

Shallow deformation of eastern Nankai Trough prism as derived from MCS reflection data (KH96-02): Constrained by ridge subduction

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Total 454 km G-gun seismic data during Cruise KH96-02 by R/V Hakuho-maru has been acquired in order to detect the detailed structure and evolution of eastern Nankai Trough. Preliminary results show that five structural units with different topography, deformation and stratigraphy in the study area have been divided according to seismic data and submersible investigation. The five units include upper slope prism, accretionary slope basin, lower prism, trough axis and Zenisu ridge, respectively. Tokai thrust, which is east boundary of upper slope prism, was considered as important lithofacies distribution and regional tectonics. Strata of the fore wall are slope basin sediments and early terrigenous sediments. More actively thrust system has been formed between lower slope prism and trough, which express duplicated thrust and imbricated thrust formed since late Pliocene. The backthrusts and extensive erosion were occurred in the lower slope. Tectonics of Zenisu ridge is considered a new following subduction zone by many scientist (Le Pichon et al., 1987; Lallemant et al., 1989) and expresses few compression structures in upper layers both from our seismic and submersible data. Decollement plane in eastern Nankai Trough expresses shallow, wavy shape, which is great different from west Nankai trough as ODP drilling (Moore, 1992). The decollement plane was affected by paleo-Zenisu (Lallemant et al, 1992; Le Pichon et al., 1996). That new coming Zenisu subduction and above-mentioned deformation features were supported the postulated paleo-Zenisu ridge has been subducted beneath the accretionary prism.

Key words : deformation, ridge subduction, Zenisu Ridge, Nankai Trough

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1. Introduction

We report the main results of the multichannel seismic (MCS) reflection data in eastern Nankai Trough (NT) during Cruise 96-02 by R/V Hakuho-maru in 1996. Total 454 km G-gun and 682km Airgun seismic data were acquired in this cruise. A box survey consisted of 8 parallel lines of which length and interval are approximately 55km and 1,600m, respectively. The four G-gun array of which each volume is 150 cubic inch were adopted as the energy source with the pressure of 2000 psi. The shot interval and receiver group interval both were 25m, the CMP stacking corresponds to 60 folds. Four large airguns were adopted as source energy with 2000 psi. The shot and receiver intervals were 50 and 25 m, respectively. And stacking corresponds to 30 fold. Processing of the MCS lines was carried out at Japan Geoscience Institute. The field data were sorted into Seg-D Data processing was dealt on the Sun 2/4 at JGI and

Software is MIT iXL. Here, we discuss inner deformation of accretionary prism and evolution of the trough axis, based on G-gun data, also referred to airgun data. The study area and seismic lines show on the Fig. 1.

Eastern NT is the surface expression of the consuming plate boundary separating the 24 Ma old Shikoku Basin crust to the South from Honshu (Kobayashi, 1995). There existed some geological characteristics of this subduction zone as follows. The first one is suggesting forthcoming great earthquake. Although the seismic activity of Nankai Trough is relatively low compared to neighboring subduction zones, great earthquakes have been repeatedly ruptured large segments of this boundary. The segment ruptured by the last great earthquake in 1944 probably did not extend east of 138°E. Accordingly, a magnitude 8 great earthquake, to be called Tokai earthquake, is now

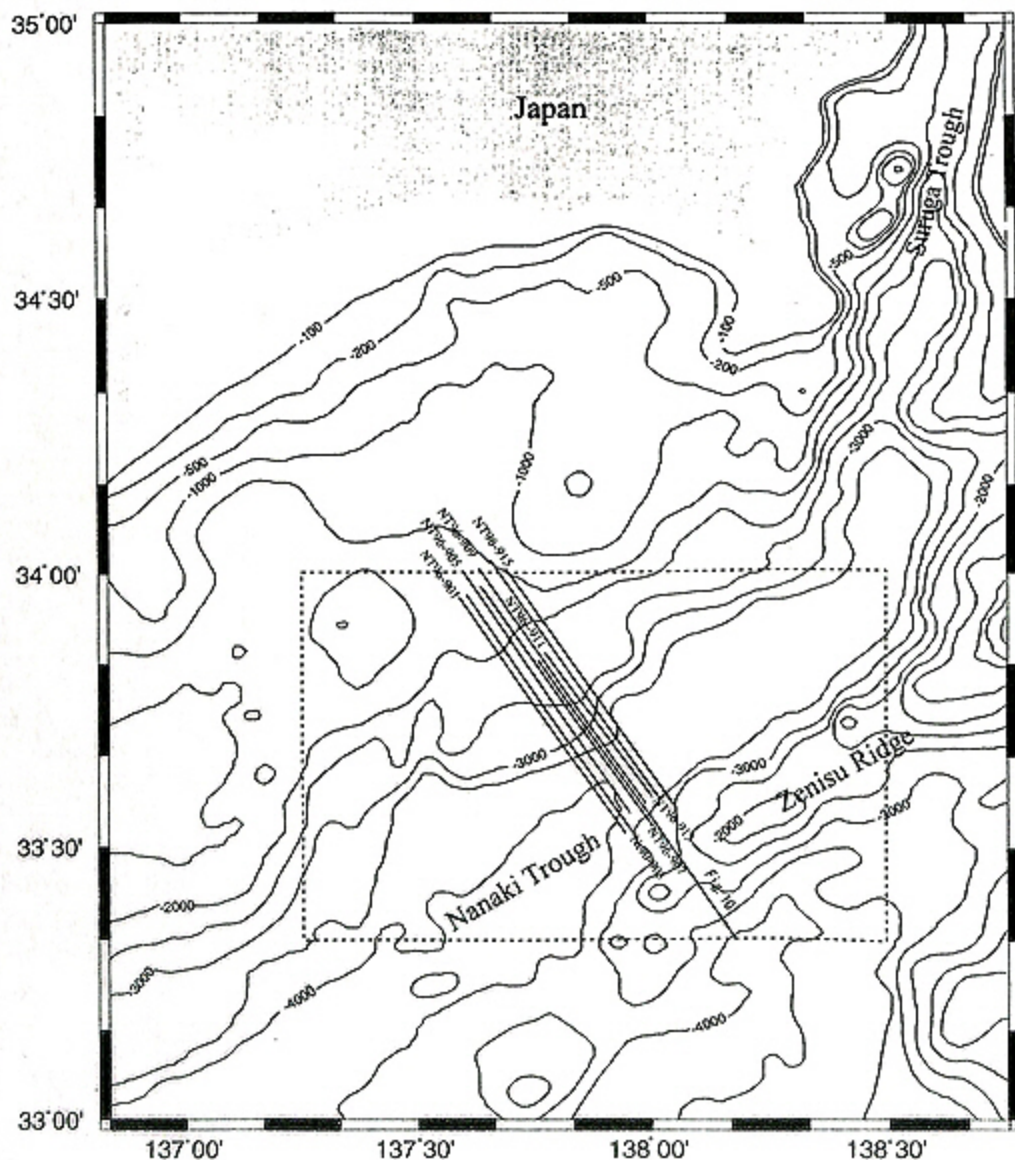


Fig. 1 Bathymetric map and seismic line location map. Solid line indicates the seismic line track. Dash line shows the seismic profiles used in this study. Box locates are shown in Fig. 3.

expected to ruptured the easternmost portion of the trough (Le Pichon et al., 1996). The second is rich seep communities and BSRs. Its dewatering processes were controlled both by the active fault and sedimentary facies (Ashi et al., 1998); The third is the issue of Zenisu ridge to southeast, which expresses a thrust zone and can be regarded a new coming subducting zone. And more, eastern Nankai prism has extensive erosion and occurrence of backthrust. An old ridge subduction, referred to paleo-Zenisu, was presented to interpret these features (Lallemand et al., 1992; Le Pichon et al., 1996). The reply to this question was contributed by the exploration of both deep tectonics and shallow deformation.

