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OKINAWA TROUGH: ORIGIN OF A BACK-ARC BASIN*

CHAO-SHING LEE[1]**, GEORGE G. SHOR, Jr.[1], L.D. BIBEE[1]***, RICHARD S. LU[2,†] and THOMAS W.C. HILDE[3]

[1] *University of California, San Diego—Marine Physical Laboratory of the Scripps Institution of Oceanography, La Jolla, Ca. 92093 (U.S.A.)*
[2] *Institute of Oceanography, National Taiwan University, Taipei (Taiwan)*
[3] *Departments of Oceanography and Geophysics, Texas A and M University, College Station, Texas 77843 (U.S.A.)*

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ABSTRACT

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The sequence of back-arc basin development in the southwestern part of Okinawa Trough has apparently been crustal thinning, involving normal faulting and fault block rotation, rifting, and crustal separation with associated magmatic intrusion. Seismic-refraction data shows a mantle depth of about 15 km beneath the central rift of Okinawa Trough while gravity data suggests that the crust thickens away from the central region of Okinawa Trough towards both the Ryukyu Arc and the continental shelf. Seismic-reflection profiles across Okinawa Trough reveal a generally continuous, undisturbed upper sediment section beneath the trough floor, unconformably overlying a highly faulted lower section which has a velocity of 4.9 km/sec. Exceptions to this structural relationship are fault grabens cutting the upper section along the axial and southeastern regions of the trough and normal faults at the extreme margins of the trough. Correlation of similar structural relationships on Taiwan suggests that extension produced normal faults in the lower section during Miocene time creating the initial expression of Okinawa Trough, and that the unconformity between the upper and lower sections is of Miocene age. Linear magnetic anomalies and high-velocity crustal rocks associated with the central trough region are interpreted as due to Pliocene to Recent magmatic intrusion associated with crustal separation. Offsets in the magnetic lineations indicate that the crust is separating along a series of short spreading centers and transform offsets.

INTRODUCTION

Okinawa Trough, also known as the Nansei-Shoto Trough, is the back-arc basin of the Ryukyu trench—arc—back-arc system. It is bounded by the Ryukyu Ridge and Trench to the south and east, and by the East China Sea

*Contribution of the Scripps Institution of Oceanography, new series.
**Now at: Texas A and M University, Department of Oceanography, College Station, Texas (U.S.A.).
***Now at: Oregon State University, Department of Oceanography, Corvallis, Ore. (U.S.A.).
†Now at: University of Texas. Marine Science Institute, Galveston, Texas (U.S.A.).

Shelf to the north and west. The entire complex is arcuate, convex toward the Pacific, from Japan to Taiwan (Fig.1). Topographic features of the region have been mapped by several early investigators (Hess, 1948; Tayama, 1952; and others) and more recently, in greater detail by Mammerickx et al. (1976). Compared with other young or active back-arc basins, such as Mariana Trough or Lau-Havre Trough, Okinawa Trough is considerably shallower; the deepest part, near Taiwan, being only 2270 m deep. It shoals gradually northeastward toward Japan, has a generally flat floor, and is underlain by about 1—2 km of sediment (0.8—2.2 sec two-way travel-time). Okinawa Trough apparently is a depositional basin with a relatively high rate of sedimentation of primarily terrigenous sediment from the continental shelf and island arc.

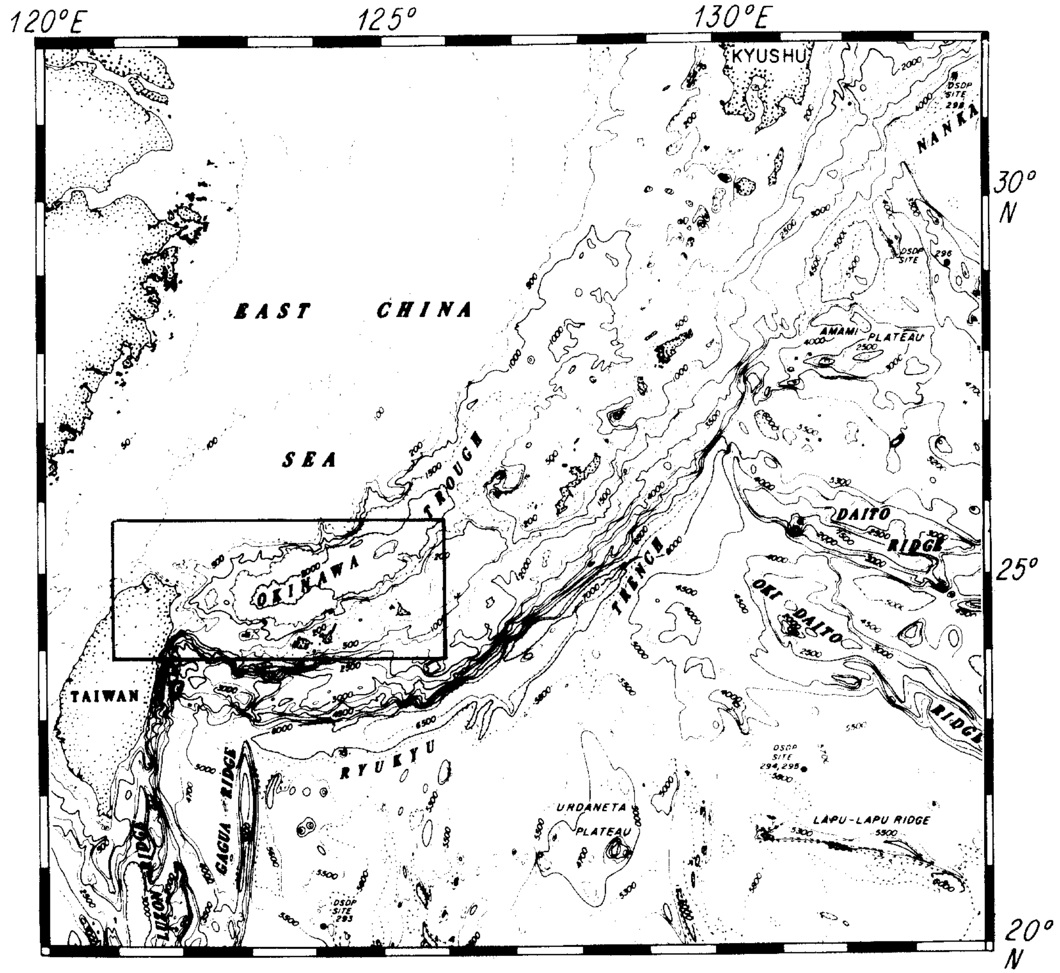


Fig.1. Bathymetry of Okinawa Trough and vicinity. (From Mammerickx et al., 1976.) The study area is outlined with a rectangle. Depths are in uncorrected meters.

High seismicity is associated with the length of Okinawa Trough and the Ryukyu Arc and Trench (Barazangi and Dorman, 1969). Katsumata and Sykes (1969) demonstrated that the seismic activity is concentrated along a northwestward-dipping plane extending from the region of the Ryukyu Trench beneath the Ryukyu Arc and Okinawa Trough to a depth of between 200 and 300 km beneath the continental shelf. These studies, and compilations of more recent events for the region (National Earthquake Information Centre, 1970), also show that a zone of shallow seismicity (0—70 km) is associated with Okinawa Trough. A regional seismic-reflection survey carried out in 1968 by Wageman et al. (1970) established the structural relationship of the Ryukyu Arc, Okinawa Trough and East China Sea, and showed that Okinawa Trough was of fault origin. They found that the margins of the trough were cut by normal faults, were underlain by complex folds and exhibited extensive slumping. Seismic-refraction studies by Murauchi et al. (1968) indicated that the crustal velocity beneath the Okinawa Trough is generally similar to that of continental crust. Mean heat flow in Okinawa Trough was found to be 2.97 ± 1.51 HFU (124.4 ± 63.2 mW/m^2) by Lee and Uyeda (1965), and a large spread of values, 0.36—5.68 HFU (15.1—237.8 mW/m^2), was reported by Yasui et al. (1970). They interpreted the high average heat flow as due to radioactivity in the continental crust and the extreme high values as due to the presence of recent, shallow igneous intrusions. Karig (1971, 1973) further suggested that the Okinawa Trough is a marginal basin, transitional between active and inactive, formed by crustal extension behind the Ryukyu Island Arc.

