

Role of normal and reverse faulting for surface cracks, tectonic erosion and *Calyptogena* colonies at northern Japan Trench

Yujiro Ogawa

Institute of Geoscience, University of Tsukuba, Tsukuba, Japan

Kantaro Fujioka, Kazuo Kobayashi, Katsunori Fujikura and Hiroshi Hotta

Deep Sea Research Department, JAMSTEC, Yokosuka, Japan

Yo Iwabuchi

Hydrographic Department, Maritime Safety Agency of Japan, Tokyo, Japan

Abstract Both the oceanward and landward slopes of the northern Japan Trench were surveyed by research submersible *Shinkai 6500*, and very remarkable ocean bottom surfaces were observed. One in the oceanward slope is straight, long open cracks at the scar of horst-and-graben structure of normal fault origin. These cracks are attributed to slope instability and earthquake shake. The other in the landward slope is en echelon *Calyptogena* colony distribution at the foot of the Sanriku Escarpment of thrust origin, best explained by left-lateral component of the oblique subduction between the Pacific and North America plates.

Introduction

The Japan Trench is one of the best surveyed oceanic trenches by DSDP-IPOD Legs 56, 57 and 87B (von Huene *et al.*, 1980; Kagami *et al.*, 1986), by French-Japanese KAIKO Project (Cadet *et al.*, 1987a, b), by Ocean Research Institute, University of Tokyo (Kobayashi, 1991), and by Hydrographic Department as well as by more than 25 times deep submersible observation during KAIKO (Cadet *et al.*, 1987b) and JAMSTEC Projects (Fujioka *et al.*, 1993), particularly in its northern area off Miyako (Fig. 1). Above all the recent submersible study by

