, R-F) are given in *Figure 10*

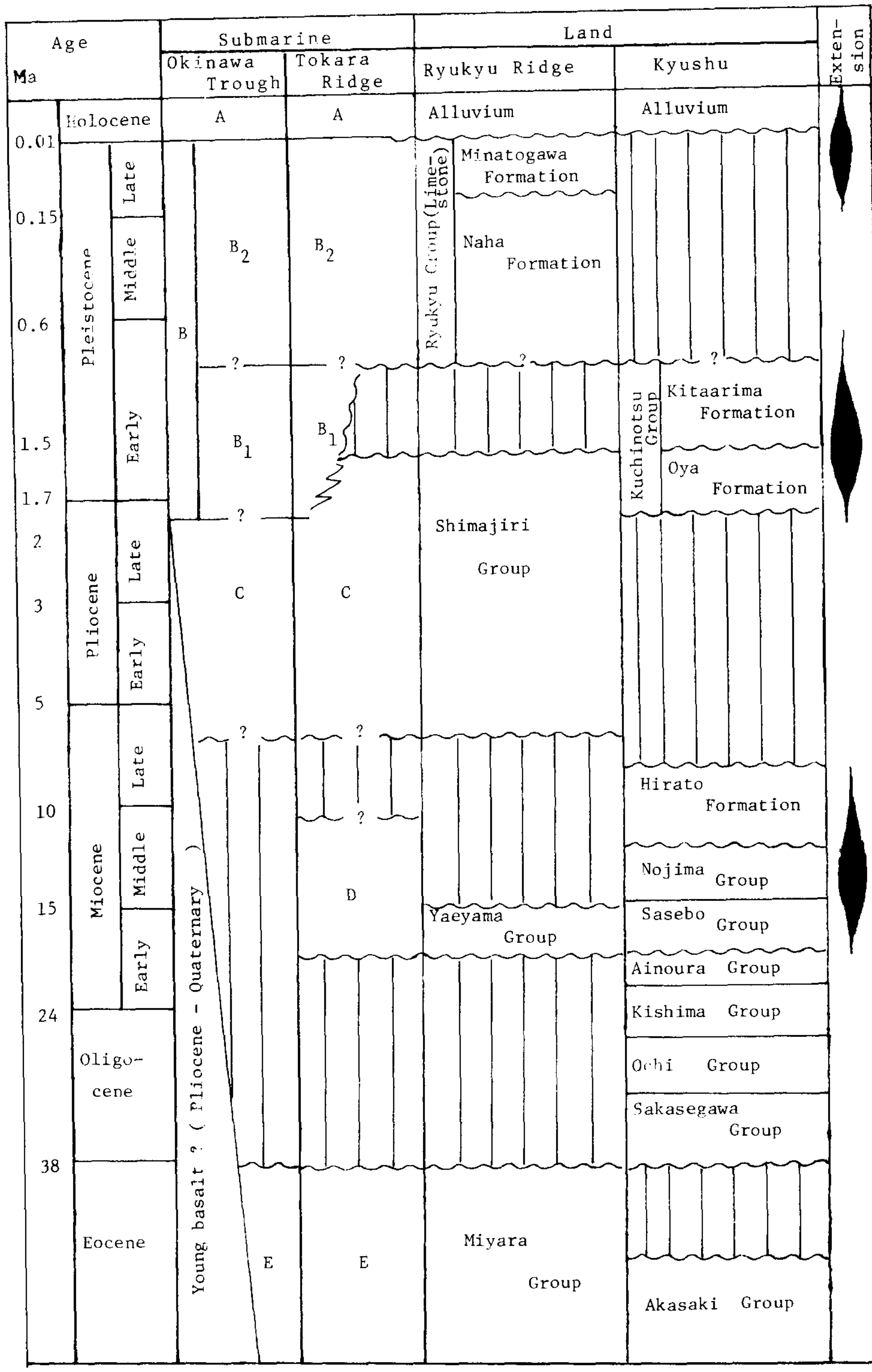

Table 1 Stratigraphic correlation table in and around the Okinawa Trough. Neogene chronostratigraphic scale is after Harland *et al.* (1982) but age of the Plio-Pleistocene boundary is after Tauxe *et al.* (1983). Age of the Kuchinotsu Group has been determined based upon the fission track method of Okaguchi and Otsuka (1980)

suggests that the main part of Layer B_1 sediments exist beneath the basins in the Okinawa Trough. B_2 is offset by the Central Graben (*Figure 14*).

Undeformed sediments of Layer A, Holocene deposits, overly Layer B conformably in the trough basins. This unit unconformably overlies older units in the areas surrounding the islands in the Ryukyu Ridge.

In the middle part of the Okinawa Trough, igneous intrusions and some apparent volcanic extrusions exist which seem to be very young (*Figure 6*). Pleistocene igneous rocks were obtained from St. 398 (*Figure 4*). Young intrusions are also observed beneath the central axis of the northern and southern Okinawa Troughs.

Unconformities

Five major post-Mesozoic unconformities are recognized in and around the Okinawa Trough (*Table 1*). (1) Unconformity between Layer D and E, formed in Oligocene time; (2) C/D unconformity in Middle to Late Miocene time; (3) B/C unconformity in Early to Middle Pleistocene time; (4) unconformity in Layer B_2; (5) A/B unconformity in Late Pleistocene time. The