Wang and Hilde (1973) studied the magnetic anomalies in the trough and concluded that linear high-amplitude zones were due to Quaternary intrusions associated with formational processes. Bowin and Reynolds (1975) noted that radiometric ages from the Ryukyu Island Arc fall into three groups: 194—175 m.y. (metamorphic rocks), 63—49 m.y. (igneous), and 21—12 m.y. (igneous). They suggested that the Okinawa Trough developed within the last 12 m.y. Based on seismic-reflection profiles and their correlations with the small basins in Kyushu, Takahashi (1975) stated the Okinawa Trough opened during the Pliocene. Classic grabens were delineated by Herman et al. (1978) in their seismic-reflection profiles of the southwestern Okinawa Trough. Based on evidence for active faulting in the grabens, the distribution of unconformable sediments and studies of dredged rocks, they concluded that the southwestern Okinawa Trough was formed by back-arc spreading since Miocene time and that extension is presently confined to a <15 km wide zone defined by two grabens. Additional seismic-reflection studies (Honza, 1976) indicate active extensional faulting in the Okinawa Trough. From gravity data taken on the same cruise, Ishihara and Murakami (1976), concluded that the trough has a thin crust.

The southwestern end of Okinawa Trough shoals westward (Fig.2) where it terminates against the northeastern coast of Taiwan, adjacent to the Quaternary Ilan Plain. A micro-seismicity suvey in the Ilan Plain (Tsai et al., 1975) has delineated a zone of subsurface vertical faulting that extends into the

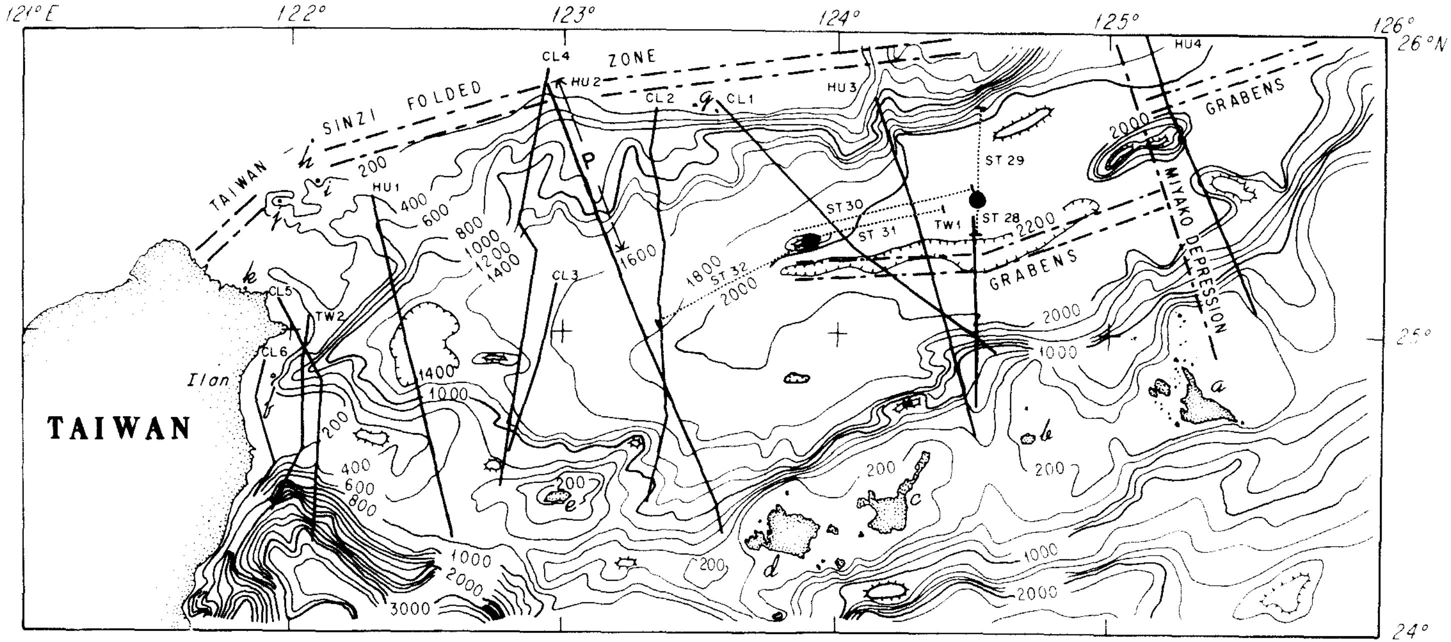


Fig.2. Bathymetry and locations of seismic-refraction station and seismic reflection profiles. Contours are based on bathymetric data of this study and on the previous compilation by Scripps Institution of Oceanography. (From Mammerickx et al., 1976.) The heavy solid lines represent the ship tracks of seismic reflection data (CL-R/V "Chiu-Lien"; TW-R/V "Thomas Washington"; HU-R/V "Hunt"). The dotted lines represent the locations of seismic refraction stations; Receiving ship positions are indicated by large dots. Name of the islands are as follows: *a* = Miyako-Jima; *b* = Tarama-Jima; *c* = Ishigaki-Jima; *d* = Iriomote-Jima; *e* = Yonakuni-Jima; *f* = Kuei-Shan Tac; *g* = Tiao-Yu Tai (Senkaku-Jima); *h* = Peng-Chia Yu; *i* = Men-Hua Yu; *j* = Hua-Ping Yu; *k* = Kee-Lung Tao.

Okinawa Trough. Volcanic ridges associated with this zone have been traced from near Taiwan into Okinawa Trough (Lee and Lu, 1976). Based on these and other data, Bowin et al. (1978) and Lu et al. (1977) have concluded that extensional opening of the Okinawa Trough continued into Taiwan, forming the Ilan Plain.

Numerous earlier studies of the Ryukyu Arc and Okinawa Trough region have emphasized the zonal distribution of rocks and structures (Koto, 1897; Hanzawa, 1935; Konishi, 1963; and many others). Hanzawa (1935) established the existence of Paleozoic rocks in the Ruykyu Islands, including glaucophane schist, greenschist, phyllite, Permian limestone and other rocks. Konishi (1965) and later others refined our knowledge of the geology and provided the early clues that rocks in the Ryukyus may have been rifted away from old geologic structures to the west and northwest.

NEW DATA

Work reported here, carried out by the R/V "Thomas Washington" and the R/V "Chiu-Lien" in 1976, has added magnetic observations to the existing data set, provided deep-refraction data along the center of the Okinawa Trough, and additional cross-structure reflection profiles. The new data are only a small portion of the whole; their most important function has been to provide some key pieces of information, permitting development of a coherent history of the Okinawa Trough. We have also utilized data collected by the Institute of Oceanography, National Taiwan University (R/V "Chiu-Lien" cruises from 1970 to 1975), the National Oceanographic and Atmospheric Administration (O.S.S. "Oceanographer" cruises, 1972) and the U.S. Naval Oceanographic Office (R/V "Hunt" cruises, 1968).

The 1976 R/V "Thomas Washington" and R/V "Chiu-Lien" surveys were part of an IPOD site survey cruise carried out as a joint U.S.—China cooperative project. Okinawa Trough was not a "prime site" for the drilling project, nor even one of the listed alternative sites. Time became available for this work only because weather problems forced us out of the "prime site" area. It is, however, an area where drilling could be employed to significantly improve our understanding of back-arc extensional basin formation above subduction zones at continental margins.

