Sedimentation processes and deformation at south flank of Zenisu Ridge, Philippine Sea revealed by 'Shinkai 6500' Dive 523 and seismic data

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We discuss the sedimentary features and deformation in the south flank of Zenisu Ridge and trace its northward extension of the active thrust fault, which were discovered at south part of Zenisu Ridge, by using JAMSTEC manned submersible, *Shinkai 6500*, and some reflection seismic data. We found a large outcrop of siliciclastic facies along the track of Dive 523 in Zenisu Ridge. The sedimentary facies observed on the slope are Pliocene poorly consolidated mudstone or sandstone, which are dominated by turbidites with typical ripple structure and grade-bedding. Sediments filled in the trough are debris flow deposits and fan turbidite systems. The rocks at lower slope have been suffered intense deformation. We observed well-developed fractures. These plus the broken fracture breccia and dipped sedimentary layers probably reflect a fault zone. Along the fault zone there occur the dead clams which represented seep biological community. The well-preserved *Vesicomyidae* clams indicate the most recently activity. The seismic profiles NT96-103 and KK31 cross the dive sites confirmed the plane of the fault dips to west and the fault exists as thrust fault. It maybe is northward extension of active compression observed on the southern scarp of south Zenisu Ridge (Le Pichon et al., 1987; Lallemant et al., 1992; Tokuyama et al., 1998). The compression is now established from south to north through the field evidence. Accordingly, the south of Zenisu Ridge is a nascent subduction zone. According to the seismic profile NT96-103 post-rifting covering strata can be divided four seismic units (Unit A, B, C & D). The strata observed during Dive 523 are a part of Unit B, which is Pliocene (4.15-2.65Ma) on the basis of the calcareous nannofossil stratigraphy. The Unit B is conformable contact with underlying strata. The tectonic uplift should happen after Unit B, so the analysis of strata suggest the building of Zenisu ridge could be since last Pliocene or Pleistocene.

Keywords : Zenisu Ridge, submersible, sedimentation, turbidite, debrite, deformation

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1. Introduction

The importance of the tectonics of Zenisu Ridge has raised in recent year. It was considered as adolescent subduction zone (Chamot-Rooke and Le Pichon, 1989; Lallemant et al., 1989; Le Pichon et al, 1987, 1992; Segawa et al., 1998; Tokuyama et al., 1998). Since Aoki et al. (1982) first proposed the compressive structures in the southern Zenisu Ridge, last two decades Kaiko-Nankai project conformed that southern Zenisu Ridge is thrusting of intra-oceanic crust as revealed by seismic data (Tokoyama et al., 1988). Manned submersible surveys were deployed to confirm the new subduction zone and confirmed the thrust through the field evidence (Le Pichon et al., 1987). There have already been nine dives on the southern Zenisu Ridge and near Zenisu Trough (Fig.1), of which several dives were successful to show the compressive structures which may be related to the nascent subduction zone. One of which is Dive 325 at southern Zenisu Ridge. The uplifted oceanic crust was found during the dive, which rose by the thrusting of inter-oceanic crust. Another dive is Dive 324. During this dive several small outcrops of mudstone and volcanic rocks were observed. The volcanic rocks with highly altered geochemical signatures were considered from arc magma (Henry et al., 1997). We don't think that these rocks represent the oceanic basement, whereas these reflect late volcanic activity. In fact, the crust of Zenisu is the spatial variation of tectonics from south to

