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A GEOMORPHOLOGICAL STUDY ON THE CLASSIFICATION AND EVOLUTION OF TRENCHES AROUND JAPAN[†]

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1. Introduction

This paper describes the geomorpholgical classification of trenches around Japan to discuss the process of formation of their topographic features which have recently been revealed by remarkable progress in sea-bottom surveys. The latest detailed morphological cata presented here are those obtained from the Nanseisyoto Trench (or Ryukyu Trench), the eastern part of the Nankai Trough, the Palau Trench, the Challenger Deep in the Mariana Trench, the Suruga Trough, the northernmost section of the Izu-Ogasawara Trench and the triple junction of trenches off central Japan. For comparison among them, published geomorphological data for several trenches covered with multibeam bathymetry were used.

In particular, the formation process of the northern Palau Trench and of Nanseisyoto Trench is thoroughly discussed using data from seismic profiling as well as geomagnetic anomaly and gravity measurements in addition to the detailed geomorphological data. These are suitable areas for examination trench morphology because these areas were already covered by dense sea-bottom survey data.

Sea-bottom topography has heretofore been comprehended by filling in the gaps between survey lines by analogical interpretation. Even though knowledge was limited to the outline of the geomorphology at that stage, distinct differences have been recognized between sea-bottom and land topography (Sato, 1969). These differences can be summarized in two principles, as follows:

i) In the formation of a topographical feature, the process of sedimentation dominates on the sea bottom while erosion dominates on land. Although there may be a number of exceptions to this principle, it is the fundamental factor in clarification of the difference between land and sea-bottom features.

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ii) Tectonic landforms can easily be preserved on the sea-bottom. This principle has a close relation to i) above. The Philippine Basin, referred to in section 3. 1. 3 below, is an apt exarple of this principle. Remarkable linear ridges and depressions formed 50 to 60 Ma ago are well preserved in the Philippine Basin. Becuse a trench zone or convergent plate boundary, as discussed in this paper, is the site of active crustal movement, many kinds of tectonic features are recognized there.

There is no doubt that a trench is formed at a convergent plate boundary, plate subduction accounting for the depth of the trench. As is wellknown, characteristic topography is recognized on both sides of the trench floor. Detailed data collected in recent years have been enabling to reveal differences in trench topography. An attempt to classify the morphological and geological structure of the trench according to the plate subduction form has been discussed elsewhere (Seely, 1978; Uyeda and Kanamori, 1979). It is, however, limited to the general tendency becuse of the existence of various parameters of plate subduction form and the lack of detailed data on trench topography.

The recent remarkable increase in detailed geomorphological data on submarine trenches has brought to light important information for the study of tectonics and the history of trench formation; however no study has been done comparing and examining the properties of trenches by means of such detailed submarine geomorphological data.

It now becomes possible to build up a hypothesis about the history of trench formation by using three dimensional and detailed geomorphological data for such features as the northern part of the Palau Trench and the Nanseisyoto Trench.

Figure 1 shows locations of the geomorphological data used in this study. The majority of the data were obtained by the Survey Vessel *Takuyo* of the Hydrographic Depmtment, Japan Maritime Safety Agency. The *Takuyo*, 2,600 gross tons, launched in 1983, is designed for use in ocean surveys and observations, and is equipped with, among others, a multi-narrow beam echo sounding system, a Sea Beam System and a multi-channel seismic reflection survey system.

Although compilation of the detailed bathymetric data on trenches is not yet completed, this paper intends to classify the trench features into several types and to examine the evolution of each type in relation to plate subduction.

2. History of trench studies

2. 1 Trench and convergent plate boundary

The subject of discussion of this paper is the convergent plate boundary where an oceanic plate subducts beneath another plate. The convergent boundary consists of a subducting boundary and a collision boundary, and a submarine trench is formed along the subducting boundary (Isacks et al., 1968). For plate subduction to occur, it is necessary that the subducting plate be of oceanic crustal structure.

The name of a submarine feature is defined by the characteristics of its configuration but not by the genesis of its formation. The definition of a trench by IHO and IOC (1985) is 'a long, narrow, characteristically very deep and asymmetric depression of the sea floor, with relatively steep sides'. A depression more than 6,000 meters deep is usually named a 'trench'. A depression shallower than 6,000 meters, even though it is located at a subducting plate boundary, is named a 'trough' in accordance with the definition of IHO and IOC (1985). Accordingly, this study deals with trenches and troughs under the IHO and IOC definition. Henceforth 'trench' in this paper refers to any depression at a convergent plate boundary,

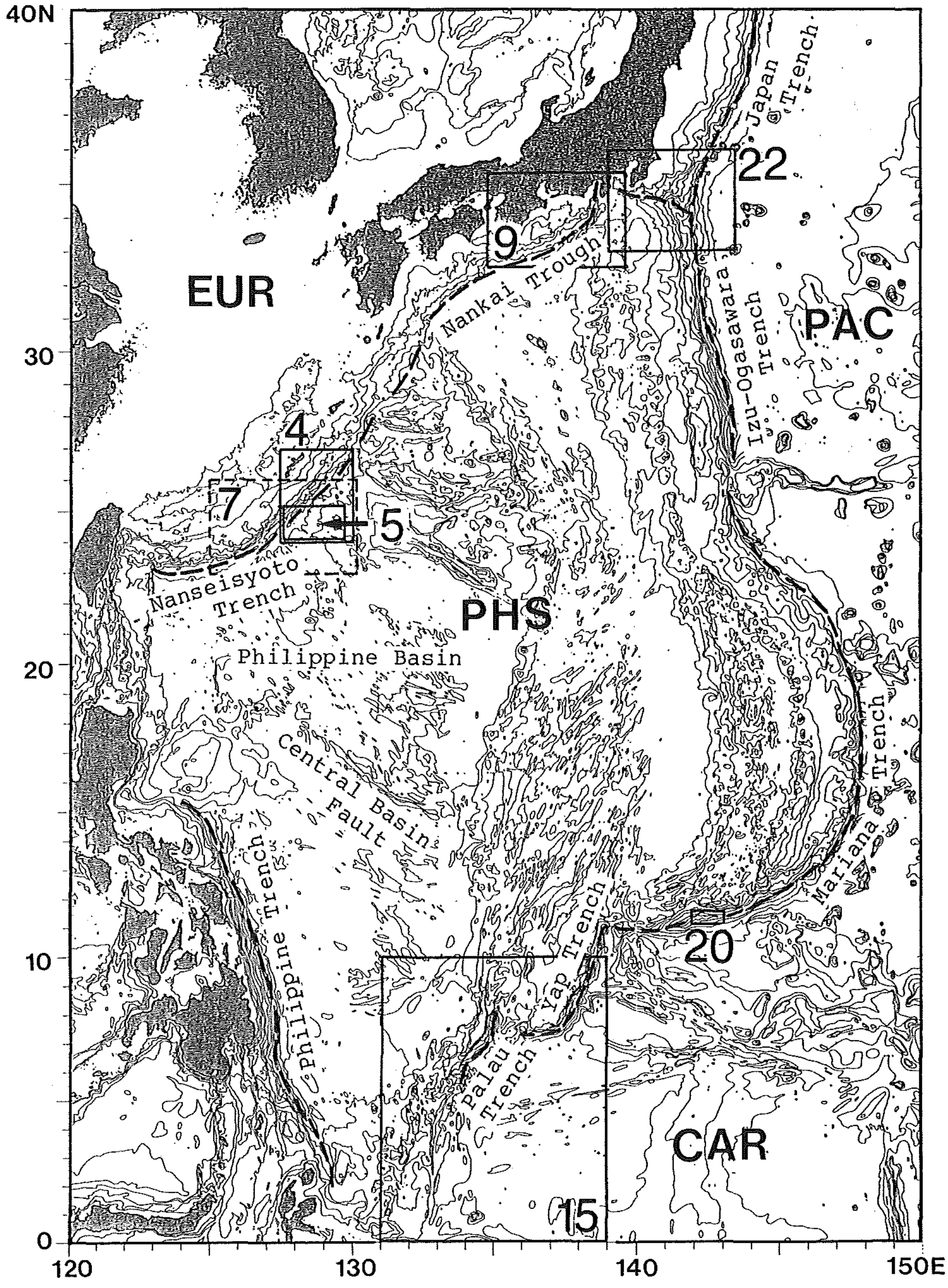


Figure 1. The distribution of the convergence boundary of plates around the Philippine Sea area. CAR: Caroline plate, EUR: Eurasian plate, PAC: Pacific plate, PHS: Philippine Sea plate. Numbered boxes indicate location of studied areas displayed in the following figures.
Bathymetry from Japan Oceanographic Data Center (1984).

including a 'trough'.

2. 2 Depth of trenches

Lead sounding surveys for laying trans-ocean submarine cables revealed the existence of trenches in the 19th century. Since then, the sounding method has been changed from lead sounding to echo sounding. A depth greater than 10,000 meters was first reported in the Philippine Trench in 1927, and the world's deepest trench was later reported there. At that time, data on trench morphology had been obtained only for several cross-sections of the trench. Nothing was known about the characteristics of trench geomorphology except that this was the deepest part of the ocean on the earth.

From the 1930s to the 1950s, scientists' interests were concentrated on the survey of ocean depths as sea-bottom survey techniques had been developed remarkably, and deep earthquake zones were discovered along some trenches. Also in this perion, the idea of the arc-trench system became conceivable, since the results of gravity measurement at trenches were related to earthquake distribution and other geological/geophysical phenomena (Otuka, 1938; Umbgrove, 1938; Hess, 1948). After World War II, the amount of geomorphological, geological and geophysical data on trenches increased rapidly. A number of morpholgical cross-sections were obtained together with other geophysical data such as gravity, geomagnetism and heat flow. It is recognized that trench geomorphology is characterized by deep sea terraces, outer ridges and benches on the landward slope, and horst and graben structure and marginal swells on the seaward slope of the trench (Iwabuchi, 1969; 1970a). Seismic profile data also became obtainable (e. g. Ludwing et al., 1966). Ludwing et al. revealed that a horst and graben structure is formed by faults, and recognized a horizontal trench fill layer in a part of the trench axis.

The characteristics of topography, crustal structure and gravity of the trench had been recognized by the 1960s as follows:

i) A trench extends along an island arc or a continental margin arc, and its axis is generally convex to the ocean side.

ii) Deep sea terraces and outer ridges are distributed on the landward slope, while marginal swells and graben-like depressions occur on the seaward slope.

iii) A deep earthquake zone or Wadati-Benioff zone inclines from the trench to the island arc or continental margin arc.

iv) A negative anomaly zone of gravity, whose minimum anomaly is located on the trench axis or slightly landward, is recognized. As low-density materials were lacking beneath the trench, it was considered that the negative anomaly was due to the downward force. The distribution of the density beneath the trench was revealed by surveys of the crustal structure using artificial seismic sources (e. g., Fisher and Hess, 1963).

v) A striped anomaly pattern of geomagnetic anomaly on the seaward area of the trench gradually attenuates from the trench landward.

vi) Heat flow values at the trench are low in general.

2. 3 The trench as a plate subducting zone

According to the theory of plate tectonics that appeared in the 1960s, trench is formed at the place where an oceanic plate is subducting. A few characteristics of the trench mentioned in the above section have been explained by the fact that the relatively heavy ocean lithosphere formed in the ocean floor subducts beneath the island arc or continental margin arc.

As the amount of trench survey data increased, a variety of ideas to explain the topography and structure of the trench were submitted. Among them, a significant concept in trench morpholgy is the accretionary prism model on the landward slope of trench (Fig. 2) proposed by Seely et al. (1974), Karig and Sharman (1975) and Seely (1978). That model is derived from the data obtained by a multi-channel seismic reflection system with high output and high resolution. Seely et al. (1974) stated that the landward slope of the trench consisted of accreted material with well-deformed imbricate structure, and that the accreted material was formed by the trench fill layer and the pelagic layer on the oceanic plate, which could not subduct with the plate and remined at the foot of the landward slope.

Isacks et al. (1968) indicated that the marginal swell on the seaward side of the trench was formed prior to subducting, and that the faults on the swell were formed by tension on the surface of the bending lithosphere. Actually, the seismic mechanism along trenches and their seaward approach supports this idea (Stauder, 1968; Yoshii, 1979). The existence of the accretionary prism was later confirmed by a number of multi-channel seismic data and data from the Deep Sea Drilling Project. The discovery of the lack of accretionary prisms in some other areas led Uyeda and Kanamori (1979), Ida and Uyeda (1981) and Uyeda (1982) to present a model in which the subduction zone was divided into two types, the Chilean type and the Mariana type (Fig. 3). Thus, they tried to explain synthetically the large-scale morphology, geology and geophysics of the trench. The difference in general characteristics of trench morphology was also examined in these types. This presentation has a significant meaning for the study of submarine trench geomorphology.

Ida and Uyeda (1981) explained that, in the Chilean type subdction zone, the bulge or margial swell on the seaward slope of the trench and the accretionary prisms on the landward slope were well developed, with a shallow trench floor in between; the Mariana type subduction zone had a well-developed graben structure on the seaward slope, presenting a deep trench, and barren trench walls on the landward slope where tectonic erosion (Hilde, 1983) occurred.

2. 4 Contemporary studies on trenches

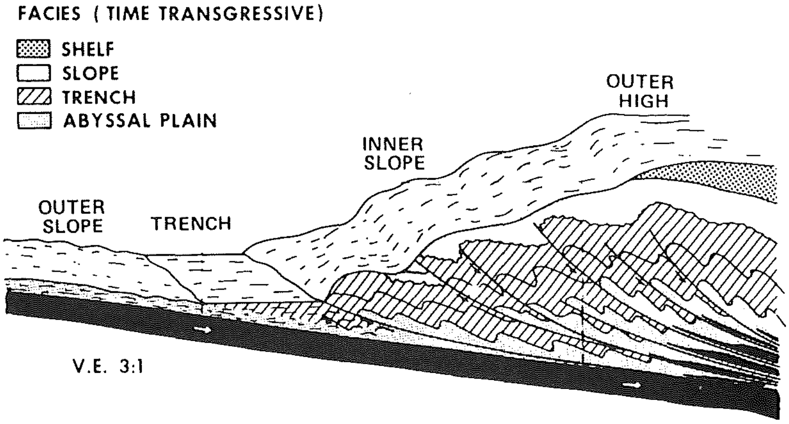


Figure 2. A model of a trench landward slope showing an accretionary prism. (Seely et al., 1974)

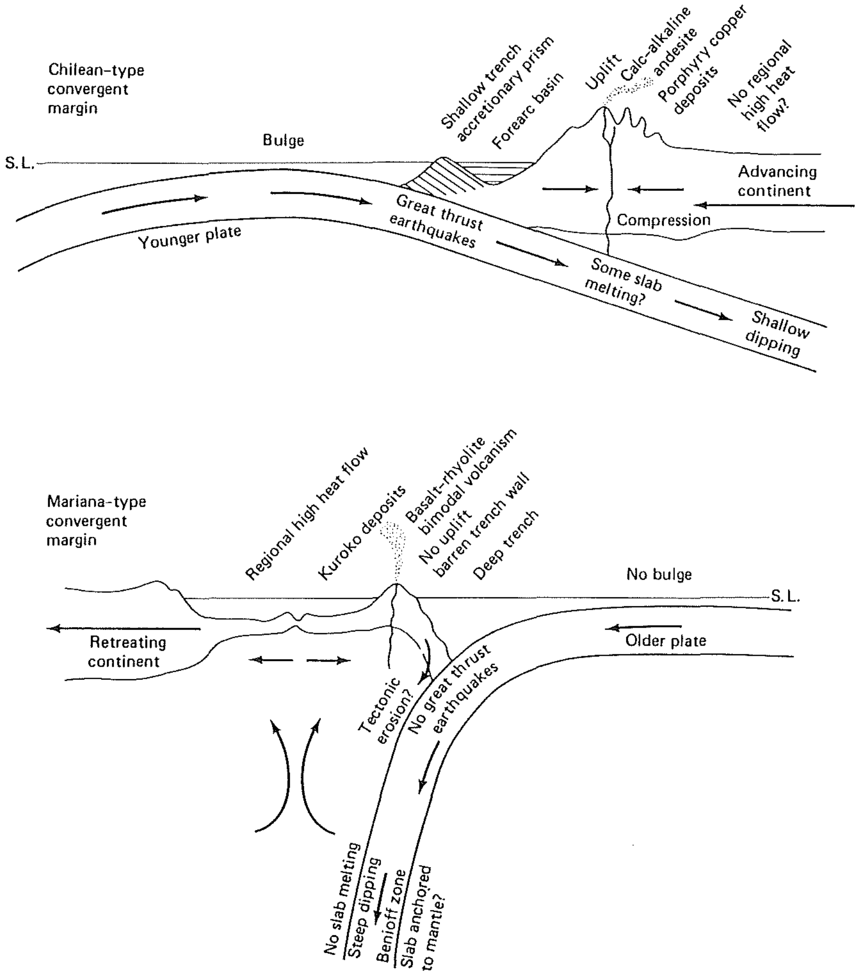


Figure 3. Diagrammatic sections showing two general models of subduction and their possible tectonic implications and causes (not to scale). (Uyeda, 1982)

As mentioned above, many studies on trench morpholgy mainly have been done with the data on cross sections of the trench, together with geophysical and geological data. But three-dimensional analysis of trench morphology, such as the analysis of the direction of faults on the seaward slope, was insufficient due to lack of detailed bathymetric data on trenches and their surrounding sea floors.

Recently, the three-dimensional analysis of trench morphology has been initiated by utilizing detailed bathymesric data. Exampls are studies on the bottom morphology surveyed by the Sea Beam system for the Deep Sea Drilling Project (Shipley and Moore, 1985; Fontas et al., 1984), the Sea Beam survey of the Japanese-French cooperative Kaiko Project (Cadet et al., 1987a, b), and the sea floor image data collected by side scan sonar for deep ocean (e. g. Karig et al., 1987). More concrete discussions (e. g. on sedimentation and deformation processes of the trench fill layers) have been started by combining the detaliled geomorphological data with other existing data.

However, such research has mostly been limited to discussions of regional tectonics, and there has been very little comparative analysis such as the research done by Uyeda (1982).

This paper intends to classify the trench features into several types and to examine the formation of each type in relation to the specific character of subduction.

3. Geomorphological description and examination of several trenches

This chapter discusses the morphology and characteristics of the Nanseisyoto Trench, the eastern part of the Nankai Trough, the Palau Trench, the Challenger Deep in the Mariana Trench, the Suruga Trough, the northernmost section of the Izu-Ogasawara Trench and the triple junction of trenches off central Japan.

These examples lead to a better understanding of the details and efficiency of geomorphological data provided by the Sea Beam system and other geological and geophysical data. The Sea Beam system, one of the multi-narrow beam echo sounding systems, manufactured by General Instruments Co., was introduced by Renard and Allenou (1979) and Asada and Nakanishi (1986).

3. 1 Nanseisyoto Trench

3. 1. 1 Outline of the Naneisyoto Trench

The Nanseisyoto Trench is the convergent boundary of the western part of the Philippine Sea plate subducting beneath the Eurasia plate (Fig. 1). On the Philippine Sea plate neighboring the trench, the Philippine Basin extends in the southern part, and the Daito Ridge group (general name for the Amami Plateau, Daito Ridge and Oki Daito Ridge) occupies the northern part.

It is believed that the direction of movement of the Philippine Sea plate in relation to the Eurasia plate in this area is northwest (Circum-Pacfic Map Project, 1981; Kimura et al., 1983; Seno and Maruyama, 1984). The Philippine Sea plate is colliding with the Naneisyoto or Ryukyu Arc at the Amami Plateau, where the bottom of the trench on the west side of the plateau is shallow (Tokuyama et al., 1985b). In the research conducted by the Deep Sea Drilling Project, the Philippine Basin was found to be a marginal sea which had been expanding since 40 to 60 Ma with the Central Basin Fault as its axis, and was believed to be older than the adjacent Sikoku Basin and the West Mariana Basin divided by the Kyusyu-Palau Ridge (Karig, 1975; Kobyashi and Nakada, 1978), The Daito Ridge group is said to be a remnant island arc formed before expansion of the Philippine Basin.

In the central part of the Nanseisyoto Trench discussed here which adjoins the Philippine Basin with depths of 5,000-6,000 m, the trench bottom is more than 7,000 meters deep. The axis of the trench forms a gentle arc convex to the southeast. The Nanseisyoto Trench is situated in a sea area where very few studies have been conducted so far despite the probability that it has a close relation to the history of formation of the Ryukyu Arc and the Okinawa Trough, a back arc basin of the Ryukyu Arc. This may be due to the fact that practically no data were available with reference to the topography and the geological structure of the trench.

The tectonics and topographical variations relative to the subducting of the Nansisyoto Trench will be considered on the basis of newly obtained data such as the detailed bathymetry of the central part of the Naneisyoto Trench, south of Okinawa Island, obtained by the Sea Beam system, seismic profiling, and geomagnetic and gravimetric measurements.

3. 1. 2 Data obtained by Sea Beam survey and other sea-bottom surveys

The data used for this study were principally those obtained by sea-bottom surveys conducted by the survey vessel *Takuyo* in December 1986 and January 1987. The survey items were a bathymetric survey by Sea Beam system, single-channel seismic profiling (352 c. in. air-gun) and multi-channel seismic profiling (1,000 c. in. air-gun and a 12-channel streamer cable).