Magnetics

Magnetic anomalies were derived by subtracting the 1965.0 IGRF (International Geomagnetic Reference Field) from the observed total field measurements but were not corrected for diurnal variations. The anomaly profiles, plotted at right angles to the ship's tracks, are shown in Fig.3. Only the N—S profiles are shown in this figure (the geological structures in this area trend in a nearly E—W direction) to present the correlation of those structures more clearly. General characteristics of the magnetic anomalies in the Okinawa Trough are as follows:

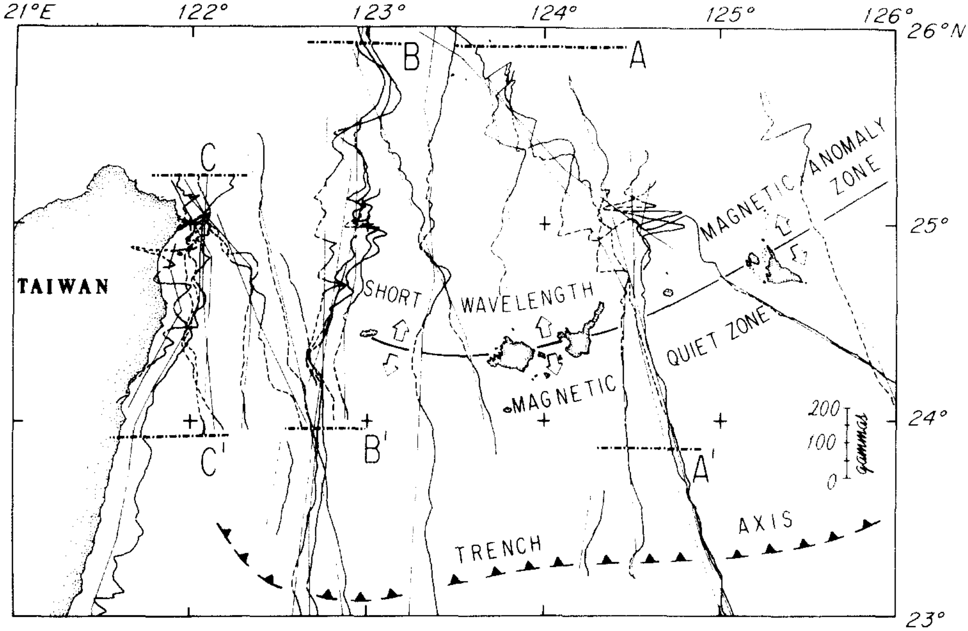


Fig.3. Magnetic anomalies in the southwestern Okinawa Trough and vicinity. Magnetic anomalies are plotted at right angles to the ship tracks. The heavy solid lines represent positive anomalies. The heavy dashed lines represent negative anomalies.

(1) Amplitudes of anomalies (peak to peak) are about 200—300 gammas, and their wavelengths range from 20 to 50 km. Compared with the magnetic anomalies over the Ryukyu Ridge and Ryukyu Trench, the trough is a zone of relatively short wavelength, high-amplitude magnetic anomalies. Along the trough, to the northeast, the amplitudes become lower and their wavelengths shorter (Miyazaki et al., 1976).

(2) Large magnetic anomalies along the edge of the Okinawa Trough are associated with the volcanic ridges.

(3) The positive anomalies on the edge of East China Sea Shelf correspond to the Taiwan-Sinzi Folded Zone (Wageman et al., 1970). The magnetic quiet zone (defined as the area where anomalies are less than 50 gammas) corresponds to the Ryukyu Ridge and Ryukyu Trench.

(4) The trend of magnetic anomalies in the Okinawa Trough is nearly parallel to the trend of the structural belts of the Ryukyu Island Arc. Based on magnetic data recorded during a short period of time, Wageman et al. (1970), Wang and Hilde (1973), and Lu and Kuo (1977) were able to contour the magnetic anomalies and show that they are linear: E—W in southwestern Okinawa Trough changing to NE—SW in the northeastern region of the trough.

Fig.4 shows the N—S profiles across the Okinawa Trough. The profiles are projected onto an azimuth of 165°, perpendicular to the bathymetric lineations. The short-wavelength magnetic anomalies are confined to Okinawa Trough. To the left, large positive anomalies (profiles B—B′) correspond to the Taiwan-Sinzi Folded Zone along the northwest of the trough. To the

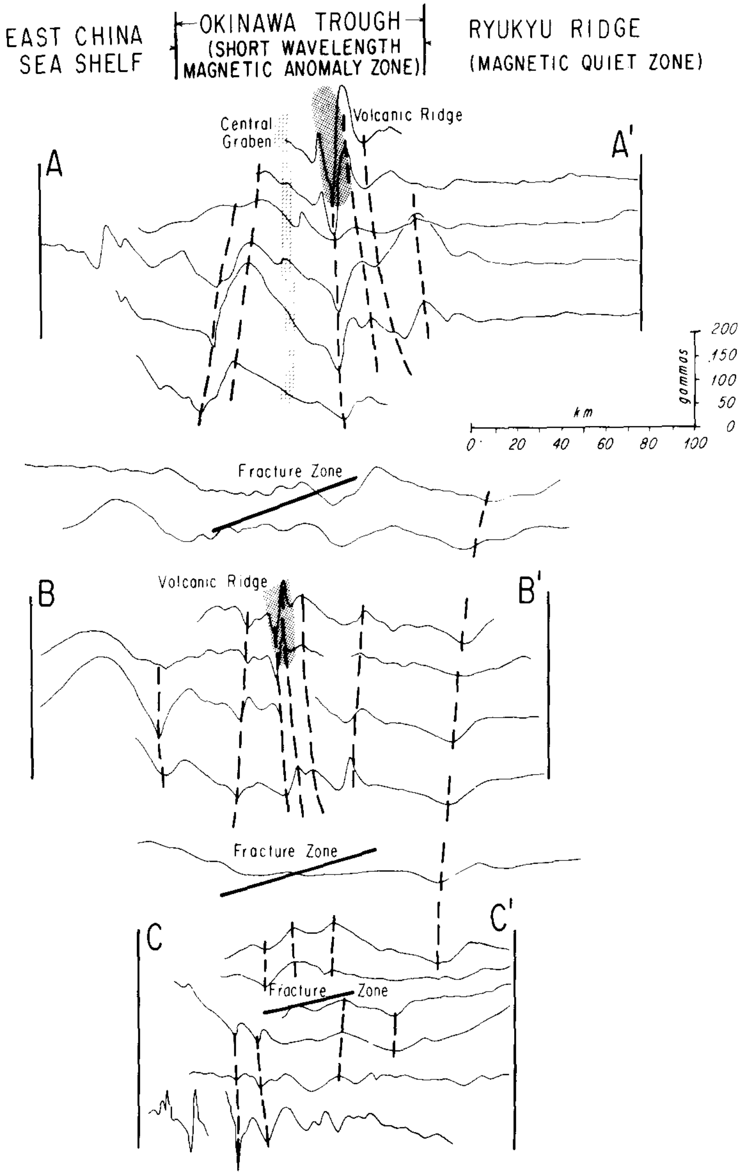


Fig.4. Magnetic anomaly profiles across the southwestern Okinawa Trough projected onto an azimuth 165°. The heavy dashed lines indicate the lineations. The heavy solid lines represent suspected transform faults. Location of profiles *A—A'*, *B—B'* and *C—C'* are shown in Fig.3.

right or southeast, low-amplitude, long-wavelength anomalies (profiles A—A' and B—B') correspond to the Ryukyu Ridge. Although our magnetic profiles are clustered in groups, the spacing between the lines in each group is sufficient and the character of the anomalies is similar enough to determine that magnetic lineations exist which parallel the topographic and structural trends.

The number of cycles of short-wavelength magnetic anomalies in the trough is too small (about 2—3 cycles) to give confidence in correlations with the geomagnetic reversal time scale. Nevertheless, the presence of these short-wavelength, linear magnetic anomalies suggests that linear intrusions have been emplaced in the Okinawa Trough and that these are reversal anomalies.

