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Tectonic implications of strike-slip fault regime at the leading edge of an accretionary prism

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Abstract

Strike-slip faults and vertical en echelon extension fractures have been observed in pelagic sediments near and in the accretionary prism. These features indicate that stress affecting the sediments have undergone a rotation from vertical consolidation away from the trench to a strike-slip regime near the toe of the accretionary prism, to compressional stress and thrust faulting in the accretionary prism itself. Before entering the trench region, pelagic sediments are generally thought to be subject to a uniaxial strain, and the stress is as follows; the maximum compressive stress (σ_1) is vertical and the intermediate (σ_2) and least (σ_3) compressive stresses are equal in magnitude and lie in the horizontal plane. This is termed the state at rest, or consolidation (K_0) stress state. After entering the trench, the sediments are subject to strike-slip faulting in a narrow region near the toe of the accretionary prism due to the increase of trench normal, horizontal compression. From this we infer that σ_2 is vertical and σ_1 and σ_3 are in the horizontal plane.

Such a strike-slip fault regime is realized much easier when an oblique sense of convergence occurs, but even in the normal convergence case it must occur. This particular stage of strike-slip faulting is exemplified in some accretionary prism toes around the Japanese trenches, and have been observed by submersibles and ROVs. Other plausible on land examples in the Miocene - Pliocene Miura accretionary prism, central Japan, are shown.

Key words: subduction zone, K_0 consolidation, Poisson ratio, stress axis, strike-slip fault, *Calyptogena* community, Riedel shear, submersible

Introduction

Stress in the crust is spatially and temporally variable. In general, the directions of principal stress axes and their quantities are not usually known. Direct measurement of stress using bore holes is still very limited (Mikada *et al.*, 2006). The directions of principal stress axes are, however, inferred in the case of earthquakes, magma eruptions and other crustal movements, when faults or intrusions occur.

In accretionary prisms or subduction zone fronts, many thrust faults occur, and we infer the stress conditions to be horizontal compression with vertical minimum stress axis. Sediments entering a subduction zone are either accreted into an accretionary prism or subducted. The first thrust for subduction is called a frontal thrust. The accreted or subducted sediments are originally deposited on an oceanic plate or on a trench floor, and suffer consolidation by vertical compression during burial, then just before being subducted or accreted they begin to deform by folding and faulting in a region called the deformation front (Moore, J. C. and Byrne, 1987; Moore, G. F. *et al.*, 1990; Moore, J. C. *et al.*, 1990, 1991; Ashi and Taira, 1992; Karig and Morgan, 1994; Mikada *et al.*, 2006) (Fig. 1). The zone of this earliest horizontal compression is also called the proto-thrust zone (Fig. 1). Thus some horizontal compression begins seaward of the thrust front.

Such outward stress transfer effect by which horizontal compression increases is due to the viscosity result. In the case of a non-accretion type subduction zone, the state of stress is approximately the same as that of an accretion type; in both cases, horizontal compression at the front is of prime importance for consideration of the state of stress around the trench, particularly in shallow levels of the crust.

Behrmann (1991) calculated the pore-fluid pressure necessary for hydrofracturing under the three different stress regimes in acrretionary prisms. His calculations suggest that soft and hard mudstones will hyrofracture more easily at deeper burial depths than for a thrust fault regime, if the stress state is for a normal or wrench (strike-slip) fault regime. His first assumption is that fluid seeps along a fracture of high permeability zone are caused by tensile type hydrofracturing. He

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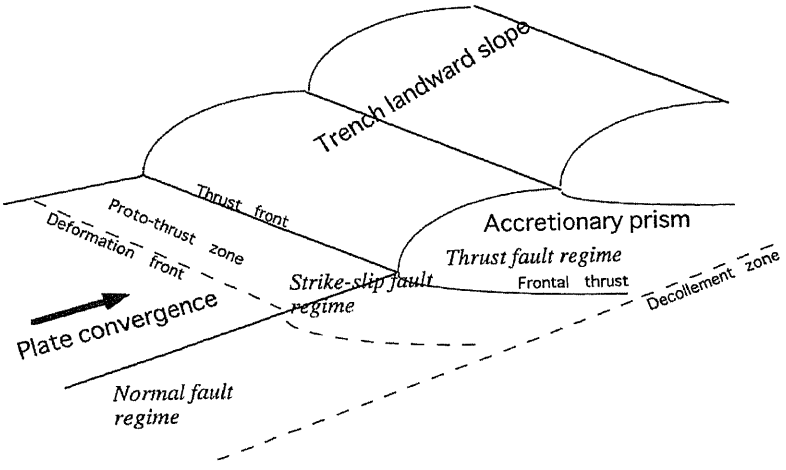


Fig. 1 Simple system of a typical subduction zone front (adopted from Karig and Morgan, 1994). In front of the thrust front where the first thrust cuts the seafloor, is the deformation front where horizontal shortening begins.

also pointed out the viability of such fluid seeps in an accretionary prism due to very high pore-fluid pressure, because in some areas fluids are venting along thrust faults against the horizontal compressive stress which may close the fractures if the pore-fluid pressure were not elevated. Such fluids usually contain methane or hydrogen sulfide, and sustain chemosynthetic biocommunities (Kulm *et al.*, 1985; Ohta and Laubier, 1987; Hashimoto *et al.*, 1989; Kobayashi, 2002), therefore the place of fluid seepage, *vice versa*, could be recognized by such biocommunity distribution.