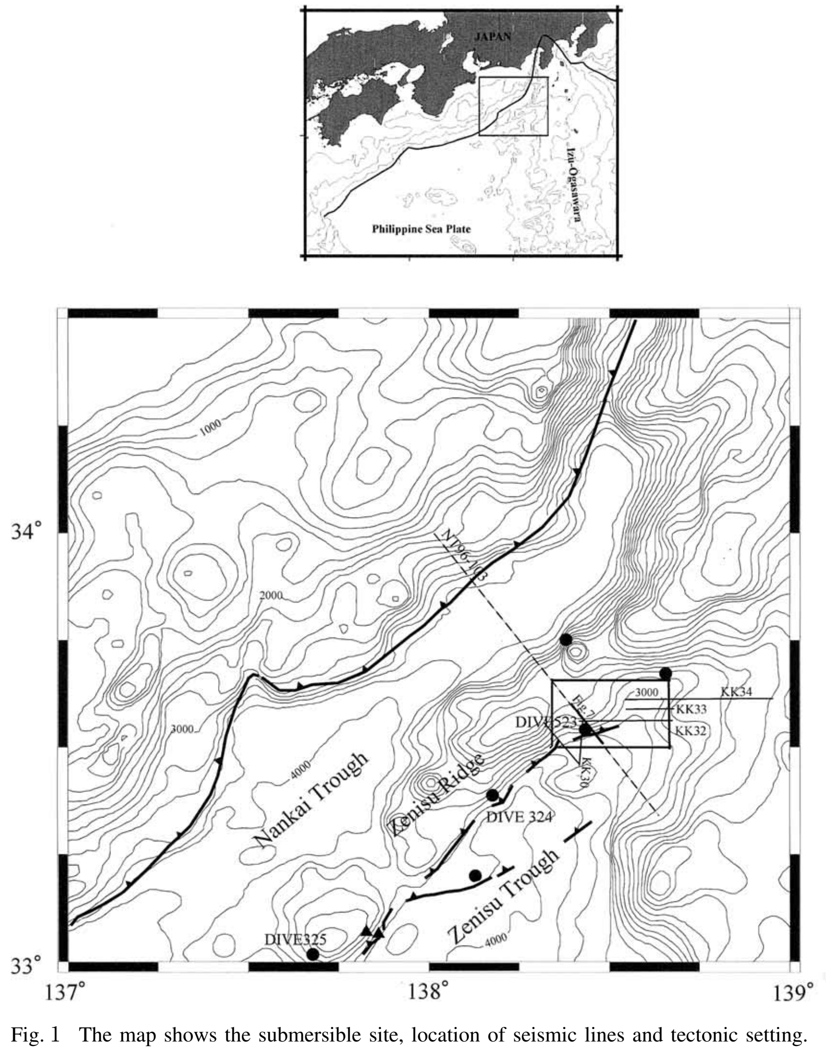

Fig. 1 The map shows the submersible site, location of seismic lines and tectonic setting. Dot represents the dive sites carried out by *Shinkai 6500*. Delta indicates dive site by *Nautile*. Dash line is multichannel seismic profile NT96-103 was gained by R/V *Hakuho* (Takahashi et al., 1999). Fine lines are single channel seismic profiles KK30 to 34 collected during *KAIKO-TOKAI* project (KAIKO I RESEARCH GROUP, 1986). The coarse lines represent thrust faults. Box indicates location of the 5.

North. The formation of southern Zenisu Ridge is considered an uplifted oceanic crust by subducting, whereas the northern was probably formed by younger volcanic activity, because thickness both the crust and covering strata increase greatly (Nakanishi et al., 1998; Takahashi, in press). The fracture system and sedimentary feature in northern Zenisu Ridge would provide important evidence to demonstrate if there exists an adolescent subduction zone. Therefore, the submersible objective is to search for active fault, sedimentation and related fluid flow at south flank of the ridge. It is effective to understand the active structure and sedimentary evolution at inner slope of the possible nascent subduction zone.

The dive site and seismic lines used in this discussion show in Fig.1. The SeaBeam bathymetric map shows the detail topography around the dive site (Sakamoto et al., 2000). Zenisu deep-sea channel is adjacent to it at south, which extends with 35° direction. The deep-sea channel extension abruptly changes at latitude of 33°40', which controlled by fault activity, generally say, it is because the rise of Zenisu Ridge that channel was constrained by tectonic subsidence at the times of tectonic quiescence as described by Catuneanu et al. (1997). The survey track is along the southeast flank of a low swell, with flat geomorphology at top, while steep at both upper and lower slope. Total of the slope inclines 18°, while the angle of upper and lower part can arrive to 30° and 35°, respectively (Fig.2).

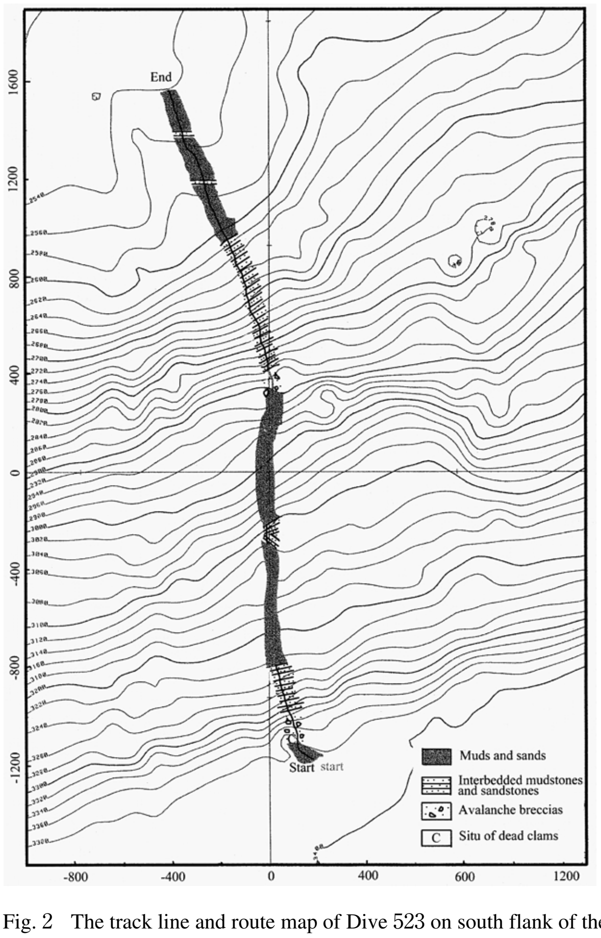

Fig. 2 The track line and route map of Dive 523 on south flank of the Zenisu Ridge.

Shinkai 6500 manned submersible, with deepest dive capability for the time being, is playing an important role in deep-sea research and resource development. The system consists of the manned submersible *Shinkai 6500*, its support R/V *Yokosuka* and a dive support system for navigation and telecommunications using acoustics and electronics. Visual records and 4 posh cores have gained during the Dive 523. Here we report the result of the dive and comprehensive interpretation together with seismic data.

2. Submersible observation of deformation and sedimentary processes

2.1. Deformation observation

The first part of the dive 523 was made over from 3400 to 3200m at lower scarp dipping to southeast. We started at 3380-3390 m of flat seafloor in Zenisu Trough. There is no sediment or erosion seafloor. After then we observed the debris flow sediments or avalanche breccia covering the foot of the slope. At dive time 11:43 to 45 there are a few shells of *Vesicomyidae* clams showing in Fig.3I. The last time we observed the clams is at 12:00:25. Poorly consolidated mudstone crops out the whole lower part of the slope. We collected the rock samples (SP#1) which are mudstone and sandstone (Fig.3II, III, IV, V, VI). The high-density fractures have been observed at lower scarp (Fig.3IV) and at the upper scarp (Fig.3VI). The direction of the fractures is northwest (normally 298°-326°); Another group is NE direction (60°-84°). Fig.4 is rose diagram of the fracture along the dive track, of which four dominated directions are N85°E, N296°W, N326°W and N356°W, respectively. We saw the rocks were broken (Fig.3II) and suggested that it was fault zone. Among the fracture observed with the submersible, it's not always possible to recognize joints and faults. A simple criterion that we used is according to the density, conti-