Bathymetric investigation shows that eastern NT is a relatively shallow with average water depth 4,000m and has existed a parallel outer ridge, Zenisu Ridge, which extends about 400 km long and declines in height toward the west until it disappears south of Kii peninsula (Fig.1). High resolution SeaBeam survey has been operated by R/V KAIREI cruise KR97-05 (Fig.2). Above mentioned five units have been expressed on this bathymetric map. The frontal steep topography outside slope basin is defined lower prism. Deepest water depth

was NT axis. And Zenisu ridge located at south most, is uplift zone with more than 1,000m height ridge. Some result from seismographic methods suggested that accretionary prism has huge thickness and subduction is gentle than Ryukyu trench and Japan Trench, but a little steeper than that of western NT, but the Benioff zone associated with the subducting Philippine plate at the trough is difficult to define the maximum depth of the Benioff zone. No normal faults appear, This means that regional stress field expresses compression in upper of subduction zone. The High heat flow and seepages have been observed in the whole area and more turbidity sediments filled in the eastern NT by submersible. In addition, Tokoyama et al. (1998) indicated that the most eastern NT is strongly affected by the arc-arc collision, accompanying with occurrence of multiple intraplate shorting on both side of the trough axis. Characteristics of the accretionary wedge will be lately discussed.

Previous MCS studies (Aoki, et al., 1982; Okuda and Honda, 1978) have been done on the eastern NT. Aoki et al. (1982) focused on the comparison between eastern and western NT tectonics, especially indicated the compression structures of upper layers in Zenisu Ridge. Okuda and Honda (1988) dis-

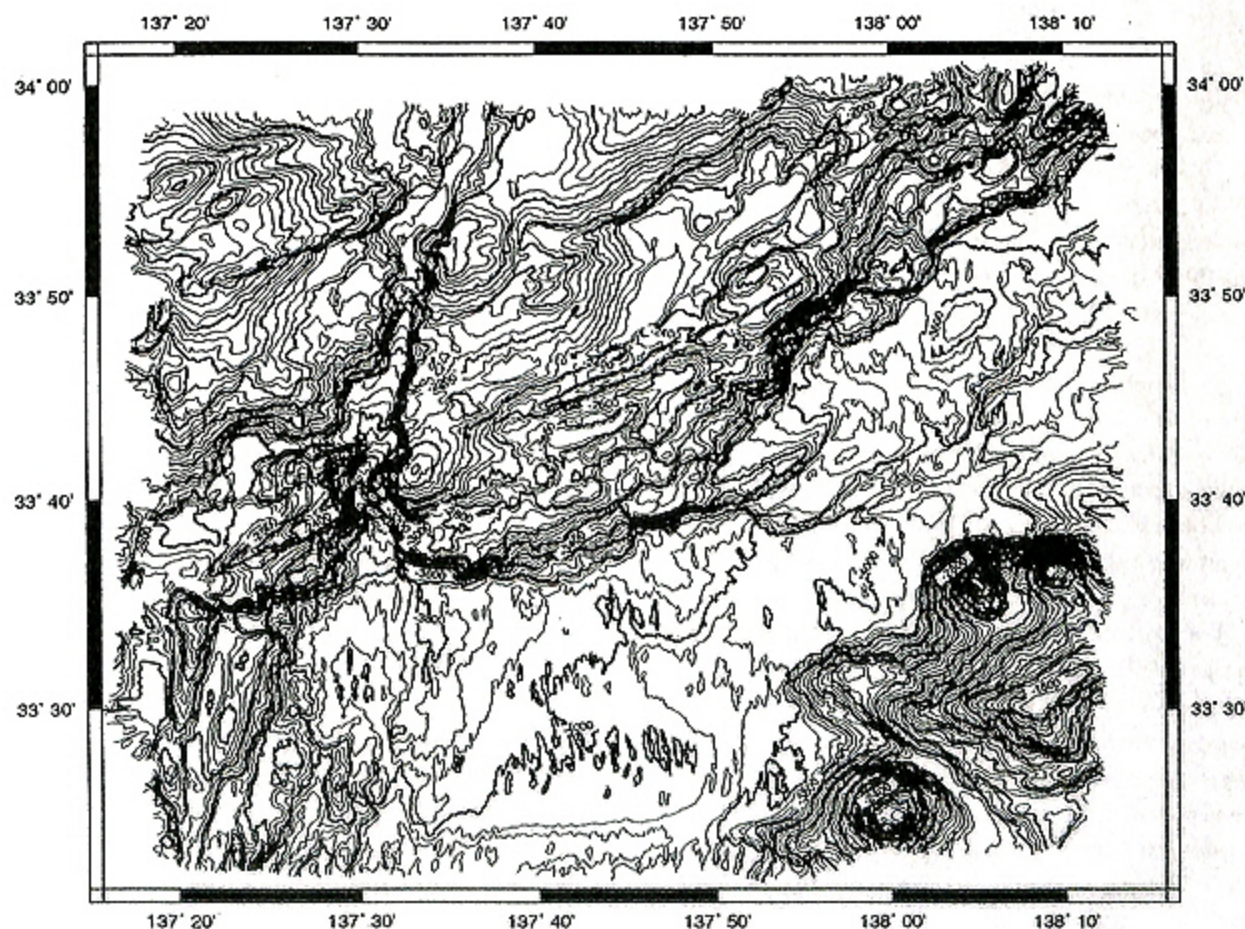


Fig. 2 SeaBeam bathymetric map surveyed by R/V Kaiyo in 1997. Contour interval is 50 m.