We have not contoured the anomalies because of gaps in our data distribution, the large diurnal variation (up to 60 gammas at the Lunping Magnetic Observatory, Taiwan) and the large secular variation (about 100 gammas). These variations complicate reduction of data that have been collected over an eight-year period. Lineations were established by matching profiles.

The lineations in Okinawa Trough are discontinuous and we have concluded that the pattern is offset by fracture zones or transform faults. Faults are observed in the seismic-reflection profiles in the areas where the lineations are offset which are not associated with the graben structures and that could be transform faults. Closely spaced seismic-reflection profiles will be required to establish their precise location and confirm their existence. However, like the magnetic features associated with the Miyako Depression to the northeast (Konishi, 1963; Wageman et al., 1970), generally broad low-amplitude anomalies are found where the magnetic lineations are offset (Fig.4). Based on focal-mechanism studies, Wu (1970) suggested NW—SE strike-slip fault motion along the Miyako Depression. This agrees with the idea of spreading centers offset by transform faults, as suggested by the magnetic data.

Heat-flow measurements made in the southwestern Okinawa Trough by T.C. Lee and R.S. Lu (pers. comm.) combined with former measurements confirm that high and low values are interspersed, as is commonly found close to spreading centers due to hydrothermal circulation in fractured rocks. Because of this, it is not possible to use variations in heat flow to confirm offsets of spreading centers on this small scale.

Seismic refraction

Five two-ship seismic-refraction lines were shot in the axial zone of the Okinawa Trough from the R/V "Thomas Washington" and R/V "Chiu-Lien" during the Sino-American cooperative program in 1976, using the methods described by Shor (1963). Locations of these lines are shown in Fig.2. Fig.5 shows the record sections obtained. Table I gives the calculated structure. Station 28 had excessive drift, and was too short to give useful results. Station 29 is a N—S run across the axial zone of the trough. The topographic variations along the run are small except for the last shot of Station 29 which was over the western side wall of the trough. The profile was computed by assuming horizontal layers, with the velocity in the first layer (sediment) assumed to be 2.0 km/sec. The 5.2-km/sec and 6.1-km/sec velocities are determined from first arrivals.

Stations 30 and 31 form a reversed pair, in a E—W direction along the axis of the trough. In each case, the receiving ship drifted about 5 km due to current. The 2.0-km/sec is assumed for the uppermost sediment layer. The

4.8, 6.0 and 6.7-km/sec layers are determined from reversed results, using the method described by Ewing (1963), with reverse times required to agree.

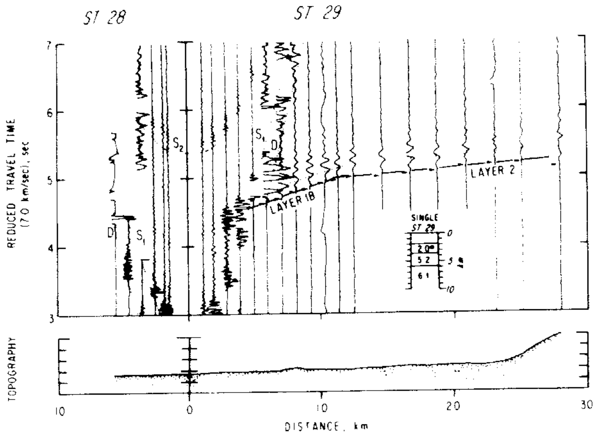
Stations 31 and 32 form a long split pair, subparallel to the axial zone of the trough. The topography is reasonably smooth except for a hill beneath the first few shots of station 32. The uppermost sediment layer is assumed to be 2.0 km/sec. The 4.8, 5.5, 6.3 and 8.2-km/sec layers are for a solution as a split, by Ewing's method, with intercept times required to agree.

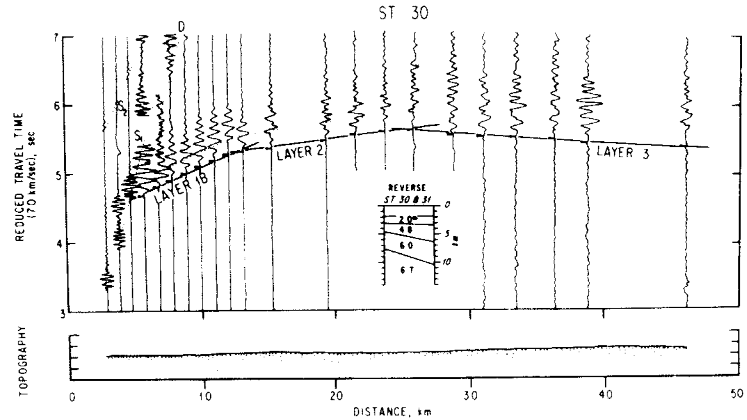
The first seismic-refraction survey in the Okinawa Trough was done by Murauchi et al. (1968). Their results indicated the foundation of the trough and the continental shelf consisted of layers with velocity 4.6 km/sec, 6.0 km/sec, and 7.2 km/sec. They found a fairly thick crustal layer, about 9—10 km in the upper crustal section, similar to that of continental crust, but did not measure total crustal thickness. Ludwig et al. (1973) shot a line across the northeastern side of the Okinawa Trough. Their results generally agree with the results by Murauchi et al. (1968). They further reported the 3.4—4.1-km/sec layer as the acoustic basement which is expressed topographically by peaks and hills in the otherwise flat sea floor (Wageman et al., 1970). Beneath this layer are rocks with velocities of 4.9—6.2 km/sec associated with a NE—SW trending ridge between Japan and Taiwan. This ridge, called the Taiwan-Sinzi Folded Zone (Fig.2), has been described by Wageman et al. (1970) as a ridge of folded and faulted sedimentary rock and associated intrusions. Leyden et al. (1973) attempted to determine the velocity—age relationship in this region. They used sonobuoy refraction results to correlate offshore structures with the stratigraphic sequences on Taiwan where there is fairly good control from drill holes (Huang, 1968), land refraction lines (Sato et al., 1970), magnetics (Bosum et al., 1970) and gravity data (Hsieh and Hu, 1972). These correlations are especially applicable to our study, since there are no published deep drill holes in the Okinawa Trough.

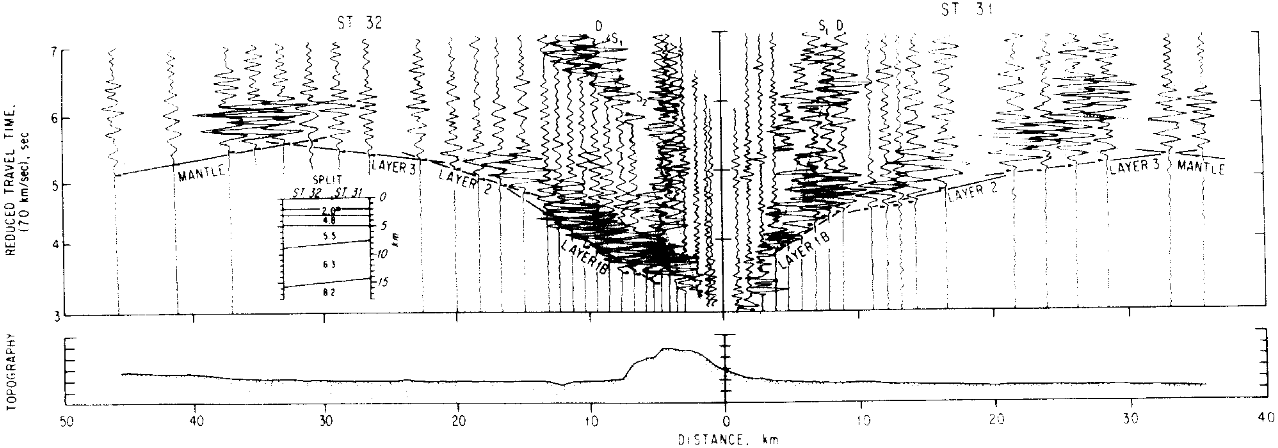
Fig.6 shows the combined results of our refraction stations in the Okinawa Trough and the previous work by Murauchi et al. (1968), Ludwig et al. (1973) and Leyden et al. (1973). The correlation by Leyden et al. (1973) of refraction data offshore with drilling data (Huang, 1968) and refraction results (Sato et al., 1970) on Taiwan is extended to the data in the Okinawa Trough. This interpretation assumes continuity of the refraction horizons, and that the major source of sediment is from the mainland; it is only feasible because of the presence of an unconformity visible in the reflection profiles (see Figs.7—10) separating the high-velocity older sediments from the overlying low-velocity sediments.