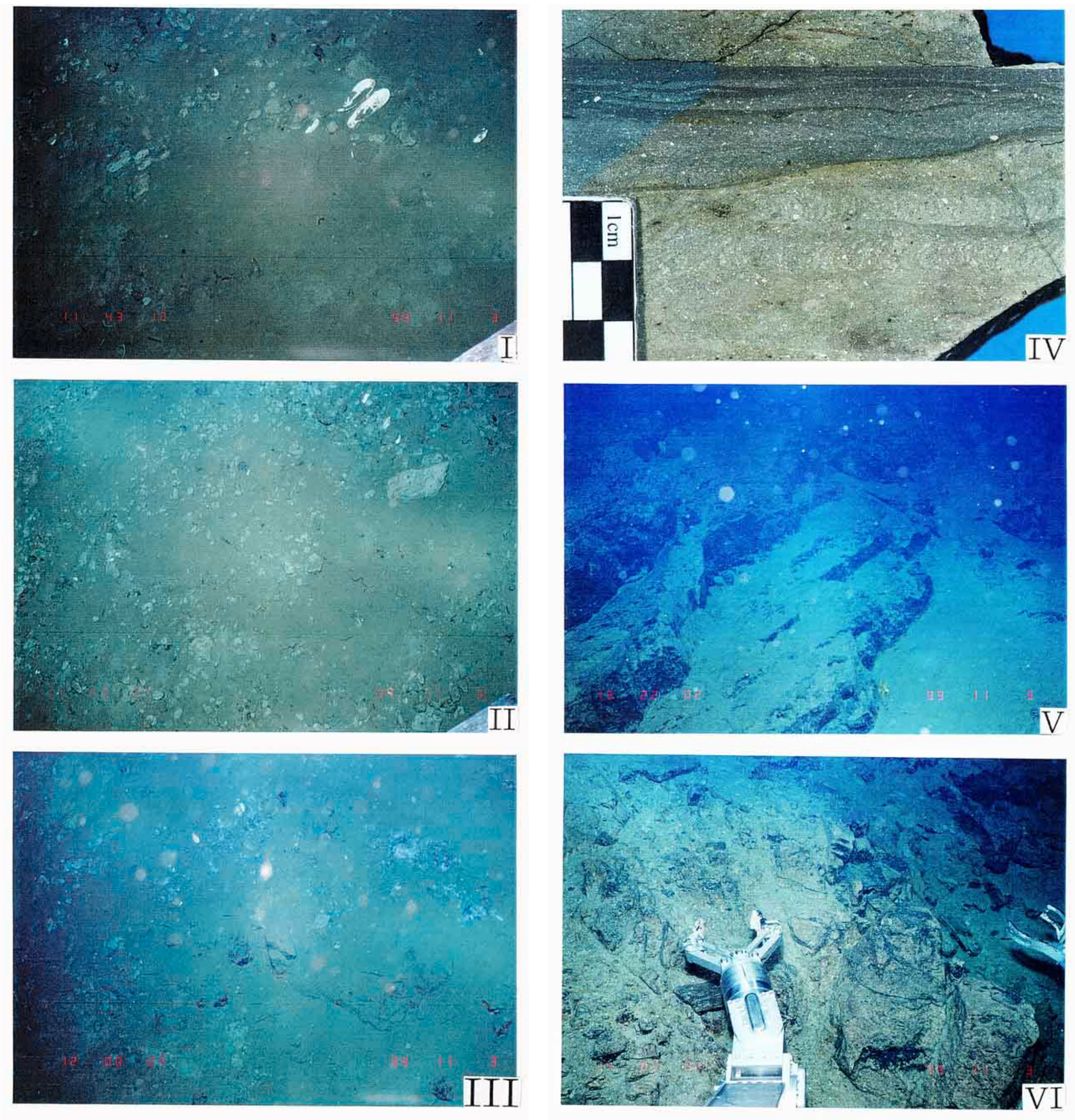

Fig. 3 Photography. Photo I: Clams discovered at the foot of slope. Photo II: The fine mud outcrop at lower scarp with broken breccia. Photo III: Inclined siltstone and sandstone. Photo IV: fined sandstone and mudstone sampled at the lower slope. Some ripples and crossbeds occurred in fine sandstone, and graded bedding developed in the strata indicated that sedimentary rocks formed by turbidity current. Photo V: Outcrop of mudstone observed from Dive 523 at south slope of Zenisu Ridge, which is dominated lithologic unit. There are two group well-developed fractures with strikes 290° and 358°, respectively. The fractures have steep inclined angle. Photo VI: Broken mudstone at upper slope, which shows the tectonic breccia.

nuity of the fractures and associated structures, like tectonic breccia exist. An examination of Fig.5 suggests that it is a fault, identified in seismic records may cross eastward to the dive and extend to more northeastward. The thrust may be occurred over seafloor because of the broken breccia and inclined strata.

After having climbed the scarp we enter the gentle slope and observe the fine hemipelagic sediment (PC2) and small outcrop (SP#2). On the upper scarp there occur a large outcrop of mudstones interbedded sandstone. The mudstone layers seem to very gentle and dip of the layers has same direction as the slope, just a little gentle at upper slope. The rocks also fully developed the fracture. At dive time 14:14:53 we found the two conjugate fracture system, that is 61°/SW/60° and 329°/SW/70°. NWW trend fracture seems to be dominated from rose diagram (Fig.6). The joints are well developed near the spine of the anticline. Northeastward anticline was induced by the second fold observed along the track, but the dive just cross the east flank of the anticline. The SeaBeam bathymetry cubic map shows the geometry of the anticline. More detailed features refer to fellow discussion revealed by seismic profiles KK31 and NT96-103.