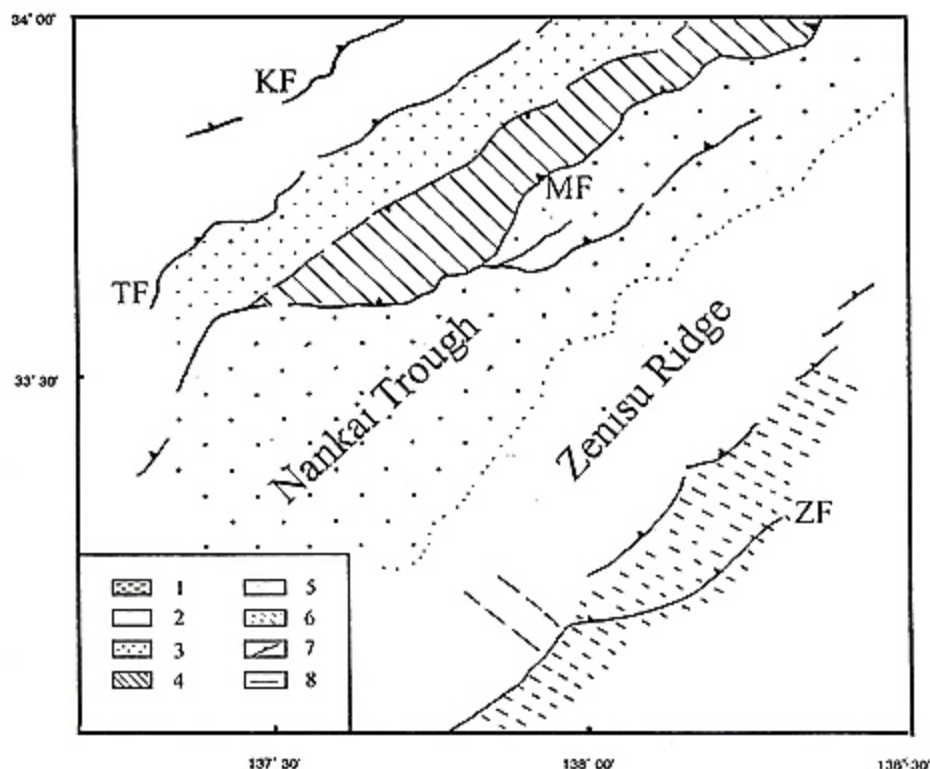


Fig. 3 Tectonic zones of the eastern Nankai trough accretionary prism derived from bathymetric map and submersible data. 1 upper accretionary prism, 2 slope basin, 3 lower accretionary prism, 4 trough axis, 5 boundary between trough and Zenisu Ridge, 6 south Zenisu Basin, 7 thrust fault, 8 lateral slip fault, KF-Kodaiba thrust fault, TF-Tokai thrust, BF-Back thrust, MF-frontal thrust.

cussed the slope sequences and origin. Recently ODP and DSDP drilling program series have been executed in the western NT, which were increased the acknowledgement of the strata and lithology of accretionary prism. The subduction tectonics have been discussed by many authors (Le Pichon et al., 1992; Kagami et al., 1985; Moore et al., 1992; Okuda and Honza, 1988; Tokuyama et al., 1998; and so on).

2. Seismic sequences and stratigraphic units

Based on our seismic data, referred to the ODP 131 and DSDP drill well data (Taira and Ashi, 1993) and many others, the trough strata and internal stratigraphic units of prism are discussed. In the trough region, acoustic basement of Shikoku Basin is recorded on lowest part of our profiles (Figs. 4, 5, 6, 7), which expresses strong energy, discontinuity reflection and high amplitude. The basement consisted of volcanic debris and oceanic basalt according ODP and DSDP drilling at west NT (Pickering et al., 1992). It represents the rifting sequence formed during Oligocene and Middle Miocene (Kobayashi et al., 1995). There are four seismic sequences overlain on the acoustic basement in the trough axis after rifting.

Sequence A, Upper turbidite sequence, with relatively reflection, lower energy and variable amplitude. The layer onlaps on the Zenisu Ridge to the east and separated the accretionary wedge by thrust to west. There has weak deformation at eastern, but its layers in the eastern have been induced by the thrust.

Some fold and small reverse faults were formed. The thickness usually is 0.5-0.8 sec in two-way time at our seismic profiles. The maximum thickness on the profile 901 arrived to 0.8 sec in two way time (Fig. 4). Total thickness is about 360m if the layer strata velocity is 1,800 m/sec. Lithology of the sequence is turbidity interbedded with abyssal clay from profile 915 turbidity channel with aggradation by stacking of acoustic units and erosion of central channel can be defined.

Sequence B, Lower turbidite sequence, with continuity reflection, moderate energy and strong amplitude. The maximum thickness is 0.6 sec in two way time. It is distributed at central trough, and faces may be mainly turbidity sand and sandy silt sediments. It onlaps on the Zenisu Ridge to the east and abruptly to west by the thrust, and the strata near the west have been involved in thrust-fold system. The early stage of sequence B with relative weak energy and moderate continuity reflection, these layers were filled in more turbidites sand and silty sediments. Upward, with more community reflection, which reflects turbidity sediments interbedded more hemipelagic sediments.

Sequence C, Relatively continued reflection and weak energy and weak amplitude in the Zenisu Ridge. Its thickness is 0.3 sec (two way time) and increases to Zenisu Ridge, whereas onlaps beneath the trough on the profile. It implicated that uplift of Zenisu Ridge is after the sequence C. The seismic face of transparent with many marked and continuous reflectors is re-

lation to turbidity sediments, which is supported by ODP site 808B and DSDP drilling results (Pickering et al., 1992; Taira et al., 1992).

Sequence D, Shikoku sedimentary sequence in Zenisu Ridge has relative continue parallel reflection, moderate energy and moderate amplitude. In ODP site 808B it consists of bioturbated hemipelagic mud and volcanic ash, while there are more terrigenous deposits and coarser sediments to the study

area, because it is near terrigenous source (Pickering et al., 1992).

But the strata of inner accretionary prism in the whole slope have been faulting and folding, which are discontinuity reflection and moderate energy and variable amplitude. There are many refraction waves because of the dip of the layer. The seismic facies of the prism are complex. The sequence overlain on the slope basin sedimentary strata up fall of Tokai which are