Seismic reflection

Seismic-reflection profiles across Okinawa Trough (Figs.7—9) show flat-lying sediment thickening toward the center of the trough beneath which is a rough surface with local evidence of volcanic intrusions and extrusions. Profiles published by Wageman et al. (1970), Honza (1976) and Herman et al. (1978) also show these features. Complex folds and faults are observed around


ST 28
ST 29
REDUCED TRAVEL TIME (7.0 km/sec), sec
TOPOGRAPHY
DISTANCE, km
LAYER 1B
LAYER 2
SINGLE
ST 29
2.0
5.2
6.1
km
D
S_1
S_2


ST 30
REDUCED TRAVEL TIME (7.0 km/sec), sec
TOPOGRAPHY
DISTANCE, km
LAYER 1B
LAYER 2
LAYER 3
REVERSE
ST 30 & 31
2.0
4.8
6.0
6.7
km
D
S_2


ST 32
ST 31
REDUCED TRAVEL TIME, (7.0 km/sec), sec
TOPOGRAPHY
DISTANCE, km
MANTLE
LAYER 3
LAYER 2
LAYER 1B
SPLIT
ST 32 ST 31
2.0
4.8
5.5
6.3
8.2
km
D
S_1
S_2

the volcanic features (such as in profiles CL3 and CL4, Fig.7) and they are generally concentrated on the southeastern margin of the trough (the right side of the profiles in Figs.7 and 8). Herman et al. (1978) interpreted basement ridges within the trough as pre-rift structures stranded within the trough during rifting on the basis of quartz-diorite and metamorphosed pillow basalt dredged from one of these features (Honza, 1976). Several of these features may be exposures of individual fault blocks from the early phase of faulting and extension. However, earlier studies (Saito et al., 1960; Flint et al., 1959) reported Quaternary volcanism along the southeast margin of Okinawa Trough and we concur with the interpretation of Wageman et al. (1970) that a ridge or zone of volcanism extends along the southeastern margin of Okinawa Trough. Recent intrusion is also evident along sections of the grabens (Fig.9) with at least one case of extrusion (profile V2, Herman et al., 1978).

A well developed graben exists in the central portion of Okinawa Trough east of 124° E (Figs.2, 7 and 8) along which extension for this region of Okinawa Trough is apparently concentrated. Sediments are downbowed towards the graben, normal faults forming the graben cut through to the sea floor, recent sediments fill the downdropped block and the most recent sediments onlap the downbowed layers to each side (Fig.9). Herman et al. (1978) also recorded seismic reflection profiles of this structure and other grabens. Mapping of their profiles reveals that they crossed at least four separate grabens, rather than only two as they concluded. All of the grabens display recent faulting. By combining our data it can be seen that these features strike parallel to the Okinawa Trough axis, are generally discontinuous and are randomly distributed along the center and southeastern side of the trough. While normal faults exist at the margins (Figs.7, 8 and 10) and throughout the basin as Herman et al. (1978) have shown, present-day extension appears to be most extensive along the central and southeastern side. If the grabens are taken as evidence for well-defined zones of extension, then the distribution of the grabens suggests a relatively complex pattern of spreading centers offset by transform faults.

Well-developed grabens are missing between 122° 15′E and 123° 30′E (profiles CL2, CL3, CL4, HU1 and HU2 in Figs.2, 7 and 8). A shallower and sometimes exposed basement is observed in this region and structures of probable volcanic origin are found south of the trough axis (profiles CL3 and CL4). Near Taiwan a graben is cut into the shelf (profiles CL5 and TW2) in direct projection with the seismically active extensional zone of the Ilan Plain. This feature may have a combined fault/erosional origin.

Fig.5. Reduced-time record section for stations *28, 29, 30, 31* and *32*. Station locations are shown in Fig.2. To expand the scale, arrival times are reduced by subtracting x/7.0 km/sec. Approximate topographic corrections have been applied with assumed velocity of 5 km/sec. This creates small errors for arrivals at higher and lower velocities. The topographic sections have ticks at intervals of 0.25 sec two-way sounding time.

TABLE I

Station	Azimuth (from north)	Velocity (km/sec)					Water depth (km)	Thickness (km)				Position of receiving station	Comments
		1A	1B	2	3	M		1A	1B	2	3		
29	013	2.00*	5.21	6.08			1.87	1.69	2.34			25° 20'N, 124° 29'E	single profile
30	253						1.86	1.51	3.07	3.97		25° 29'N, 124° 27'E	St. 30-31 reverse
		2.00*	4.81	5.96	6.73								
31	083						1.87	1.20	1.56	3.07		25° 21'N, 123° 54'E	St. 31-32 split
		2.00*	4.81	5.53	6.26	8.16	1.87	1.11	1.84	3.96	6.93		
32	238											25° 21'N, 123° 54'E	

*Assumed velocity

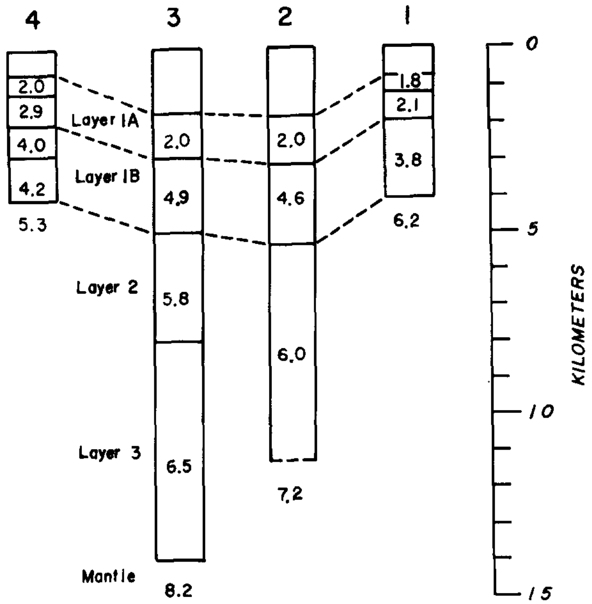
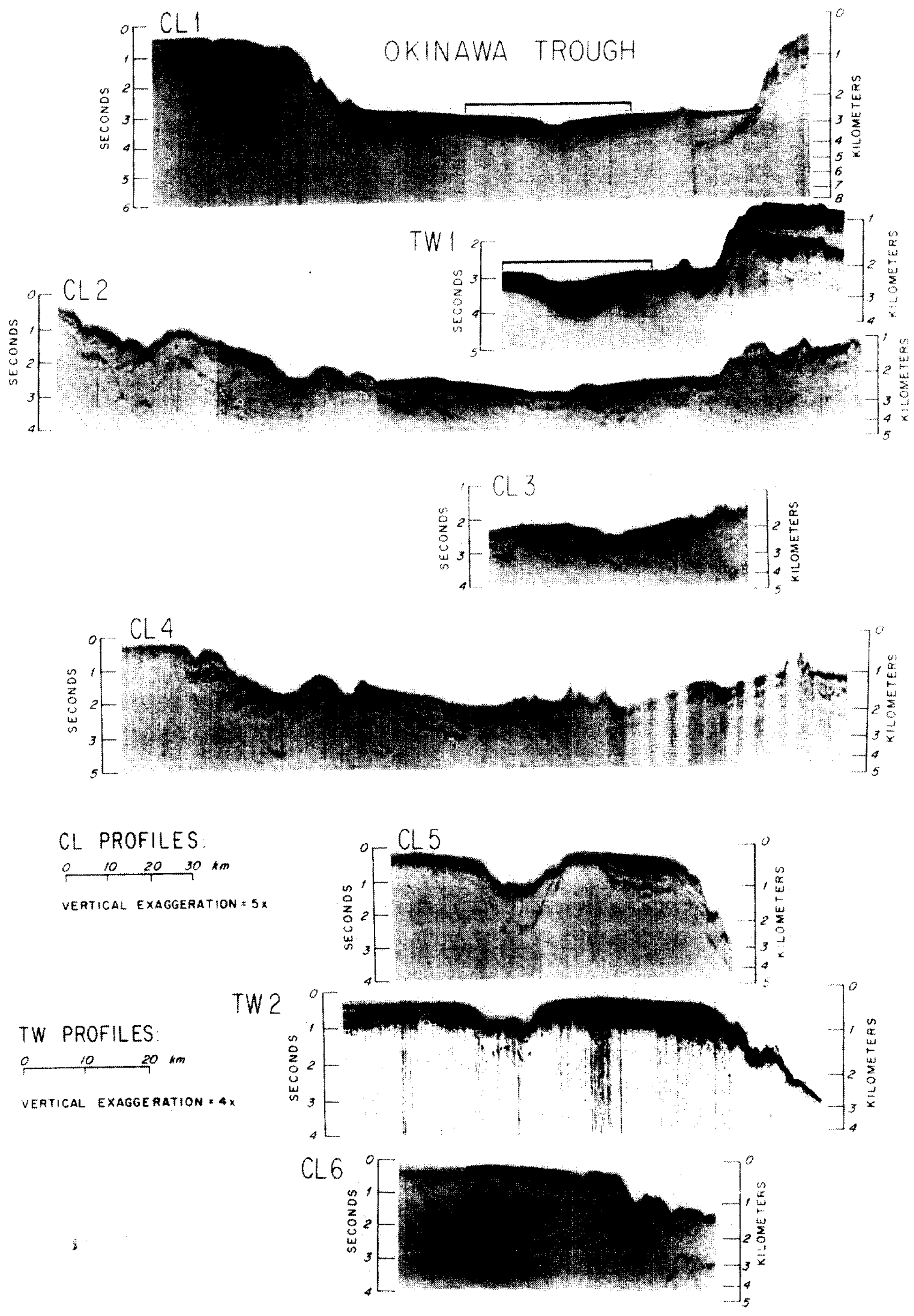