As shown in Fig. 4, the survey lines were set in an east-west direction at intervals of five nautical

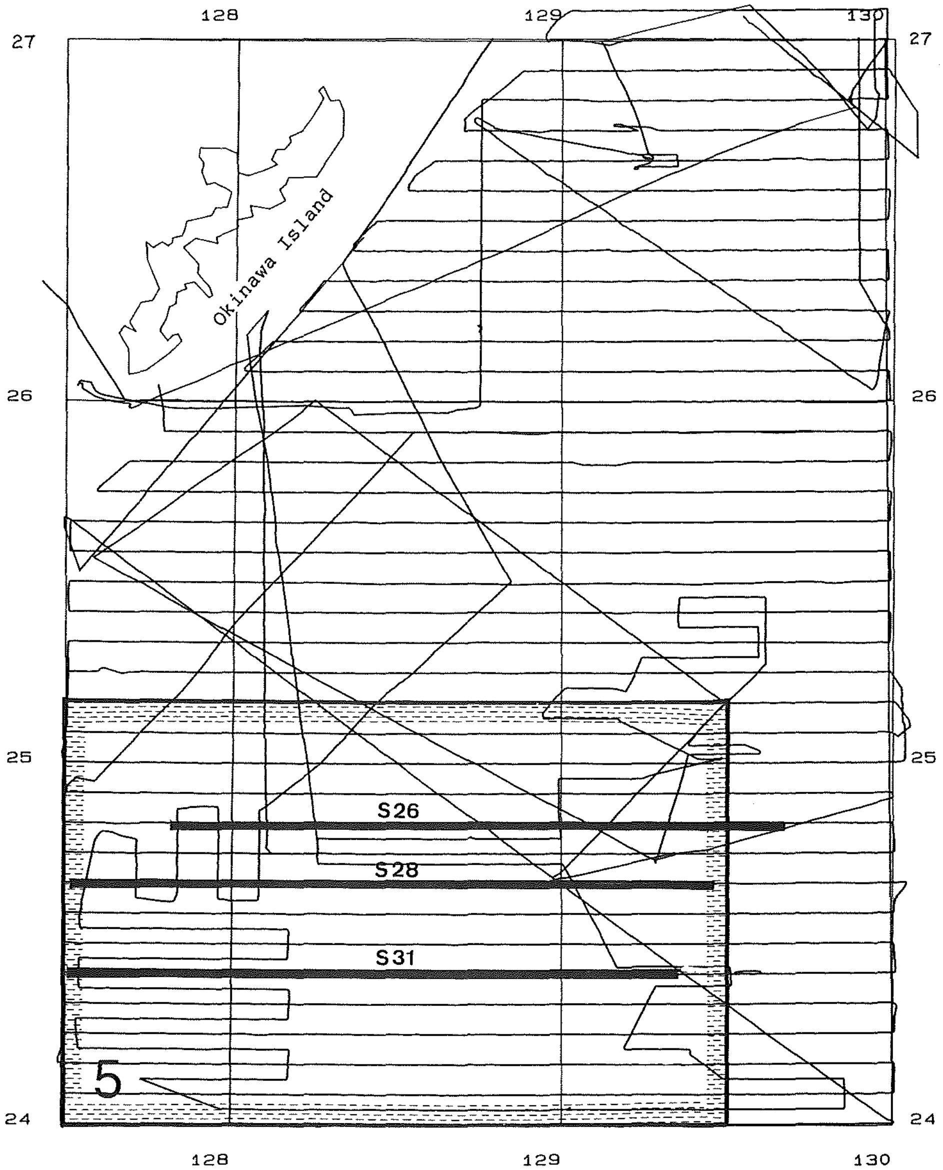


Figure 4. Track lines of the seabottom survey by the S/V *Takuyo* in the Nanseisyoto Trench. Box shows the location of Fig. 5. Lines S26, S28 and S31 show the seismic sections in Fig. 6.

miles. The survey lines near the Nanseisyoto Trench were spaced at 2.5 nautical miles. Thus, over 70% of the ocean floor was covered by Sea Beam, and detailed configuration of the ocean floor revealed. These data certainly gave highly precise and, moreover, homogeneous geomorphological details of this area for the first time. With these data it became possible to observe the very isteresting submarine morphology of the Nanseisyoto Trench and the Philippine Basin.

3. 1. 3 Minor ridge province and the Northern Border Tectonic Line of the Philippine Basin

In the Philippine Basin near the Nanseisyoto Trench, linear ridges in parallel are developing in NW-SE direction; these are called 'minor ridges' by Iwabuchi (1982), who originally gave this name to the group of parallel ridges found in the Sikoku Basin and the West Mariana Basin. Parallel ridges 200 to 1,000 meters high rise from the floor of the Philippine Basin with depths of over 5,000 meters. Long, narrow depressions separate these ridges, some exceeding 6,000 meters in depth. A major feature of these ridges is that practically all extend uniformly in the N45° W direction. The bathymetric map of this area and line drawings of the seismic profiles are shown in Figs. 5 and 6, respectively.

In this area, positive and negative geomagnetic anomal belts extend in the same direction as the topography. Figure 7 is taken from a geomagnetic anomaly map prepared by the U. S. Naval Oceanographic Office (1976). Since this is based on an aerial magnetic survey, it covers a wider range than the sea bottom survey by the S/V *Takuyo*. According to Fig. 7, the amplitude of anomaly is 150 to 450 nT, and an emergence interval (wavelength) from positive to positive is 40 km on the average, which is several times longer than the interval of the minor ridges. The difference in emergence intervals of the geomagnetic lineation and the minor ridges in the marginal sea has already been pointed out by Kasuga

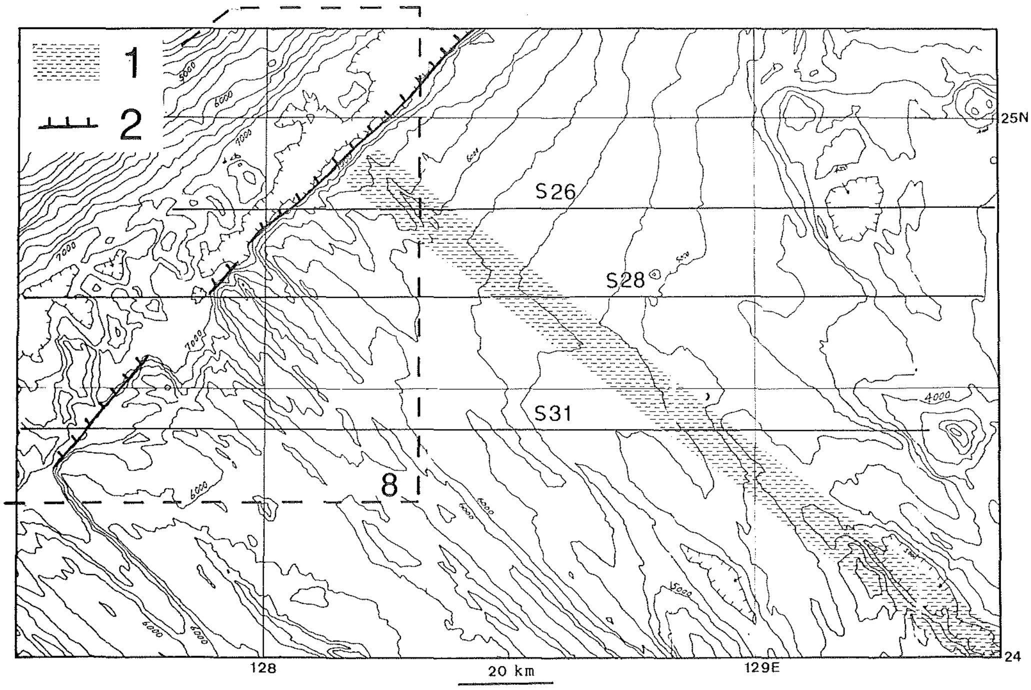


Figure 5. Bathymetric map of the Nanseisyoto Trench. 1: Northern Border Tectonic Line of the Philippine Basin, 2: Large normal Fault. Lines S26, S28 and S31 show the seismic sections in Fig. 6. Contour interval 250m. See Figs. 1 and 4 for location.

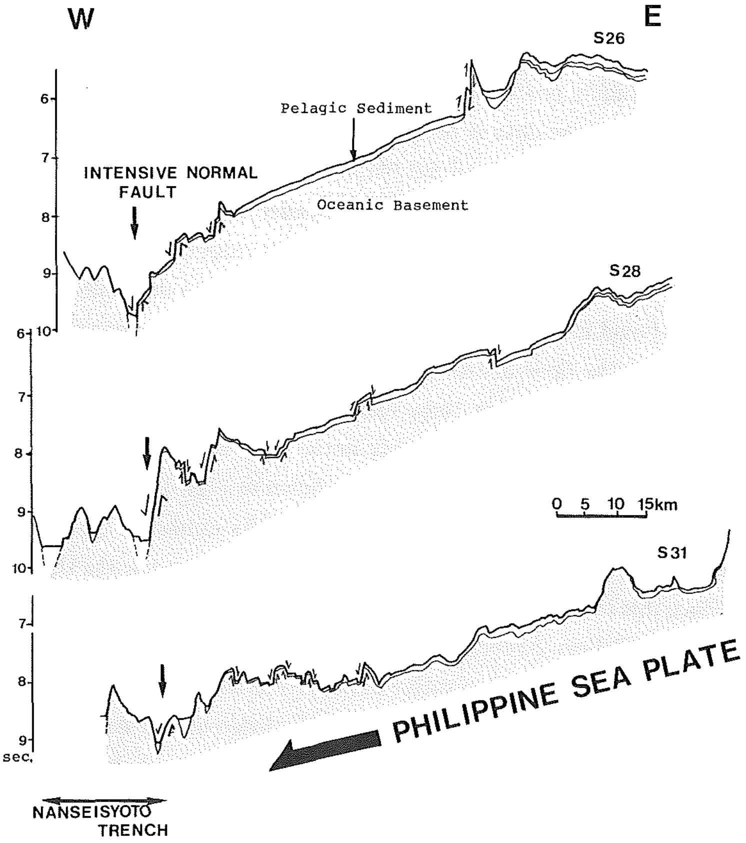


Figure 6. Line drawings of three seismic sections across the Nanseisyoto Trench.

et al. (1987) in the southern part of the Sikoku Basin.

From the afore-mentioned anomalous distributions of morphology and geomagnetism, it is thought that the floor of the Philippine Basin near the Nanseisyoto Trench may be an ocean floor expanding in the NE-SW direction.

The geomorphological province of the minor ridges of the Philippine Basin stretches to the southwest of a line extending southeast from a position at 25°N, 128°10'E. On the other hand, the area to the northeast is a flat ocean floor consisting of a smooth basement on which a sedimentary layer with an acoustic thickness of about 0.1 to 0.2 second lies. These two provinces are extremely contrastive (Figs. 5 and 6). Similar to the geomorphology, the geomagnetic anomaly map also shows this contrastive feature, with its northeastern part being smooth while the southwestern part with development of lineations due to the minor ridges.

If the minor ridge province in the Philippine Basin was formed by expansion of the marginal seas, the boundary of the geomorphological province extending southwest from the position of 25°N, 128°10'E may be considered the significant tectonic line (called the North Border Tectonic Line) delimiting the north margin of the expanding Philippine Basin.

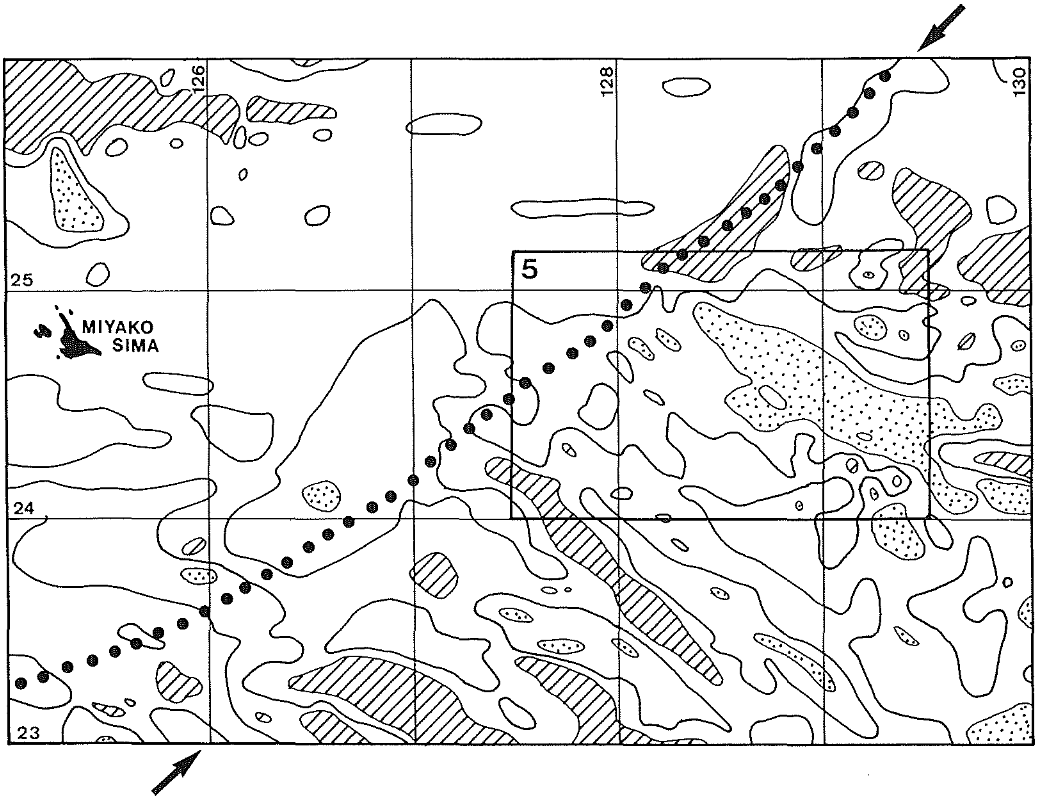


Figure 7. Gemagnetic total intensity anomaly distribution, adapted from U. S. Naval Oceanographic Office (1976). Dotted area : +100 nT, hatched area : below −100 nT, solid line : 0 nT, thick dotted line : trench axis, arrow : large normal fault outside the trench and its extension.

3. 1. 4 Large fault on the seaward side of the trench

A large normal fault divides the geomorphological province of the minor ridges from the Nanseisyoto Trench. This fault is slightly different from the faults outside such trenches as the Japan Trench (Cadet et al., 1987a) and the Middle America Trench (von Huene and Aubouin, 1982; von Huene et al., 1982) and has the following features:

(1) Its length is over 200 km.

(2) It is extremely straight.

(3) It runs almost parallel to the foot of landward slope, indicating the position of the trench. The interval between the fault and the foot of the landwamd slope, however, becomes wider toward the southwest, the latter forming a gentle arc.

(4) The relative height of the fault exceeds 1,000 meters around 25°30'N near the trench axis, while it is under 500 meters around 24°30'N, slightly distant from the trench axis.

(5) It is almost orthogonal to the direction of the minor ridges of the Philippine Basin.

While a number of bending faults develop generally elsewhere on the outside of and in parallel with the trench, this long fault is conspicuous,and there is actually no remarkable fault running parallel to this fault.

It is believed that this feature indicates the concentration of stress due to bending of the plate along the long, straight and weak tectonic line originally formed on the floor of the Philippine Basin. If the stress due to bending is concentrated on one fault, displacement will accumulate on the fault as the fault approaches the trench, and a greater relative height of the fault will be attained, which is in harmony with feature(4) above.

A matter which may come first to mind when considering a straight, weak tectonic line on the floor of a marginal sea is a fracture zone as a remnant of a transform fault orthogonal to the axis of expansion of the plate. Features (2) and (5) above indicate that the fracture zone was reactivated as a bending fault near the trench. This idea may be supported by the fact that the geomagnetic lineation observed in the geomorphological province of the minor ridges in the Philippine Basin, shown on the geomagnetic anomaly map in Fig. 7, becomes obscure on the northwest side of this fracture zone and its southwest extension.

3. 1, 5 Mesh-shaped structure in the trench floor

The floor of the Nanseisyoto Trench (Fig. 8) is narrowed by a large normal fault on the seaward side and the landward slope, showing an extremely complex configuration. Short lineations in the floor, which show two directions crossing almost orthogonally, can be recognized from this topography. The directions of these are in conformity with those of the trench axis and of the minor ridges in the Philippine Basin, presenting a "mesh-shaped" geomorphological structure. This mesh-shaped structure may be considered a composite of old and new lineations, i. e., the lineation of the old minor ridge on the Philippine Basin (NW-SE) and that of the new bending faults (NE-SW) on the outside of the trench.

On the trench floor, only a thin sedimentary layer about 0.5 second thick was recognized. The flat portion of the trench floor covered with sediment was limited to a narrow area. The mesh-shaped structure of the trench floor may be developed under the following three conditions: (1) orthogonal intersection of the directions of the minor ridges and the trench, (2) preservation of the configuration of the minor ridges not buried in sediments, and (3) poor supply of sediments on the trench floor.

3. 1. 6 Conclusive remarks on the Nanseisyoto Trench

The bathymetry, geological structure, magnetic anomaly and gravity anomaly of the central part of the Nanseisyoto Trench were clarified by recent sea-bottom surveys. A summary of the results which have newly been confirmed is as follows:

(1) On the floor of the Philippine Basin, minor ridges have been well developed, accompanied by the geomagnetic lineation running in the same direction as these ridges. This fact implies that this basin is a marginal basin formed by expansion of the sea floor.

(2) The large normal fault seaward of the trench limits the northwest margin of the area where the minor ridges are developed. This fault may be a reactivated fracture zone made by the bending of the trench formation. There is a possibility that, with progress in surveys of the Philippine Basin in the future, other fracture zones parallel to this fault will be discovered.

(3) Short lineations with two directions crossing almost orthogonally are recognized in the floor of the Nanseisyoto Trench. This 'mesh-shaped' structure may be considered a composite of old minor ridge lineations and new bending fault lineations.

3. 2 Eastern part of the Nankai Trough

3. 2. 1 "Ribge and trough zone"

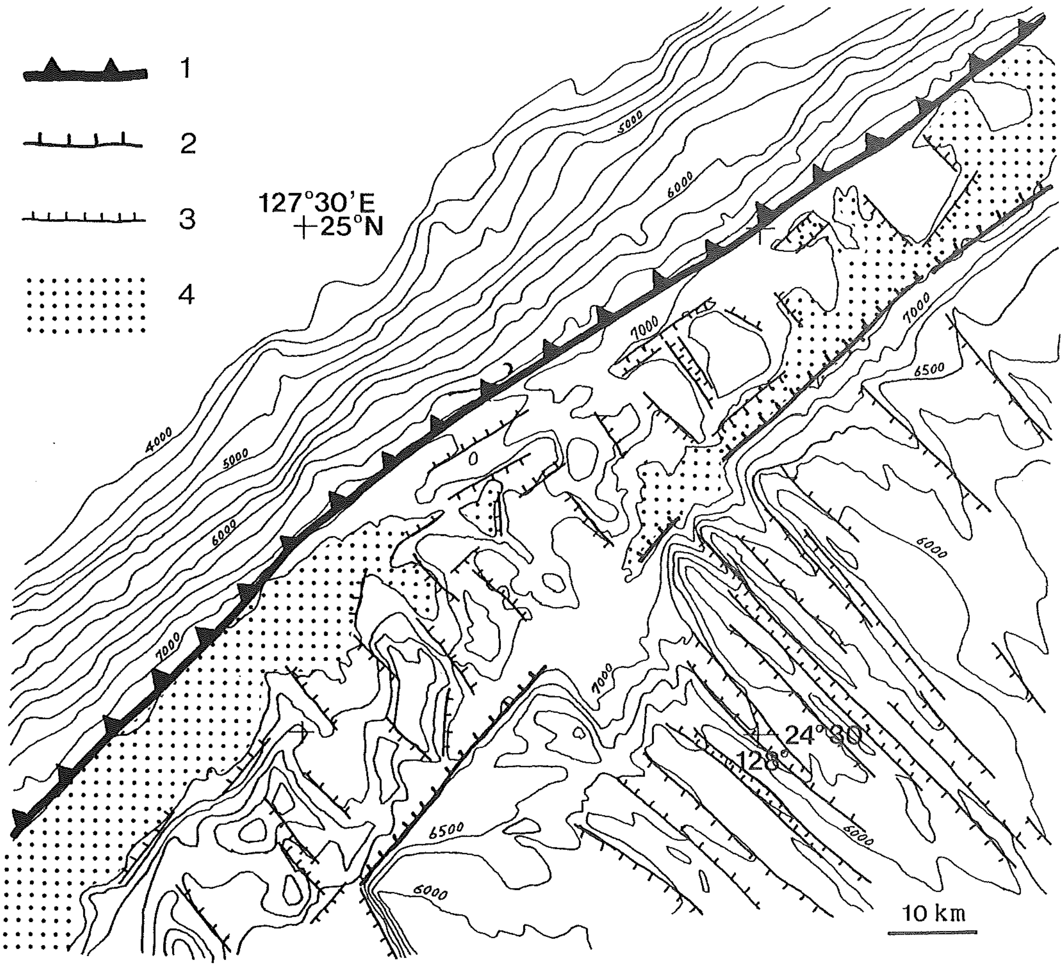


Figure 8. Mesh-shaped structure in the Nanseisyoto Trench floor. 1: Thrust fault at the foot of landward slope, 2: Large normal fault, 3: Faults and lineaments, 4: Trench floor below 7,250m depth.

There is a well-undulated zone on the landward slope of the eastern part of the Nankai Trough off Kumano Nada and Ensyu Nada, which is the convergent boundary of the north border of the Philippine Sea plate. This zone, 30 km wide, was called the 'ridge and trough zone' by Iwabuchi (1970b), as it shows a peculiar configuration of ridges or elevations and troughs or depressions alternately running in parallel with the axis of the Nankai Trough (Fig. 9). The ridges are, in general, 10 to 40 km long, 5 to 10 km wide and 500 to 1500 m high. The geological structure of this zone has been identified to some extent by a number of multi-channel seismic reflection profiles across the Nankai Trough (Kato et al., 1983; Aoki et al., 1983; Kato, 1987). Migrated depth sections and their line drawings are shown in Figs. 10 and 11, respectively.