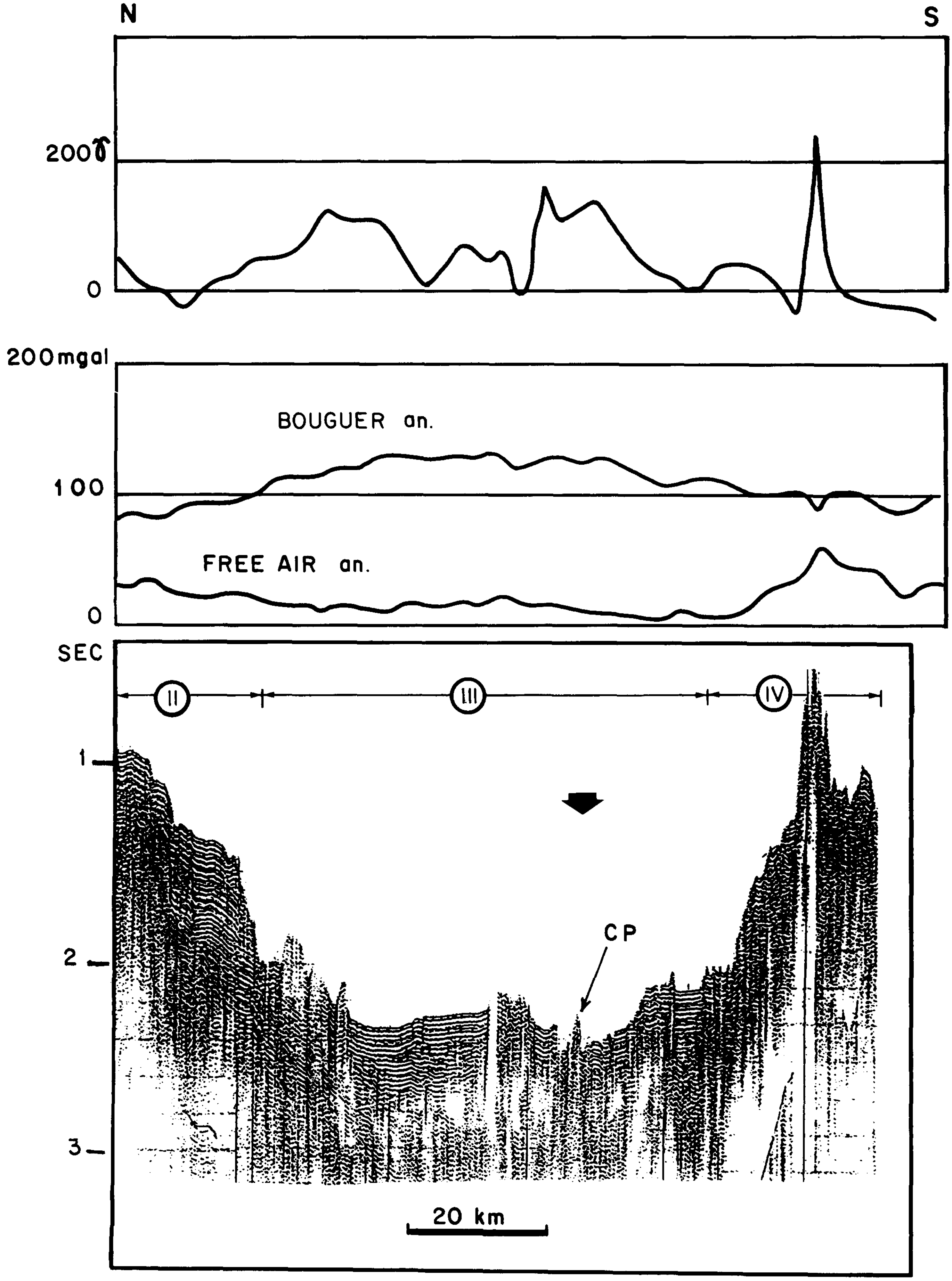

Figure 8 Seismic reflection, gravity and magnetic anomaly profiles (L2) in the southernmost part of the Okinawa Trough. Location is shown in *Figure 2*. (γ) magnetic and (mgal) gravity anomalies (Ishihara and Murakami, 1976). The arrow shows the Central Graben; CP, Central pinacle (volcanic intrusion; Yonaguni Knoll, Kimura, 1983b)

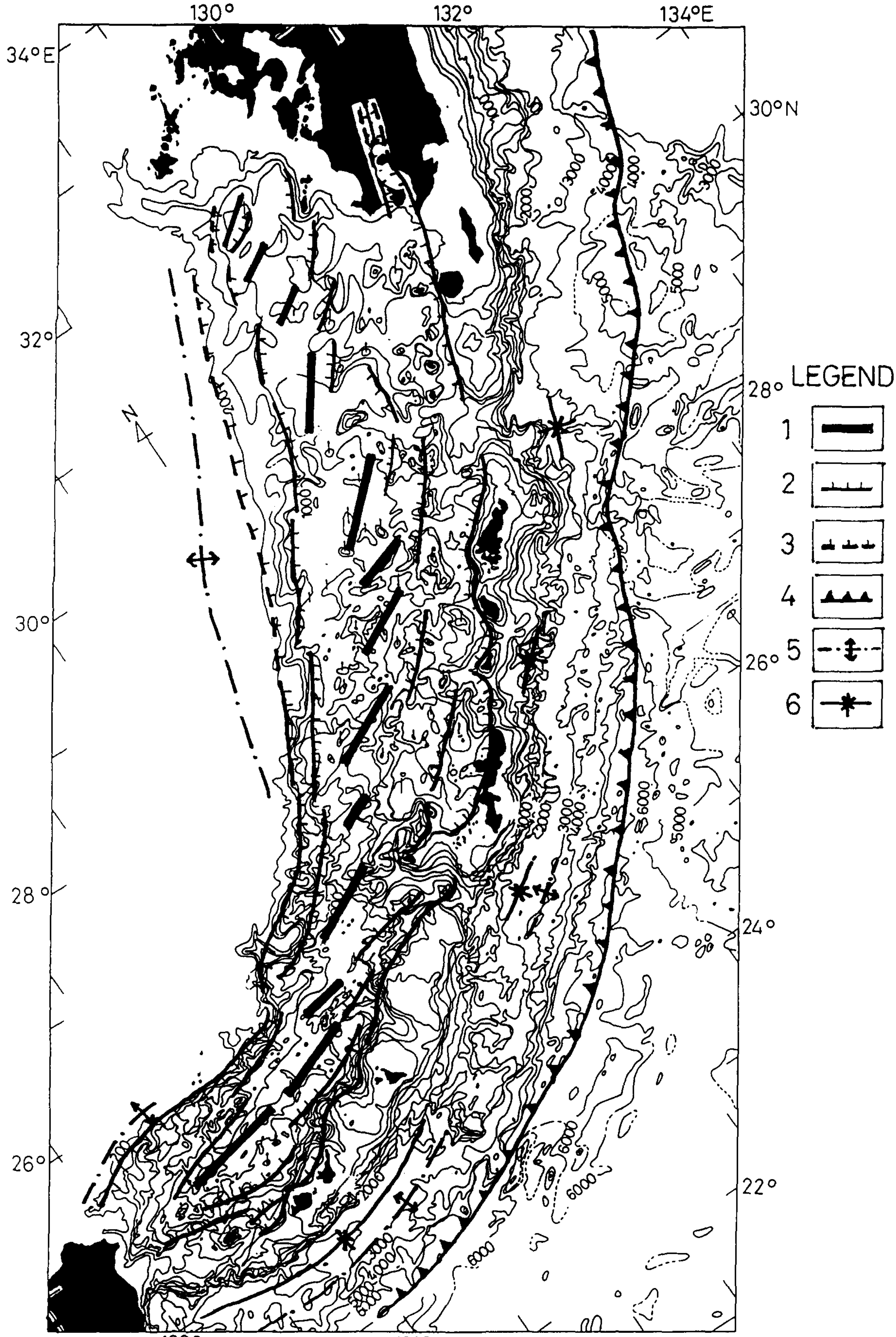

Figure 9 Major Pleistocene fault and rift systems related to the formation of the Okinawa Trough. Legend 1, Central Graben; 2, fault, hatching on the down thrown side; 3, buried fault; 4, trench; 5, anticline; 6, syncline