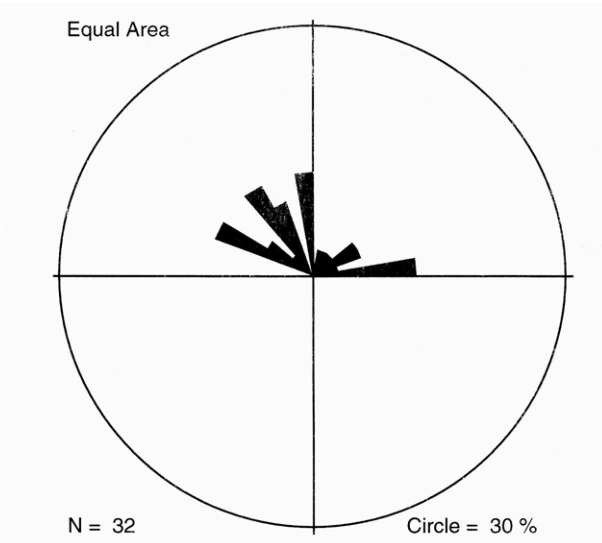

Fig. 4 Rose diagram of joint observed during the Dive 523.

2.2. Sedimentary processes

There have three types of sedimentation facies in the study area (Fig.5). One is the turbidity current sediment with different age, which distributed on the bottom and flank of trough. Second is debris deposit along the feet of the slope. The third is hemipelagic mud sediments on the slope, including biological deposits.

Turbidites include three sub units with different age (Fig.5). The youngest (UnitA1) is channel or trough filled channel-levee system, its distribution shows as Unit A1in Zenisu deep-sea channel and Zenisu Basin. Its age should be the last Pleistocene fine sand and mud deposits. The sediments were mainly transported from the Izu-Ogasawara Arc via Zenisu deep sea channel. But the seafloor are erosion during the highstand sea-level in Holocene. The second kind of turbidite is Unit A2, it is typical channel-levee system in the most part of Fig.5, but the sedimentary face varies into fan system to southward. It was suggested the sediments less than 1Ma by Tokuyama et al. (1998). Our data suggested that Unit A2 is Pleistocene. The older turbidites (Unit B) exposed along the dive track and south flank of Zenisu Ridge. The rock samples (SP#1) show the grade bedding and cross-stratification and erosion surface. The above features indicated that rocks formed by turbidity current according to deep-sea facies description

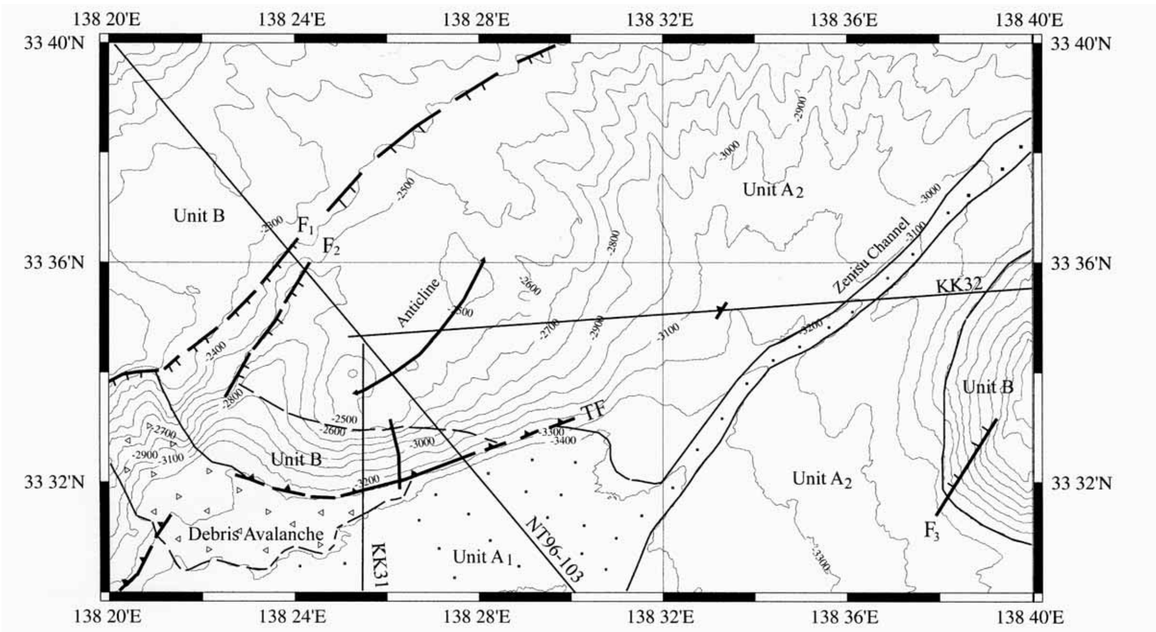

Fig. 5 Geological map of the study area. Its location shows box of Fig.1. Coarse lines are faults, of which F_1, F_2, F_3 are normal fault; whereas TF represents thrust fault. Unit A_1, A_2, B show surface distribution of seismic sequences.