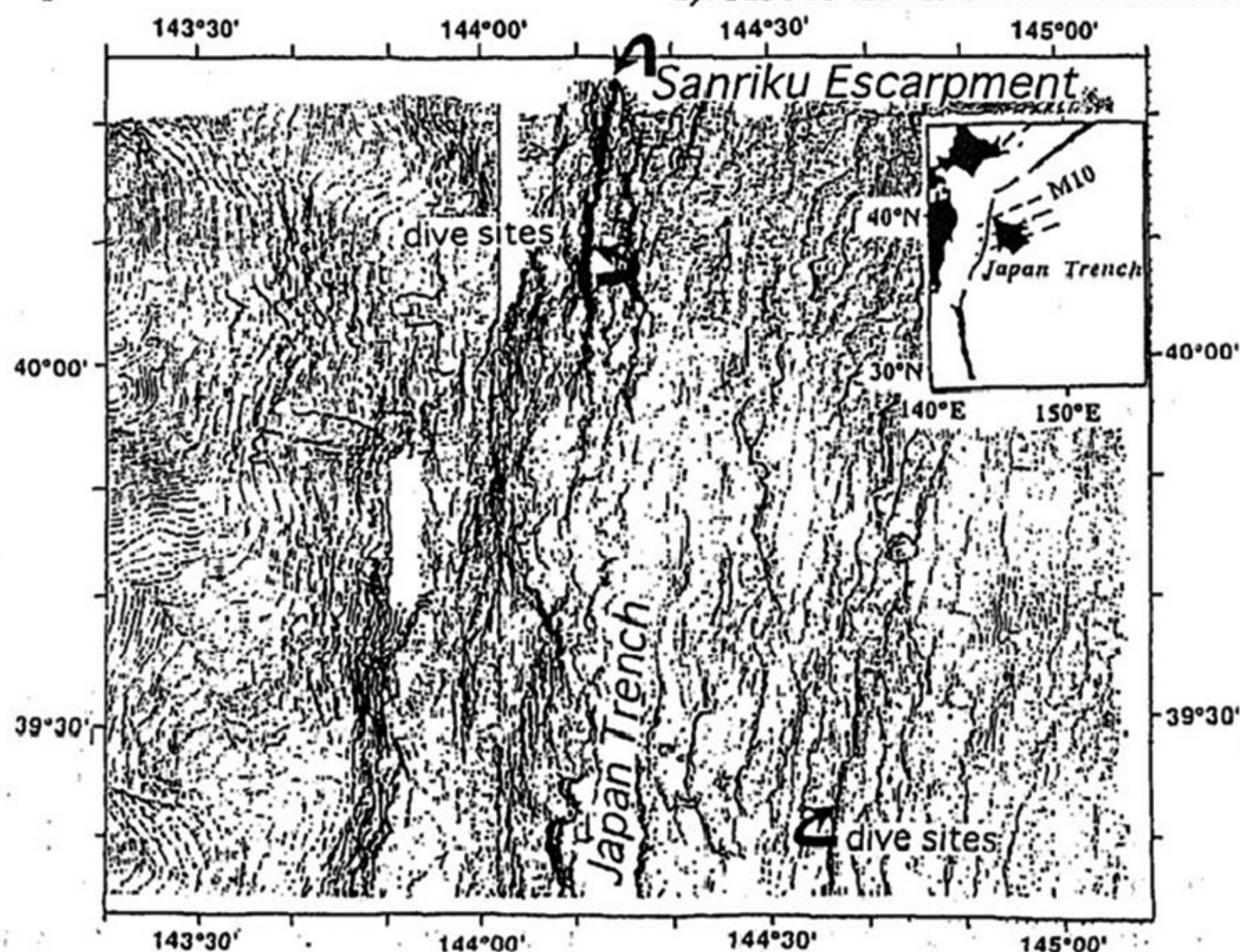


Figure 1. Location of dive areas shown by arrows for the northern Japan Trench. Bathymetry is after data of Hydrographic Department, Japan.

JAMSTEC provided many relevant informations enough to discuss the subsurface and surficial geology concerning normal and reverse faulting in and around the subduction zone.

Recently we have found surface cracks on the oceanward slopes and en echelon *Calypptogena* colony arrangements on the landward slope by *Shinkai 6500* (Ogawa, 1994; Ogawa *et al.*, 1996). This paper reviews our results on topographic features related to important tectonism in this subduction zone.

Oceanward slope and surface cracks

The oceanward slope is underlain by Early Cretaceous (M10) Pacific plate; the magnetic lineament trends N60°E, critically appeared as straight topography by normal faults in the Kuril Trench (Kobayashi *et al.*, 1995) but not significantly in the Japan Trench. In the northern Japan Trench oceanward slope, N-S (parallel to the trench trend), N20°-40°E, and N20°-30°W lineaments are clear (Fig. 1). The first must be of a normal fault origin due to the horizontal tension stress by bending of the subducting plate, the last corresponds to the previous fracture zones or transform faults. The oceanward slope is thus well controlled by normal faulting and related steep scarps upto several hundred meters high with 10 to 30 degrees inclination. The scarps are further composed of several sets of gentle and steep slopes.

Six dives were carried out over the scarps of the graben at 6000 to 6500 m in depth in 1991 and 1992. The dive area is close to the epicenter of a great Sanriku tsunami earthquake in 1933 (M8.1) (Kanamori, 1971) which was exerted by a big normal fault cutting the downgoing Pacific plate. The scarps are as steep as 15° to 20° on average and are divided into many sets of terraces and cliffs up to several tens of meters high.

We discovered a series of prominent cracks, which are a few meters deep and in some cases can be traced for as long as 200 m (Fig. 2). Microtopographic examination by submersible has indicated that the majority of the cracks are situated either on the very gentle or horizontal bottom surfaces, or rarely but significantly on the upward-convex top, in all cases near the edge of the steep cliffs of the terraces (Fig. 2). The

cracks are mostly straight, and often make an en echelon or zigzag pattern of trends. In case of en echelon arrangements, the cracks are juxtaposed in several meters spacing. Predominating directions of the cracks are N-S to N10°E, or N30°E to N40°E and N10°W. There seems to be no dislocations due to cracking, neither lateral nor vertical, rather the cracks are just open fractures, although there are only small amounts of rare listric scars which originated from gravity sliding in the Japan Trench (Hotta *et al.*, 1992).