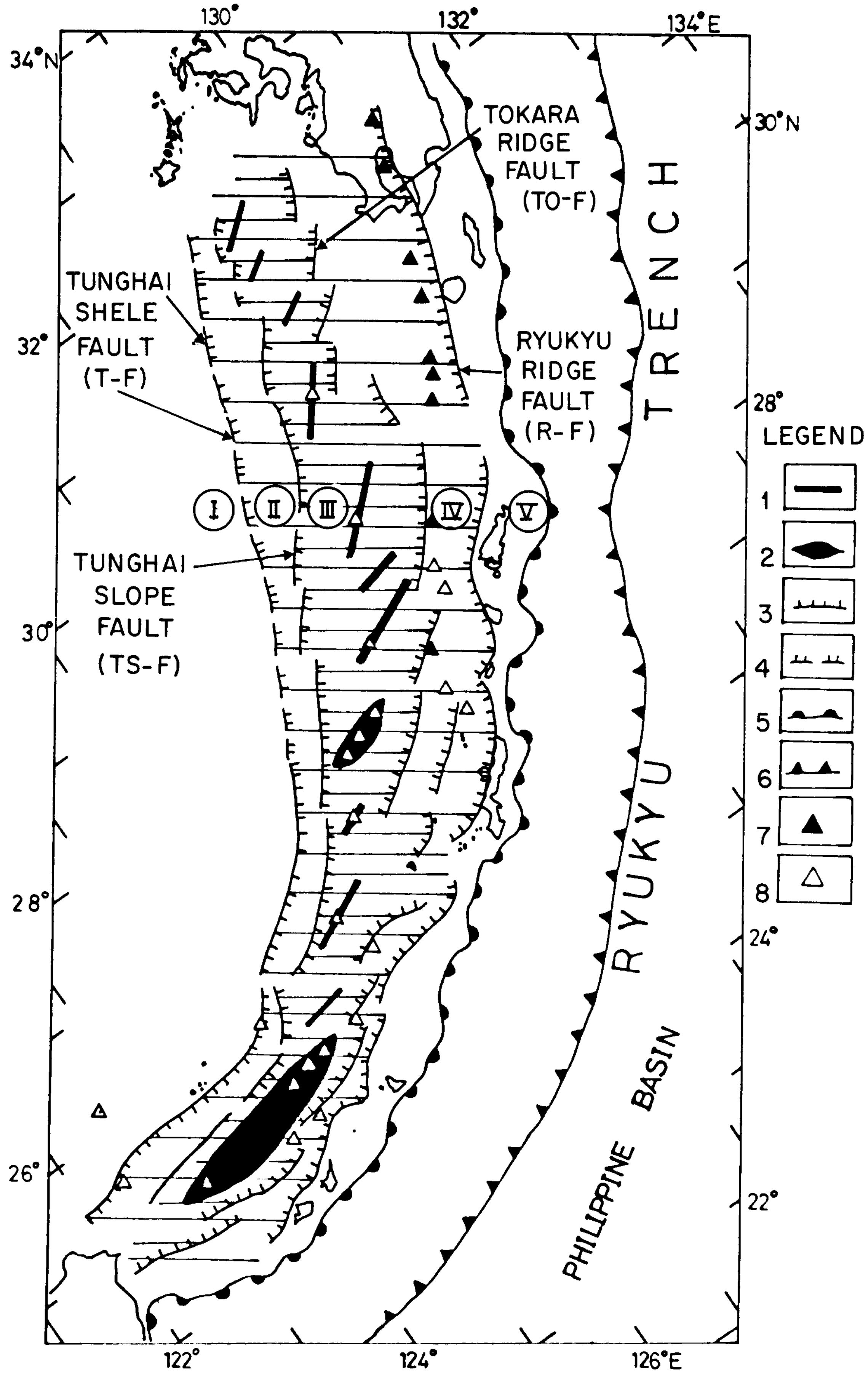

Figure 10 Pleistocene tectonic framework of the Okinawa Trough. Legend 1, Central Graben; 2, basin occupied by Pleistocene igeneous intrusions; 3, major fault and fault scarp; 4, buried major fault or fault scarp; 5, eastern boundary of the Ryukyu Ridge; 6, trench; 7, active volcanoes; 8, submarine intrusions or volcanoes estimated since Late Pleistocene time. Tectonic provinces can be distinguished by tectonomorphological similarities from the west to the east as: (I) Tunghai Shelf; (II) Tunghai Slope (western rifted margin); (III) Okinawa Trough; (IV) Tokara Ridge (eastern rifted margin); (V) Ryukyu Ridge