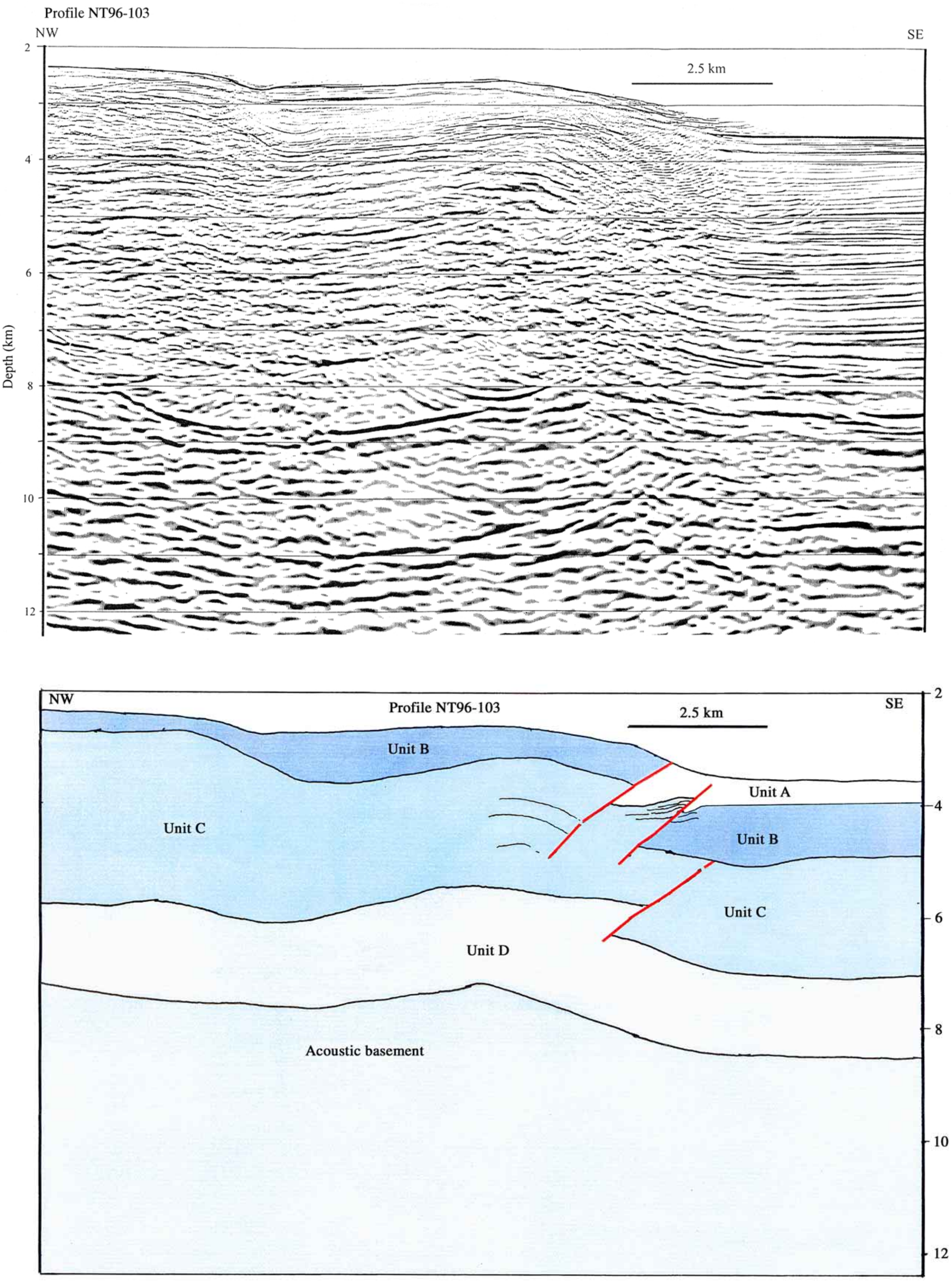

Fig. 6 Profile NT96-103 shows seismic stratigraphic units (Unit A, B, C & D). A large thickness of sediment overlaid on the acoustic basement in northern Zenisu Ridge. Total strata thickness is over 5 km. The strata (Unit A, B and C) are characterized by a huge thickness turbidites. The shallow thrust is interpreted at southern part, but it is not clear to deep layer.

(Pickering et al., 1991). The Unit B distributed in the southeast flank of the anticline rose by the thrust.

Debris flow deposits are distributed along the foot of the slope. The deposits are distributed at a small area in dive area. To the southwest, we distinguish a big submarine landslide which consists of well-developed structures from SeaBeam bathymetry (Fig.5), including: Normal fault at upper scarp of the frank characterized by steep geomorphology which show extension fault and erosion surface. About 5x5 square kilometer debris avalanche encountered in the lower part of the slope and trough seafloor. The abundance of submarine landslides demonstrates the mass-wasting processes play an important role in the sedimentation processes of trough floor and evolution of the ridge. The frank of it has steep scarp, which is the source area for one of the typical landslide. The structural features and internal fracturing of the slide support the origin of debris flow deposits.

The third type of sediment is modern fine sediment covered on the flat of frank, which was sampled by push core (PC1, 2, 3). It consists of fine mud and a few biota. Besides, there found the number of dead clams at feet of the dive, and there are probably some living clams (Fig.3I), which indicate the underground fluid flow and active structure.

2.3. Biostratigraphy resulted from rock samples of the dive 523

We analysis nannofossil from four rock samples during Dive 523. The calcareous nannofssils identified from Sample 6K523R3 include: *Discoaster asymmetricus, Discoaster brouweri, Discoaster pentaradiatus, Discoaster surculus, Discoaster tamalis, Pseudoemiliania lacunosa, Reeticulofenstra pseudombilica etc*. From ODP site 808C I Nankai Trough the last occurrence of Discoaster tamalis occurs within the upper part of zone NN16. And the top of zone 15 (3.65Ma) as marked by the last occurrence of Reticulofeuestra pseudoumbilica. The first occurrence of Discoaster asymmetricus represents the NN13, the age data is about 4.1 Ma (Olafsson, 1993). It can contrast with subzone CN11b to 12a of Okuda and Bukry (1980), it represents Pliocene strata (4.16-2.65 Ma). We deduce that strata observed in the Dive 523 could be Late Pliocene.