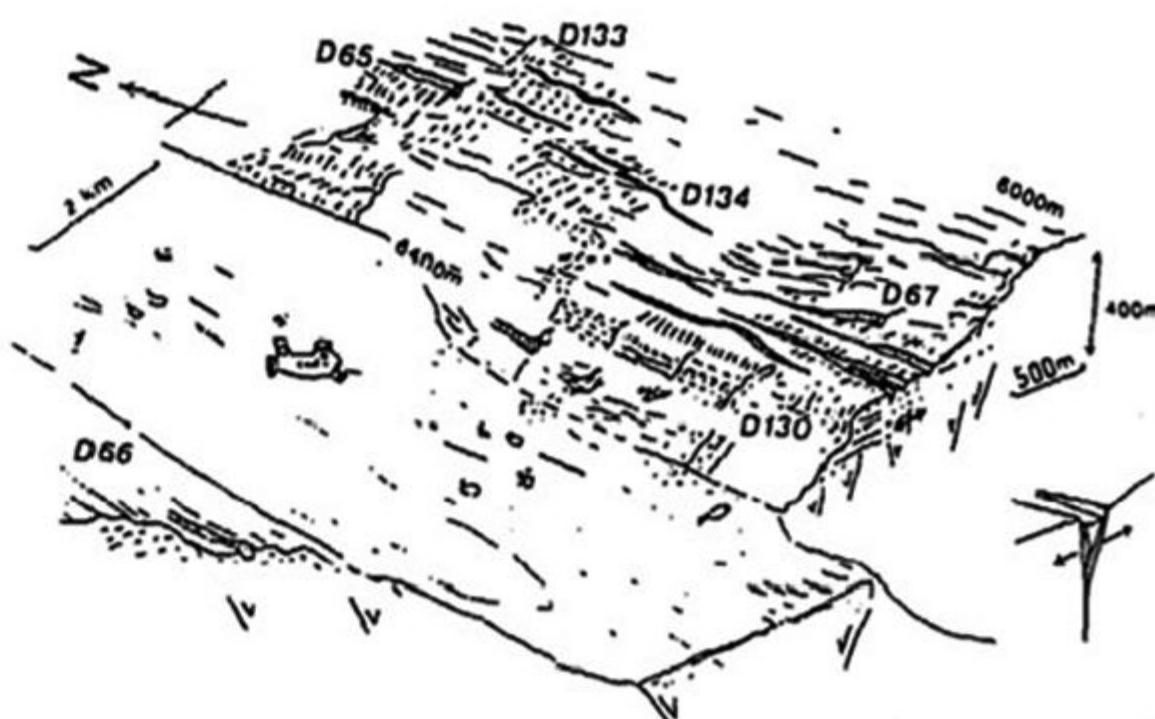


Figure 2. Schematic whale view of the dive sites in the oceanward slope of the Japan Trench, illustrating the crack distribution.

Most of the walls of the cracks have sharp edges suggesting a very young origin. Sediment with horizontally bedded diatomaceous clay with a few tephra layers can be clearly observed at the walls. The surface of the bottom outside the cracks (normal bottom) appears to be coated by ferro-manganese oxides (Ito and Ogawa, 1994), and is overlain by a fine pelagic mud, dominantly containing diatoms (Nishimura *et al.*, 1993). At several sites, cracks are branching into a Y-shape and merging within a few tens of meters to form a small graben by dislocation from the inner walls (Fig. 3). At one site, a linear mud pressure ridge, made of soft sediment squeezed from the inside of the closed crack was observed, suggesting a closure of once opened crack. On the upper slope, where the crack edges are not sharp but eroded, and due to the erosion inside structure of the sediment is revealed to the ocean bottom. Many fractures after vein structure, almost paralleling the crack direction, are revealed by strong bottom current.

The both sediments, inside and outside of the cracks, are strong enough to keep the cliff configuration, although being very soft. This means the sediments have cohesion and strength due to siliceous fossils being intermingled each other in addition to cementation by clay materials.

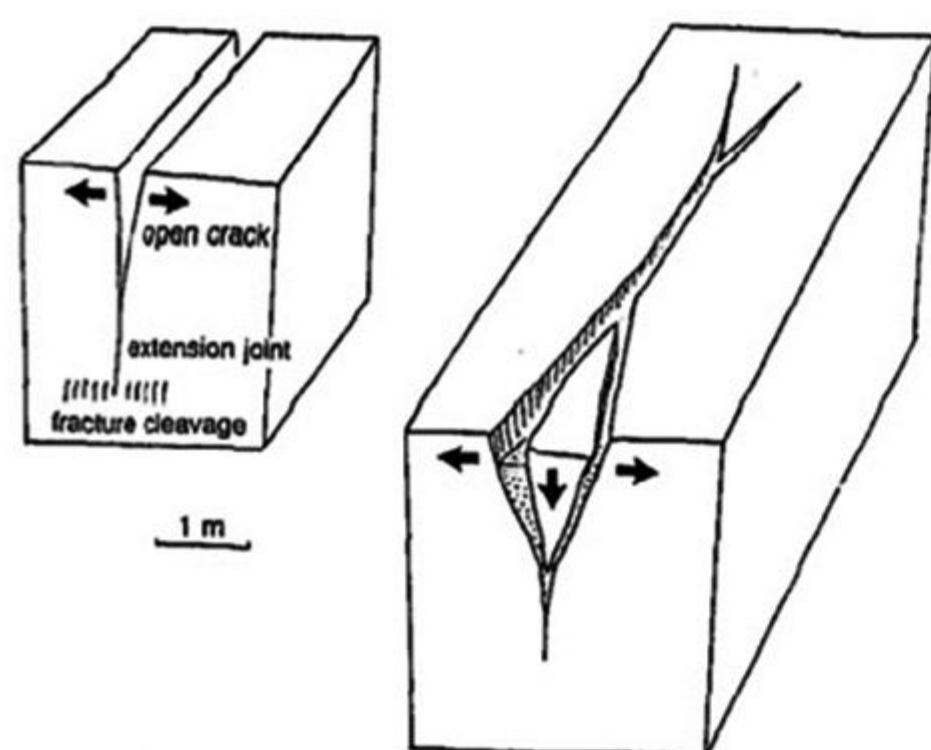


Figure 3. Schematic figures showing formation of cracks on the sea bottom.