The landward slope of the Nankai Trough along every survey lile in Fig. 10 consists of well-deformed and acoustically obscure layers. In these layers, there are many thrust faults and fold structures due to

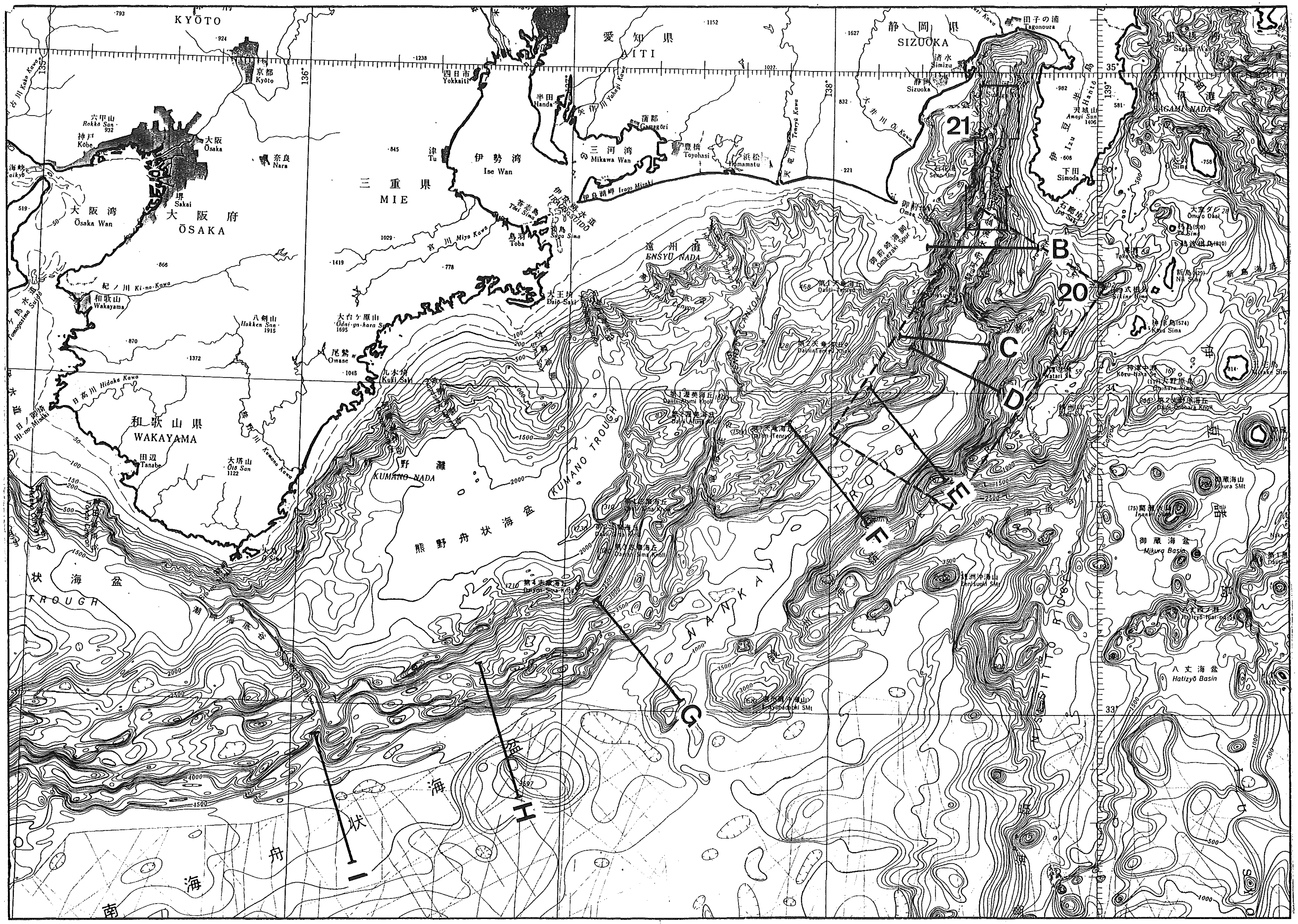


Figure 9. Bathymetric map of the eastern part of the Nanakai Trough (Hydrographic Department, Maritime Safety Agency, 1982) and locations of the multi-channel seismic reflection lines. Box with broken thick line shows the location of Fig. 13. Box in the Suruga Trough shows the location of Fig. 21. Contour interval 100m.

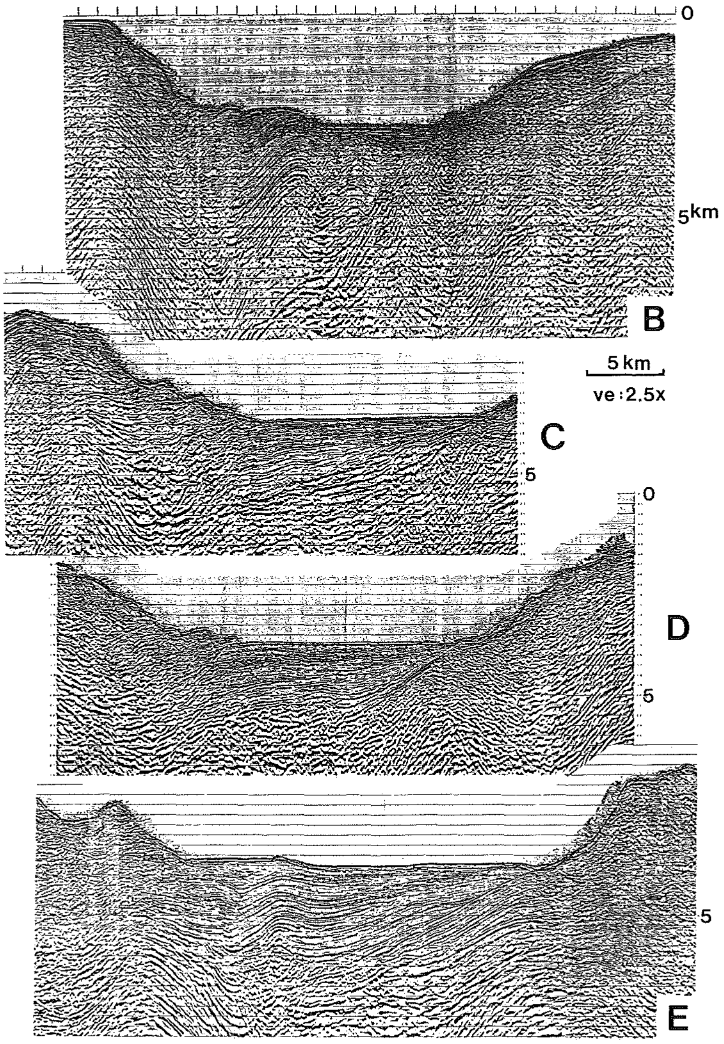


Figure 10. Depth sections of the multi-channel seismic reflection survey across the eastern part of the Nankai Trough. For location of profiles, see Fig. 9.

horizontal compression. The deformed layers at the foot of the landward slope on lines G and I are overthrusting onto the trough fill horizontal layers. From this it is considered that the layers of the landward slope resulted from the deformation of the trough fill layers and pelagic sedments deposited in the Sikoku Basin. The structure of the thrust faults at the foot of the landward slope along line I is the best example for examining of the process of the formation of landward slope layers (Fig. 12). An anticline is recognized as a newly built accretionary ridge at the foot of the landward slope. After the folding had occurred, the trough fill layer was displaced by the thrust faulting. An over-riding folding in western Nankai Trough, which seems to be a well-developed type of such deformation, was examined by the data from the Deep Sea Drilling Project (Moore and Karig, 1976). The faint anticline along seismic line E in the northeastern part of the Nankai Trough floor is thought to be a nascent ac-

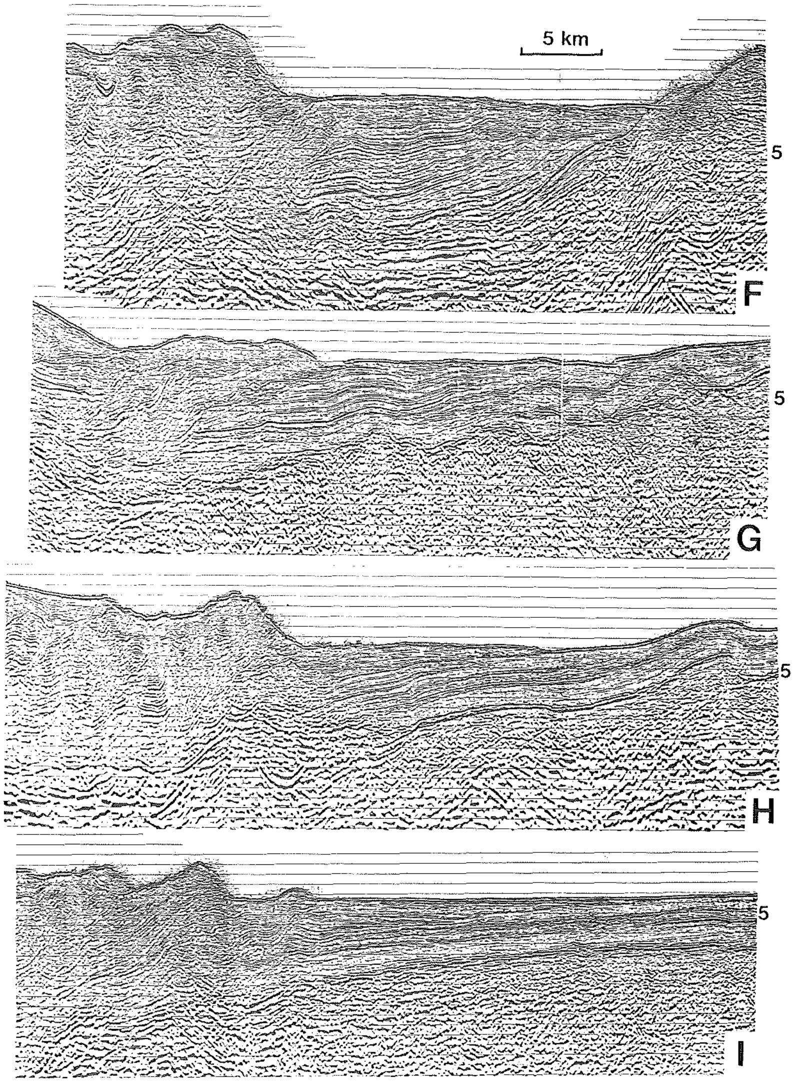


Figure 10. (Continued)

cretionary ridge, which will develop into a ridge on the landward slope. These seismic data indicate that the structure of the landward slope of the eastern part of the Nankai Trough presents typical imbricated tilt-shape deformed layers, or a so-called accretionary prism. The landward slope zone with a very undulated configuration along lines E and I, the so-called ridge and trough zone, is considered to be the morphological expression of an accretionary prism, an imbricated structure of the trench or trough fill and hemi-pelagic layers deformed by compressional stress due to plate subduction. These layers are welldeformed and divided into many inclined tilt-like blocks mutually bordered by thrust faults (Seely et al., 1974). The eastern part of the Nankai Trough has been surveyed by many sesimic surveys but only partially by Sea Beam survey, as shown in Fig. 13. Accordingly, it is difficult to discuss the detailed

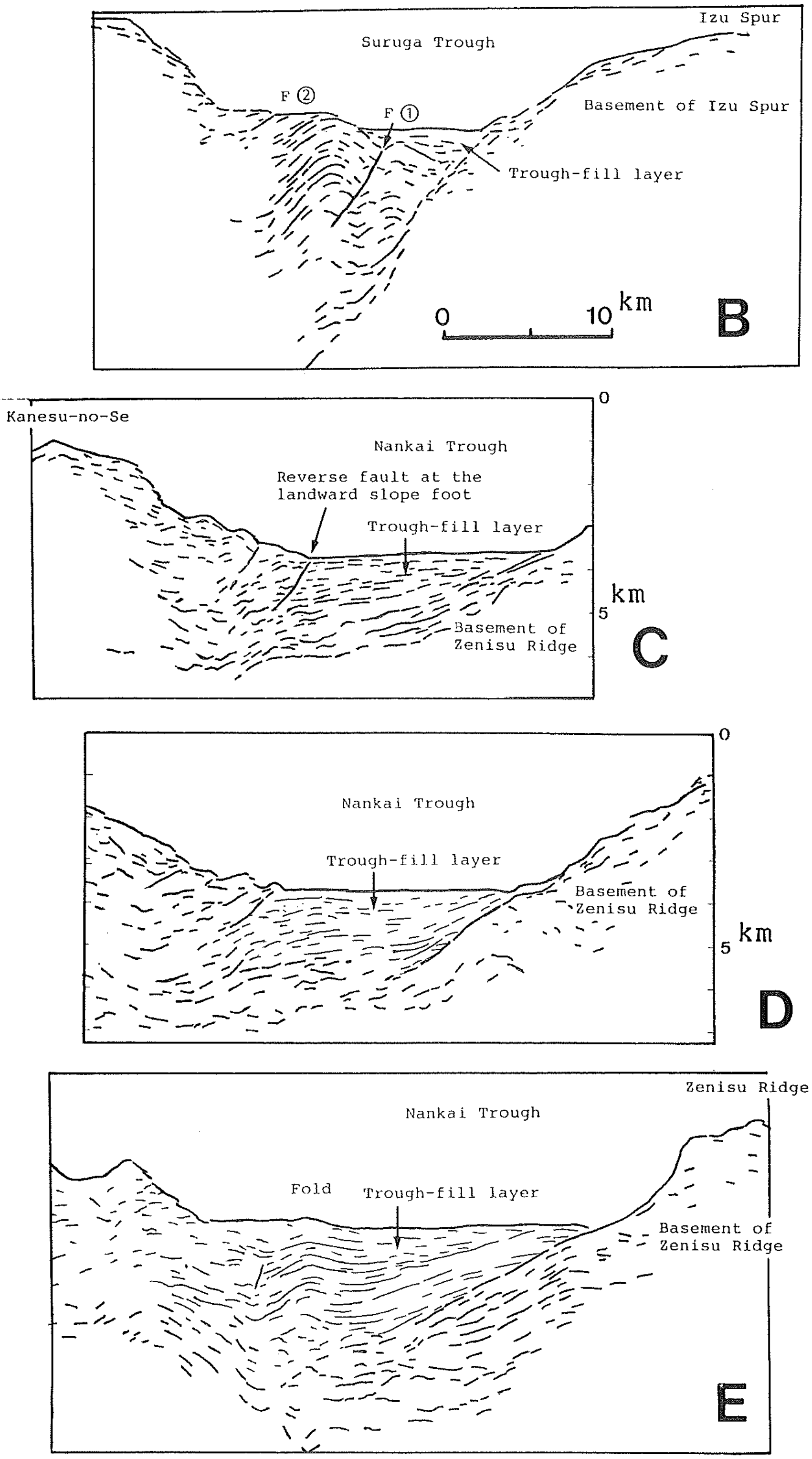


Figure 11. Line drawings of the multi-channel seismic profiles across the eastern part of the Nankai Trough. For location of profiles, see Fig, 9.

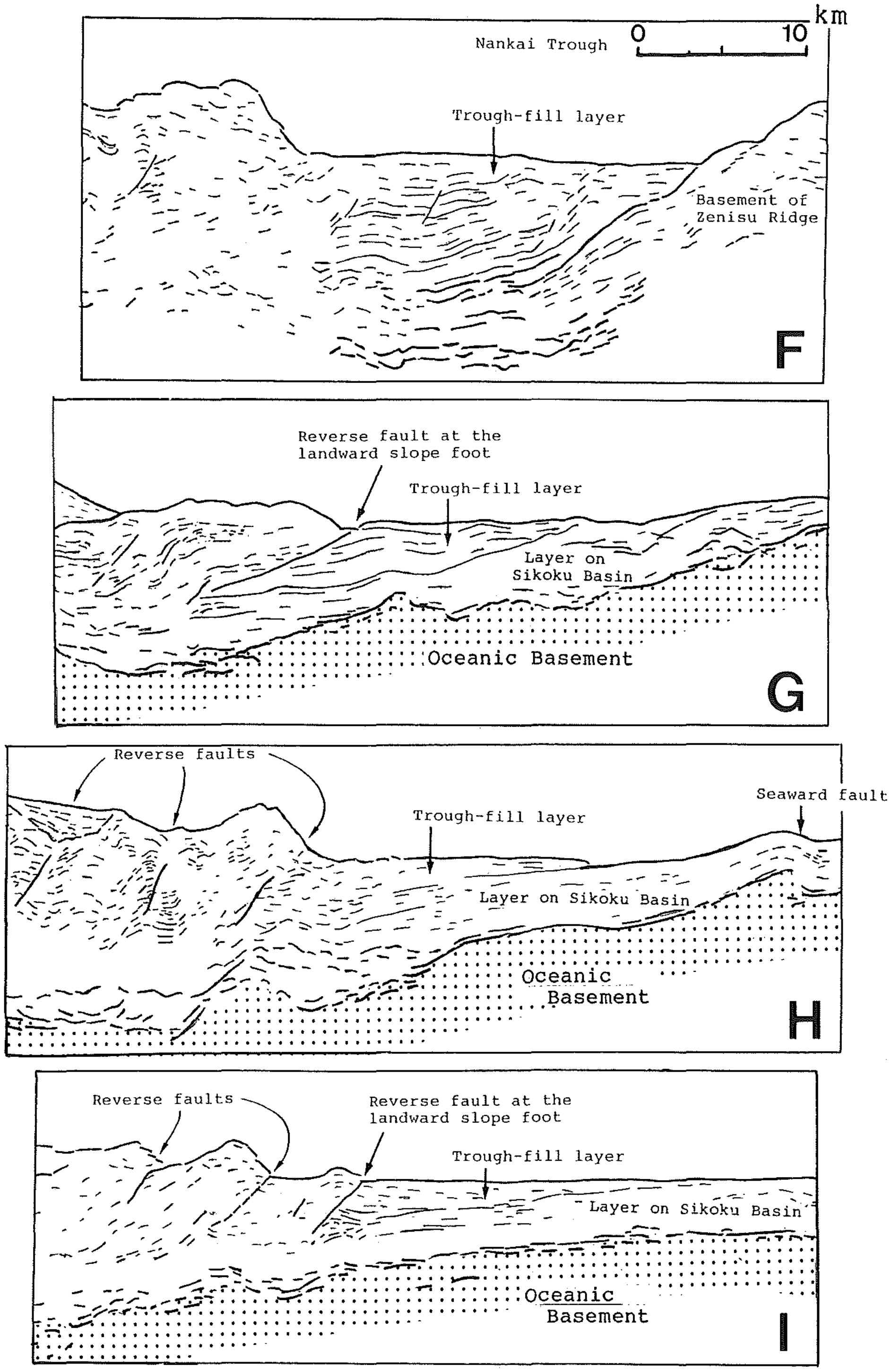


Figure 11. (Continued)