3. Seismic sequences on the south flank of Zenisu Ridge

3.1. Seismic stratigraphic units

Four seismic units (Unit A, B, C, and D) in northern Zenisu Ridge have been divided based on the seismic reflection data in last two decades. Here we show the seismic profiles NT96-103 (Fig.6A) and its interpretation section (Fig.6B).

Unit A was distributed on both side of Zenisu Ridge. It has relatively continuous reflections, lower energy and variable amplitude. The sedimentary layers onlap on the underlying Unit B in both side of Zenisu Ridge. Unit A represents channel-filled sequence observed by the dive since the Zenisu Ridge rose. The sedimentary facies were considered as turbidite in Nankai Trough by DSDP and ODP results (Taira and Niitsuma, 1986; Pickering et al., 1993). The unit A in the trough floor around Dive 523 is turbidite sand and sandy mud in deep-sea channel system according the sampling, and it probably represents Quaternary deposits inferred from the underlying strata aged data and sedimentary rate evaluation.

Unit B has relative continuous reflection and weak amplitude. Its thickness varied, but it has 500-800 m thickness of stable strata in the Zenisu area and increases from south to north (Tokuyama et al., 1998). It is semi-consolidated turbidites confirmed by Dives 523. We saw the typical graded bedding, wavy and ripple laminated divisions (Fig.3IV). The sedimentary unit is interpreted fan turbidite deposits. The microfossils in the rocks represent the Middle to Late Pliocene. It is like the upper part of Lower sequence I of Tokuyama et al. (1998).

Unit C has marked and continuous, parallel reflection, moderate energy and moderate amplitude. The thickness of NT96-102 is about 500-900m, whereas it increases to 3000m. The large thickness of strata represents more turbidites and intense subsidence. It is possible that the strata are likely bioturbed hemipelagic mudstone and sandstone, volcanic ash and lava as observed by Dive 324 (Henry et al., 1997). It represents the strata of Shikoku basin. We think that it deposited during Late Miocene-Early Pliocene, even though no reliable age data are designed.

Unit D has strong energy and high amplitude. Our interpretation of Unit D is proximate volcaniclastic

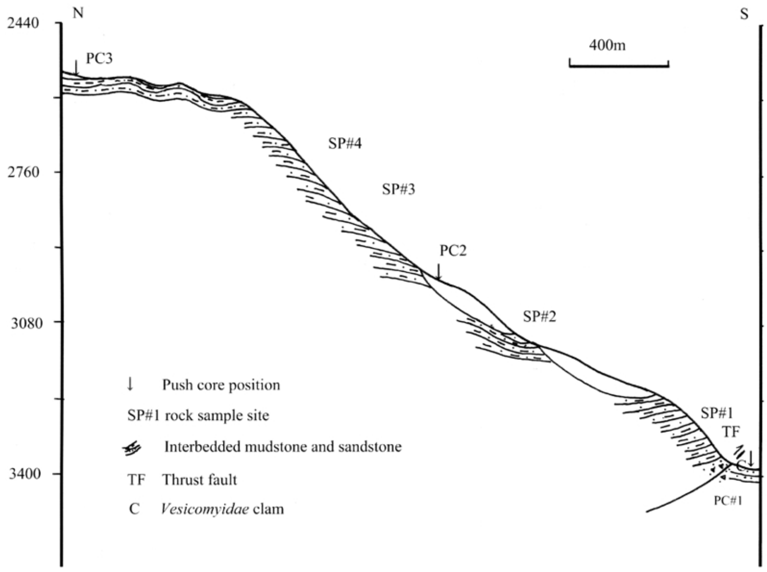

Fig. 7 the geological section along the dive track. The inclined strata at lower part and parallel strata at upper part, which induced broken faulted breccia and steep cliffs, may be deduced by the adolescent subduction zone.

detritus. It may contrast with lower Shikoku Basin strata, that is Miocene- Pliocene strata (Pickering et al., 1993). The seismic facies and interpretation of Unit D are same as the Lower sequence II of Tokuyama et al. (1998). Unit D has unconformable with the underlying igneous acoustic basement, which has discontinuous reflection, high energy and an important unconformity.

3.2. The thrust faults revealed from seismic data

The seafloor geomorphology and field observation above mentioned revealed the possibility of fault (Fig.7). But we still lack of the underground data to be defined the geometry of the fault. Therefore we checked the seismic data near the dive site. There three seismic profiles (Fig.6, 8, 9) are near the dive place.