When applying the earth pressure theory, the cracks might have occurred by either of the following two mechanisms; one is by instability of the inclining slope whose surficial layer is subjected to horizontal tension; the other is sudden horizontal extension during resonance shaking at a big earthquake (e.g. Sanriku earthquake, 1933) which produces horizontal inertia to make the surface sediments cracked. No dislocation in between the two edges of the cracks does not suggest these are related to any submarine sliding but are just open cracks. Subsurface sediments eroded by bottom current expose vein structure which parallels the cracks (Fig. 3). This further indicates the two have the same origin. The vein structure is now understood as a kind of "seismite" which is formed by shaking during seismic activity (Hanamura and Ogawa, 1993; Brothers *et al.*, 1996). This strongly supports the cracks are of the earthquake origin (Ogawa, 1994).

Trench axial area

The trench axial area, maximum depth attains 7400 m, has not yet been studied by submersible due to its being beyond the ability, but detail bathymetric charts and profiles by Ocean

Research Institute and Hydrographic Department could elucidate that large scale submarine sliding ubiquitously occurs from the steep (upto 30°) slopes to the trench floors through the boundaries between the subducting and overlying plates. The slid sediments fill the trough of the oceanward slopes to make the landward slope be eroded continuously. This is what was previously considered as so-called sediment subduction and tectonic erosion at subduction zone by Hilde (1983). Assuming the volume of the graben on the oceanward slope equal the subducted sediment, the rate of retreating of the trench is calculated as 5 to 6 km/Ma. If the erosion began at 20 m.y.B.P., the retreat should result in 100 to 120 km enough to explain the "near-trench" magmatism during early Miocene time. This value of trench retreat is comparable to the other explanations by von Huene and Lallemand (1990), von Huene *et al.* (1993) and Lallemand (1995).

Trench landward slope and distribution pattern of *Calyptogena* colonies

The landward slope is very complicated in topography and geology. Detail bathymetric mapping by Hydrographic Department clearly showed that several different lineations in the lower slope deeper than 4500 or 5000 meters, above which a wide mid-slope terrace occurs (Cadet *et al.*, 1987a). Beside the scarps which parallel normal-fault scarp in the oceanward slope, a sharp trench oblique lineament demarcates an escarpment of more than 600 meters high from N-S for a distance as the Sanriku Escarpment (Fujioka and Murayama, 1992) (Fig. 1). The rocks of the escarpment are composed of Miocene to Pliocene siliceous claystone (Cadet *et al.*, 1987b; I. Koizumi, 1996 pers. com.), suggesting no deposition at present but surface erosion. The foot of the Sanriku Escarpment has been considered to be the trace of a large detachment zone with normal displacement (Cadet *et al.*, 1987a; Aubouin, 1989; von Huene and Culotta, 1989). However, more recently it has been considered to be a megashear composed of sets of thrust faults (Fujioka and Murayama, 1992). In the latter model, the thrust zone acts as a mechanical

boundary with the Pacific plate subduction beneath the North America or Okhotsk plate. In fact, a thrust-type big earthquake (Sanriku-oki, Japan, Earthquake, 1994, Mw 7.7; Tanioka *et al.*, 1996) occurred along this subduction boundary.