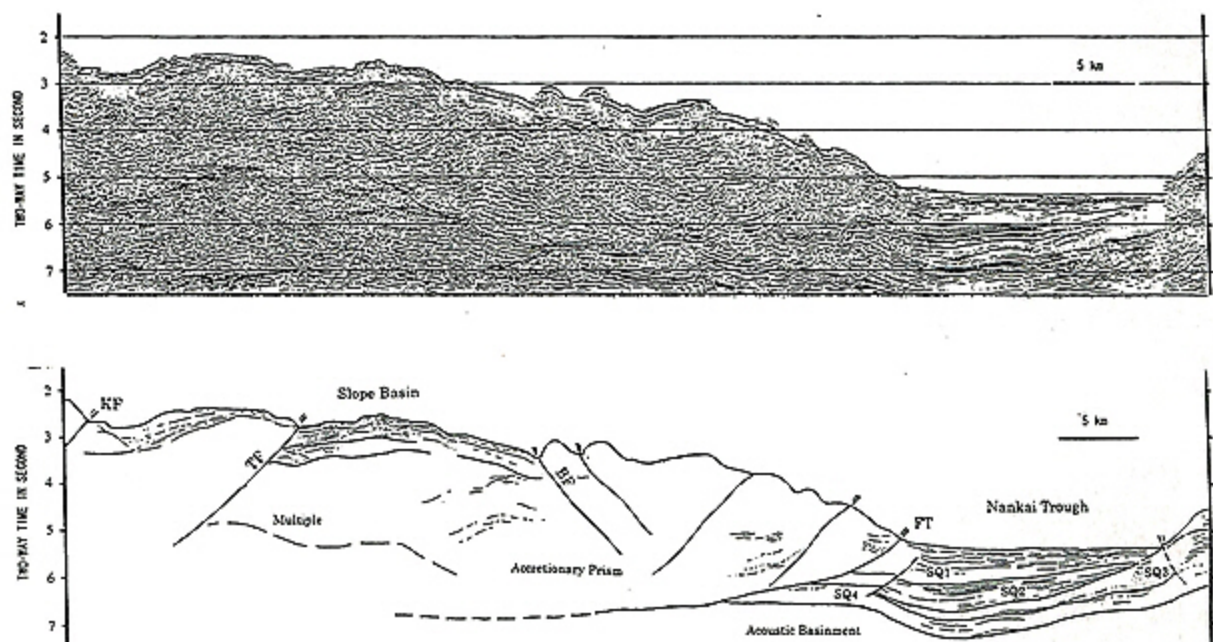


Fig. 4 Migrated time section of the profile NT96-901

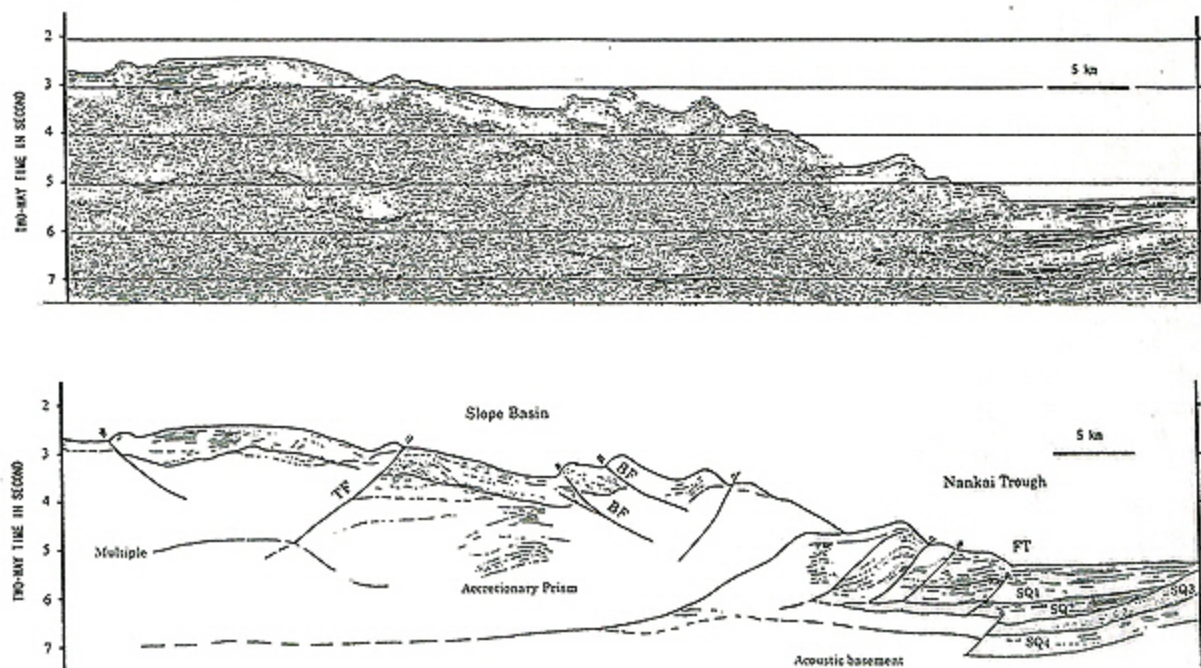


Fig. 5 Migrated time section of the profile NT96-905

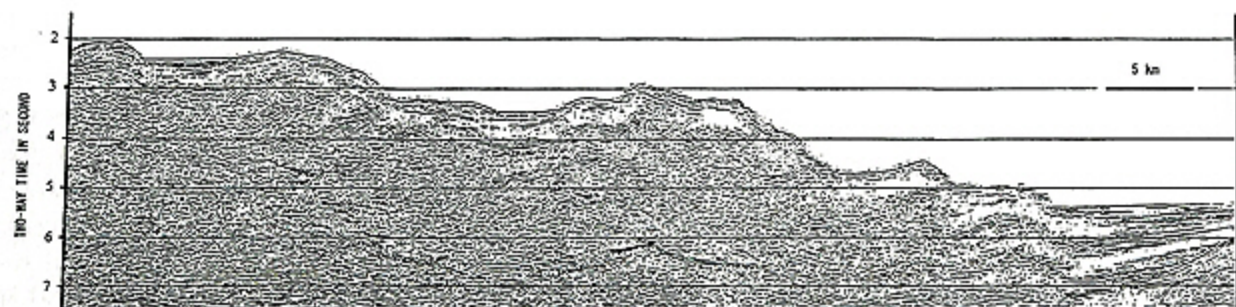


Fig. 6 Migrated time section of the profile NT96-909

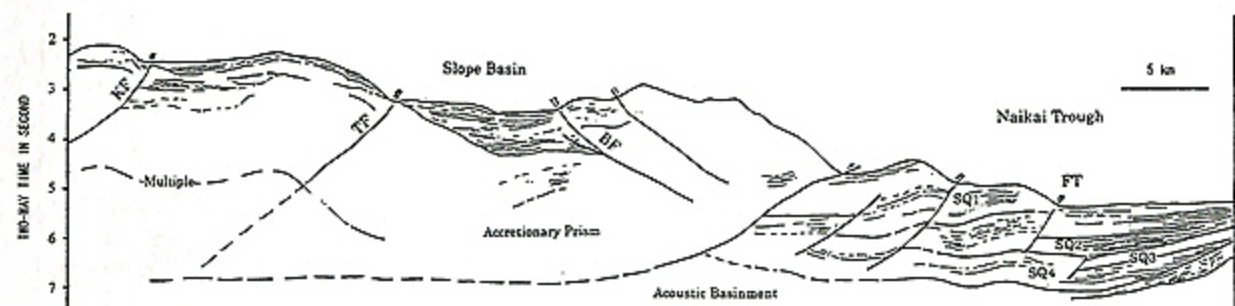


Fig. 7 Migrated time section of the profile NT96-915

hemipelagic sediments in top of the outer ridge is composed of sediment of T formation of Miocene age (Okuda and Honda, 1988), which have been deformed. T formation is correlated with the consolidated mudstone dredge from St 362 and is overlain by K formation with a clinounconformity in the outer ridge (Inoue, 1980). The strata consist of terrigenous sediments.