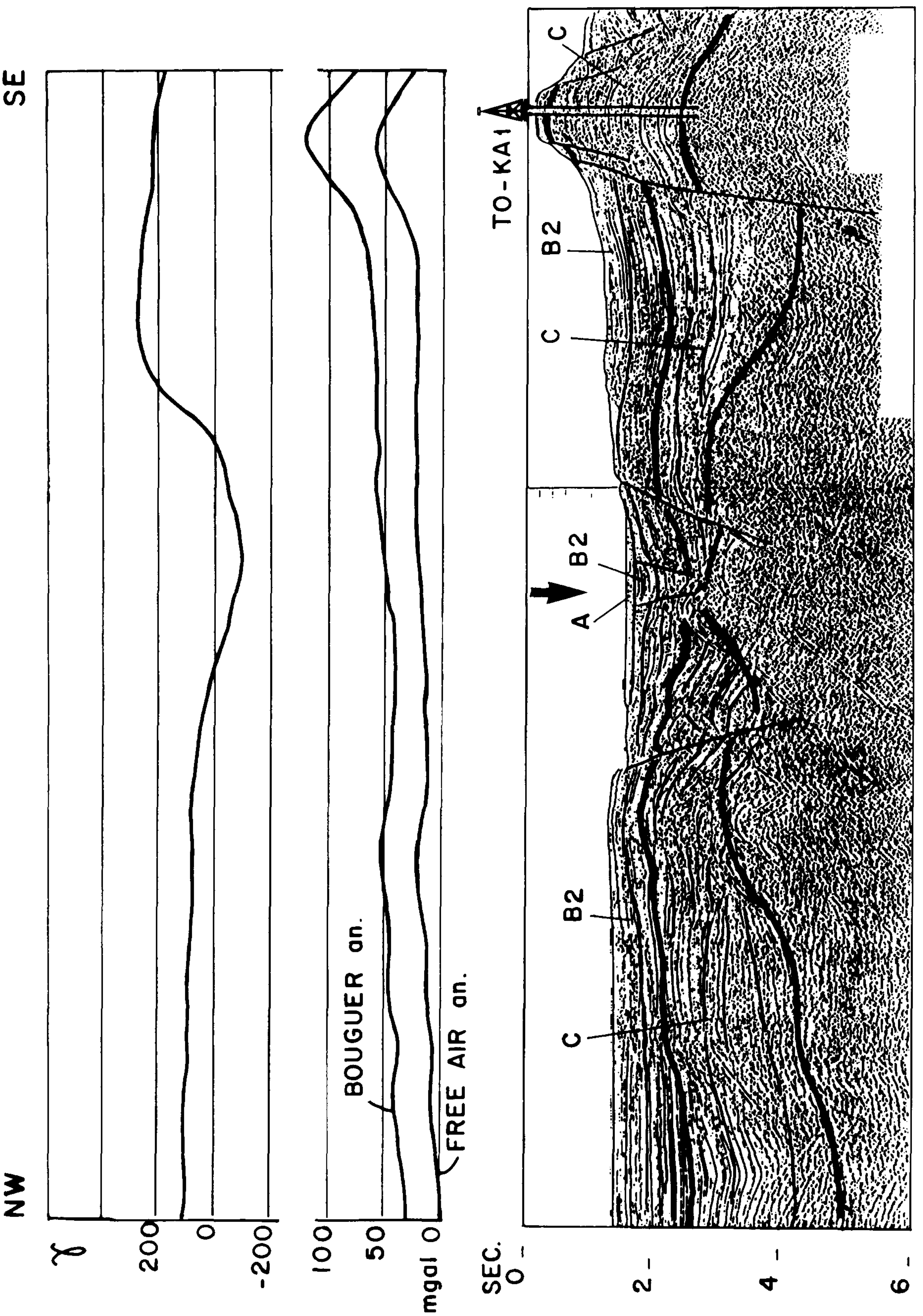

Figure 11 Multi-channel seismic reflection profile (A) crossing Yokogansone Bank. Location is shown in *Figure 2*. Layer C fills the northern part of the middle Okinawa Trough. Thick double bar shows the portion drilled by TO-KA-1 (*Figure 4*). The arrow represents the Central Graben. (γ) Magnetic anomaly, (mgal) gravity anomalies. Notation of strata are given in *Table 1*. 'Sec' represents two way travel time

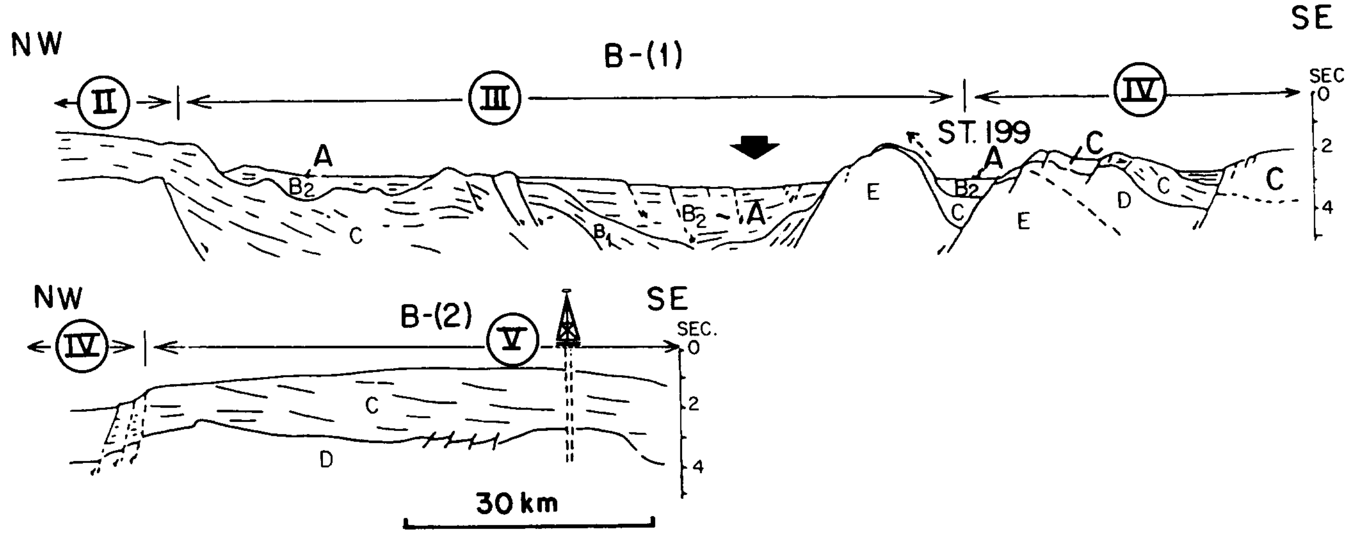

Figure 12 Interpreted cross-sections of the northern part of the southern Okinawa Trough based upon the multi-channel seismic reflection profiling records B-(1) and B-(2). Locations are shown in *Figure 2*. Tectonomorphologic division (I to V) are given in *Figure 10*. Notation of strata are given in *Table 1*. 'Sec' represents two way travel time

intra Layer B_2 and A/B unconformities occur only on the Ryukyu Ridge. The C/D unconformity is of Late Miocene age in the Ryukyu Ridge. It is found not only in the Tokara Ridge but also in the arc-trench gap, and the Tunghai Shelf. The unconformity estimated to be of Middle to Late Miocene age occurs well beyond the immediate Okinawa Trough region (Ishiwada, 1981). The unconformity proposed by Herman *et al.* (1978) in the southern Okinawa Trough in III zone is not found. However, it may correspond to the boundary reflector between Layers B_2 and B_1 which are conformable.