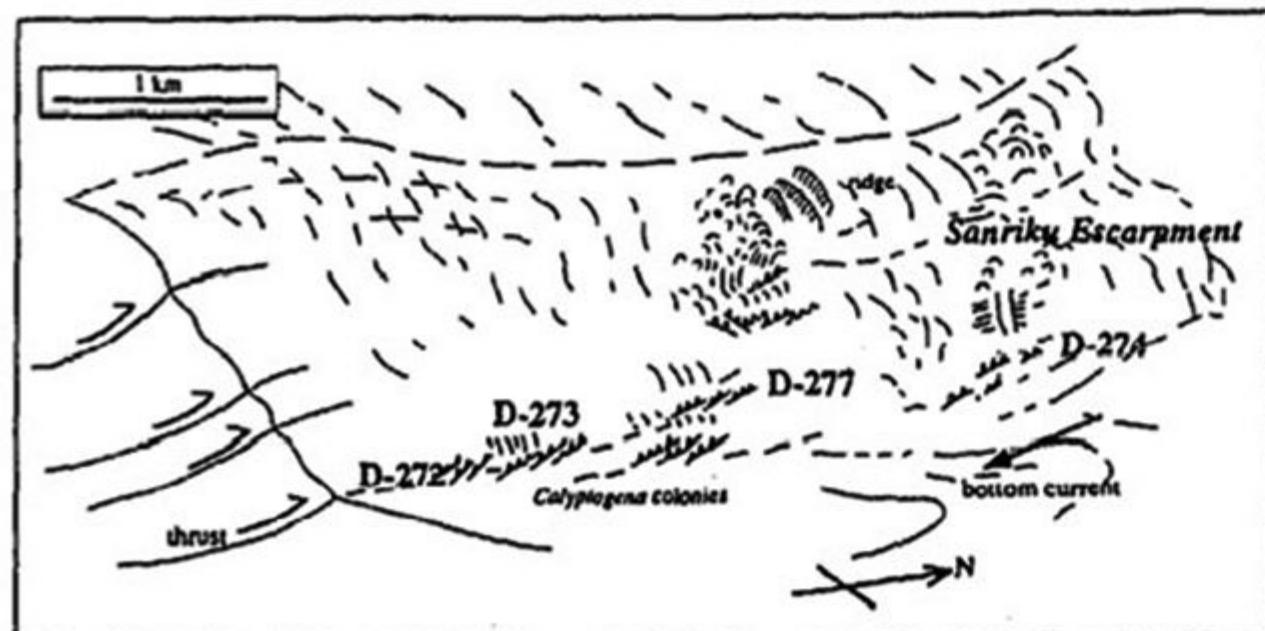


Figure 4. Schematic whale view of the dive sites in the Sanriku Escarpment, illustrating an echelon pattern of *Calyplogena* colonies.

The *Calyplogena* colonies supported by methane-seepage are known mostly from foot of this escarpment. Calcite-cemented breccias are largely distributed along the escarpment (Fig. 4). These lines of fact support the escarpment is not of a normal fault origin but a reverse fault along which methane-bearing fluid seeps. Colonies are composed of many *Calyplogena* individuals (*Calyplogena phaseoliformis*; Ohta and Laubier, 1987), and the total number in one colony ranges from 10 to 100 individuals, with a smaller number of gastropods, sea anemones and sea lilies. Some clam colonies are very long and narrow, being > 5 m long but less than several tens of centimeters wide (Fig. 5).

First, it is known that small valleys or gullies are oriented perpendicular to the strike of the escarpment, and support those colonies as reported by Fujioka and Taira (1989).

During dives by *Shinkai 6500* at around lat 40° 07'-08'N, long 144° 11' E (Fig. 1) in 1995, we found significant trends in the patterns of *Calyplogena phaseoliformis* colonies on the same escarpment (Ogawa *et al.*, 1996). Many colonies form a trend in the patterns within a significant zone; that is, each colony makes a right-stepping en echelon pattern, and the zone of the colonies are aligned along the escarpment strike, close to

north-south (Fig. 4).

In Fig. 5, three directions occur. The most plausible model for the arrangement of the colonies is that they are situated on fractures caused by the differential stress related to the movement of the fault at the foot of the escarpment. The fault mechanism for the Sanriku-oki, Japan, earthquake in 1994 is a very shallow-dipping thrust of north-south strike with left-lateral strike-slip component (Matsuzawa *et al.*, 1995; Tanioka *et al.*, 1996). The relative motion of the overriding plate at this escarpment is about 300°, at a rate of about 8.3 or 7.8 cm/yr (Fig. 6). If all of the strike-slip component is taken up by this fault zone, we calculate about 4 cm/yr of left-lateral strike-slip component.