3. Structures of the eastern NT prism as derived from MCS reflection data

In our studying area, five tectonic units (Fig.3) have been divided from landward slope to the Zenisu Ridge as follow: (1) upper slope prism (USP); (2) accretionary basin (AB); (3) lower slope prism (LSP); (4) trough; and (5) Zenisu Ridge. based on the topography and deformation. USP (Fig. 4-9) located the

west of Tokai thrust (TF), which is important seismicity (Tokuyama, 1988). LSP is limited by the frontal major thrust (FT) and backthrust (BT). AB is between the TF and BT, expressing compressing fold and listric thrust faults and filling with sediments derived from uplift subduction complex (Dickson and Seely, 1979). The trough sedimentation and deformation express on the MCS reflection on the east of profiles (Figs. 4-9). But our profiles can only reveal a part of Zenisu Ridge structure, so we also referred the air-gun depth section 96-102 (Fig. 10). The major deformation characteristics of the subduction zone have been discussed from west to east as following:

3.1 upper slope prism (USP)

USP is belong to the part of the outer ridge, is composed of probable Neogene sediments with discontinuity reflection,

moderate energy. It was suggested that most of the sediment layers formed during Miocene, named M formation (Okuda and Honda, 1988). The ages of rock samples from uppermost sedimentary layers are 5.6-8.2 Ma. These can contrast with T formation as described forearc basin (Mazzotti et al., 1996). The strata have been deformed since Miocene. There are two important thrust faults existed at east Boundary and inner, respectively.

Tokai thrust system, occurred at the UPS margin, where most step geomorphology and old slope sediments outcrop in the seafloor leaving avoided recent sedimentation. The fault express most recent activity, the old slope sediments thrust over Quaternary sediments as showed on many profiles (Figs. 4, 5, 6, 7, 8). A lot of tulas have been discovered by submersible (Ashi, 1997), it suggests that TF was more intensive if one overthrust accompanied more talus sediments. Deformation of fall wall occurred the inclined strata on the upper section, which

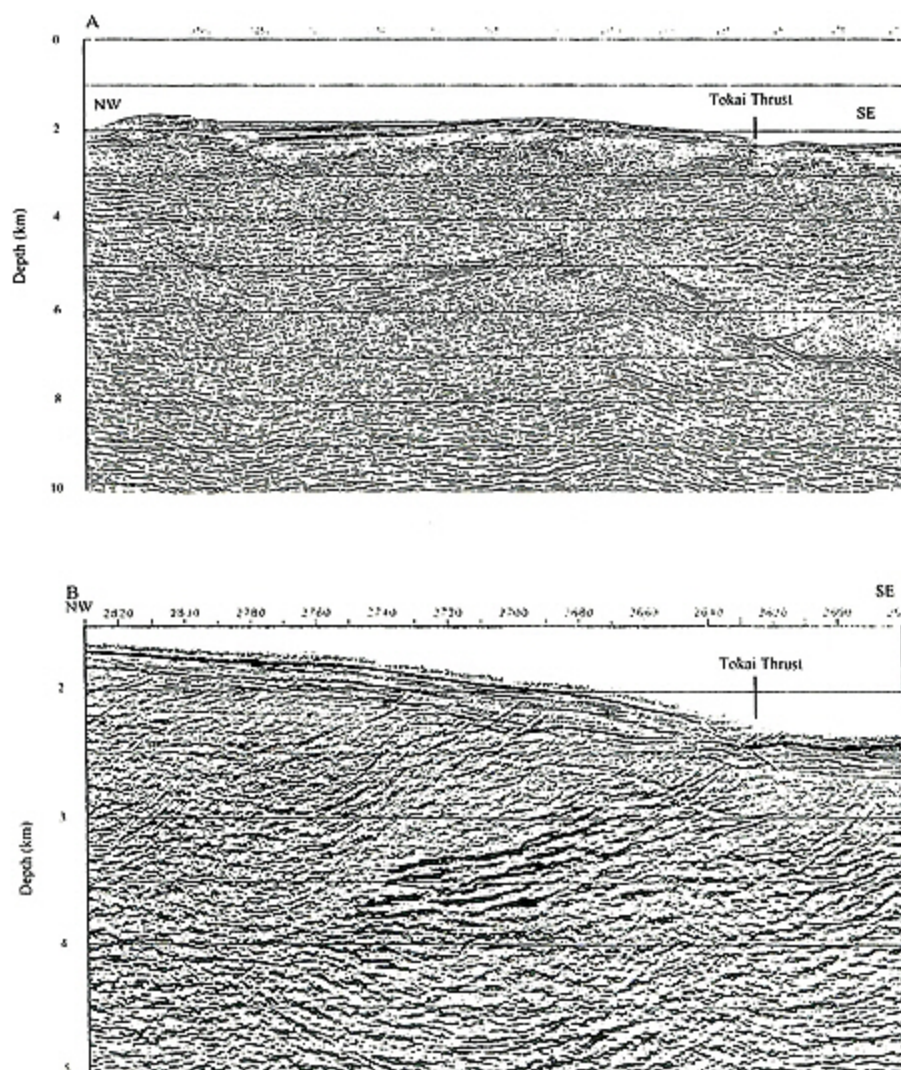


Fig. 8 Depth section showing the Tokai thrust fault and adjacent slope basin. 8A: part off depth section NT96-907, 8B: part of depth section NT96-909.

are gravity flow sediments, while complex folding and faulting formed on lower part of profile 909 and 915 (Figs. 6, 7). But in the north profiles, there are two reverse faults formed beneath the inclined strata. The fault usually extend to surface it happened at the fringes of folds with small throw. The fault can be trace to deep, but muzzled by multiple on the profile (Figs. 8A and 8B).

Kodaiba Fault (KF) extends more than 70km long in spatial, expresses as a thrust fault on the seismic profiles, and is still active. The fault has been observed by several submersible dives (Mazzotti et al., 1996; Le Pichon et al., 1994; Thoue et al., 1995). The west wall of fault occurred Upper Miocene outcrops and the terrace are most probable Lower-Middle Miocene strata (Okuda et al., 1983; Okuda and Honda, 1988). The fall wall of the fault found a lot of talus and compress fault plane.

The fault is a thrust but doesn't extend to acoustic basement.