Fig.6. Correlation of seismic refraction results in the Okinawa Trough. Data are taken from: *1* = Ludwig et al. (1973); *2* = Murauchi et al. (1968); and *3* = this study and *4* = Leyden et al. (1973).

At the margins of Okinawa Trough the structures beneath the uppermost unconsolidated sediment are clearly revealed in the seismic-reflection profiles. These structures correspond to layer 1B as determined by the seismic refraction data (Fig.6) and are unconformably separated from the comparatively undisturbed overlying sediments. Folding and large-scale normal faults are ubiquitous throughout this layer which was broken into large tilted fault blocks with the dip on the faults towards the trough. This is particularly well displayed in the northwest portion of the profiles (Figs.7 and 8). An enlargement of a northwest portion of profile HU2 illustrates this faulting associated with the early phases of extension (Fig.10). It is clear that extensive faulting occurred prior to the deposition of the upper, well-stratified sediments, but offsets in this depositional unit testify to some continued movement.

The tilted and rotated fault blocks found here are typical of structures found elsewhere that are associated with the early extension and rifting of continental crust. De Charpal et al. (1978) mapped continental-margin structures that developed with Early Cretaceous rifting in the Bay of Biscay that are nearly identical to what we see here. They found tilted and rotated blocks of stratified rocks of probable Jurassic age bound by lystric faults that are underlain by a thinned continental crust and overlain by undisturbed Tertiary and Lower—Upper Cretaceous sediments. As in Okinawa Trough (Fig.10) the fault pattern forms half-grabens and fault blocks 5—10 km in width. The velocity structure is also nearly identical with 4.9 km/sec for the layer composed of the tilted fault blocks.


CL1
OKINAWA TROUGH
SECONDS
KILOMETERS
TW1
CL2
CL3
CL4
CL5
TW2
CL6
CL PROFILES
0 10 20 30 km
VERTICAL EXAGGERATION = 5x
TW PROFILES
0 10 20 km
VERTICAL EXAGGERATION = 4x

DISCUSSION

The uppermost low-velocity layer of sediments (layer 1A) is about 1.3 km thick in the center of Okinawa Trough. It is a well-stratified unit which in the central and southeastern areas of the trough is cut by normal faults and grabens. In other areas it is relatively undisturbed. Cores taken by GSJ (Honza, 1976) and LDGO (Herman et al., 1978) have yielded turbidites, clays and ashes contributed from the adjacent continental areas, islands and volcanoes. If our correlations are correct, this layer is composed of Quaternary—Pliocene sediments.

Beneath the well-stratified, low-velocity sediments, separated by an unconformity, is the folded and highly faulted layer of tilted fault blocks (layer 1B). Our refraction results near the center of Okinawa Trough show that this layer is about 2.1 km thick with a velocity of 4.9 km/sec. In places beneath the grabens in the central and southeastern areas of the trough, this layer and the overlying sediments have been intruded by volcanics. Sediment cover over this layer thins toward the margins of the trough. The unconformity separating layers 1A and 1B has been variously placed within Miocene—Pliocene time (Wageman et al. 1970; Leyden et al., 1973; Herman et al., 1978). Based on correlations with similar structural relationships on Taiwan and the nearby velocity—age correlation of Leyden et al. (1973), we have assumed this unconformity to be in the Upper Miocene and layer 1B to be composed of primarily Miocene rocks.

Below these units in the central region of southwestern Okinawa Trough is Layer 2 with a velocity of 5.8 km/sec. Thickness of this layer is about 3.2 km. Because we are able to map magnetic lineations in several small areas of the central and southeastern parts of Okinawa Trough in this region we speculate that the 5.8-km/sec layer represents relatively young basalt emplaced in conjunction with the extensional tectonics. Ishihara and Murakami (1976) also concluded that the trough is floored by sea-floor spreading basalts and Herman et al. (1978) reported relatively fresh pillow basalts dredged from a piercement structure in one of the grabens.

Beneath these shallower layers we find a "main crustal layer" 7 km thick with a velocity which may be as high as 6.7 km/sec (reversed solution of stations 30-31) and averages 6.5 km/sec. These velocities are high for continental crust; a similar velocity is found only on the Murauchi et al. (1968) station 15 near the center of the trough and not on stations farther from the center. It may represent material with the properties and composition of the main crustal layer found in deep-sea refraction profiles. It is significant that the highest velocity is determined from a reversed pair close to and parallel to the trough axis; it may well be that there is a zone along the axis with higher velocity than elsewhere in the trough, and that we sampled varying amounts of high- and low-velocity crust in our refraction lines.

Fig.7. Seismic reflection profiles across the Okinawa Trough by the R/V "Chiu-Lien" and R/V "Thomas Washington" (see Fig.2 for locations).