Discussion

The crustal structure of the Okinawa Trough based upon seismic refraction data is shown in *Figure 13*. Six units are denoted as U 1, U 2, U 3, U 3′, U 4 and U 5 in the Okinawa Trough and in the areas surrounding the Okinawa Trough. Strict correlations between seismic reflection and refraction profiles are difficult to make but the following correlations are suggested: U 1 (1.7–3.2 km s^{-1}) may be mainly composed of Late Miocene to Recent semiconsolidated and unconsolidated sediments (Layer A + B + C); U 2 (3.5–4.4 km s^{-1}) may correlate with the Tertiary consolidated to semiconsolidated sedimentary rocks (Layer C, D and E); U 3 (4.5–6.2 km s^{-1}) with pre-Tertiary layers (Layer E and granitic or metamorphic continental layer); U 4 (6.4–6.9 km s^{-1}) with gabbroic rocks; and U 5 (8.2 km s^{-1}) with the mantle.

Lee *et al.* (1980) stated that the 5.5 km s^{-1} layer at St. 31-32 (*Figure 4*) is correlative with relatively young basalt emplaced in conjunction with the extensional tectonics. This is deduced from the existing evidence of linear magnetic anomalies and of the relatively fresh pillow basalt dredged from a piercement (V 3 in *Figure 4*) in one of the Central Graben. The seismic reflection records often show igneous bodies intruding Layer B in the Central Graben in the southern Okinawa Trough. This interpretation is also supported by gravity data which suggests that the basaltic layer is shallow in this region (Ishihara and Murakami, 1976). Lee *et al.* (1980) stated that the velocity of 4.8 km s^{-1} observed at the uppermost part of U 3′ in the southern Okinawa Trough (*Figure 13B*) is primarily Miocene rocks. This velocity in my view is too high to represent sedimentary rocks in this area. Late Miocene andesitic pyroclastics and lavas were drilled from the layer showing a velocity of 4.6 km s^{-1} at TO-KA-1 (Nash, 1979b) in the trough (*Figure 4*). Therefore, the 4.8 km s^{-1} layer is regarded as igneous rock and U 3′ in *Figure 14B* is defined to include the whole 4.7–6.0 km s^{-1} layer, showing intermediate to basaltic transitional velocities. The crustal cross-section compiled from the seismic refraction data (*Figure 13B*) shows that the transitional velocity layer thus defined exists beneath most of the width of the southern Okinawa Trough. As a result, sedimentary layers of mostly Layer B and its younger layers are thought to make direct contact with shallow basalt in the southern Okinawa Trough basin. The crustal structure seems to be similar to that of the Mariana Trough which is a classic example of a back-arc basin (Karig, 1971).

In the Mariana Trough, the 4.5–5.4 km s^{-1} layer of average thickness 1 km is composed of volcanics, and is covered with surface sediments (2.0–3.0 km s^{-1}) (Bibee *et al.*, 1980). The southern Okinawa Trough profile (*Figure 13B*) also shows that the high velocity layer of 4.7–5.8 km s^{-1} (U 3′) is covered with a low velocity layer of 1.8–3.0 km s^{-1} (U 1) without the intermediate velocity layer of U 2 found in the northern Okinawa Trough. In addition to this evidence, the central basin of the southern Okinawa Trough lacks U 2 (3.5–4.4 km s^{-1}). The northern Middle Okinawa Trough well data (TO-KA-1) shows that the Okinawa Trough is filled by the Late Miocene to Early Pleistocene Shimajiri Group and its younger sediments (*Figure 11*). Multi-channel reflection profiling data show the seismic interval velocity of Layer C at TO-KA-1 as 3.5 km s^{-1} (Nash, 1979b). Therefore, U 2 in *Figure 13A* in the northern Okinawa Trough is thought to include the Shimajiri Group (Layer C) and its admixture with volcanics. This means that formations older than Layer B may be lacking beneath the southern Okinawa Trough basin.