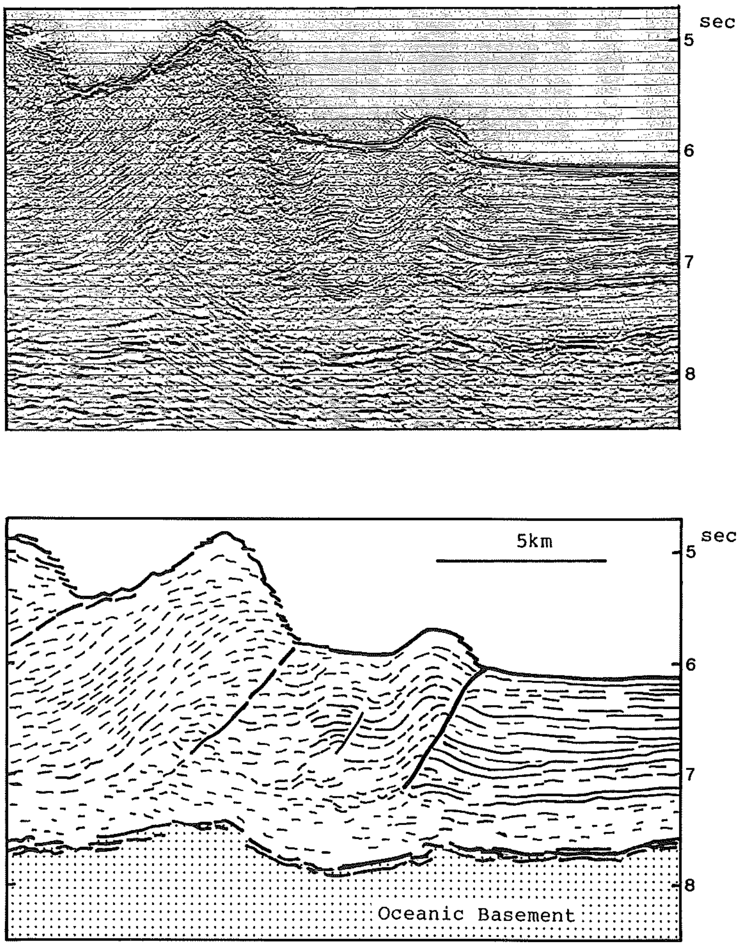


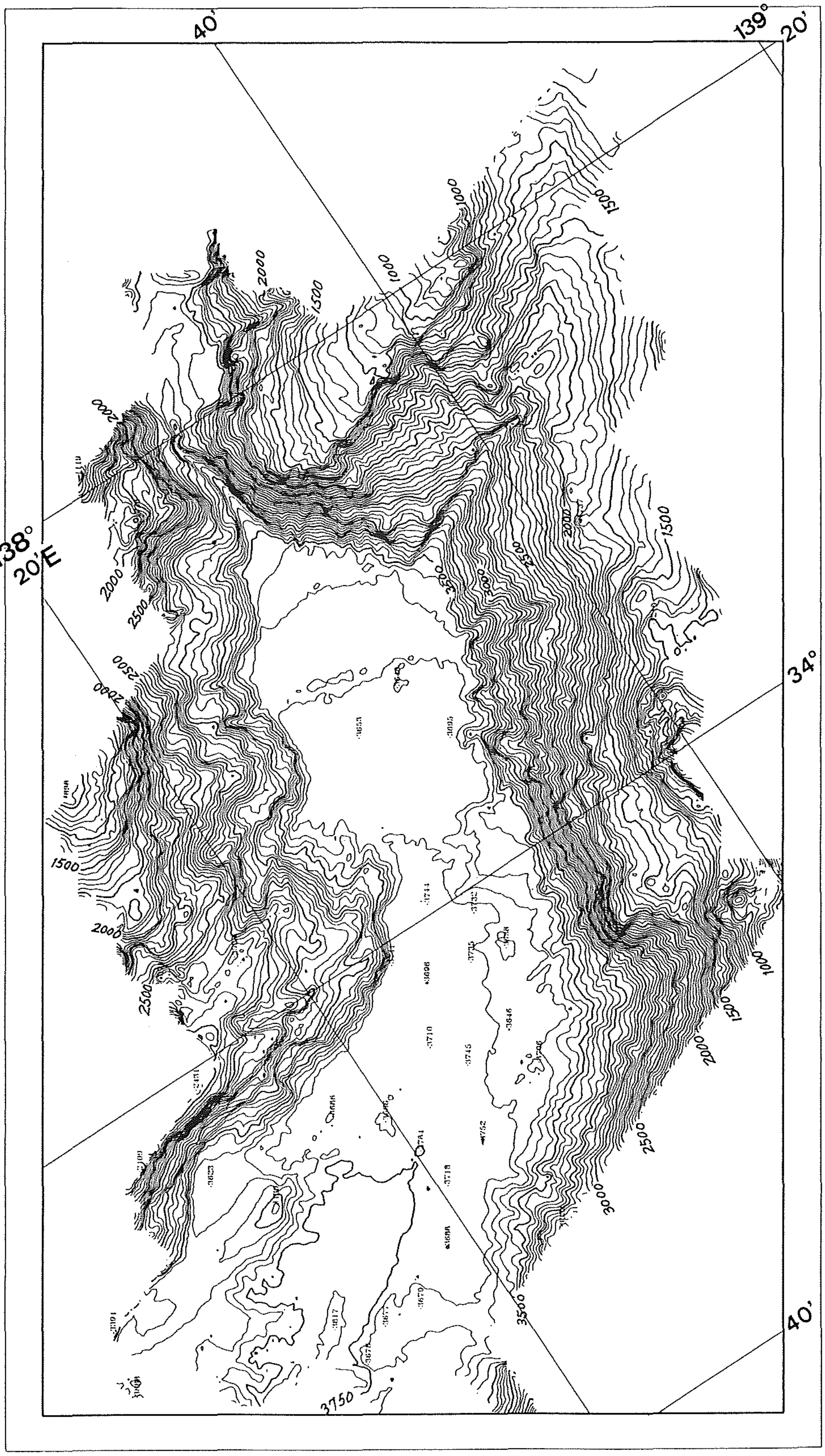
Figure 12. Enlarged migrated time section of the landward slope foot along line I across the Nankai Trough (above) and its line drawing (below).

geomorphology of this region at the moment. As and when detailed data become available, detailed discussion will be possible on this subject.

The trough fill layer in the eastern part of the Nankai Trough is very thick, so that there are sufficient materials to form accretionary prism, even though the hemi-pelagic sediment is thin. The landward slope of the Nankai Trough, including its western part (Kagami, 1985; Moore and Karig, 1976), is the most developed region of the accretionary prism on the landward slope of the plate boundary mentiond in this paper.

3. 2. 2 Flat trench floor and channels

The eastern part of the Nankai Trough off Kumano Nada and Ensyu Nada has a flat trough floor more than 10 km in width (Fig. 9). The multi-channel seismic sections in Fig. 10 show that the flat trough floor is formed by a wedge-shaped trench fill layer 2 to 3.5 km in thickness. Some channels are



CONTOUR INTERVAL = 50

Figure 13. Sea Beam bathymetric map of the northeast end of the Nankai Trough (Kaiko I Research Group, 1986). See Fig. 9 for location.

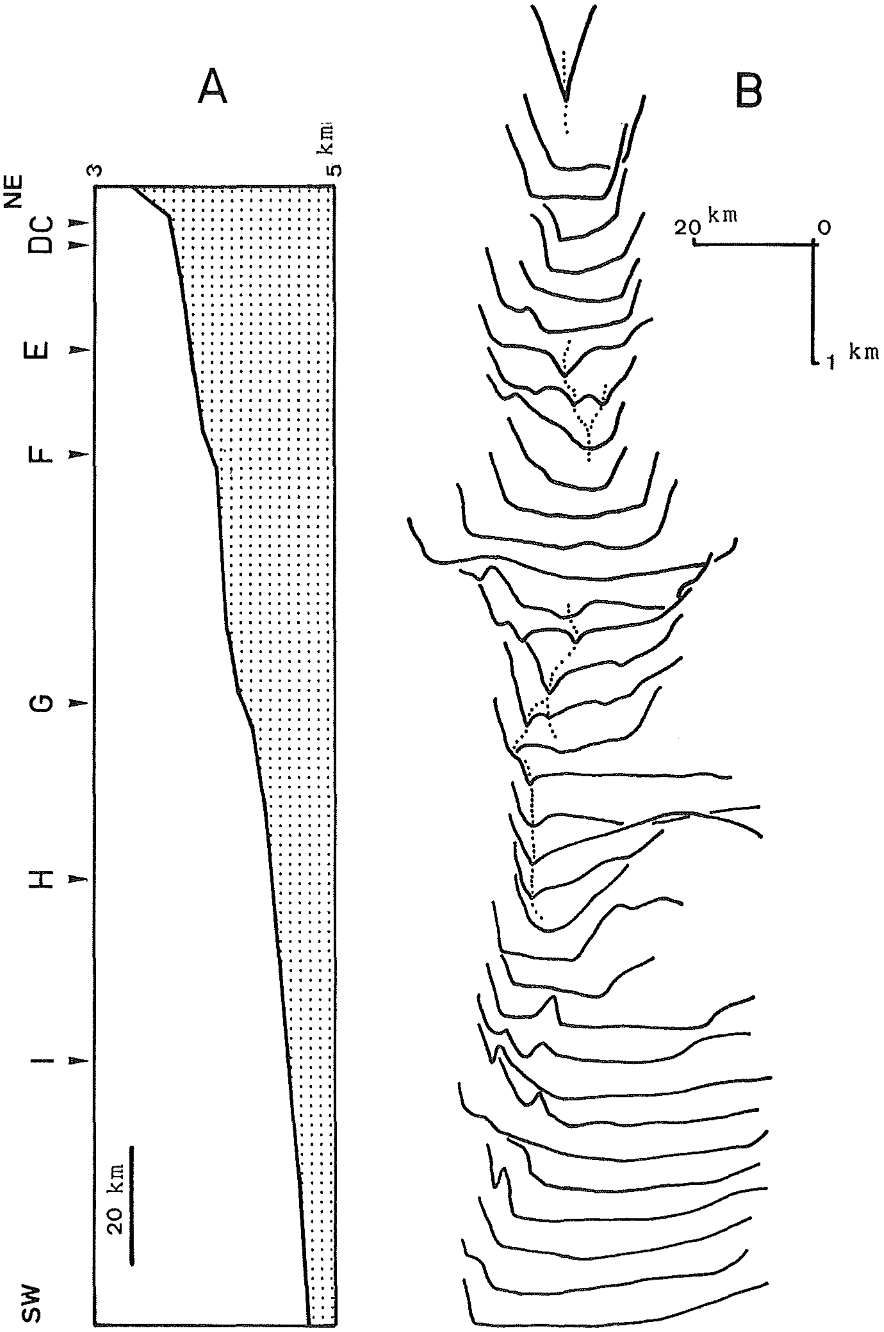


Figure 14. Bathymetric profiles of the eastern Nankai Trough. A: Longitudinal profile along the axis of the trough. C to I show the cross points of the seismic lines of Figs. 10 and 11. B: Cross-sections every 10 km; dotted lines show the small channels in the trough floor.

recognized on the trough floor from the bathymetric map of this area shown in Fig. 9. These channels, slightly meandering, can be traced to the SW or WSW. Remarkable channels are seen on the lines of seismic profiles F and G in Fig. 10. In some parts of the trough floor, however, no channel is seen. It appears that trough floor with channels and very flat floor without channels alternate. Longitudinal and cross-sections of the eastern part of the Nankai Trough are shown in Fig. 14. Here the trench floor deepens gradually to SW. The trough floor with channels shown by dotted lines in Fig. 14 corresponds to the slightly steep portion on the longitudinal section. On the other hand, the very flat trough floor without channels corresponds to the more gentlly sloping portion.

This difference in the degree of development of channels may be due to undulations of the subduction plate along the trough axis, and these undulations may owe their origin to fingering subduction. The finger-like configurations of the Philippine Sea plate are recognized in the micro earthquake zone beneath the Tokai district (Yamazaki and Ooida, 1985), supporting the above-mentioned theory of the origin of the undulations.

The trough fill layer mainly consists of terrigenous turbidite transported through the Suruga Trough (Taira et al., 1984). Therefore, it is probable that the channels on the trough floor served as routes for the sediment flow towards the SW. On the multi-channel seismic sections in Fig. 10, there is a relatively old trough fill layer, slightly deformed by the fold structure and faults, at lines F and G where channels are developed. In contrast to this, the trough fill layer across seismic lines C, D and I shows a very flat feature without channels, consisting of an undeformed horizontal Quaternary layer.

From these observations itis inferred that the trough floor without channels may be the area where turbidite is being deposited, while the trough floor with channels may be the area where sedimentation of turbidite has been suspended. The distribution of the channels in the eastern part of the Nankai Trough has been examined on the bathymetric chart prepared from the data of sounding along tracks spaced at 2 nautical miles. This specific feature is also recognized on the detailed bathymetric map prepared by the Sea Beam system data (Fig. 13). Almost all of the area shown in Fig. 13 shows a very flat trough floor without a channel, and a channel head is recognized in the western part from 138°20' E.

3. 3 Palau Trench

3. 3. 1 Outline of the Palau Trench

The Palau Trench is situated in the southernmost part of the Izu-Ogasawara-Mariana Trench system extending along the eastern margin of the Philippine Sea. The Yap Trench and the Palau Trench are arranged in right-stepped manner from the southern extremity of the Mariana Trench. Tayama (1935) described it as follows: "The Palau Trench lies in echelon on the west side of the Yap Trench. It extends north and south in a slightly convex form towards southeast. The width of the trench is 30 nautical miles, and the maximum depth is 8,138 meters located to the east of Babelthuap Island, which is the main island of the Palau Islands".

Fisher (1974) reported that rugged peaks and ridges lie on the seaward slope of the trench axis and that the trench bottom is V-shaped on the basis of the analysis of several bathymetric profiles of the trench. Weissel and Anderson (1978) considered that the Palau Trench is located at the boundary where the Caroline plate is subducting beneath the Philippine Sea plate. The geological structure indicating subduction was recognized by the onboard monitoring of multi-channel seismic propiling carried out across the Palau Trench (Tokuyama et al., 1985a). The convergence rate of the subduction boundary has been estimated as very low (Wu, 1979; Circum-Pacific Map project, 1981).

Bathymetric survey of the Palau Trench using a Sea Beam system was carried out by the *Takuyo* (Kato et al., 1986). This chapter presents the geomorphological description of the northern Palau Trench on the basis of the detailed bathymetric map Prepared and discusses the tectonics and geomorphological

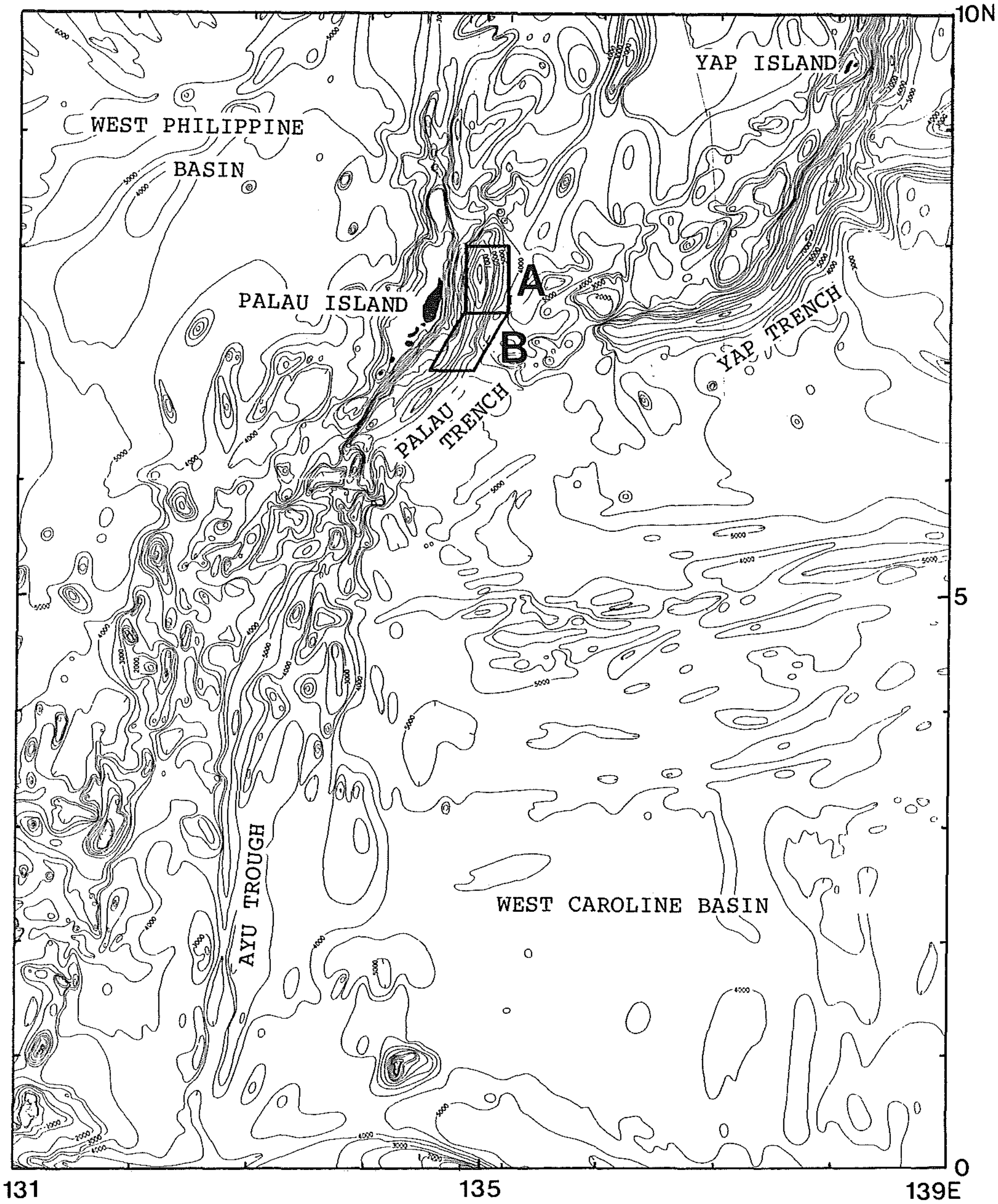


Figure 15. Bathymetry of the Palau and Yap Trenchs and Sea Beam survey areas. A: Northern box (Fig. 16), B: Central box (Fig. 18).

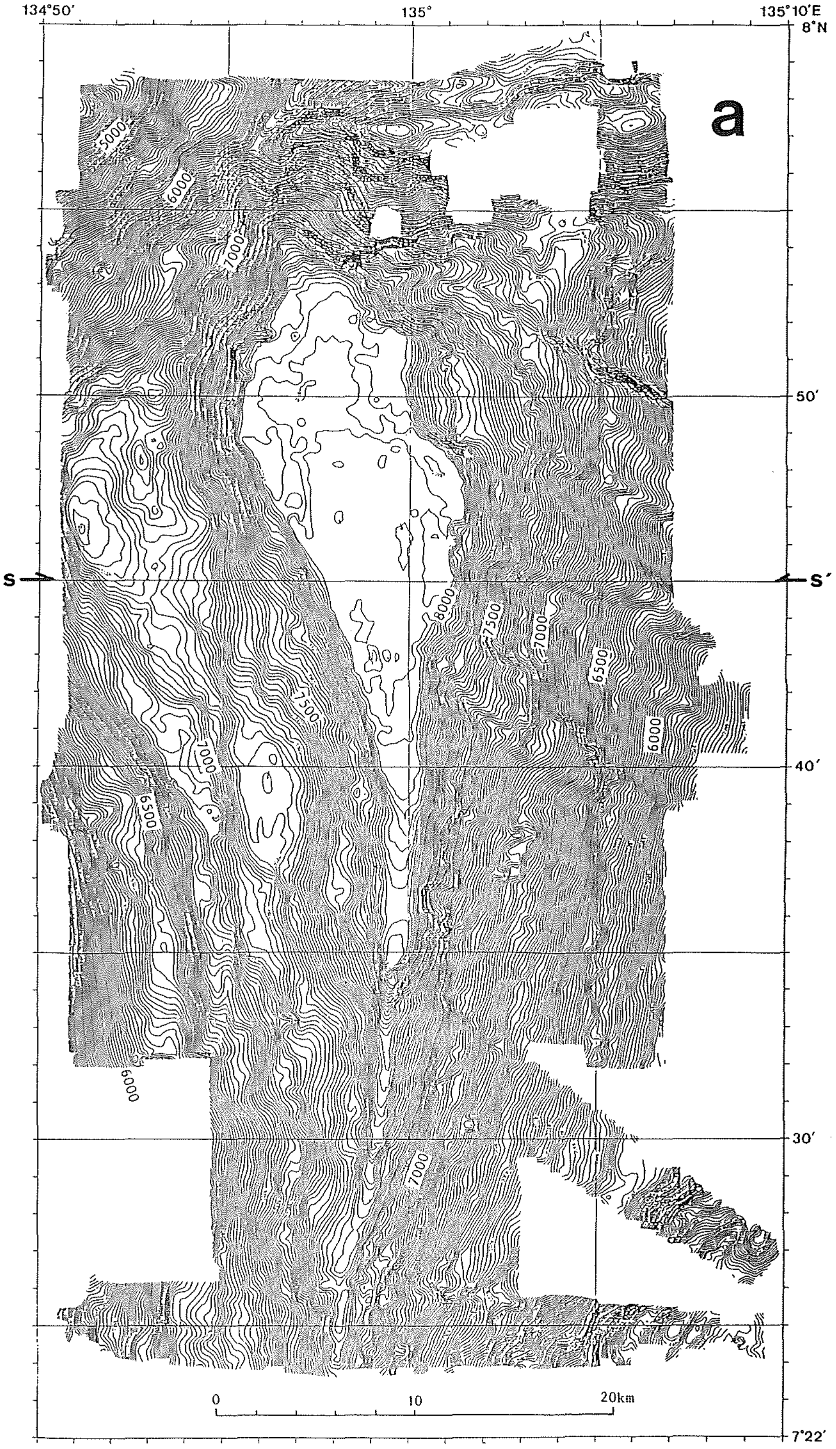
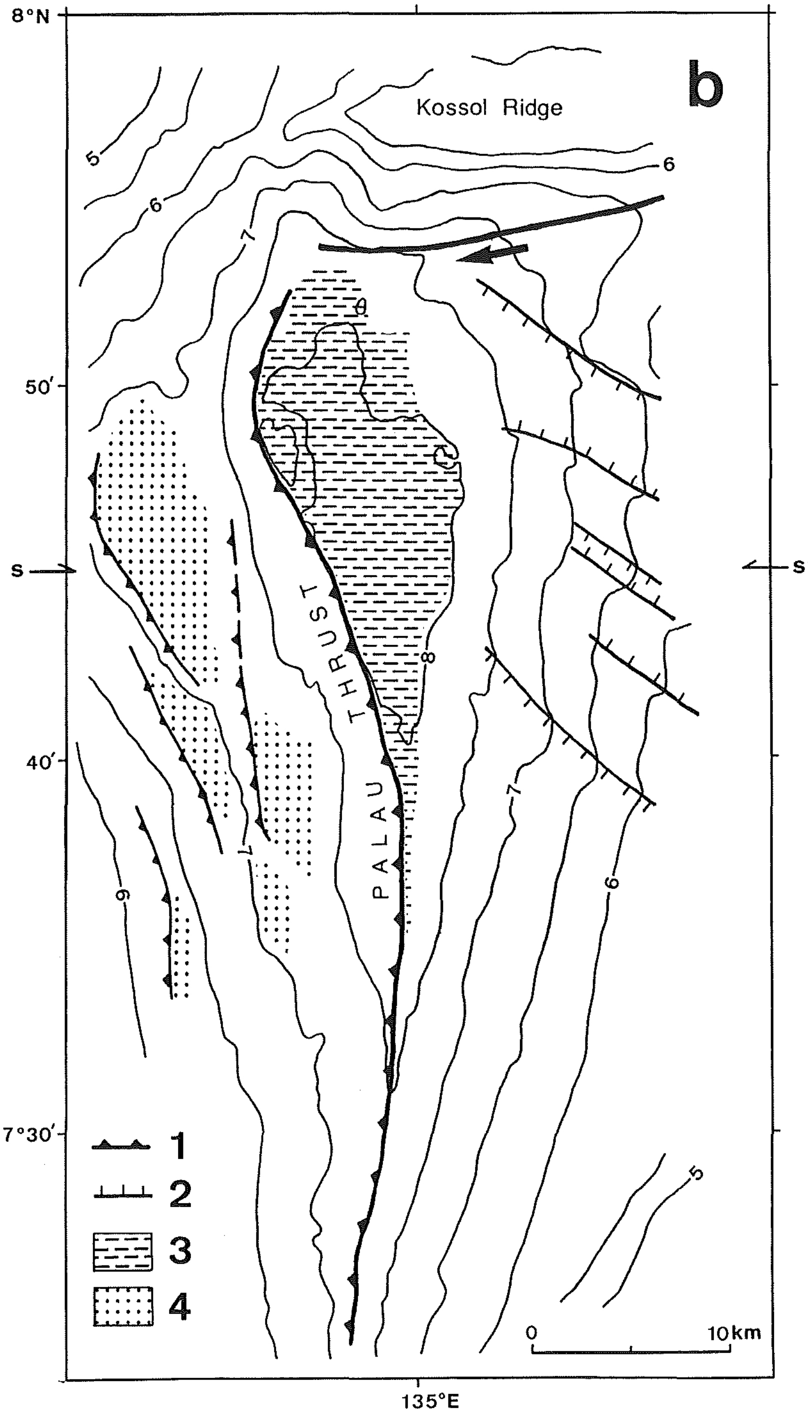


Figure 16. Detailed bathymetry of the northern part of the Palau Trench. Line s-s' shows the location of the seismic profile in Fig. 19. a: Sea Beam map. Contour interval 20 m. b: Structural features. 1: Thrust fault, 2: Normal fault, 3:"Tear drop" flat trench floor, 4: Step in the landward slope.