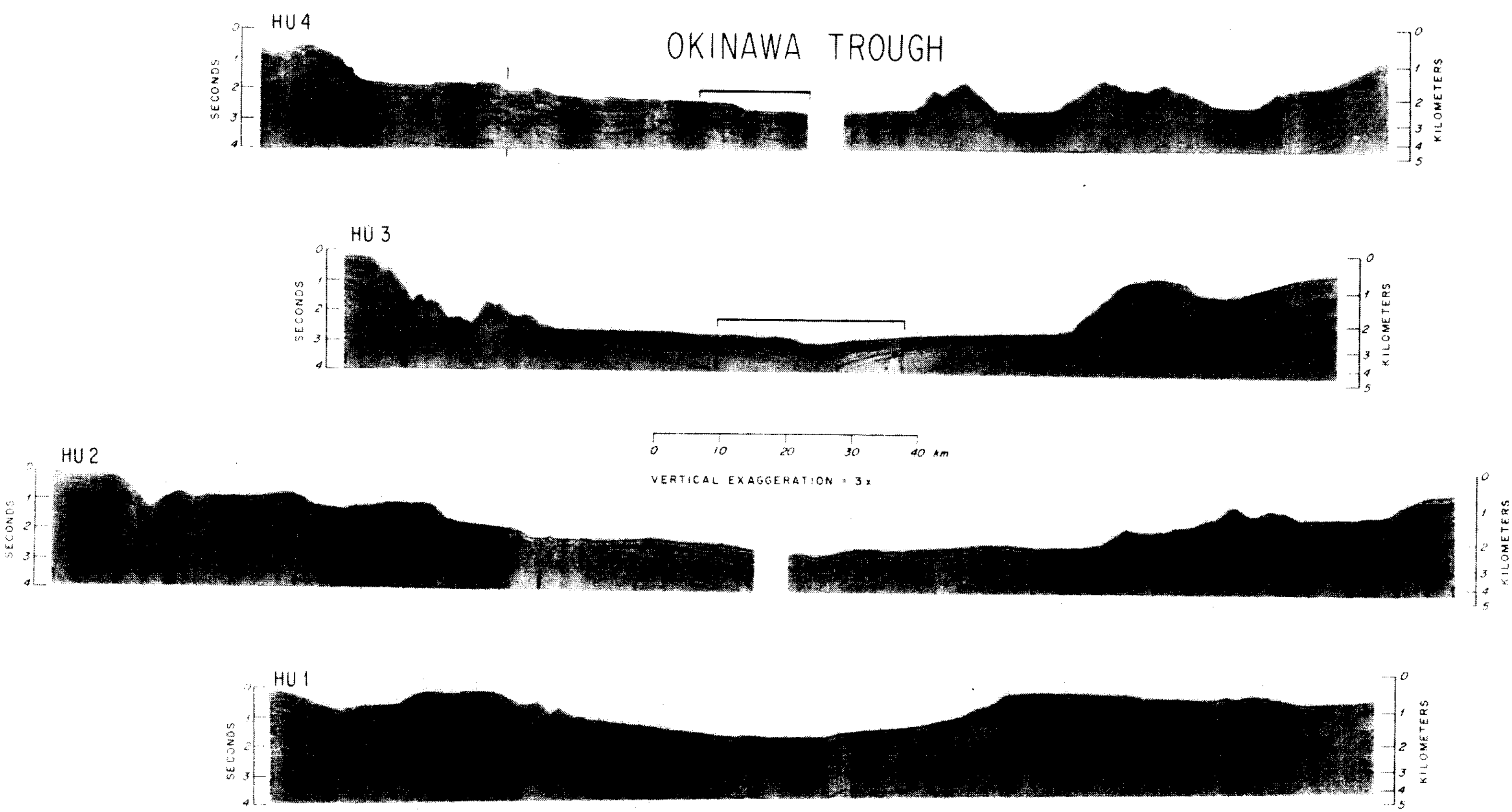


Fig.8. Seismic reflection profiles across the Okinawa Trough by the R/V "Hunt" (see Fig.2 for locations).

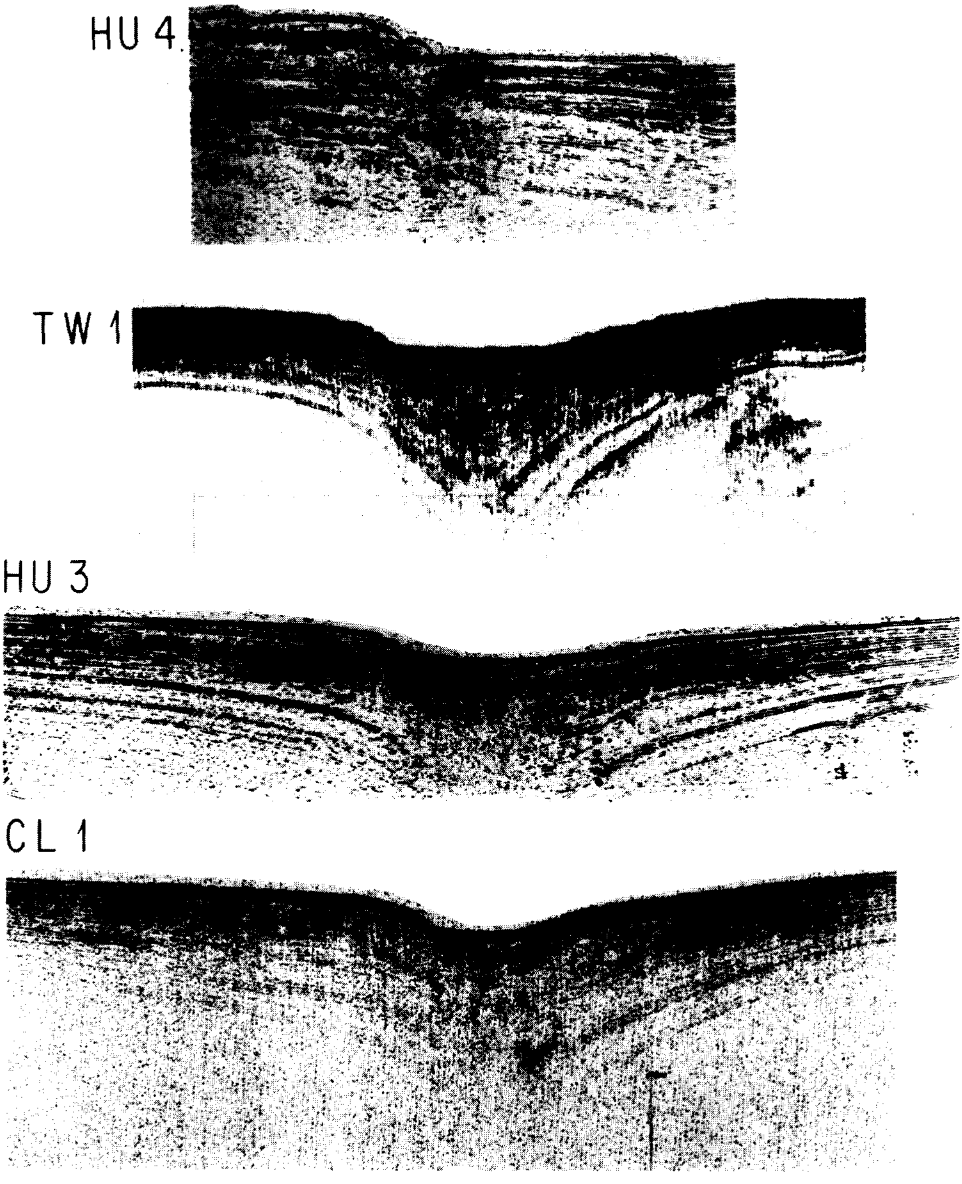


Fig.9. Enlargements of seismic reflection profiles across central graben. Refer to Figs.7 and 8 for complete profiles.