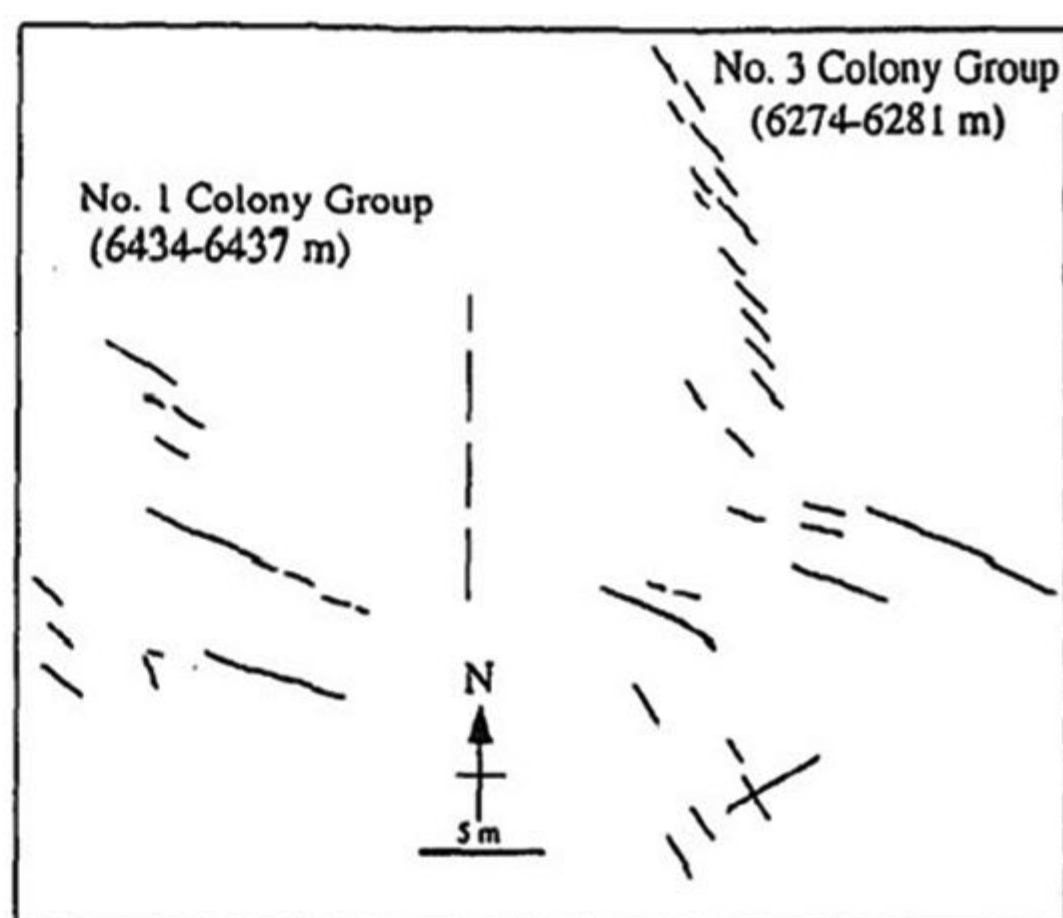


Figure 5. Distribution of *Calyplogena* colonies at dive 277 site.

If we accept the left-lateral strike-slip displacement along the foot of the escarpment, we can easily consider a two-dimensional model of shearing due to this strike-slip component on the fault. The first fractures on the sea-floor surface will be either extension fractures or Riedel shears. Two directions of Riedel shears are known (Morgenstein and Tchalenko, 1967; Dresen, 1991), synthetic Riedel shear (R1), and antithetic Riedel shear (R2) (Fig. 6).

In view of those results, the directions of the clam colonies at 250° - 270° and 330° are attributed to the R2 and R1 shears, respectively, and the directions of 300° might be extension fractures (T) under the strain regime of left-lateral

strike-slip component-bearing shear (Fig. 6).