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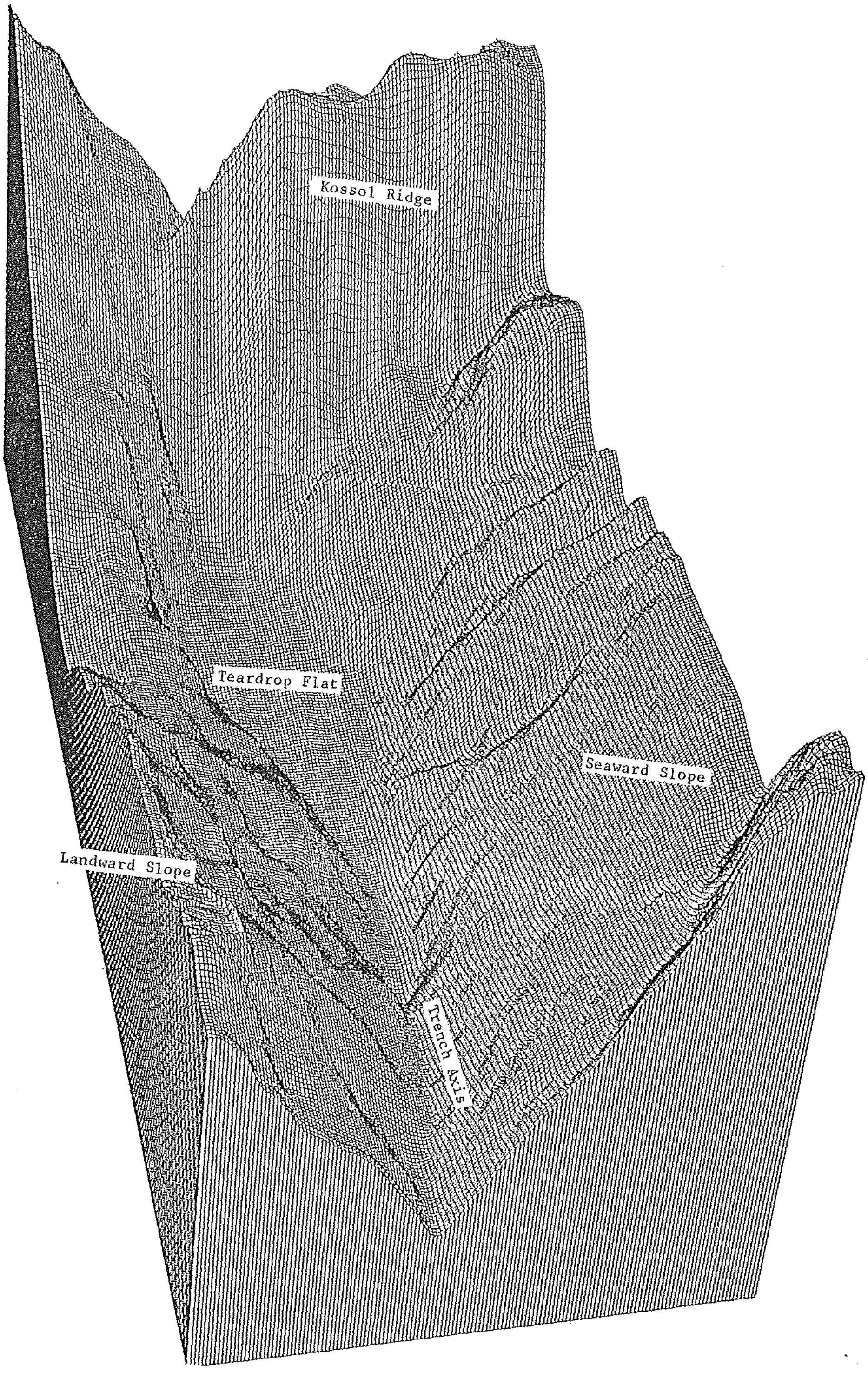


Figure 17. Three-dimensional image map of the northern part of the Palau Trench.

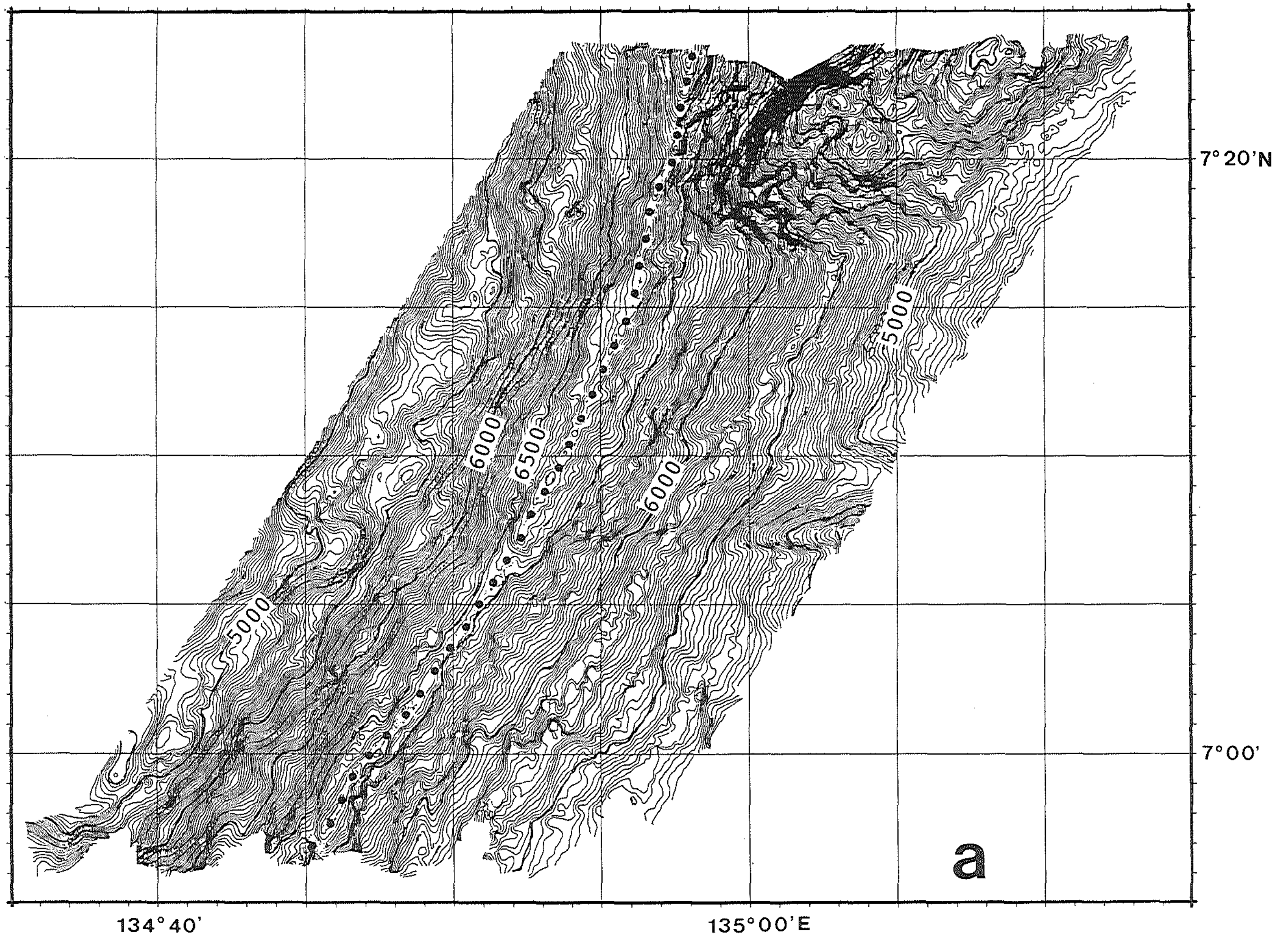


Figure 18. Detailed bathymetry of the central part of the Palau Trench. a: Sea Beam map. Dotted line shows the axis of trench. Contour interval 10m. b: Structural features. 1: Thrust fault, 2: Lineament, 3:Step in the landward slope, 4: Seamount in the seaward slope.

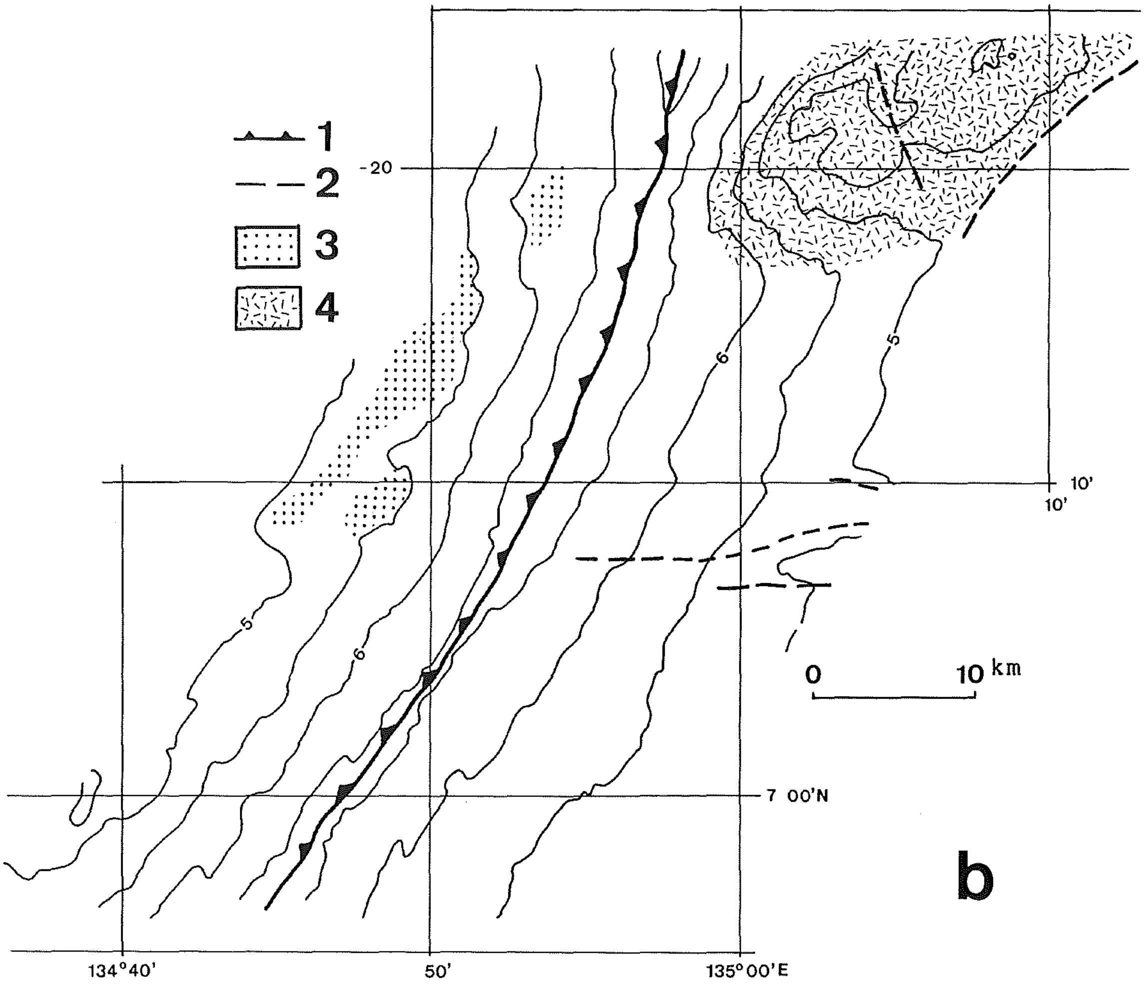


Figure 18. (Continued)

history of the Palau Trench.

3. 3. 2 Sea Beam survey and detailed morphology of the northern Palau Trench

The survey area is shown in Fig. 15. A bathymetric chart obtained from this survey is shown in Fig. 16a. Figure 17 is a three-dimensional view of the area drawn on the basis of Fig. 16a, viewed from the SSW and exaggerated vertically about 8 times.

Geomrphologically, the area surveyed consists of a trench axis-floor, a landward slope, a seaward slope and the Kossol Ridge. A flat broad trench floor, 9 km wide and 23 km long, exists at the extreme north of the trench. Water depths to the floor range from 8,000 to 8,040 meters. This flat floor is in a teardrop shape, wider in the north and narrower to the south. A trench with a V-shaped profile axis like a canyon extends from the teardrop-shaped flat southward to the central part of the Palau Trench, as

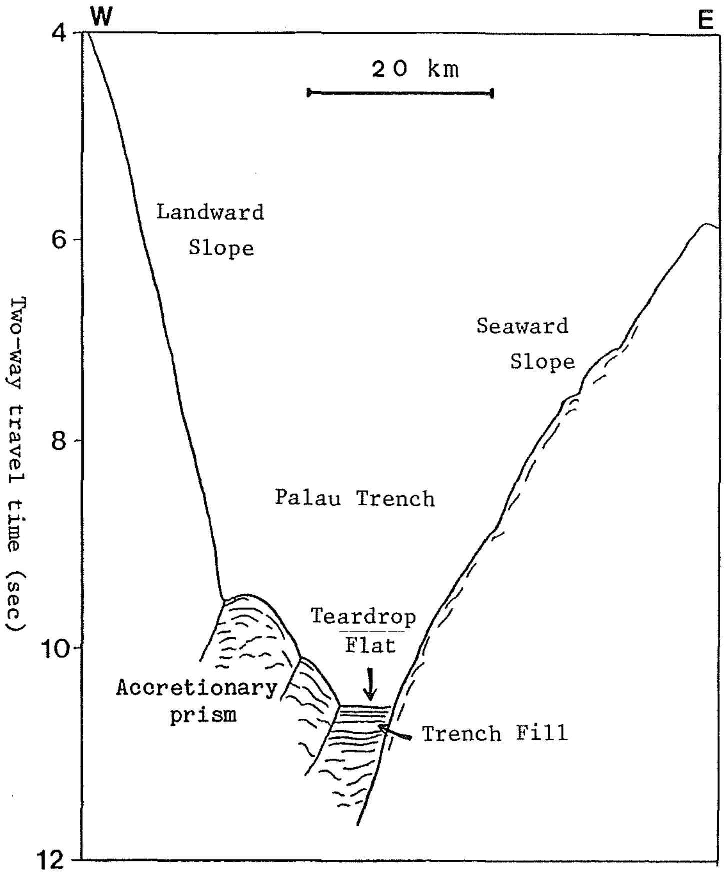


Figure 19. Line drawing of a seismic section across the northern part of the Palau Trench (Tokuyama et al., 1985a). For location of seismic line, see Fig. 16.

shown in Fig. 18, decreasing in depth.

Several deep sea steps at depths of 6300 to 7200 meters are recognized on the landward slope of the trench. The largest deep sea terrace in this area is located to the west of the teardrop flat, while small terraces are distributed to the south.

The seaward slope of the trench monotonously inclines at about 10 degrees without such steps as on the landward slope. However, many parallel lineations in NW-SE direction are recognized on the seaward slope to the north of 7°50'N.

A ridge extends east-west at the north of the trench. This ridge is named "Kossol Ridge" in this paper because it is situated east of Kossol Reef in the Palau Islands. Kossol Ridge puts an end to the Palau Trench as if it collided against the eastern slope of the Palau Islands. The summit of the Kossol Ridge is 5,000 to 5,200 m deep, and about 3,000 meters heigher than the teardrop flat. The southern slope of the ridge is the steepest slope in the survey area and extends to the east.

3. 3. 3 Discussion on the formation of the trench features

The detailed bathymetric data thus presented allow some interpretation of the geological history of the trench with reference to the seismic profile there (Tokuyama et al., 1985a). The geological structure indicating the subduction can be recognized on the seismic profile illustrated in Fig. 19. The profile runs east-west across the teardrop flat along 7°46'N (s-s' in Fig. 16).

Tokuyama et al. (1985a) pointed out the existence of a turbidite wedge layer beneath the trench floor, slight development of an accretionary prism on the lower part of the landward slope, and a graben structure on the seaward slope.

With reference to the above-mentioned geological structure, it may be considered that the tectonics and the development of the morphology of the northern Palau Trench are as follows:

The Caroline plate probably subducts beneath the Palau Island arc from the east. The convergence rate at the Palau Trench has been estimated as 1 cm per year by Weissel and Anderson (1978). Depths of over 8,000 meters indicate that the Palau Trench is subducting at a plate boundary. Compared to the other trenches, the Palau Trench has peculiar characteristics such as lack of volcanoes along the Palau arc, obscurity of the deep earthquake zone, i. e. the Wadati-Benioff zone (Circum-Pacific Map Project, 1981), proximity of the axis of the Palau arc to the trench axis, and small-scale geological structures only indicating the subduction. The reason for this may be considered as follows: the Palau Trench is a nascent convergent boundary, where the convergent rate is very low, or the subducting dip is very steep.

The teardrop flat has been filled by turbidite supplied mainly from the south via the V-shaped trench axis. The wedge-shaped trench fill layers are pressed against the slope, due to the subduction of the plate. Consequently, an accretionary prism was developed at the lower part of the landward slope. The accretionary prism is more developed in the northern part of the Palau Trench, which is filled with thicker trench fill sediments. At the northern Palau Trench, the trench axis is close to the axis of the island arc. An accretionary prism forms step-like topography. Another type of step-like topography formed by accretion is recognized along the Suruga Trough where the landward mass is close to the trench axis and the subduction slub subducts at a steep angle (Kato et al., 1983).

There is a possibility that the Kossol Ridge constitutes the western end of the Yap island arc, and that the southern margin of the ridge is the right-lateral transform boundary. This is based on the morphological characteristics of the Kossol Ridge. Discrepancy in strikes between the Palau and the Yap arcs is obvious. Accordingly, a plate boundary connecting the Palau Trench and the Yap Trench is expected to exist between them. To find its exact location, more extensive data are necessary.

Lineations of NW-SE direction on the seaward slope (Fig. 16b) probably correspond with the faults bounding graben structures or anticlinal-synclinal structures. In general, a graben structure of the seaward slope is caused by the tension of the plate bending. The strike of the structure, NW-SE, may suggest, however, that the stress field due to bending is distorted by the effect of the existance of the Kossol Ridge, which might show westward collisional movement relative to the Palau arc. On the basis of these assumptions, a tectonic map of the northern Palau Trench is drawn as in Fig. 16b.

3. 3. 4 Central part of the Palau Trench

As is clear on the Sea Beam map in Fig. 17, the central part of the Palau Trench shows a V-shaped axis, and the seaward slope shows a smooth, moundless surface, inclining at 4 to 6 degrees. Small-scale lineaments, possibly due to normal faults, are distributed on the seaward slope of the northern part of the Palau Trench, but no lineament or fault is recognized on the seaward slope of the central part of the Palau Trench (Fig. 18b).

3. 4 Characteristics of other trenches around Japan

3. 4. 1 Challenger Deep in the Mariana Trench

The Challenger Deep in the southern part of the Mariana Trench, which was said to have the deepest point on the earth, is selected as an example of the Sea Beam survey results. Many bathymetric surveys were carried out at the deep in the 1960s.

The Mariana Trench, a part of the Izu-Ogasaxara-Mariana Trench system, is largely arched toward the east. The Pacific plate eastward of the Mariana Trench subducts WNW-ward at a rate of 11 cm per year (Circum-Pacific Map Project, 1981). The Mariana Trench is divided into several parts by seamounts belonging to the Magellan Seamounts on the Pacific plate (Sato, 1969). The Challenger Deep is situated in the southern part of the Mariana Trench, where the trench axis extends in the east-west direction (Fig. 1).