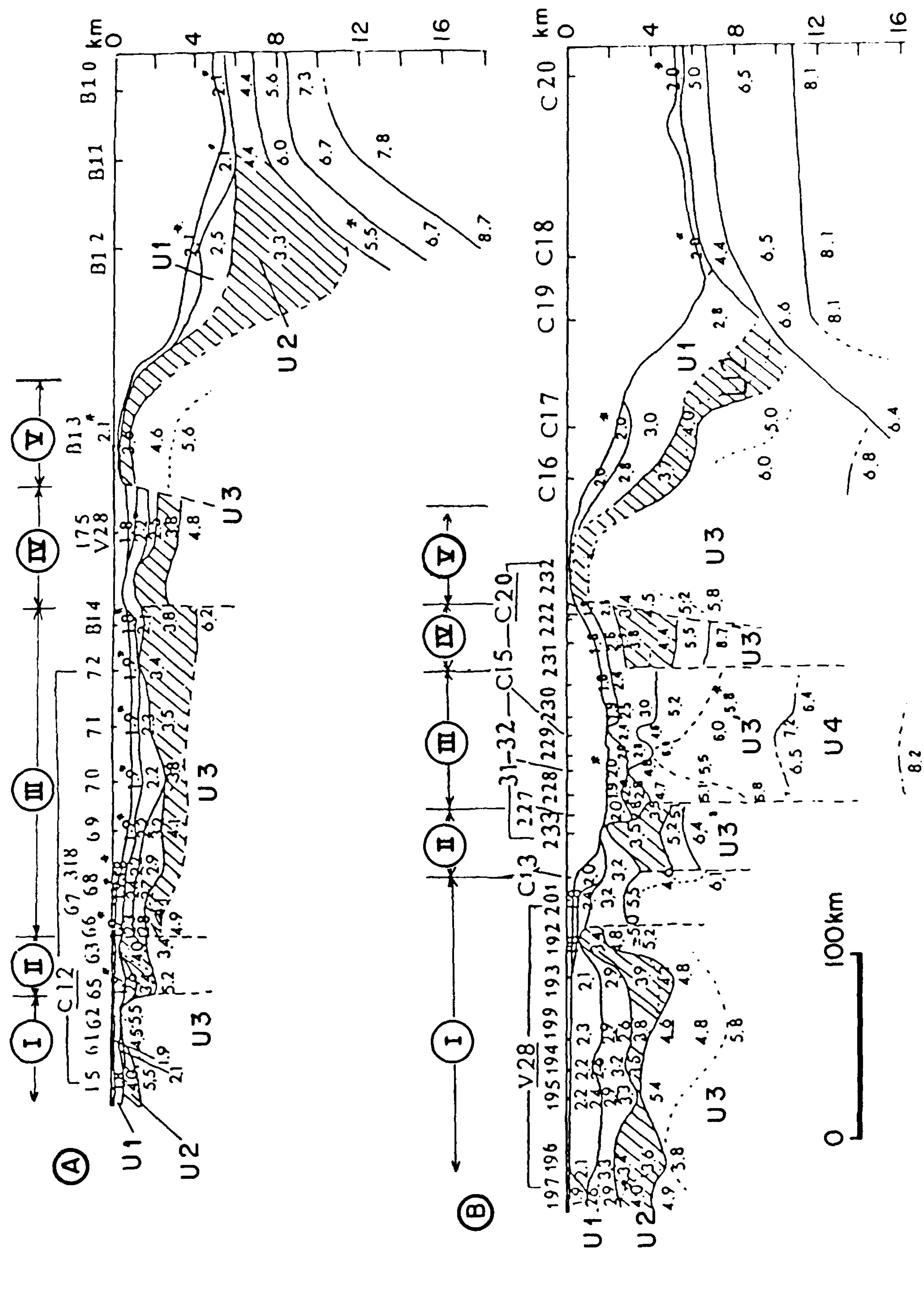

Figure 13 Crustal cross-sections compiled from sonobuoy and two-ship refraction data. Numerals in crustal sections represent the crustal sonic velocity (km s^{-1}). Locations are shown in *Figure 4*. Tectonomorphologic divisions (I to V) are shown in *Figure 11*. (A) Northern Okinawa Trough area, (B) Southern Okinawa Trough area. St 31-32 are based upon data by Lee *et al.* (1980)

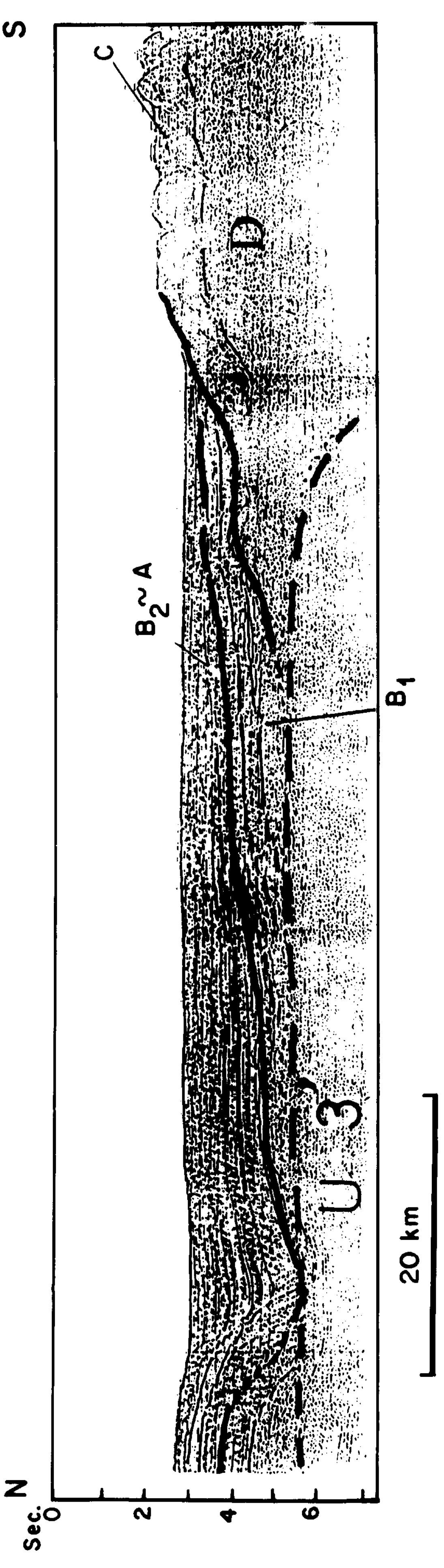

Figure 14 Multi-channel seismic reflection profile (C) in the southern Okinawa Trough basin showing the spreading of the basin. Location is shown in *Figure 2*. Notation of strata are given in *Table 1* and *Figure 13*. Latest Pliocene to Early Pleistocene sediment B_1 pinches out towards the central axis of the trough. 'Sec' represents two way travel time

Sedimentary Layer B in the southern Okinawa Trough basin can be divided into two parts; the upper (B_2) and the lower (B_1) sequence. Though Layer B_1 pinches out towards the central axis of the trough (*Figure 14*), Layer B_2 conformably overlies Layer B_1 and is seen to be slightly offset by normal faults at the Central Graben. This suggests that the spreading of the trough may have occurred during the deposition of Layer B_1 in the basin (*Figure 15*) and that the spreading became very slow or stopped during the deposition of B_2 and later sediments. This evolution explains the lack of Layer C in the southern Okinawa Trough basin. Correlation between the seismic reflection record and seismic refraction result leads to the interpretation that the Early Pleistocene layer (Layer B_1) is in contact with basalt formed by young spreading produced basalt; strongly suggesting that spreading has occurred since about 2 Ma (*Table 1*). In the southern Okinawa Trough linear magnetic anomalies have been found by Lee *et al.* (1980). Our data seem to show that the magnetic anomaly pattern of L 2 in *Figures 8* and *16* correlates with the magnetic reversal time scale since 1.9 Ma (Kimura *et al.*, 1985). However, other magnetic profiles in the southern Okinawa Trough in *Figure 16* (L 3, L 6, L 7, L 8 and L 1) lack the peak corresponding to the Brunhes Normal Epoch except L 9. Therefore, it may be suggested that the central parts of the southern Okinawa Trough spread from the Oldvai Event to just before the Brunhes Epoch, and spreading has restarted in the Brunhes Epoch only at the northern and southern most part of the southern Okinawa Trough (*Figure 16*). This is in the right relation to mode of sedimentation in Layers B_1 and B_2. Therefore, two main periods of extension are recognized.