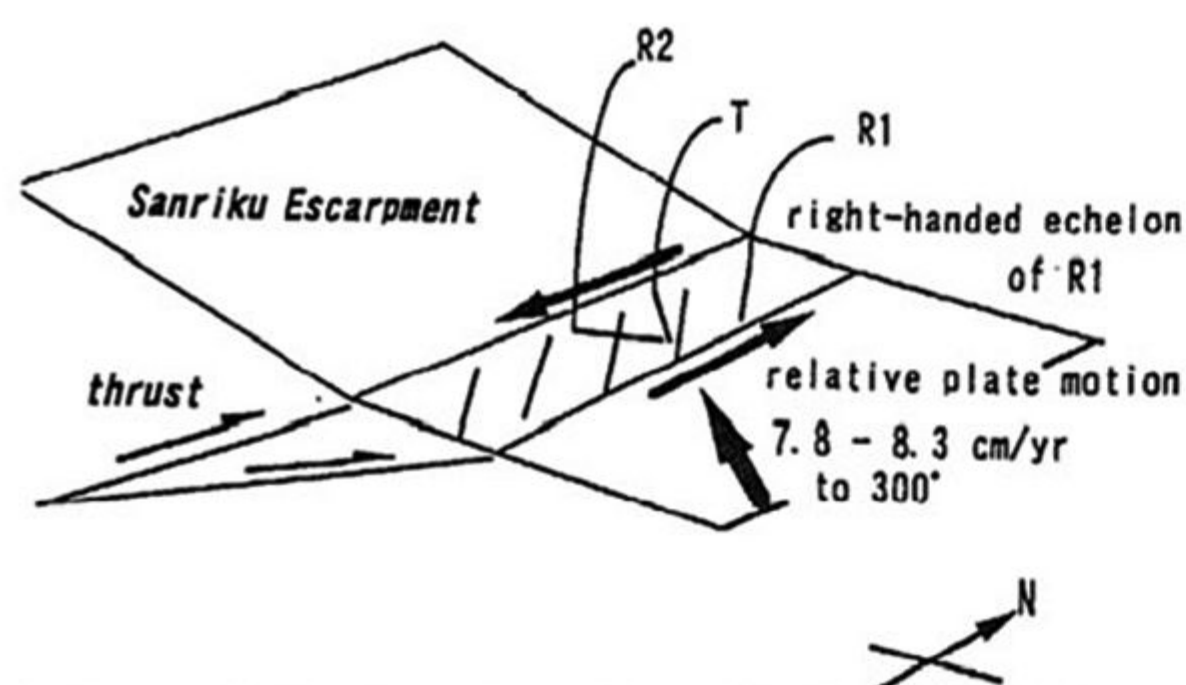


Figure 6. Explanation of synthetic Riedel shear (R1), antithetic Riedel shear (R2) and tension fracture (T) under left-lateral compressional stress regime along the Sanriku Escarpment.

We now know that *Calyptogena* individuals prefer to live where methane-hydrogen sulfide seepage occurs, that is, along fractures connecting thrust faults, and so the colonies show the fracture patterns. Our observations show these colonies are arranged in an echelon pattern which is related to the relative plate motion along the escarpment. We therefore confirm that the clam colonies indicate the potential geometry to provide sensitive kinematic indicators in plate margin setting.

Conclusions

The Japan Trench is one of the best erosional type trenches in the world, and many characteristic surfacial features are recognized. However, the very deep along the trench axis from 6500 to 7400 meters in depth has not yet been observed. We expect the coming ROV *Kaiko* mission must elucidate the unknown world to know much in detail of the particular trench.

Acknowledgments. We are grateful to the crew and technical staff of the *Shinkai 6500* and her support vessel, *Yokosuka* of JAMSTEC, in particular to the operation team. N. Izumi, A. Inoue, K. Tamaki, T. Seno, I. Koizumi and Lee In Tae are appreciated for various informations during and after the cruise.

References

- Aubouin, J., Some aspects of the tectonics of subduction zones. *Tectonophysics*, 160, 1-21, 1989.
- Brothers, R.J., A.E.S. Kemp, and A.J. Maltman, Mechanical development of vein structures due to the passage of earthquake waves through poorly-consolidated sediments. *Tectonophysics*, 260, 227-244, 1996.
- Cadet, J.-P. and 17 others The Japan Trench and its juncture with the Kuril Trench: cruise results of the *Kaiko* project, Leg 3. *Earth Planet. Sci. Lett.*, 83, 267-284, 1987a.
- Cadet, J.-P. and 11 others Deep scientific dives in the Japan and Kuril Trenches. *Earth Planet. Sci. Lett.*, 83, 313-328, 1987b.
- Dresen, G., Stress distribution and the orientation of Riedel shears. *Tectonophysics*, 188, 239-247, 1991.
- Fujioka, K. and 5 others, Contrasted nature between landward and seaward slopes of the Japan Trench off Miyako, Northeast Japan. *Proc. JAMSTEC Symp. Deep Sea Res.*, 9, 1-26, 1993.
- Fujioka, K., and M. Murayama, *Calyptogena* community from landward slope of the Japan Trench and mega shear. *Proc. JAMSTEC Symp. Deep Sea Res.*, 8, 17-27, 1992.
- Fujioka, K. and A. Taira, Tectono-sedimentary setting of seep biological communities - a synthesis from the Japanese subduction zone. In: Taira, A., and Masuda, F. (eds.) "*Sedimentary Facies in the Active Plate Margin*", p. 577-602, 1989.
- Hanamura, Y., and Y. Ogawa, Layer-parallel faults, duplexes, imbricate thrust and vein structures of the Miura Group: Key to understanding the Izu fore-arc sediment accretion to the Honshu forearc. *The Island Arc*, 3, 126-141, 1993.
- Hilde, T., Sediment subduction versus accretion around the Pacific. *Tectonophysics*, 99, 381-397, 1983.
- Hotta, H., K. Kobayashi and Y. Ogawa, Recent crustal activity revealed on the bottom surface in the oceanward slope of the northern Japan Trench - Report of research dives 65, 66 and 67 of "*Shinkai 6500*". *Proc.*