The thrust and drape fold can be revealed from seismic section NT96-103 (Fig.6). In the hanging wall, anticline structure is presumably growing over the thrust influencing the deep-sea channel migration pattern. The uplifted anticline can be reflected in the transparent seismic face (Unit B), and clearer in the underlying high-amplitude reflections. From the NT96-103 we can defined two parallel thrusts along the boundary between trough and ridge according to reflector discontinuity (Fig.6A and 6B). One of the thrusts extends from deep to erosion seafloor. Deep-water turbidites onlap the

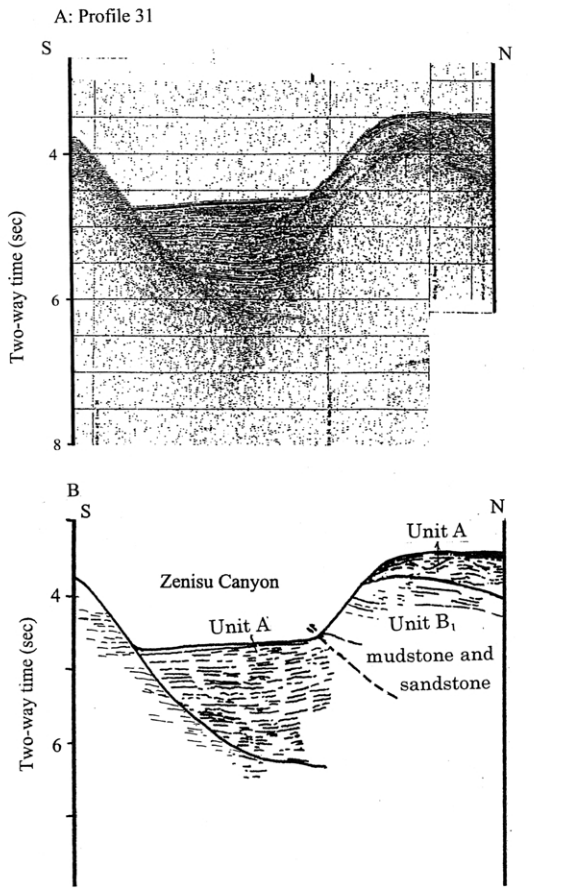

Fig. 8 Seismic section KK31. 8A: the single channel seismic profile KK31; 8B: the geological interpretation of single channel seismic profile KK31, showing the underground geology, especially the thrust fault.

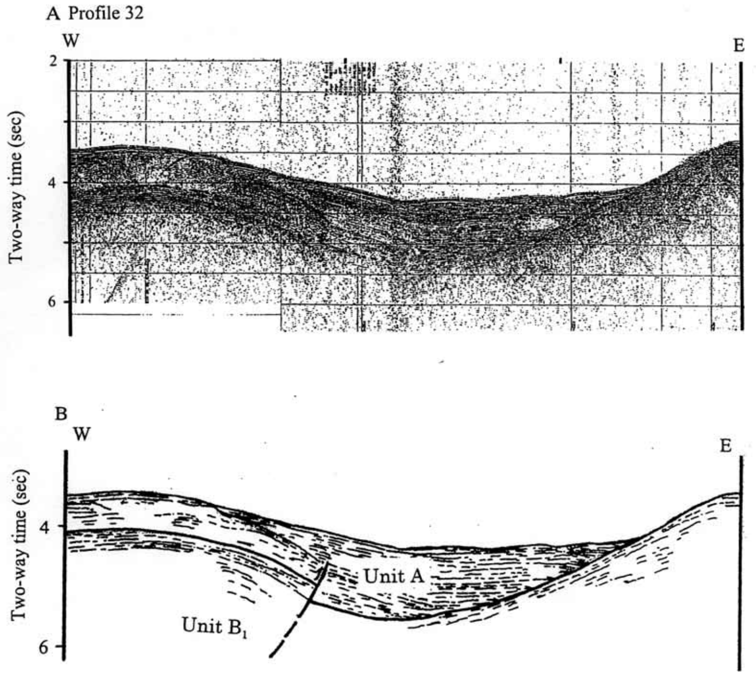

Fig. 9 Seismic section KK32. 9A: the single channel seismic profile KK32; 9B: geological interpretation of seismic profile KK32, which showing the possible thrust and anticline structures.

back of the ramp, where the crest of anticline structure may undergo erosion, with the progradation of a denudation complex basinward from the front of the thrust. So it shows the thin strata (Unit B) and extensive erosion on the seafloor. The deformation style discussed by Catuneanu et al. (1997).

Seismic section KK31 was a single channel seismic profile cross the dive place, which gained by Kaiko-Tokai project (Kaiko I Research Group, 1986). On the seismic profile KK31 there possible exists the evidence of thrust. At the foot of slope we discern inclined reflection layers and not clear faulted reflection (Fig.8A). On the upper part of the section the reflectors dip same as the slope. At top of the slope it shows the parallel reflections (Fig.8B).

Seismic profile KK32 is E-W direction section (Fig.9A). It shows the blind thrust and associated anticline structure from the profile (Fig.9B). The upper sequence of the section is channel-levee turbidite deposits, whereas the underlying layer can contrast with Unit B.

The central Zenisu Trough have been deposited a thick turbidites sequences (Units A_1, A_2, B, C). The thrust, most of them are blind faults, with drape fold have been interpreted from seismic data (Le Pichon et al., 1987; Takahashi et al., 2000; Tokuyama et al., 1988). The contact between the uplifting of acoustic basement of Zenisu Ridge and filled turbidites sequences is thus possibly a reverse fault, which is ascertained on the seismic profiles in southern Zenisu (Tokuyama et al., 1998). The associated fold observed by our dive (Fig.5) and Le Pichon et al. (1987) also support the interpretation. This kind of thrust can be existed as a blind fault and accompanied by a drape fold (Lallemant et al., 1989; Le Pichon et al., 1987), but it overthrusts the seafloor on the seismic profile NT96-103 in the study area (Fig.6).

4. Discussion and Questions

4.1. The active fault and nascent subduction zone

A primary purpose of the dive was the documentation of active compressive deformation. NEE-SWW trend faults were observed along at the south scarp of south Zenisu Ridge, which control the uplift of Zenisu massif. This offset is generally 2-3 km on the seismic profile, which also clear expressed 4km offset in the Kaiko seismic profiles. Le Pichon et al. (1987) suggested the only thrust fault could represent the nascent subduction zone.