A bathymetric survey in the Challenger Deep was carried out by the S/V *Takuyo* in February 1984, along the trench axis and at the deepest portion reported. Track lines are shown in Fig. 20a. In order to measure exactly the depth of the world's deepest point, and additional line was surveyed across the point right above the deepest portion after finishing the survey along the planned lines. The reason for this was to obtain the maximum depth with a vertical beam of the Sea Beam System. The vertical beam is more accurate than the slant beam as the latter contains more scattering reflection and requires additional correction to the beam bending due to the difference in sound velocity through the water column. The soundings were corrected by the directly measured sound velocity data which were provided in the survey area by continuous measurement of vertical water temperature and salinity down to 4,500 meters deep with a continuous depth, temperature and salinity measurement system. For sound velocity data of deeper zones, the deep-sea measurement results by Mantyla and Reid (1978) were used. The data shallower than 4,500 meters collected by the *Takuyo* were harmonized with the data deeper than 4,500 meters by means of the method of Mantyla and Reid (1978).

The deepest depth of the Challenger Deep was obtained as 10,924 meters by the survey of the *Takuyo* during that cruise. This depth was obtained by the multi-narrow beam sounding which covered almost 100% of the target area, and was carefully corrected for the velocity of sound in sea water. The survey also revealed that the deepest point was located not in the previously reported positions, but rather at the eastern part of the Deep (* in Fig. 20).

The characteristics of the geomorphology of the Challenger Deep are illustrated in Figs. 20b and 20c. The axis of the trench extends from ENE to WSW, and echelon depressions are formed along the axis. Linear ridges are recognized at 5 to 7 km intervals on the seaward slope of the trench. The ridges, with relative heights of 200 to 700 meters, extend obliquely to the trench axis. The angle between the direction of these ridges and the trench axis is about 5 degrees. These oblique ridges may be formed by the resultant force of the oblique subduction and the bending of the Pacific plate. The landward slope of the trench in the survey area presents a mono-slope inclining 3 to 13 degrees.

3. 4. 2 Suruga Trough

The Suruga Trough extends NNEward into Suruga Bay from the eastern extremity of the Nankai

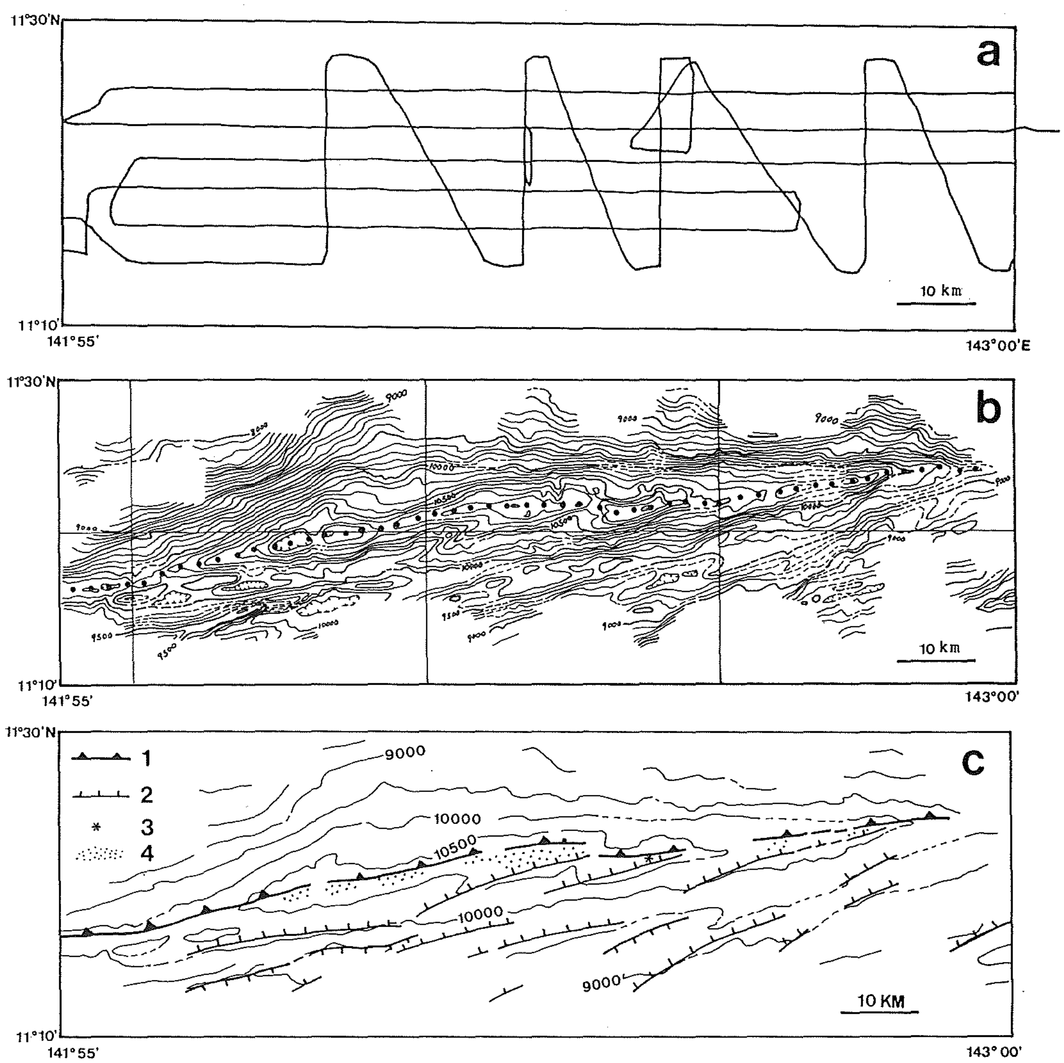


Figure 20. Detailed bathymetry of the Challenger Deep in the Mariana Trench. a: Track chart. b: Sea Beam map. Dotted line shows the trench axis. Contour interval 100m. c: Structural features. 1: Thrust fault, 2: Normal fault, 3: Deepest point of the Challenger Deep, 4: Flat floor of the trench axis.

Trough, and is believed to be the plate boundary where the Philippine Sea plate subducts beneath the Eurasian plate as well as the Nankai Trough. The floor of the Suruga Trough is very narrow less than 5 km in width, compared with that of the Nankai Trough, which is 10 to 30 km in width. The landward slope of the Suruga Trough is characterized by a step-shaped configuration in the middle of the steep slope, each step of which is 1 to 2 km in width and 2 to 4 km in length. This step-shaped topography is obvious on the bathymetric map from Sea Beam data shown in Fig. 21. The structure of the landward slope of the Suruga Trough can be detected in the multi-channel seismic reflection profiles shown in Figs. 10-B and 11-B.

The lowest part of the slope consists of layers with distinct fold structures, and the axis of the anticline renders an elevated configuration. There is a fault inclined to the west between the eastern

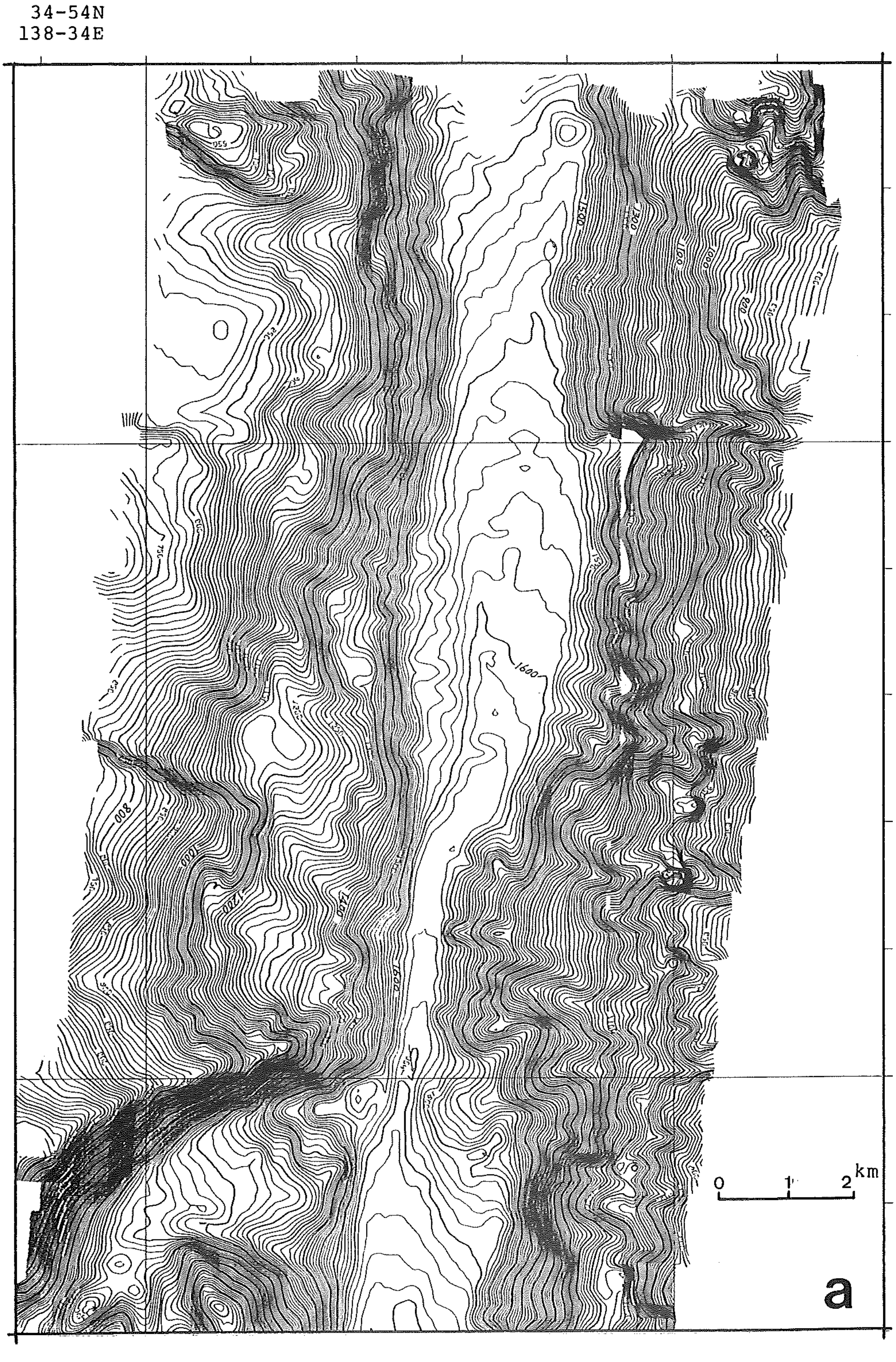
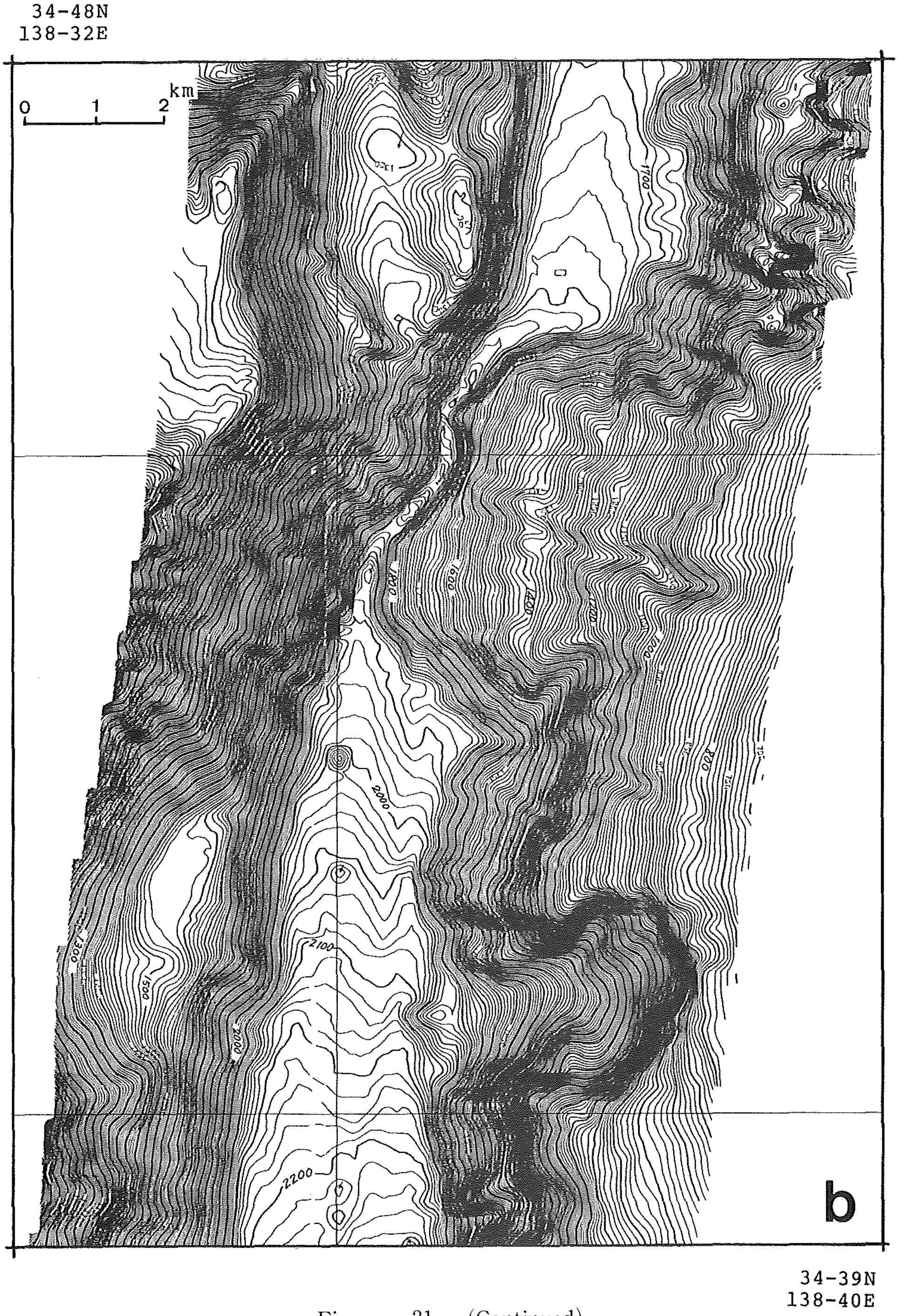


Figure 21. Sea Beam map of the Suruga Trough. Contour interval 10m. a: northern part, b: central part, c: southern part.



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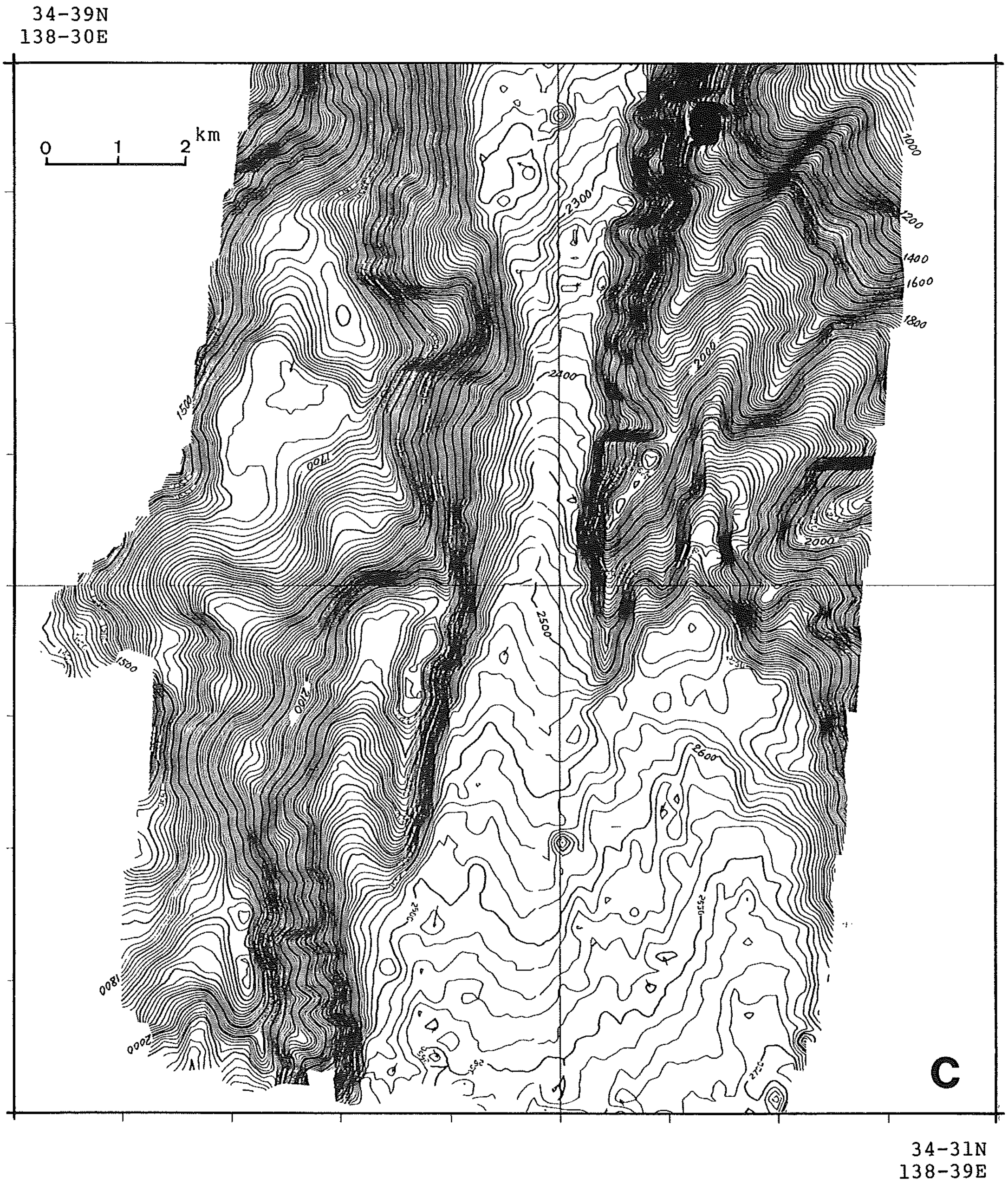

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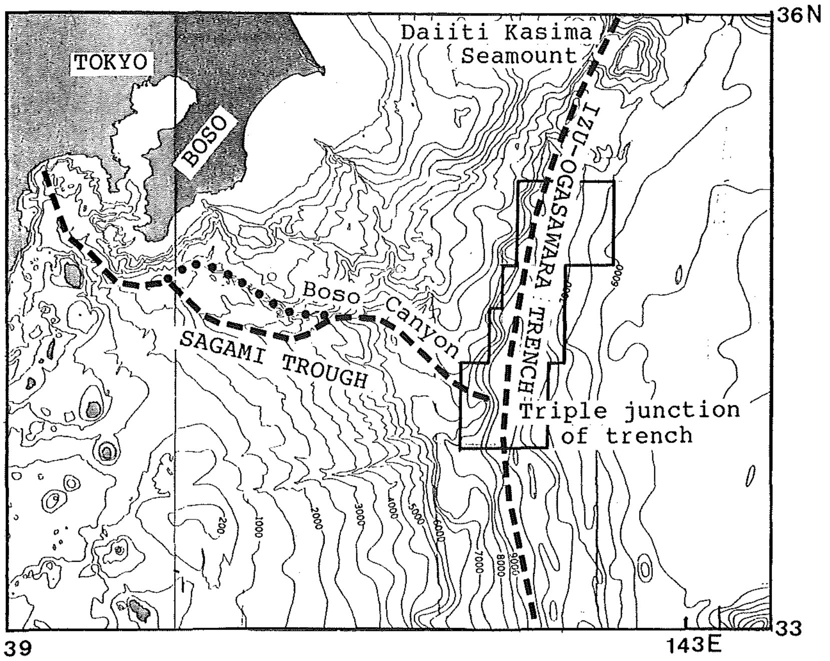


Figure 22. Location map of the triple junction of trenches off Central Japan. Broken line shows the plate boundary; box shows the location of Fig. 23. Bathymetry from Japan Oceanographic Data Center (1984).

wing of the fold and the horizontal layer of the trough floor (F1 in Fig. 11-B). This fault is thought to be a reverse fault because of the form of the acoustic reflectors. Many steps are developed in the middle of the landward slope. Although it is difficult to detect the continuity of the fault line from the acoustic refectors, a reverse fault is known to form the step geomorphology at F2 in Fig. 11-B. From the above, it appears that the reverse faults incline to the west from the foot of step-shape morphology, and the deformed structure shows the accreted layer of the trough floor, or accretionary prism.

Narrow flats and gorges lie alternately on the Suruga Trough floor. On the detailed bathymetric map of the Suruga Trough shown in Fig. 21, the gorges appear to be the transportation route for turbidite, as there are no trench fill layers.