- JAMSTEC Symp. Deep Sea Res., 8, 1-15, 1992.
- Ito, T., and Y. Ogawa, Origin of ferromanganese nodules from the Japan Trench oceanward slope. *Jour. Geography, Tokyo Geogr. Soc.* 103, 684-695, 1994.
- Kagami, H., Karig, D. E., and Coulbourn, W.T. et al., *Initial Reports of the DSDP*, 87, U.S. Govnt. Print. Office, 1986.
- Kanamori, H., Seismological evidence for a Lithospheric normal faulting, the Sanriku earthquake of 1933. *Phys. Earth Planet. Inter.*, 4, 289-300, 1971.
- Kobayashi, K. (ed.), *Preliminary Report of the Hakuho Maru Cruise KH 90-1*. Ocean Research Institute, University of Tokyo, 174pp, 1991.
- Kobayashi, K. and 17 others, Normal faulting of the Daiichi-Kashima Seamount in the Japan Trench revealed by the Kaiko I cruise, Leg 3. *Earth Planet. Sci. Lett.*, 83, 257-266, 1987.
- Kobayashi, K., K. Tamaki, M. Nakanishi, J. Korenaga and Y. Ogawa, Rejuvenation of 130 m.y.-old fabrics on the outer wall of the western Kuril Trench. *Proc. Japan Acad.*, 71, Ser. B, 5-9, 1995.
- Lallemand, S., High rates of arc consumption by subduction processes: Some consequences. *Geology*, 23, 551-554, 1995.
- Matsuzawa, T., N. Umino, S. Horiuchi, A. Hasegawa, and T. Hirasawa, Aftershock activity of the 1994 far east off Sanriku earthquake observed by a microearthquake observation network. *Proceedings, Union Earth and Planetary Science of Japan Annual Meeting*, p. 36, 1995.
- Morgenstein, N. R. and J. S. Tchalenko, Microscopic structures in kaolin subjected to director shear. *Geotechnique*, 17, 309-328, 1967.
- Nishimura, H., T. Kawata, and Y. Ogawa, Microfabrics of deep sea bottom sediment collected by research dive 134 of "Shinkai 6500". *Proc. JAMSTEC, Deep Sea Res.*, 9, 49-64, 1993.
- Ogawa, Y., Characteristics and origin of the cracks observed by research submersible "Shinkai 6500" in the oceanward slope of the northern Japan Trench. *Jour. Geography, Tokyo Geogr. Soc.* 103, 706-718, 1994.
- Ogawa, Y., K. Fujioka, K. Fujikura and Y. Iwabuchi, En echelon patterns of *Calyptogena* colonies in the Japan Trench. *Geology*, 24, 807-810, 1996.
- Ohta, S. and L. Laubier, Deep biological communities in the subduction zone of Japan from bottom photographs taken during "nautilie" dives in the Kaiko project. *Earth and Planetary Science Letters*, 83, 329-342, 1987.
- Tanioka, Y., L. Ruff, and K. Satake, The Sanriku-oki, Japan, earthquake of December 28, 1994 (Mw 7.7): Rupture of a different asperity from a previous earthquake. *Geophys. Res. Lett.*, 23, 1465-1468, 1996.
- von Huene, R. and R. Culotta Tectonic erosion at the front of the Japan Trench convergent margin. *Tectonophysics*, 160, 75-90, 1989.
- von Huene, R., D. Klaeschen, B. Cropp, and Miller, J. Tectonic structure across the accretionary and erosional parts of the Japan Trench margin. *J. Geophys. Res.*, 9, 22, 349-22,361, 1994.
- von Huene, R. and S. Lallemand, Tectonic erosion along the Japan and Peru convergent margins. *Geol. Soc. Am. Bull.*, 102, 704-720, 1990.
- von Huene, R., M. G. Langseth, N. Nasu and H. Okada, Summary; Japan Trench transect. *Init. Rept. DSDP*, 56 & 57, Pt. 1, 473-488, 1980.
-
- Yujiro Ogawa, Institute of Geoscience, University of Tsukuba, Tsukuba 305, Japan (e-mail: yogawa@arsia.geo.tsukuba.ac.jp)
- Kantaro Fujioka, Kazuo Kobayashi, Katsunori Fujikura and Hiroshi Hotta, Deep Sea Research Department, JAMSTEC, Yokosuka 237, Japan (e-mail: fujiokak, kobayashik, fujikurak, hottah@jamstec.go.jp)
- Yo Iwabuchi, Hydrographic Department, Maritime Safety Agency of Japan, Tokyo 104, Japan (e-mail: iwabuchi@cue.jhd.go.jp)