3.2 Slope basin

Slope basin is located between TF and BF. Slope basin is compression basin bounded by thrust faults, which means this is a sedimentary basin accompanied subduction. The sequences of which are consisted of one opaque seismic face (sequence B) and transparent seismic face (sequence A) can be contrasted with trough sequences. There are thickness sedimentary layers with moderate to strong amplitude, discontinuity reflector and moderate energy beneath slope basin, which suppressed intensive compression. The layer with more strong energy and more continuity reflectors differed from the face in the west wall of TF. We induced it formed during Middle-Upper Miocene. It is probable the middle Miocene to early Pliocene prism (Taira

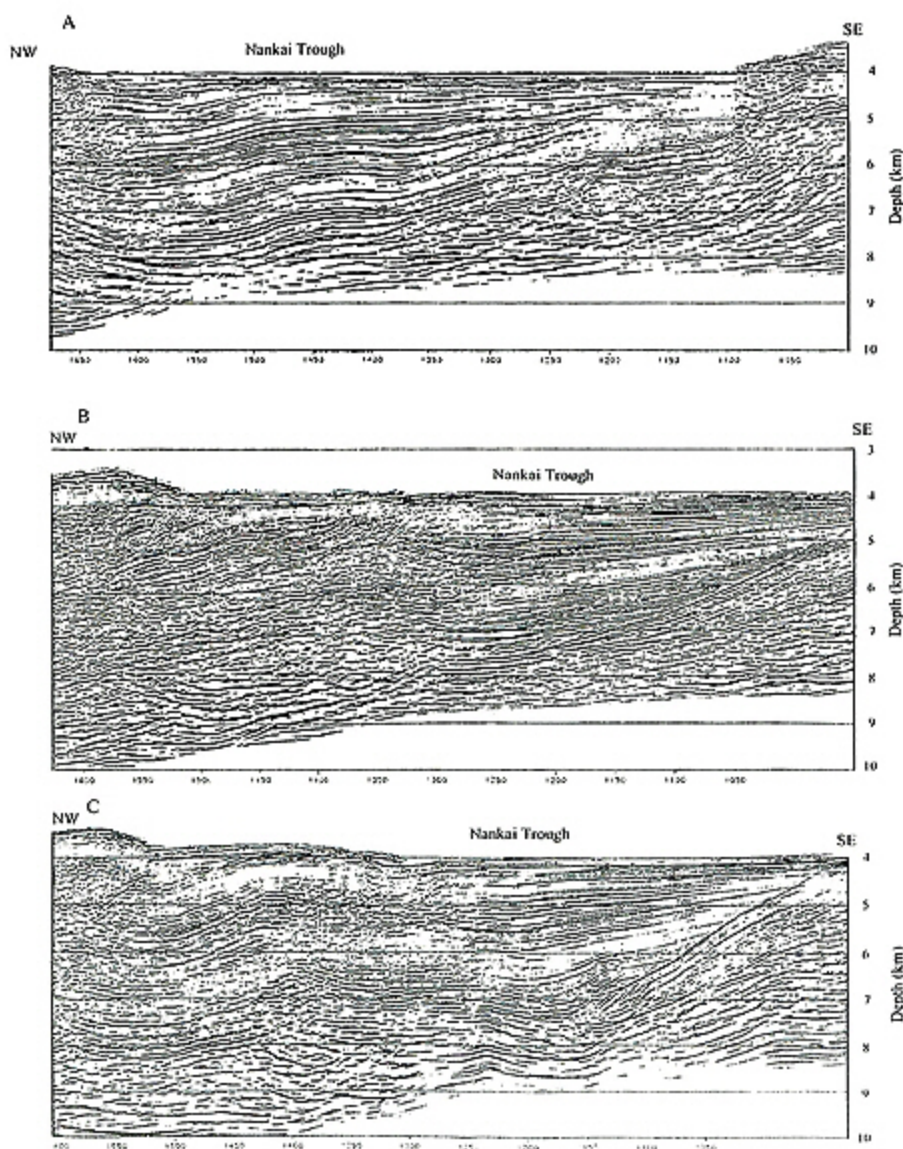


Fig. 9 Depth migration section showing the sedimentation sequences and deformation of Nankai Trough axis: 9A: Depth section of profile NT96-901, 9B: Depth section of profile NT96-909; 9C: Depth section of profile NT96-911

and Ashi, 1993). There exists a rugged reflector at 6km depth of profile 96-102 (Fig. 10), of which the acoustic character is same as acoustic basement of Zenisu Ridge.

3.3 Lower slope prism (LSP)

LSP is distributed in Outer ridge lower, bounded by FT and BF occurred three parallel thrust faults. FT actually is major fault zone. There occur a series thrust faults on the seismic profile (Figs. 4, 5, 6, 7, 9). While it is not so clear on the profile on the profile 915. The thrusts usually extend deeply to the decollement surface. Thrust surfaces are wavy, which suggest that different lithologic units existed. To landward slope, some reverse thrust fault with very lower angle, which overlay the old sequence to the Quaternary slope fan, have been formed. The backthrust fault also showed moderate angle thrust and more recently on the seismic profiles discussed by submersible data (Le Pichon et al., 1992).

3.4 Trough axis

Trough can be divided two part: one is prot thrust system, which is characterized by box-folds and two high-angle thrust

faults in the trough filled sequences (Fig. 9), but second thrust faults also exist flank of the folds, which disappear to seafloor. The sediment to east has not involved in deformation. Its boundary with Zenisu Ridge is not clear because there are many slump sediments covered on it. But it only interpreted a reverse fault on profile 901. The basement does not involved the deformation, where are limited the trough filled sediments. The strata of Shikoku Basin sequences and trough fill sequences or within the hemipelagic layers of Shikoku Basin exist an apparent decollement.

The present Nankai Trough was assumed to be formed since late Pliocene (Shimamura, 1989). Before the time, the region of Nankai Trough was an old swell, because the sequence C decreases from Zenisu Ridge to trough. The structure is probably like the Zenisu Ridge tectonic uplift.

3.5 Structures of Zenisu Ridge

For the tectonics of Zenisu Ridge, a few authors indicated it as a new subduction zone. The shallow reverse faults have been revealed by the seismic profile (Aoki et al., 1982; Okuda and Honda, 1988). The following submersible observation also