3. 4. 3 Triple junction of trenches off central Japan

The triple junction of trenches whose detailed bathymetric map is shown in this section is the meeting point of the Izu-Ogasawara Trench and the Sagami Trough off the Boso Peninsula of central Japan (Fig. 22). It is believed that the southern part of the Sagami Trough belongs to the Philippine Sea plate and the eastern area of the Izu-Ogasawara Trench belongs to the Pacific plate. The northern part of the Sagami Trough has been considered to belong to the Eurasian plate (Sugimura, 1972). However, Nakamura (1983) and Kobayashi (1983) proposed a nascent plate boundary between northeast Japan and

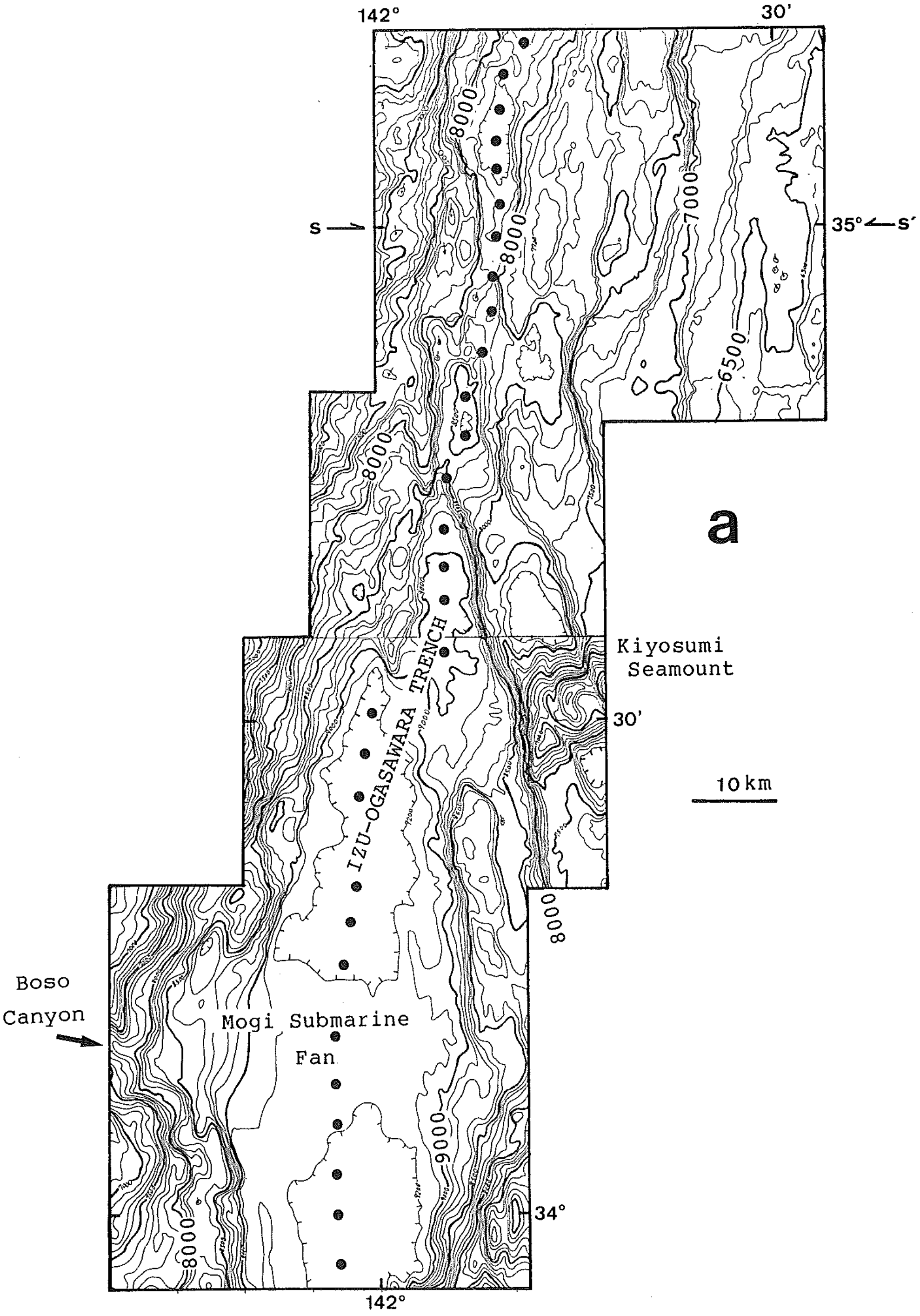
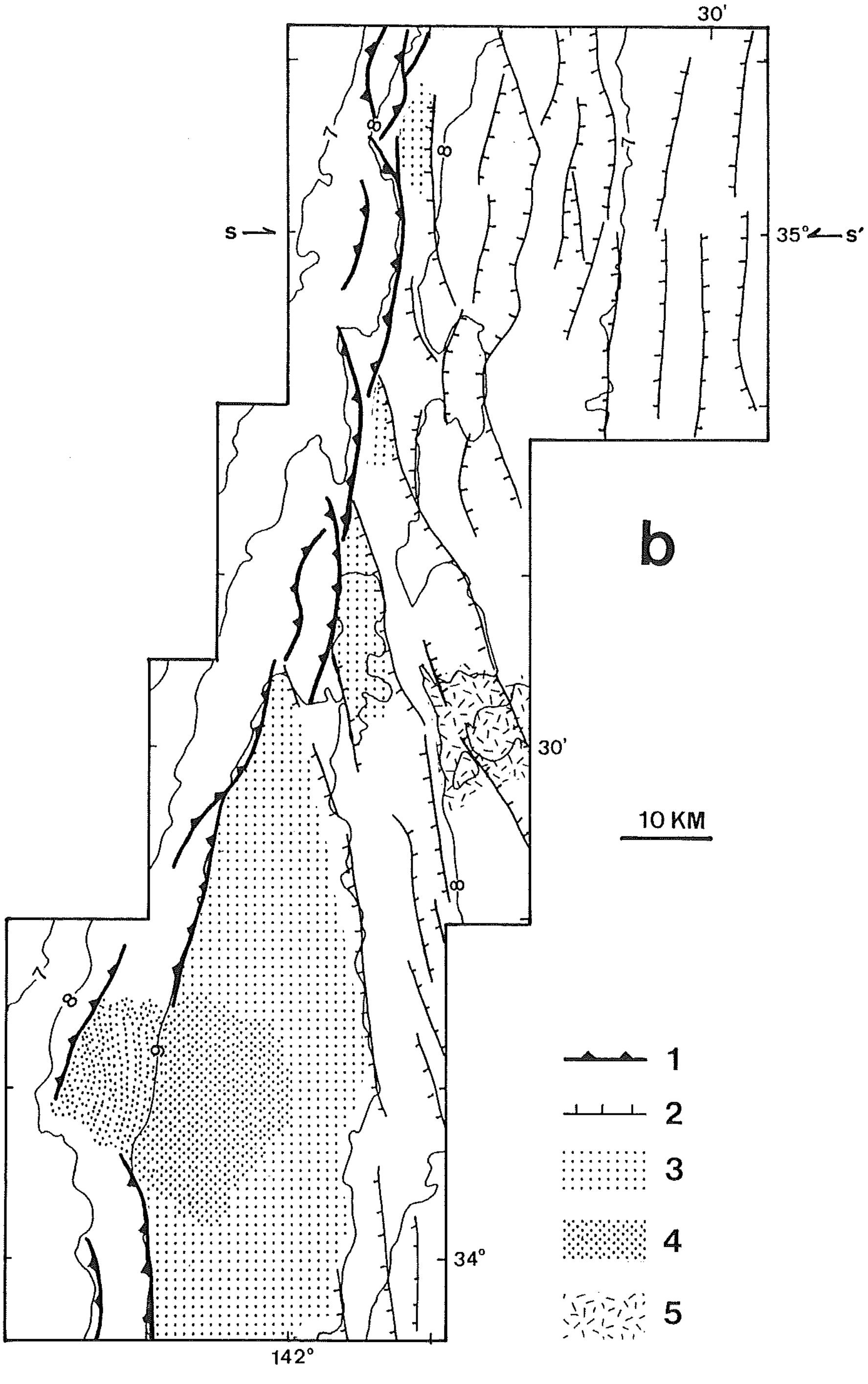


Figure 23. Detailed bathymetry of the northernmost part of the Izu-Ogasawara Trench. Line s-s' shows the location of the seismic profile in Fig. 24. a: Sea Beam map. Contour interval 100m. Dotted line shows the trench axis. b: Structural feature of the northern end of the Izu-Ogasawara Trench. 1: Thrust fault, 2: Normal fault, 3: Flat trench floor, 4: Mogi Submarine Fan at the eastern end of the Sagami Trough, 5: Kiyosumi Seamount broken by the normal faults.



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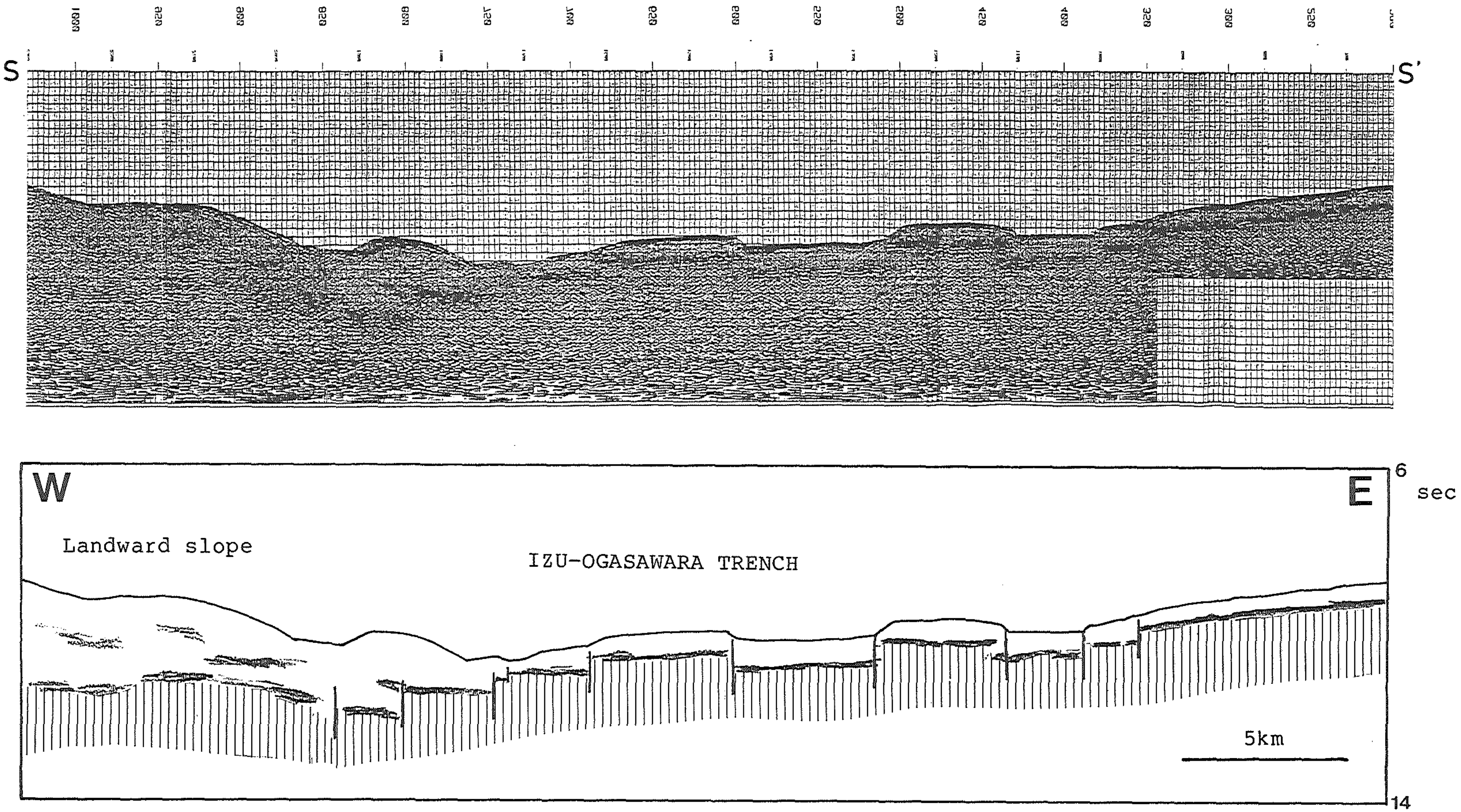

Figure 24. Migrated time section of the multi-channed seismic survey across the northernmost part of the Izu-Ogasawara Trench (above) and its line drawing (below). Location is shown in Fig. 23.

the Japan Sea, and the north side block of the Sagami Trough is now considered to be a part of the North American plate (Niitsuma, 1985) or a micro-plate of northeast Japan (Ishibashi, 1984). This block is called 'the northeast Japan block' in this study. The Pacific plate subducts benecth the northeast Japan block at the Izu-Ogasawara Trench at the average rate of 10.5 cm per year, while the Philippine Sea plate moves NW towards the northeast Japan block at the average rate of 4 cm per year (Circum-Pacific Map Project, 1981).

The morphology of the trench floor at the triple junction in the Izu-Ogasawara Trench is characterized by a very wide, extremely flat floor 20 km in width at depths of 9,100 to 9,200 meters of water. This extremely flat trench floor is formed by the deposition of thick trench fill, wihch is supplied via the route through the Boso Canyon after flowing through the Sagami Trough (Kato et al., 1985). Fig. 23a shows the detailed bathymetric map prepared from the Sea Beam survey by the S/V *Takuyo*. In this map, a deep sea fan, named the Mogi submarine fan, is recognized at the end of the Boso Canyon. This deep sea fan shows a distorted morphology (Kato et al., 1985). The middle part of the fan is steeper from 8,600 to 9,000 metrs than the other part of the fan. Because of this, an uphaval is considered at the upper western part of the fan, in contrast to its lower eastern part.

The Izu-Ogasawara Trench floor becomes suddenly narrower to the north, as is discussed in section 3. 4. 4, from the triple junction area.

3. 4. 4 Northernmost part of the Izu-Ogasawara Trench

Depressions arranged in echelon are recognized at the floor of the northernmost part of the Izu-Ogasawara Trench, from 34°30'N to 34°50'N, which lies to the north of the triple junction area discussed in 3. 4. 3.

These depressions are 10 to 20 km in length and 3 to 5 km in width. A multi-channel seismic reflection section, shown in Fig. 24, indicates that trench fill layers there are thin. The trench floor feature with depressions in echelon is formed by the faults on the seaward slope obliquely crossing the trench axis. All of the cliffs or steep slopes bounding the echelon depressions continue as far as the faults on the seaward slope.

Many large-scale normal faults are distributed on the seaward slope of the northernmost part of the Izu-Ogasawara Trench (Fig. 23a). These faults range in height from 200 to 500 meters, with a few exceeding 1,000 meters. They are dislocated toward either west or east. Those toward the west are predominant over those toward the east. According to the multi-channel seismic reflection section shown in Fig. 24, these faults dislocated the basement together with its overlaying pelagic layer of nearly uniform thickness.

There are two local characteristics of these normal faults:

(1) The Kiyosumi Seamount, located at 34°30'N, 142°15'E, is divided into three portions by the normal fault dislocation, as recognized on the bathymetric map shown in Fig. 23a. The Daiiti Kasima Seamount, divided at a trench in a way to the Kiyosumi Seamount is the best-known seamount (Mogi and Nishizawa, 1980; Kobayashi et al., 1987).

(2) Strikes of normal faults differ on the north and the south sides of a zone along the 34°50'N parallel. The strike of the faults on the north side is in the NNE-SSW direction, which almost coincides with that of the trench axis. On the other hand, the strike on the south side shows NNW-SSE direction, crossing the trench axis at an angle of 30°. The relationship between the strike of normal faults on

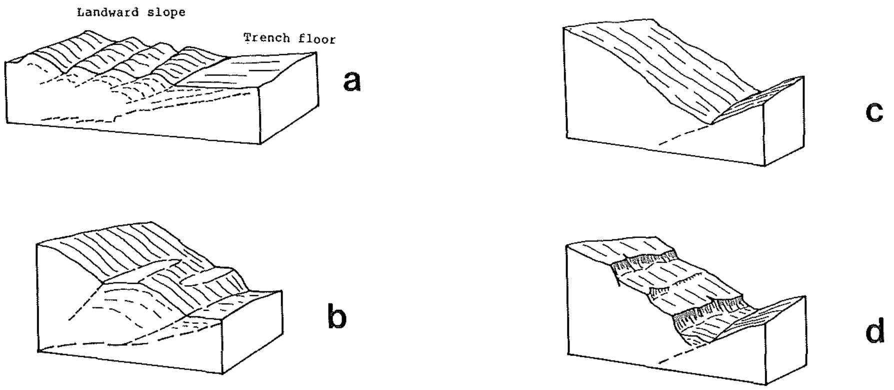

Figure 25. Geomorphological types of the landward slope of the submarine trench. a: Ridge and trough type, b: Step type, c: Mono-slope type, d: Slump scarp type.

the seaward slope and the trench axis will be discussed in section 4. 3.

4. Characteristics of the trench morphology deduced from case studies

In this chapter, the author classifies the geomorphological features of trenches into several types according to the landward slope, Trench floor and seaward slope of the trench, and examines their history of formation. The landward slope, in this case, does not include the continental slope, the deep sea terrace and the outer ridge, although both the deep sea terrace and the outer ridge, which borders the trench side of the terrace, may undergo the influence of plate subduction. It is likely, however, that these features have no direct relation with plate subduction in the late Quaternary.

In the consideration of the seaward slope of a trench, marginal swell is excluded because of the lack of detailed morphological data, although it seems to have a closer relation with the plate subduction in the late Quaternary.

4. 1 Landward slope of the trench

The growth of the accretionary prism controls the morphology of the landward slope. The lower part of the landward slope of the Challenger Deep in the Mariana Trench is estimated to lack accretionary prisms (Fig. 20-b). The eatsern part of the Nankai Trough and the Suruga Trough, as described in 3. 2. 1 and 3. 4. 2, have well-developed acretionary prisms. Based on these examples, classification of the morphology of the landward slope is considered in this section.

Table 1 shows the geomorpholgical characteristics of the several trenches mentioned in chapter 3. On the basis of such case studies, schematic types of landward slope morphology of the submarine trench can be drawn as shown in Fig. 25, and the following conclusions are obtained.

The degree of development of the accretionary prism dominates the geomorphology of the landward slope of the trench. The best example of a developed accretionary prism is the eastern part of the Nankai Trough (c. f. 3. 2. 1), called the ridge and trough zone, where large-scale undulated topography is formed by the accretionary prism (Fig. 25a).

Another well-developed type of accretionary prism has a step-shaped configuration, which can be

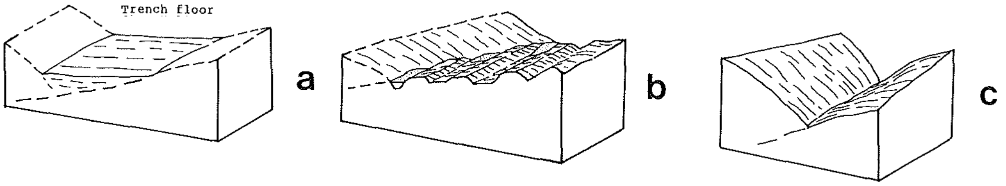

Figure 26. Geomorphological types of the trench floor. a : Flat floor type, b : Echelon type, c : Gorge type

seen in the Suruga Trough and the northern part of the Palau Trench (Fig. 25b).

In contrast to these, the landward slopes of the northern part of the Izu-Ogasawara Trench, the central part of the Palau Trench and the Callenger Deep in the Mariana Trench have steep and smooth surfaces. No remarkable accretionary prism is recognized on the seismic profiles in these trenches (Fig. 25c). From Table 1 it can be inferred that the accretionary prism of the landward slope of a trench has a strong correlation with the volume of sediments and the rate of sedimentation at the trench fill layer. In other words, a large-scale accretionary prism is formed along a trench where sedimentation rate is high or where the trench fill layers are thick and vice versa.

Although it may be considered that the pelagic sediments have also contributed to the growth of the accretionary prism morphology, the trench fill layer is more closely and directly connected with the growth, especially at the lower part of the landward slope. Pelagic sediments appear to be important material for underplating (Kagami, 1985), due to decollement under the middle or upper part of the landward slope of the trench.

It is difficult to form the accretionary prism morphology in an area where the landward slope is steep and smooth and the trench floor lacks trench fill sediments. There are cases where cliffs formed by land sliding develop on the landward slope, such as in the Japan Trench (Fig. 25d).

Formation of the two types of accretionary prism morphology i. e., the ridge and trough type and the step type is considered to be related to the difference in the dip angle of the subducting slub. Where the dip angle near the trench is small, for example, 3 to 5 degrees, as seen at the eastemn part of the Nankai Trough, the ridge and trough type morphology develops (Kato et al., 1983). This dip angle value is measured by using the multi-channel seirmic reflection profiles on lines D to I in Fig. 10. In contrast to this, where the dip angle of the subducting slub is larger, for exarple 23 and 10 degrees, as seen at the Suruga Trough and the northern part of the Palau Trench, respectively, the step type accretionary prism morphology develops. These values are also derived from the seismic sections obtained by multi-channel reflections.

These data, although small in number, indicate that the ridge and trough type is formed when the slab is subducting gently at an angle of 5 degrees or less, while the step type is formed when the slab is subducting steeply at an angle of 10 degrees or mere. When the dip angle of the slab is small, a wide zone can be reserved for the formation of the ridge and trough type accretionary prism. In the case of a large dip angle, the ridge and trough type can hardly be formed because of the proximity of the trench axis and the landward mass.

4. 2 Trench floor

From the cross-section of the trench there are recognized two types of trench axis morphology, i. e. the flat floor type and the V-shaped type. The eastern part of the Nankai Trough has the flat floor type with channels; and the triple junction of trenches off central Japan has the extremely very flat trench floor discussed in sections 3. 2. 2 and 3. 4. 3.

The V-shaped type can further be divided into two types: alternatively arranged V-shape canyons and narrow flats, and small depressions arranged in echelon along the trench axis. The Suruga Trough is an example of the former type, and the northern part of the Izu-Ogasawara Trench is the latter type. The cofigurations of trench floors can be classified into several types, and major factors in the formation of these types will be discussed in this section.

Typical features of the trench floor can be classified into the three types shown in Fig. 26. Main factors forming the trench floor morphology are (1) volume and sedimentation rate of the trench fill layer, and (2) morphology of the adjoining seaward slope. Supply of a large quantity of sediments into a trench forms a wide flat trench floor (Fig. 26a), no matter what configuration lies beneath the trench fill sediments.

When the trench is well supplied with sediments continuously, or the sediments are trapped by something as a barrier, a very flat trench floor is formed. On the other hand, there is a case in which terrigenous turbidite cut the trench fill sediments to form channels. These channels are formed where the trench floor inclines with relatively large gradient in the trench axis direction.