Active fault is the important structure of a subduction zone. This structure, compared with other data, such as gravity, earthquake and crust structure data supported the interpretation of nascent subduction zone (Lallemant et al., 1989; Le Pichon et al., 1987; 1989; Tokuyama et al., 1998). The field survey of active faults extend northward is important for study of the tectonics of Zenisu Ridge.

We considered active fault still exists in the lower scarp. The evidences include as follow: (1) steep geomorphology; (2) inclined strata; (3) broken rocks; (4) dense fractures; (5) associated anticline structure; (6) seismic reflectors of faulted planes; and (7) distribution of seep community. An important result during this dive is the discovery of benthic community, *Vesicomyidae* specie at the lower scarp of the northern Zenisu Ridge. The seep community was characterized by temperature anomalies, a decrease in sulfate and high CH_4 concentration demonstrating the existence of cold seepage associated with active fault and discovering of the accretionary prism in the Nankai Trough area (Le Pichon wet al., 1987; Gamo et al., 1992).

This active fault was interpreted from the seismic profiles and observed by the field study of surface structure. The compression is now established through field evidence. Accordingly, the Zenisu Ridge is the product of intra-plate shorting. The shorting is presently active and results in the formation of nascent subduction zone. This phenomenon in the southern Zenisu previously proposed by Nicolas and Le Pichon (1980), and emphasized lately by Le Pichon et al. (1992). They suggested that the shorting have two single crustal fault, each accounting for about half of total offset of 3-4km.

Subduction along the Nankai Trough (Honda, 1985; Kagami, 1985; Moore et al., 1990) is main subduction zone at present. But a new subduction zone occurs along the south margin of Zenisu Ridge. The subduction could be migrated southward. The jumps of subduction zone is most possibility by experiment by Shemenda (1994). He indicated that the jumps of subduction zones and location of the lithosphere failure, especially in the flexural sag behind the outer rise caused by subduction of the extended ridge or strong resistance from mantle. The Zenisu ridge exists in outer rise of Nankai Trough and there is also proposed the paleo-ridge may be existed under the eastern Nankai prism (Lallemant et al., 1992; Le Pichon et al., 1996). Therefore, the big resistance exists in the region and lead to the failure along the south of Zenisu Ridge. The tectonic line can extend northward and become a shorting zone from the intra-oceanic crust to the intra-arc (Soh et al., 1998).

4.2. The sedimentary strata and implication for the formation of Zenisu Ridge

Covering strata Unit C and D can contrast with the strata of Shikoku Basin, but richer turbidites and debrite deposits in northern Zenisu Ridge because this region is near the source area. Large of thickness deep-sea turbidites (Unit B) deposited on the underlying strata with conformable or parallel unconformity contact. Unit B represents Middle to Upper Pliocene. So no evidence shows that Zenisu rose before Quaternary. It should be formed during Quaternary. Zenisu area was subjected to intensive compression occurs during subduction of Philippine Sea Plate. High pressure leads to failure of the lithosphere in a new place resulting in the initiation of a new subduction zone and Zenisu ridge was formed. The sedimentary thickness, basement uplift and deformation features between segmented Zenisu massif have differences. It controlled most probably by NW-SE transcurrent faults (Lallemant et al., 1989).

The basement rose at southern with 1-2km buried depth on profile NT96-102 (Takahashi et al., 2000), but it buried at least 5 km on the profile NT96-103 (Fig.6). The large thickness turbidites (Unit A, B, C) overlaid over the basement. The acoustic basement at southern Zenisu was part of Shikoku Basin suggested by many authors (Lallemant et al., 1989; Le Pichon et al., 1987; Tokuyama et al., 1998). OBS data supported the basement of whole Zenisu Ridge is consist of oceanic crust, but its thickness is thicker than normal oceanic crust and increase northward (Nakanishi et al., 1998). We consider that same kind acoustic basement possible extends northward to 33°40'N where exists an east-west fault, just overlay trough and channel filled thick sequences at northernmost. But IAB volcanic rocks were discovered within covering strata between 33°20'N and 33°40'N. This kind of volcanic rocks formed during Quaternary (Lallemant et al., 1989). Sakamoto et al. (2000) indicated the volcanic rocks are originated from island arc basalt. The aged data are variable, of which youngest sample is 2.03Ma based on K-Ar aged methods. But he indicated that it is not typical oceanic crust or typical arc tectonic environment. The generation of the volcanic rocks between 33°20'-33°40' is originated from arc tectonic background and mixed the oceanic crust.

5. Conclusion

An important discovery during this dive is the existence of active compression on the south scarp of the northern Zenisu Ridge. This was interpreted on the seismic profiles and field study of surface structure. The compression is now established through field evidence. The shorting is presently active and results in the formation of nascent subduction zone. This phenomenon in the southern Zenisu previously proposed by Nicolas and Le Pichon (1980), and emphasized lately by Le Pichon et al. (1992). And they suggested that the shorting have two single crustal fault, each accounting for about half of total offset of 3-4km.

The thickness turbidites have been observed both from the seismic data and dive track. The aged data of the Unit B are younger late Pliocene, which has conformable contact with the underlying strata, so it means that deformation happened after the deposition. We infer that uplift of Zenisu ridge could be since late Pliocene or early Pleistocene (after 2.65Ma).

The discovery of dead clams and/or living deep-sea biological community, Vesicomyidae clam, is an important result at the foot of slope, which may be reflected the active fault and dewatering processes.

Acknowledgement

We are indebted to the pilots and support crews of Shinkai 6500 submersible and captain and crews of R/V Yokosuka.

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(Manuscript received 10 October 2000)