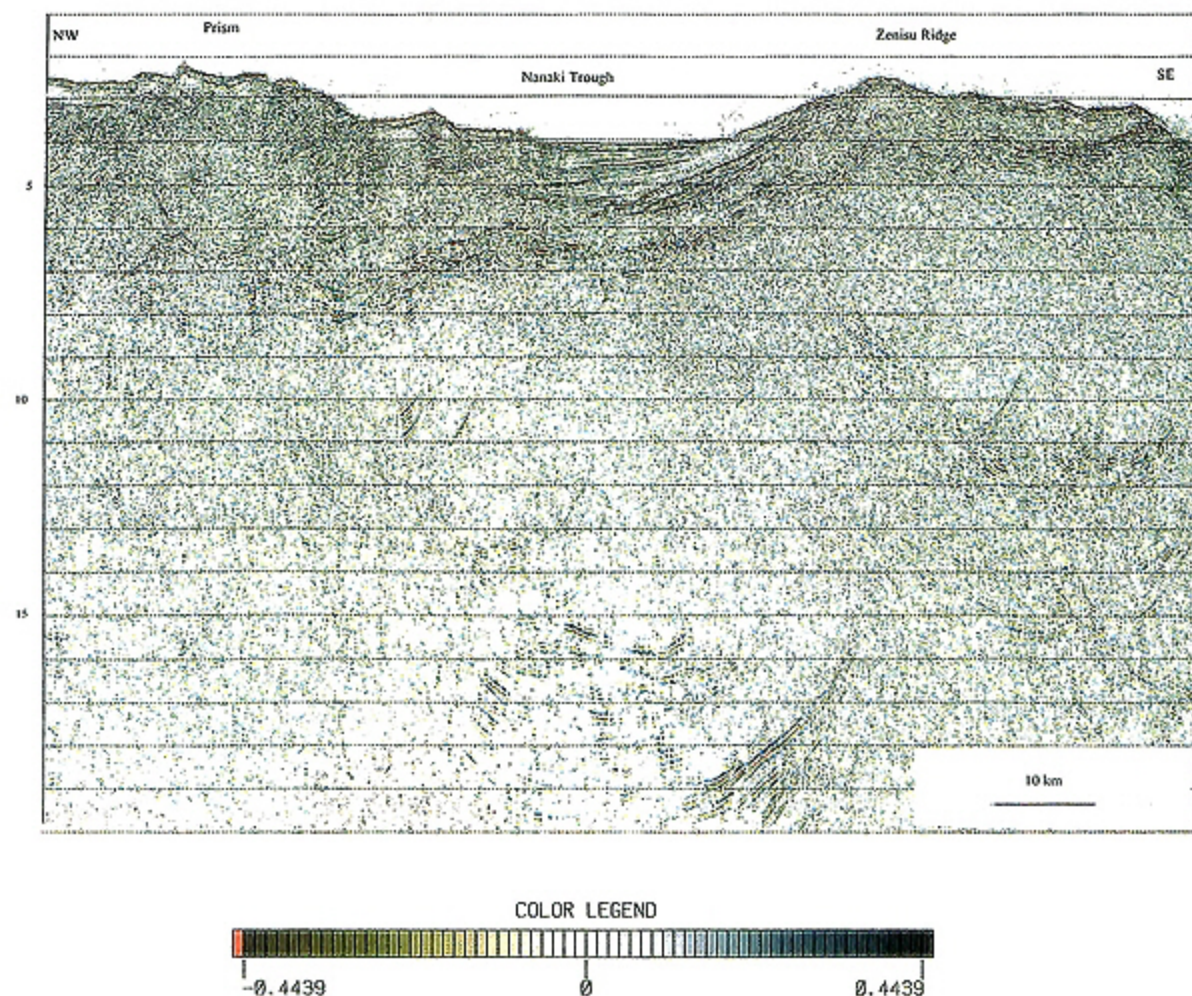


Fig. 10 Depth section (NT96-102) across the Zenisu Ridge and depth structure of the prism and the central trough

found some thrust faults on the east flank of Zenisu Ridge (Le Pichon et al., 1987; Lallemand et al., 1989; Tokuyama, et al., 1998). From our data there is no any fold formed at west flank of the ridge. Profile 102 (Fig. 10) also show gentle fold of ridge, maybe accompanying by overthrusting in the east margin. Recently, Segawa (1998) considered that some evidences suggested the Zenisu thrust as a new subduction zone. The free-air gravity anomaly map found some signification negative free-air gravity anomaly in the southeast foot of Zenisu. And activity of earthquakes happen along the southeast foot, which is the highest in the Tokai area (Takanishi et al., 1994). Some other evidence is based on the measurement by GPS positioning since 1994 showing that Zenisu Ridge is moving northwestwards at a speed of 2.5 cm a year (Segawa, 1998). But from the reflection data there seem not exist the intensive subduction zone. It will be more important compression zone by the collision between Izu-Bonin and Honshu Arcs.

3.6 Decollement plane

The characteristics of decollement has been drilled by 19.2 m thick zone of intense faulting and brecciation at hole 808C of the ODP 131 (Pickering, et al., 1992) and clearly showed on seismic profiles in the west NT (Aoki et al., 1982; Moore and Shipley, 1993; Moore et al., 1992). The decollement under the NT accretionary prism is imaged seismically as a high-amplitude, reversed-polarity reflection. The decollement is a 19-m-thick zone of the intensive breccia where it was penetrated on the Leg 131.

But in the eastern NT, decollement plane exists at 5-6 sec (two way time) in our time section (Fig. 4, 5, 6, 7). It is near 5 km below sea surface at the lower prism, but slowly increases to 6 km below the Tokai thrust (Fig. 8). It was a slight incline to

west. The plane expresses intensive reflection beneath lower prism, but not clear near Tokai thrust because the multiple reflector, which seem to some undulation. It was interpreted by the ridge subduction (Lallemand et al., 1992; Le Pichon et al., 1996).

4. Evolution of the prism

A few models for the accretion in the NT were presented to interpret the evolution of prism (Honza and Murakami, 1985; Okuda and Honda, 1988; Kagami, 1985; and so on). The issue on evolution of prism has existed because the deformation is complex and deep tectonics is not clear. The eastern Nankai Trough prism has specific morphological characters in the study area, which were concluded by many authors as follow (Lallemand et al., 1992 and Le Pichon et al., 1992). First, it has a significantly steeper regional slope. Second, its orientation is 50° N instead to 70° N. Third, it has a tighter style of folding. Forth, it has been affected by very strong erosion that has left huge scars and fifth, the wedge is significantly narrower. All these characteristics can be explained by the ridge subduction, paleo-Zenisu ridge, which has indeed been subducted below this wedge during the last 2 million years.

USP consisted of Miocene strata (Okuda and Honda, 1988), which was major subduction zone since early Pliocene, and it continues active as internal thrust of prism. The arc volcanic activity existed on the Honshu Island and subduction of Shikoku Basin down to the Honshu Island since Miocene (Kobayashi et al., 1995) suggest that exist a subduction zone, while the modern subduction began since Late Pliocene. Where is the subduction zone. Many scientist suggest that TF was this stage subduction zone. The key problem is found the accretionary basin. We think the sediment layers with relative layer reflection.