Two groups of ages of volcanic rocks were obtained from the middle Okinawa Trough. One is a group of rhyolite and basalt which has been dredged from the seamount at St. 398 in *Figures 4* and *6*. The rhyolite has been dated as 0.79 ± 0.39 Ma (Shibata *et al.*, 1984). Another is that of dacite, andesite and basalt which are younger than 0.4 Ma (Kaneoka *et al.*, 1985) (St. S and D-6 in *Figure 4*). Taken together, this geological evidence shows two main periods of extrusion of magmas such as one between 1.9 and 0.8 Ma and another since 0.4 Ma. *Figure 17* shows magnetic profiles from this region projected to 340°, the perpendicular direction to the Central Grabens in the northern Okinawa Trough. These show that the otherwise generally narrow sharp central anomaly is superimposed on low amplitude anomaly profiles. This axial anomaly coincides with the most recent igneous intrusion (olivine basalt) (St. D-1 and D-6 in *Figure 4*). The Central Graben could coincide with a central magnetic anomaly of a normal event (*Figure 17*).

Herman et al. (1976) considered that back-arc spreading in the Okinawa Trough initiated sometime after Late Miocene–Early Pliocene time (during the deposition of their Unit B), and that the Ryukyu Arc was rifted from the continental margin. They concluded that the rate of spreading in the southern Okinawa Trough changed to only a few mm yr^{-1} at the time corresponding to their unconformity between their Units A and B, because Unit B is deformed and was probably deposited in the basin before the major period of spreading ceased. In contrast, Unit A is not deformed except in the Central Grabens. Though the

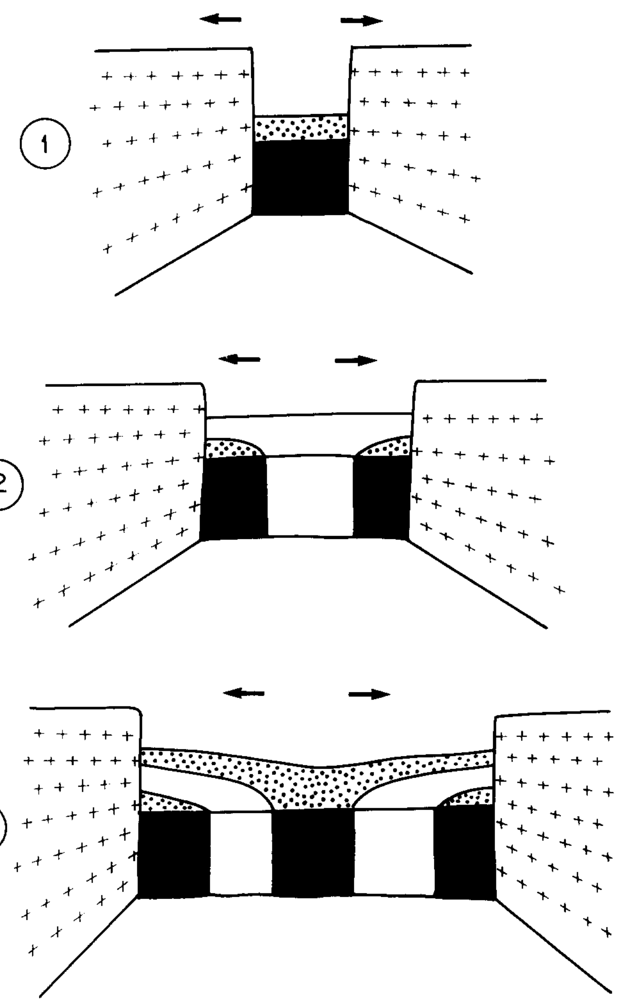

Figure 15 Model showing relationship between sea-floor spreading and mode of sedimentation of Layer B_1. Black and white basement represents new crusts formed in the normal and reversal magnetic polarization time

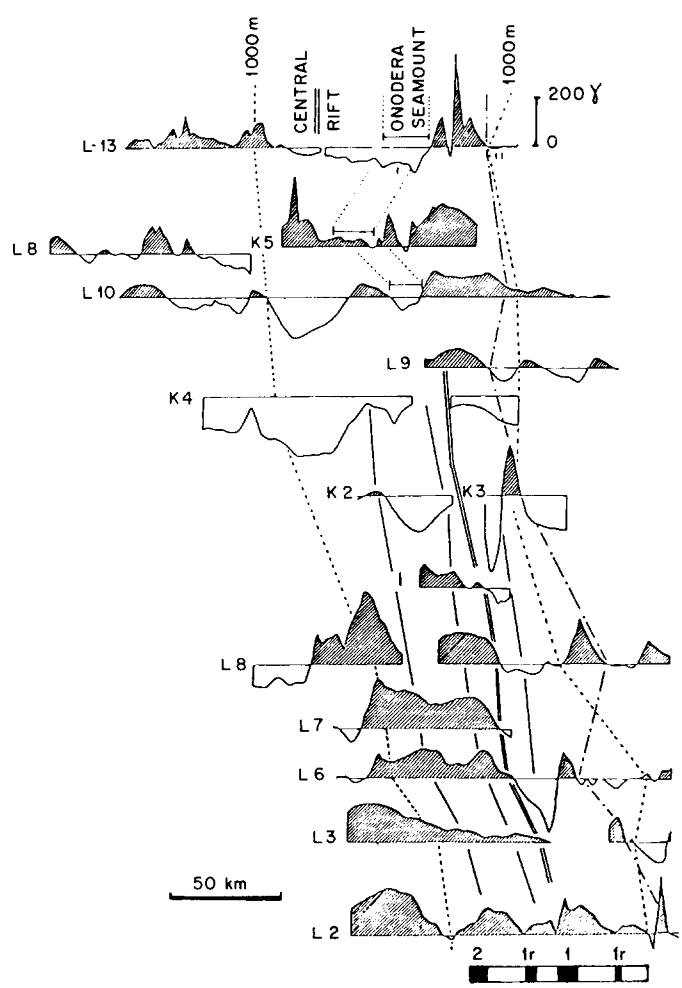

Figure 16 Correlation of magnetic anomaly profiles in the southern Okinawa Trough. Locations are shown in *Figure 3*. The bottom side shows geomagnetic reversal time scale correlated by Kimura *et al.* (1985). 1, Brunhes; 1r, Jaramillo; 2, Olduvai Normal Event

boundary separating their Unit A from Unit B cannot be regarded as an angular unconformity in the present study, their conclusion is the same as that of this paper if their Unit B correlates with Layer B_1. Herman *et al.* (1978) stated that the spreading speed slowed before the deposition of Unit A (Layers B_2 and A in the present paper). However, the sedimentary structure of Layer B_2 shows that the spreading practically ceased during the deposition of Layer B_2. It seems that the activity reforming the Central Graben started in Late Pleistocene. Lee *et al.* (1980) concluded that crustal separation (spreading) started in Pliocene time and has continued to the present; they considered that the trough basin is filled by Pliocene to Recent sediments, and that the Central Grabens offset those sediments. In my view, the axial zone of the southern Okinawa Trough, at least 40 km wide, lacks the 3.5 km s^{-1} layer (U 2, including Pliocene Shimajiri Group, Layer C) and Layer B_1 is regarded to cover the young basaltic layer directly as stated previously. On this basis, it would seem that crustal separation in the axial zone has been occurring only since 1.9 Ma. Average half spreading rate is estimated as about 2 cm yr^{-1}.