The total thickness of the crustal section, while significantly greater than normal oceanic sections, is thinner than continental crust and similar to those reported by Menard (1967) from other marginal basins. Although mantle depth has not been determined by refraction methods in the adjacent areas of continental shelf, Vajk (1964) estimated, from gravity data in the area north of Okinawa, that the crust is about 30 km thick beneath the

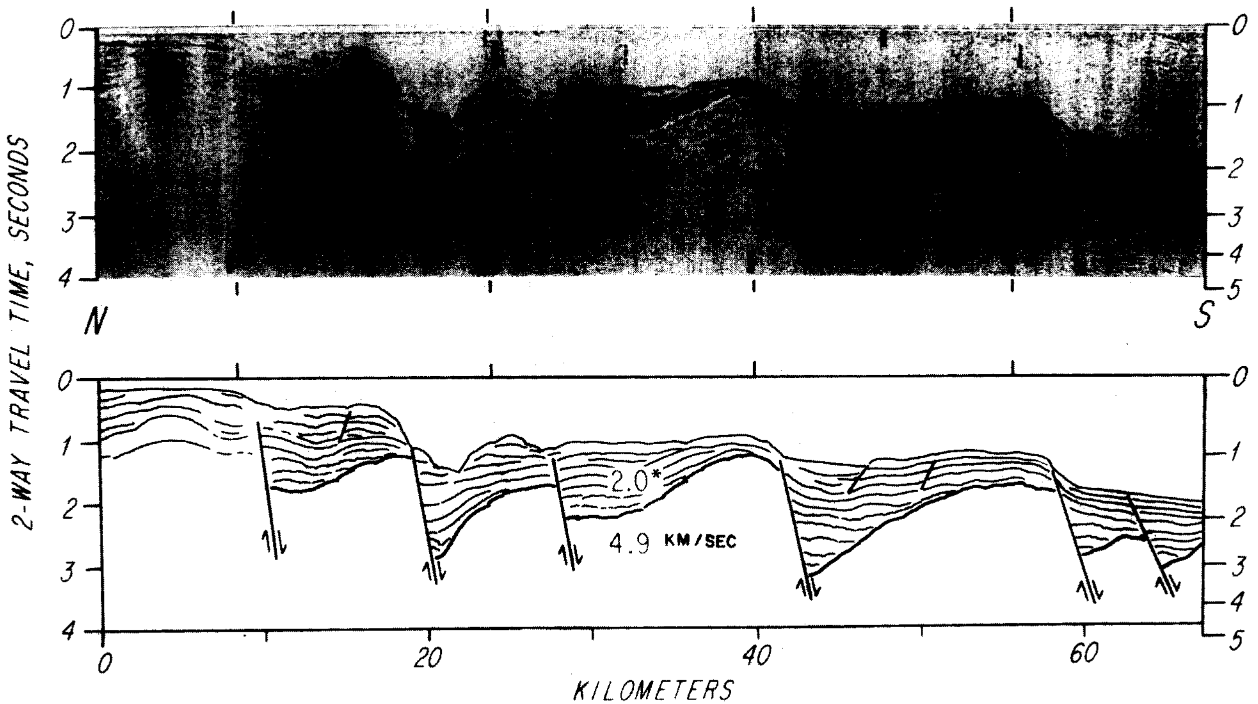


Fig.10. Seismic reflection profile and interpreted line drawing across the north side of Okinawa Trough. Location is shown in Fig.2, marked "P".

Ryukyu Ridge, thins slightly beneath the Okinawa Trough, and then thickens again beneath the continental shelf. While the thickness that we have determined (15 km) is significantly less than that reported by Vajk (28 km), his observations may be in an area at an earlier stage of spreading than the area we have examined in the southwestern part of the Okinawa Trough.

Reflection data, showing a set of inward-dipping normal faults separating tilted blocks of layer 1B and overlying folded sediments (Fig.10), provide evidence for crustal thinning by "block extension". If a large block, subject to tension, fails by brittle fracture rather than flow, it normally fails along a series of normal faults. As the ends of the large block move apart, and if no new material is injected into the faults, each small block will not only slide with respect to its neighbor but will also rotate (see Fig.11). The length of the fractural block will increase and the average thickness will decrease by the same ratio. In terms of observable angles, the lengthening is $\sin a/\sin(a-b)$, with the angles defined as in Fig. 11, and the thinning the inverse. In the present case the angle of dip is not sufficiently well defined to give a quantitative check of the thinning of the crust, but qualitatively one can see that there is both slip and rotation which would agree with thinning of the crust across the trough.

The general structure around the Okinawa Trough is continental, with thick crust. The center of the trough itself, however, has relatively thin crust (intermediate between continental and oceanic), with the velocity of the lower crust approaching that typical of the ocean basins. While older rocks of volcanic origin are found in the Ryukyu Arc and near the edges of the Okinawa Trough, they do not produce linear magnetic anomalies of the type associated with sea-floor spreading. Young volcanics have been dredged in the center of the trough, and magnetic surveys indicate that there are linear anomalies (parallel to the trough axis) offset by transform faults. The uppermost sediments are relatively flat, and have low seismic velocities. There is a pronounced unconformity beneath these low-velocity sediments; this unconformity can be traced back to Taiwan where it is of Miocene age. The sediments beneath the unconformity are of relatively high velocity, are folded and they and the basement beneath them are cut by a set of normal faults dipping in toward

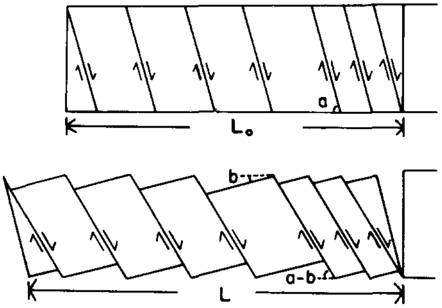


Fig.11. Geometric model of block extension.

the Okinawa Trough from both sides. Heat flow is high, and extremely variable, as it is in oceanic spreading centers and other active marginal basins.

From these observations one can derive the following sequence of events (see Fig.12) for Okinawa Trough and probably for other cases in which an oceanic plate is being subducted beneath an area of thick continental crust.

Initially, soon after subduction starts, heating causes thermal expansion of the mantle of the continental plate. This "doming" apparently occurred in Early Tertiary time at the eastern edge of the Asian plate. This thermal expansion would cause uplift of the continental crust. Subjected to tension by the expansion of the more plastic heated mantle below, the brittle continental crust fractures. Normal faulting and fault block rotation extend and thin the crust, lowering the surface level. This is the "rifting phase". New sediments are deposited after initial rotation of the fault blocks, possible erosion and subsidence.

As extension continues the crust thins, heating reaches shallower depths and some intrusion and extrusion of igneous rocks occur, but not continuously along a central rift as in the classical case of an oceanic spreading center. Intrusion is along short spreading centers, connected by transform faults; it is sufficiently organized to produce areas of oceanic-type crust (with magnetized basement rocks exhibiting lineated magnetic anomalies) that can be identified by seismic refraction measurements. This "drifting" stage was apparently reached during Pliocene time in Okinawa Trough, and is continuing. As spreading continues the depth to the mantle should continue to decrease, the depth to the base of the sediments (and possibly

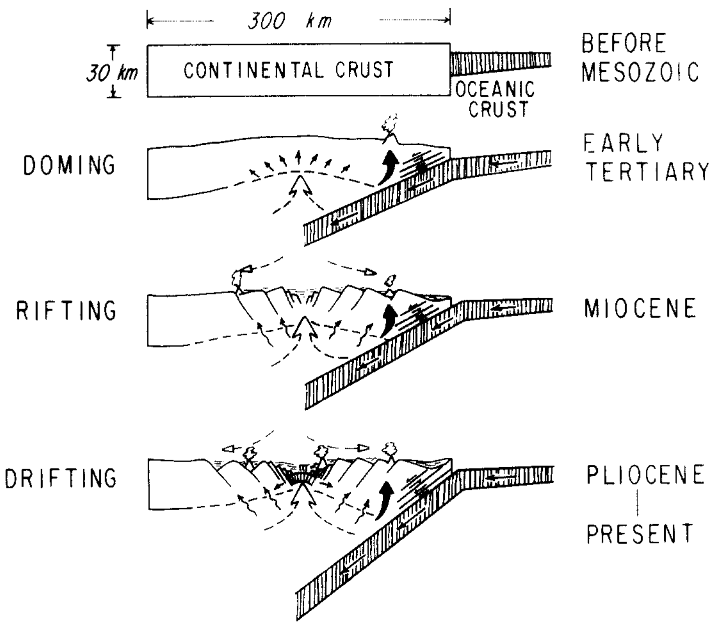


Fig.12. Cartoon of evolutionary stages of the Okinawa Trough.

the ocean depth) increase and the spreading centers re-align into longer segments more closely resembling a mid-ocean spreading ridge.

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