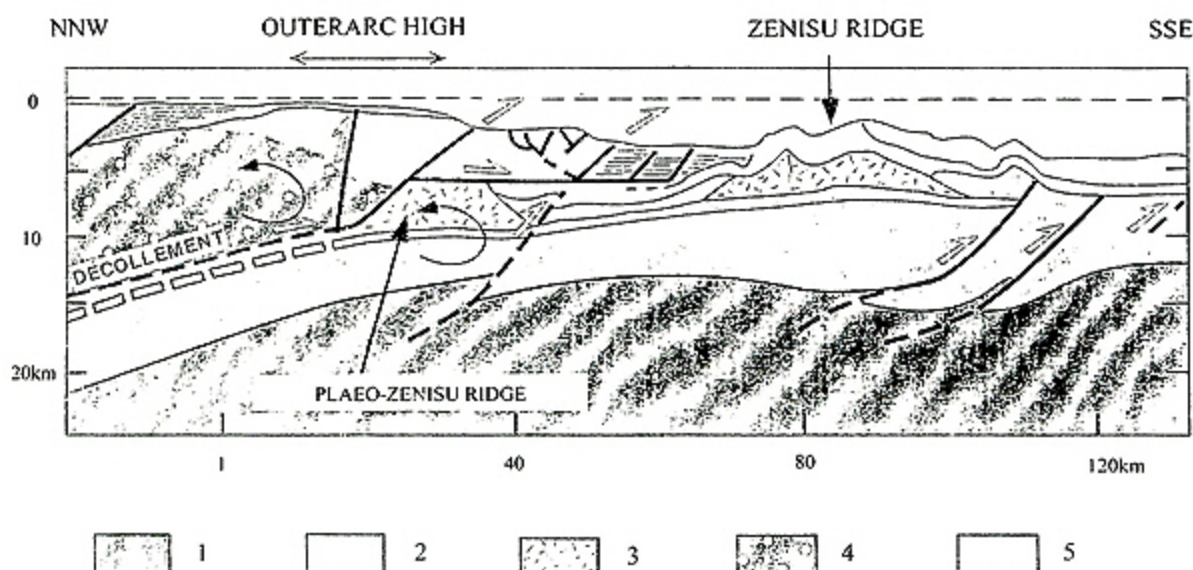


Fig. 11 Schematic diagrams shows the tectonics characteristics of Nankai Trough (referred to Le Pichon et al., 1996). 1. Mantle; 2. oceanic; 3. The two igneous bodies of Zenisu and plaeo-Zenisu; 4. continental backstop; 5. sedimentary body.

tion represents Miocene and Early Pliocene trough. TF continued active during Quaternary. It expresses the internal thrust within the prism. But the frontal major thrust has already move to FT, which extend deeply to the detached fault.

Second stage is ridge subduction began at 2 Ma as Le Pichon et al. (1996). By the subduction of paleo-Zenisu beneath the prism, compression is expected in front of it, uplift on the top and erosion behind. That is why TF is still activity. And the accretionary prism is uplift and extensive erosion. FT fault have been development along trough axis since Late Pliocene, based its involved strata. The east NT is located at intensive compression region between collision of two arcs. Whole area submitted compression and subduction angle is relatively gentle so main subduction zone transfers backward, but now it is transfer from TF to FT. The prism with a steeper frontal slope, evidence of backthrusting, a sharp slope break are interpreted with a past ridge subduction (Lallemant et al., 1989; Le Pichon et al., 1996).

5. Question and discussion

5.1 Ridge subduction : Zenisu ridge and paleo-Zenisu

Zenisu ridge has been considered as intra-oceanic subduction by many authors (Le Pichon, 1987; Chamot-Rooke and Le Pichon et al., 1989; Lallemant et al., 1989). The past this kind of ridge now buried beneath the eastern Nankai trough prism has been postulated in order to explain some of the characteristic of eastern Nankai accretionary prism (Lallemant et al., 1992). Le Pichon et al. (1996) demonstrated that ridge, referred to paleo-Zenisu, existing beneath eastern Nankai prism, based on evidence of geomagnetism, gravity and OBS velocity structures.

Zenisu Ridge is important thrust tectonics. Based our seismic data, the ridge uplift since Late Pliocene. Because our seismic data show that the sequence D expresses parallel reflection layer, it means the gentle geomorphology existed during Pliocene. It is clearly that hemipelagic sediment layer in central trough is thinner than that beneath prism, which showed that existence of old trough fill layers beneath the prism. The faulting in the thicker sediment need more strong stress to be formed, so that the folds in sedimentary strata have been formed in the former trough fill sediment by the compression.

Whither Zenisu is a new subduction zone or just an intraplate shorten is still difficult to answer. The key question is the existence and evolution of paleo-Zenisu. Paleo-Zenisu was of course important to evolution of prism. Profile 102 shows some ridge shape structure at fall wall of Tokai thrust. There exists a weak amplitude, weak energy, reflection, may be interpreted paleo-ridge.

5.2 Volume of accretionary prism

A lot of factors contribution to build of the Nankai prism has been discussed by many authors (Ashi and Taira, 1992; Okuda

and Honda, 1988; Allemande et al., 1992, 1994). As to the eastern Nankai prism, three important factors control the volume of the prism. One is compress stress in overriding plate. The stress is stronger; the accretionary prism is bigger. The upper crust in eastern Nankai Trough has extensive compression that led to the large prism. Second factor benefit to formation of prism is the high sedimentation rate in this area. The third is the ridge like relief existed which increase the volume of prism. That is the important factor to enlarge the prism.

There also have many other factors, which were effected on the prism. A small tapered prism would suggest a lower friction in the decollement and/or stronger wedge material, based on the Coulomb failure criteria (Davis et al., 1990). A larger wedge taper should promote dewatering due to a rapid increase of tectonic overburden. The cold seepages in eastern Nankai trough have widely been found suggested that interpretation. Such a shape difference may origin from decollement depth indirectly controlled incoming basement relief.

6. Conclusion

The conclusion include as follows:

- (1) In trough area, four seismic sequences have been divided according its seismic internal and outer form feature. Sequences A and B are trough fill turbidite and hemipelagic sediment. It formed during Late Pleistocene and Holocene. Sequences C and D represent upper turbidite sequences and hemipelagic sedimentary layers in Shikoku Basin. The accretionary internal was very complex sedimentary layers formed during Miocene and Early Pliocene.
- (2) In spatial, five deformation units have been observed, which include upper slope prism, accretionary basin, lower slope prism, trough and Zenisu Ridge. There are three major thrust zones, Tokai thrust zone, frontal thrust zone and Zenisu thrust zone. Former subduction began during Miocene, when the major subduction zone happened along the Tokai fault. Recently major subduction thrust formed since the Pliocene. Ridge subduction zones occurred on the eastern NT. This led to the huge thickness accretionary and large intraplate throwing.
- (3) Tectonics of Zenisu ridge is compressed structure from the seismic data. But there are now occurred thrusts discovered by recently submersible. There is an apparent intra-oceanic thrust, it was postulated a newcoming subduction zone by collision between Honshu and Izu-Bonin Arc.

Acknowledgement

One of the authors, Dr. S. Wu, wishes to express his thanks to Japan Science & Technology Agency and the Japan Marine Science & technology Center for their financial support. And thanks also to H. Kinoshita, former Director of Deep-sea research department and T. Fujisawa, International affair division for their kind helps.

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(Manuscript received 5 August 1999)