The trench fill layer consists almost entirely of terrigenous turbidite (Taira et al., 1984), and the quantity of the layer is mainly influenced by the characters of the land area that supplies the sediments. When the continental margin or the island arc has a wide and rugged land area close to a trench, the trench fill layer is easily thickened, as source of sediment supply is available on the land area. On the other hand, when the island arc is almost under the sea surface, sediment supply is less readily available.

Seeing the wide flat floors which are recognized at the eastern part of the Nankai Trough and the triple junction of trenches off central Japan, as shown in Table 1, it is considered that a wide area of the adjoining land and the erosion there have supplied a tremendous amount of sediment to form such wide flat floors.

The quantity of a layer, strictly speaking in this case, relates to the sedimentation rate relative to the convergence rate of two plates. That in, in order for a wide flat floor to form in a trench, a high rate of sedimentation is required when the convergence rate is high, while a relatively lower rate of sedimentation is sufficient when the convergence rate is lower.

When the sedimentation rate is low and the trench floor is narrow, small flat portions are distributed intermittently, along the trench axis. This feature is mostly formed in a trench associated with an undulated seaward slope. From this fact, it is thought that, when the sedimentation rate is low, the formation of a trench floor is controlled by the configuration of the seaward slope of the trench. When the trench axis is oblique to the faults on the seaward slope, such as in the northernmost part of the Izu-Ogasawara Trench and the Challenger Deep in the Mariana Trench, the small flats are arranged in

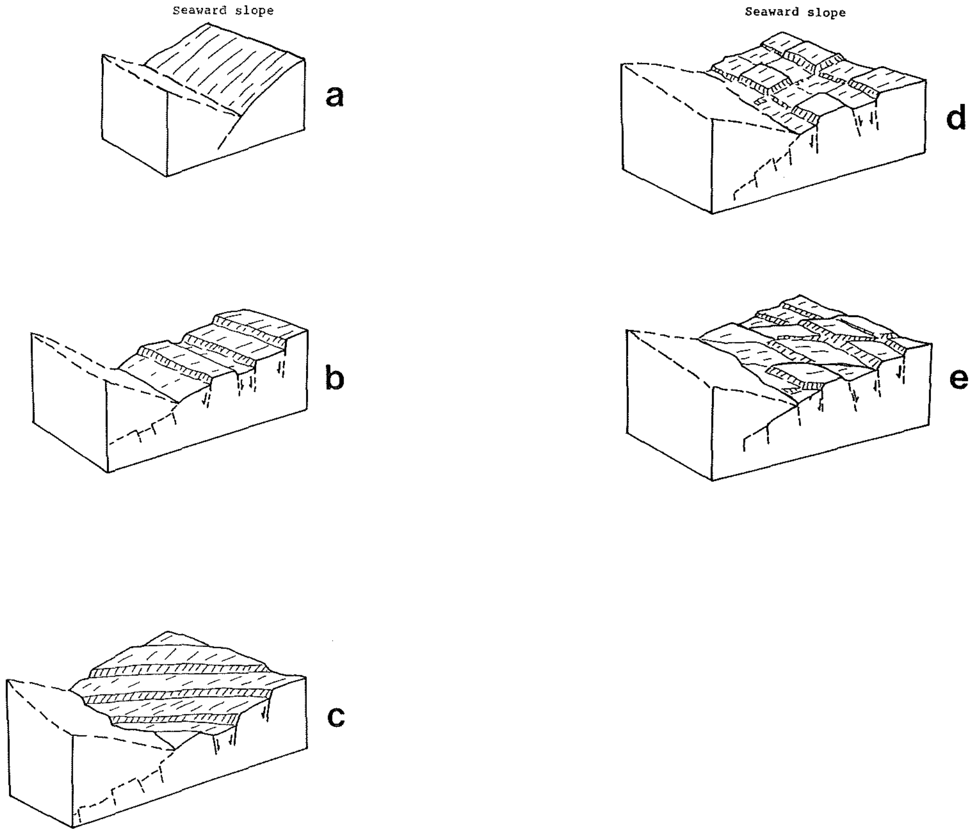

Figure 27. Geomorpholgical types of the seaward slope of the submarine trench. a: Mono-slope type, b: Oblique faults type, c: Parallel faults type, d: Grid structure type, e: Lozenge structure type.

echelon (Fig. 26b); that is, the fault scarp and horst on the seaward slope divide the depression along the trench axis to form such small flats in echelon. Small flats intermittently arranged along the trench axis are considered to be more common than in the case of a wide flat extending along the trench axis, as shown in Table 1. In a case where there is no sediment supply or where sediments are not trapped but carred away even if they are supplied in good quantity, the trench axis shows a canyon-like morphology (Fig. 26c). In this case, the seaward slope of the trench axis needs to be smooth. The central part of the Palau Trench is an excellent example of such topography (Fig. 18).

4. 3 Seaward slope of the trench

The morphology of the seaward slope of a trench will be classified into several types, and the degree of development of normal faults in this section will be discussed as a major factor in the formation of the seaward slope.

Several examples of the morphology of the seaward slope of a trench ard illustrated in Fig. 27. It can be pointed out that the major factor conrolling the geomorphic structure is the scale and distribution of normal faults caused by bending accompanied by the subduction of the lithosphere. It seems that the strike and distribution of normal faults are closely related to a weak zone in the oceanic lithosphere in addition to the thickness or age of the plate, physical properties, and dergee of bending of the subducting plate.

There are cases in which seaward slopes lack the normal faults formed by beniding (Fig. 27a). The central part of the Palau Trench and the Suruga Trough are apt exmples. From Table 1 it may be inferred that normal bending faults are not formed when the plate is young or heated by magmas, or when the plate, even of it is old, is subducting at a low angle. Because the young or heatedplate is warm, thin and ductile, tension at its surface is not great enough to cause normal faults. The tension on the surface of an old plate is also weak when the plate subducts at a low angle. In such cases, it is likely that the seaward slope is formed with a smooth surface.

There are two cases where normal faults develop, i. e., faults parallel with (Fig. 27b) and oblique (Fig.

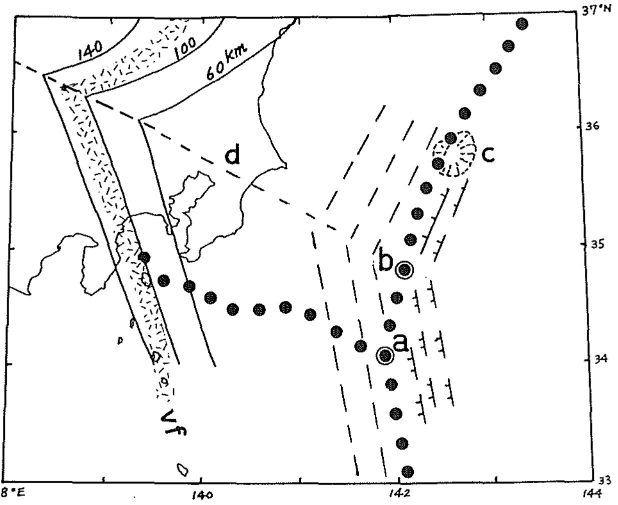

Figure 28. Interpretive tectonic map around the triple junction of the trenches off central Japan. Dotted line shows the plate boundary. Contour lines in the island arc show the depth of deep earthquakes (Maki, 1984). a: Turning point of the trench axis, b: Turning point of strike of faults on the seaward slope of trench, c: Daiiti Kasima Seamount, d: Break line of the subduction slab beneath island arc, vf: Volcanic front (Sugimura and Uyeda, 1972).

27c) to the axis of the trench. The faults in the former case can be recognized in the area adjacent to the Daiiti Kasima Seamount in the Japan Trench (Oshima et al., 1985; Kobayashi et al., 1987), the Mariana Trench (Rangin et al., 1988), the Middle America Trench off Mexico and Guatemala (Aubouin et al., 1982; Shipley and Moore, 1985) and the northernmost of the Izu-Ogasawara Trench discussed in section 3. 4. 4.

Normal faults on the seaward slope of the trench caused by bending of the oceanic plate are inferred to be parallel with the axis of the trench, irrespertive of the subducting direction of the plate against the trench. It has been proved that the mechanism of earthquakes that occur near the trench yields tension orthogonal to the trench axis (Stauder, 1968). Despite this, however, there are cases where normal faults occur oblique to the trench axis, e. g. the Challenger Deep of the Mariana Trench, the northern part of the Palau Trench, the northernmost part of the Izu-Ogasawara Tranch and the Nanseisyto Trench.

The faults in the northern part of the Palau Trench are considered to be caused by a tensional stress field due to bending which is distorted by the effect of the Kossol Ridge (cf. 3. 3. 3).

In the northernmost part of the Izu-Ogasawara Trench, there is a possiblility that the strike of normal faults having NNW-SSE direction may indicate the direction orthogonal to the largest dip direction of the subducting slub, because this area is close to the turning point of the trench axis. As mentioned in 3. 4. 3, it is considered that the Pacific plate may be subducting with dip direction WNW in the region north of 34°50'N and W in the region further south.

According to the deep seismic distribution (Utsu, 1977; Maki, 1984; Ishida, 1986) which shows the configuration of the subducting plate beneath the island arc, a bend turn of the seismic distribution (d in Fig. 28) does not extend as far as the triple junction of plates (a in Fig. 28), but extends to the turning point of strikes of the normal faults further north on the seaward slope (b in Fig. 28).

Renard et al. (1987) estimated, with the data obtained from the Kaiko Project, that the strike of normal faults on the seaward slope gradually changes from the triple junction of plates to the Daiiti Kasima Seamount (c in Fig. 28) located to the north of the Izu-Ogasawara Trench. Whereas the above-mentioned turning point of strike of the normal faults has newly been recognized at 34°50'N (b in Fig. 28), it is considered that the break of the subductiong slab at d, the location of which is estimated by the deep earthquake distribution under the Japan arc (Utsu, 1977) and by the sharp break of the volcanic front (Sugimura and Uyeda, 1972), started from lat. 34°50'N (b in Fig. 28) in the northernmost part of the IzuOgasawara Trench.

There is a long and linear fault near the Nanseisyoto Trench slightly oblique to the trench axis, as mentioned in 3. 1. 4. It is inferred that this fault have been formed by the reactivity of the fracture zone due to the bending fault in the subducting plate. In other words, the tension accorpanying bending of the trench has been spent on the reactivity of the fracture zone, resulting in formation of a fault oblique to the trench axis along the previous fracture zone, that is, a weak zone on the subducting plate.

On the basis of the above, it is considered that there are two types of development of faults oblique to the trench axis on the seaward slope due to the bending of the plate: (1) disorder of the tension on the seaward slope due to a discrepancy between the position of the turn of the trench axis and that of the break is the subduction slab, or due to collision with a seamount or a ridge, and (2) development of normal faults along the weak zone on the seaward plate, although the direction of tension is orthogonal to the trench axis.

The magnitude of normal faults on the seaward slope varies greatly from one trench to another. The faults in the northernmost pars of the Izu-Ogasawara Trench are well-developed ones. On the other hand, normal faulting is rarely seen at the central part of the Palau Trench. The difference in the magnitude of normal faults on the seaward slope seems to depend on the age and the angle of the subducting plate. The age of the plate is almost proportional to its thickless. In a case where the plate is thick, the tension on the surface of the plate caused by bending becomes so strong that large-scale faults are formed. This idea, fundamentally proposed by Ida and Uyeda (1981), is well supported by the examples studied in this paper.

There are cases in which it is difficult to explain the fault development by the age or thickness of the plates alone. This is the case with the northern part of the Japan Trench and the Izu-Ogasawara Trench, which are nearly the same age (Kaiko I Research Group, 1986). In this trench system, the scale of faults increases to the south, towards the triple junction. This may be explained by the fact that the bending curvature of the subducting plate becomes larger toward south. It is known that the slab beneath the Izu-Ogasawara arc is remarkably steeper than that beneath the Northeast Japan arc, based on the deep earthquake distribution (Utsu, 1977). Such a difference in the slab angle is considered to be one of the cause of differences in the fault scale on the seaward slope.

The grid structure in the Nanseisyoto Trench (cf. 3. 1. 5) is a complex structure made of faults caused by the plate bending and minor ridge structure on the oceanic plate, which was formed before the deformation occurring near the trench (Fig. 27d). This grid structure is a rare case because the minor ridges should run perpendicular to the trench axis; a lozenge structure may be mere common on the seaward slope (Fig. 27e), although examples have not yet been reported.

5. Summary and conclusions

In this paper the author presents detailed geomorphic data on the Nanseisyoto Trench, the eastern part of the Nankai Trough, the Palau Trench and other trenches around Japan, and explains topographic features of the landward slope, axial floor and seaward slope of the trenches. Then, by classifying them into several types, the main factors in the formation of such trenches are discussed.

In the seaward slope of the Nanseisyoto Trench, linear minor ridges mutually in parallel are developing in the NW-SE direction. At their NW edge is a long, linear fault. The fault may be a reactivated fracture zone created by the bending of the trench formation. From the seaward slope to the axial floor of the Nanseisyoto Trench, a grid structure is formed by minor ridges and bending faults crossing almost orthogonally.

In the eastern part of the Nankai Trough, it appears that a trough floor with channels and a very flat floor without channels extend alternatively. The former may be the area where sedimentation of turbidite has been suspended, and the latter may be the area where turbidite is being deposited. The difference in the degree of development of channels may be due to undulations of the subduction plate along the trough axis, and these undulations may owe their origin to fingering subduction. In the landward slope of the Nankai Trough, a ridge and trough zone is developed. The zone is formed by an imbricated tilt-shaped deformed layer or so-called accretionary prism.

In the Palau Trench, a flat broad trench floor exists at the extreme north of the trench, and a trench axis with a V-shaped profile like a canyon extends from the northernmost flat to the central part of the

Table 1 Geomorphological characteristics of the several trenches.

Name of trench	Figure number	Landward slope morphology (accretionary prism)	Trench floor morphology (thickness of layer)	Seaward floor morphology	Age and property of subducting plate
Nothernmost part of the Izu-Ogasawara Trench	22 23	smooth and steep (unknown)	echelon depression (slight)	well-developed faults parallel with trench axis	130 Ma ocean floor
Triple junction of trenches off central Japan	22 23	spur (unknown)	broad flat floor (very thick)	well-developed faults oblique to trench axis	130 Ma ocean floor
Suruga Trough	21	step (small)	gorge and small depression (thin)	smooth	younger than 30 Ma volcanic arc
Eastern part of the Nankai Trough	9 13	Ridge and trough (large)	broad flat floor channel (very thick)	Zenisu Ridge	20 to 30 Ma marginal sea floor
Nanseisyoto Trench	5 8	smooth and steep (unknown)	grid structure (slight)	large linear fault oblique to trench axis	50 to 60 Ma marginal sea floor
Challenger Deep in the Mariana Trench	20	smooth and steep (unknown)	echelon depression (slight)	well-developed faults slightly oblique to trench	older than 150 Ma ocean floor
Northern part of the Palau Trench	16	step (small)	teardrop flat floor (thick)	small faults oblique to trench axis	30 Ma marginal sea floor
Central part of the Palau Trench	18	smooth and steep (unknown)	gorge (little)	smooth	30 Ma marginal sea floor

trench. A step-like topography formed by the accretionary prism was recognized in the landward slope of the northern part of the Palau Trench. Similarly, in the Suruga Trough, accretionary prism topography is distributed in the landward slope.

Faults oblique to the trench axis in the seaward slope of the trench exist in the Challenger Deep in the Mariana Trench as well as in the northern part of the Izu-Ogasawara Trench. The oblique faults in the Challenger Deep may be formed by the resultant force of oblique subdction and beniding of the Pacific plate. In the case of the Izu-Ogasawara Trench, the oblique faults are considered to be formed by the discordance between the turn of the trench axis and the break of the subducting slub.

The triple junction of trenches off central Japan is characterized by a very wide flat trench floor with a deep-sea fan. The flat trench floor is formed by the deposition of a thick trench fill layer which is supplied via a route through the Boso Canyon.

The geomrpholgical characteristics of the several trenches mentioned above are summarized in Table 1.

The geomrphological features of a trench are classified into several types based on the landward slope, trench floor and seaward slope (Figs. 25-27), and their evolution is examined.

(1) The landward slope of the trench is geomorphologically classified into a ridge and trough type, steptype, mono-slope type and slump scarp type (Fig. 25). It is deduced that the main factors in the differentiation of these types are the degree of development of the accretionary prism and the difference of inclination of the subducting slub. The mono-slope and slump scarp types develop in slopes that lack an accretionary prism. The ridge and trough type and step type are formed when the accretionary prism is well developed. In this case, a low angle of the subduction slab makes the ridge and trough type, and a high angle makes the step type.

(2) The trench floor topography is classified into a flat floor type, echelon type and gorge type. The main factors in forming such trench floors are the quantity and rate of sedimentation and the topographic features of the adjoining seaward slope.

When the trench is well supplied with sediment, the trench floor formed is very flat. Lack of sediment supply makes echelon type or gorge type. The morphology of the echelon type is controlled by the configuration of the adjoining seaward slope of the trench.

(3) The morphology of the seaward slope of the trench is classified into a mono-slope type, parallel fault type, oblique fault type, grid structure type and lozenge structure type. It is deuced that the main factor in the creation of these types is the development of faults with or without previously existing weak zones on the seaward plate caused by plate bending. The oblique fault type, in which faulting is oblique to the trench axis, is formed when (1) there is a discordance of positions between the turn of the trench axis and the break of the subducting slub, (2) the tension on the seaward slope is oblique to the trench axis due to collision with a seamount or ridge, or (3) the faulting occurs along weak zones on the seaward plate.

The magnitude of normal faults on the seaward slope varies greatly from one trench to another. The difference seems to depend on the age and the bending curvature of the subducting plate. The faults on an old plate or a well-curved plate become larger.

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A GEOMORPHOLOGICAL STUDY ON THE CLASSIFICATION AND EVOLUTION OF TRENCHES AROUND JAPAN

日本付近の海溝地形の分類と発達に関する地形学的研究（要旨）

加藤　茂

1．日本周辺の海溝のなかで，南西諸島（琉球）海溝，南海トラフ東部，パラオ海溝等について，詳細な地形等のデータを示し，これらの海溝の陸側斜面，海溝底，海側斜面の地形についてその特徴をまとめ，さらに，これらのデータをもとに，海溝の地形をいくつかのタイプに分類し，地形形成の主因子について考察した。

2．南西諸島海溝の海側斜面には，海溝軸とほぼ直交するマイナーリッジが多達している。その北西縁には，長大な直線的断層があり，断裂帯が海溝海側のbending断層として再活動したものと考えられる。また，南西諸島海溝の海側斜面から海溝底には，平坦面はほとんどなくマイナーリッジと海溝海側のbending断層とが直交して，格子構造を形成していると考えられる。

南海トラフ東部は，厚い海溝底堆積物からなる平坦な海溝底を有し，非常に平坦な底が広がるところとトラフ軸と平行するチャネルが発達するところが交互してあらわれる。前者は堆積期にあることを，後者が堆積休止期にあることを示すものであり，また，この繰り返しは，スラブの短冊状沈み込みによるものと考えられる。南海トラフの陸側には海溝底堆積物及び半遠洋性堆積物によって構成される付加体からなるリッジ・トラフ帯が非常に発達している。

パラオ海溝は，最北端に海溝底平坦面を有しているが，これより南の海溝軸は峡谷状を示す。陸側斜面にはわずかに付加体によるステップ状の地形が発達し，海溝中部の海側斜面にはbending断層がほとんど発達していない。

このほか，ステップ状の付加体地形を陸側斜面にもつ駿河トラフ，海溝軸と斜交するbending断層が海側斜面に発達し，小さな凹地に平坦面が断続する海溝底をもつマリアナ海溝チャレンジャー海淵付近及び伊豆・小笠原海溝北端部，そして，2つの海溝が会合し広い海溝底平坦面に大規模な海底扇状地が発達する中央日本沖の海溝三重点付近の地形についても検討した。

3．これらのデータをもとに，海溝の陸側斜面，海溝底，海側斜面のそれぞれについていくつかのタイプに分類した。

a．陸側斜面にはリッジ・トラフ型，ステップ型，平滑型，そして，地滑崖型に分類された。付加体の発達の程度と沈み込むスラブの角度の違いによってこれらの地形の違いがあらわれると考えられる。付加体が発達しない場合には，平滑型かあるいは地滑崖型が発達する。付加体が発達する場合には，リッド・トラフ型やステップ型が形成される。付加体が発達する場合，スラブの角度が小さいとリッジ・トラフ型に，大きい場合はステップ型になる。

b．海溝底は，広い平坦面型，小凹地断続型，峡谷型に分類され，海溝底への堆積物の供給量と供給速度（プレートの収束速度との相対的なもの），そして，隣接する海側斜面の地形が海溝底の地形の主因子と考えられる。堆積物の供給速度が大きい場合は広い平坦面が形成され，小さい場合，小凹地断続型または峡谷型となる。小凹地断続型は，海溝海側斜面の断層に規制されて形成される。

c．海側斜面の地形には，平滑型，海溝軸と並行する断層群型，海溝軸と斜交する断層群型，格子構造型，菱形構造型が認められた。これらの型は，海洋プレート上にある弱線に規制されたプレートのbendingによる正断層群の発達の程度が，主な因子と考えられる。断層が海溝軸と斜交する場合は，海溝軸の屈曲点とスラブの屈曲地点の位置が異なる場合，沈み込むプレート上の弱線にbending断層が生じる場合が考えられる。

海側斜面に発達する正断層の大きさは，海溝によっておおきな違いがある。この違いは，沈み込むプレートの年令や屈曲度によるものと推定される。古いプレートあるいは大きく屈曲するプレートの場合，断層が大きくなる。