Tectonic development

The regional tectonic development has been discussed by Letouzey and Kimura (1985). Therefore, this discussion is focused only on the development of the Okinawa Trough, referring to *Table 1*. The first erosional crustal thinning may have been occurring since at least Oligocene time. A large Oligocene regional unconformity is known in the area surrounding the present Okinawa Trough (*Table 1;* Ishiwada, 1981). It is likely that doming of the crust occurred as a result of uprising of the basaltic layer during Oligocene time, which caused the older sediments to be severely eroded, thereby producing the D/E unconformity. At this time, in contrast, thick sediments were deposited in the old Ryukyu Trench (Kimura, 1983). Due to the early extensional movement normal faulting may have developed in the upper part of the crust, and grabens may have formed in Early Miocene time. Then; sandstone and minor mudstone (Yaeyama and Sasebo Groups; Matsumoto, 1979) were deposited in these grabens and dacitic to andesitic Neogene igneous activity (so-called Green Tuff activity) occurred. The graben might have included at least a part of the eastern margin of the Taiwan-Sinzi folded zone (Emery *et al.*, 1969; Wageman *et al.*, 1970) on the Tunghai Shelf to the Ryukyu Ridge. After the deposition of Layer D, the crust was uplifted again to create the widespread C/D unconformity of Middle to Late Miocene time, possibly due to magmatic supply beneath the crust. Then Layer C was deposited, over-

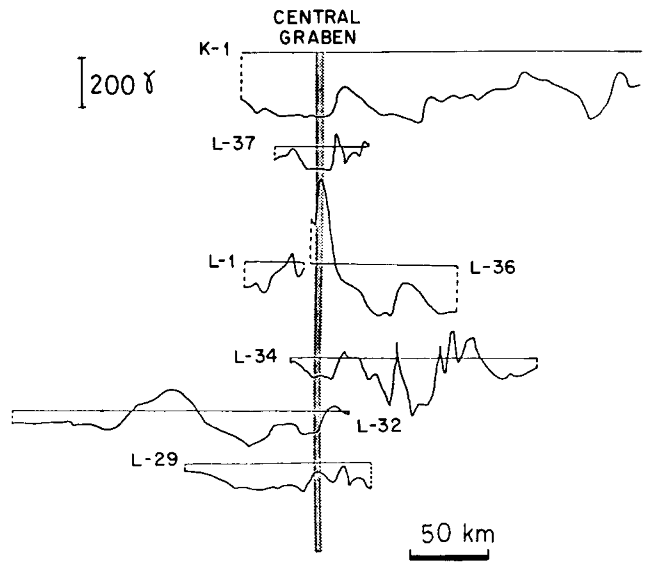

Figure 17 Correlation of magnetic anomaly profiles in the northern Okinawa Trough (Kimura *et al.*, 1985). Locations are shown in *Figure 3*

lying the widespread C/D unconformity. At the end of the deposition of Layer C, in Late Pliocene to Early Pleistocene time, the crust was again uplifted, and continental, crustal rifting may have started. At that time, areas surrounding the trough were uplifted and shallow facies sediments were deposited in the surrounding areas of the Okinawa Trough. During Late Pliocene and Early Pleistocene time, while Layer B_1 was being deposited in the trough basin and before the deposition of Layer B_2, spreading may have occurred in the southern Okinawa Trough and major faults that define the Greater Okinawa Trough progressively developed and rifted crustal blocks tilted against the axis of the trough. Then spreading stopped and Layer B_2 was deposited conformably or partly unconformably in the trough. During this stable period, the top of the Ryukyu Ridge was truncated by marine erosion and coral reefs were extensively developed to form the Ryukyu Limestone on the isolated Ryukyu Ridge.

During Middle to Late Pleistocene time, another uplift of the Ryukyu Ridge occurred and the unconformity was formed in the Ryukyu Group (*Table 1*). At this time spreading started again but only in the northern half and in some parts of the southern Okinawa Trough. This is suggested by the fact that the Central Grabens offset Layer B_2 (*Figure 7*) and volcanics younger than 0.4 Ma intrude Layer B_2 in many parts of the Central Grabens as shown in *Figures 8* and *10*. Since the start of the Late Pleistocene spreading, shallow water foraminiferal sandstones and reefal limestone were formed on the Ryukyu Ridge. Subsequently, the newest faults offsetting Layer B_2 in the trough basins and in the Ryukyu Ridge were formed.

This history shows two main periods of extension such as a Pleistocene phase between 2 and 0.5 Ma and the present day phase, and that the position of the uplifted centre of the Ryukyu Arc region before the formation of the Okinawa Trough was not on the Ryukyu Ridge but rather on the present back-arc Okinawa Trough. The Tokara Ridge and the Tunghai Slope regions are regarded as the flanks of the previously uplifted axial zone. The Quaternary island arc activity is located in the back-arc rift zone.

Conclusions

Stratigraphy of sediments, magnetic anomalies and the crustal structure of the Okinawa Trough show that the crustal separation started about 1.9 Ma and continued intermittently to Recent time in the southern Okinawa Trough. The width of the spreading was less than several tens of kilometres and the average half spreading rate was about 2 cm yr^{-1} in the southern Okinawa Trough. New spreading or rifting occurred from 0.4 Ma to Recent time. Magmatic intrusions occurred in many parts along the Central Grabens in the whole Okinawa Trough. The Okinawa Trough is thought to be floored by a thinned and subsided continental crust except for the southern part, and then only rifting is seen on the surface of the northern most Okinawa Trough.

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