Very clear distribution patterns of chemosynthetic biocommunites have been documented on the Nankai Trough slope (Chamot-Rooke *et al.*, 1989; Kobayashi, 2002), Sagami Bay (Hashimoto *et al.*, 1989; Masuzawa *et al.*, 1992; Gamo *et al.*, 1988), Japan Trench slope (Fujioka and Taira, 1989; Ogawa *et al.*, 1996a, b), and Monterey Bay Transform Zone (Orange *et al.*, 1999). In some areas, injection bodies intrude to form mud volcanos around the thrust front (Brown and Westbrook, 1987; Ashi and Taira, 1992). Some mud injections are known even away from the trench floor on the oceanic plate side in Barbados (Westbrook and Smith, 1983), in the Japan Trench (Ogawa and Kobayashi, 1993), and in the Nankai Trough (Ashi and Taira, 1992).

In strike-slip (wrench) fault stress regimes, Behrmann (1991) considered two cases for the stress state; 1) when the convergence direction changes from normal to oblique, and 2) when the stress in an oblique convergent boundary is partitioned to horizontal compression. In order to explain the systematic distribution of chemosynthetic biocommunities in the Japan Trench, Ogawa *et al.* (1996a, b) considered Riedel shear fractures to be evidence for stress partitioning, with oblique convergence resulting in strike-slip type shear at the thrust front. In Behrmann's (1991) case, he calculated the stress state under the assumption that $\sigma_2 = 1/2\,(\sigma_1 + \sigma_3)$, where $\sigma_1 > \sigma_2 > \sigma_3$.

However, consideration of the state of stress in detail, specifically with regards to horizontal compression transfer toward the oceanic plate, the system would result in the formation of a strike-slip regime. At the same time, we can explain some examples of strike-slip type deformation observed by submersibles and ROVs from the trench floor or trench slope near the deformation or thrust front in the Japanese trenches. Similar examples from the on land Miocene-Pliocene accretionary prism in the Miura Peninsula, Central Japan, have been also documented. These examples can shed light on the state of stress in the sediments which undergo horizontal compression and strike-slip type faulting or fracturing.

Stress state in consolidated pelagic sediments at the leading edge of the deformation front

The stress state in the ocean floor before entering the trench region is called the "stress at rest" (Moore, J. C. and Byrne, 1987), because the sediment is just deformed by overburden load without any horizontal strain; this is the uniaxial strain. If we only consider elastic deformation, the horizontal stress σ_h is expressed as

$$\sigma_h = \sigma_x = \sigma_y = \nu/(1 - \nu)\,\sigma_z$$

where x, y and z coordinates are horizontal stress per-

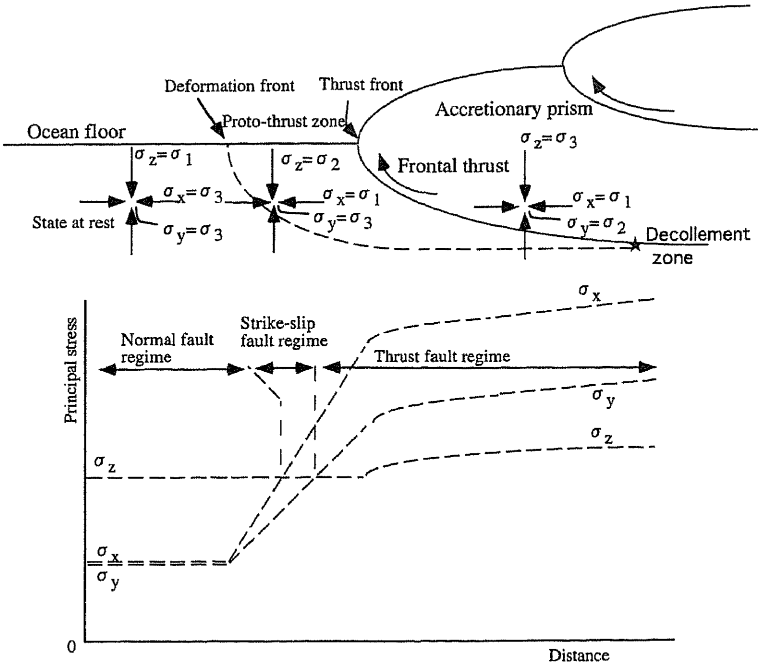


Fig. 2 Simplified schematic model for stress regime in the subduction front (Adopted from Ogawa *et al.*, 2006). The principal stress axes are assumed either to be vertical or horizontal. In the ocean floor realm the state at rest is assumed, where uniaxial strain is realized, and in the accretionary prism the strain is assumed to be plane strain for the elastic deformation when the fault, fractures or injection occurs. For the ocean floor case, the quantity of K_0 is assumed to be 0.5, then $\sigma_x = \sigma_y = 0.5\sigma_z$. After the deformation front realm, it is under the assumption of Poisson's ratio ν, being 0.2 to 0.9, $\sigma_y = 0.2\ (\sigma_x + \sigma_z)$ to $0.9\ (\sigma_x + \sigma_z)$. See text in detail.

pendicular to the trend of the trench, horizontal stress parallel to the trend of the trench, and vertical, respectively, and ν is Poisson's ratio (Jaeger and Cook, 1969, p. 107). Poisson's ratio is difficult to obtain for soft sediments (Karig and Morgan, 1994), but ranges from 0.2 to 0.9 depending upon the kind of sediment or rock. We assume it is approximately 0.2 to 0.4 for clayey sediments (Jones, 1994; Karig and Morgan, 1994). If we assume Poisson's ratio to be 1/3, we obtain $\sigma_x = \sigma_y = 1/2\sigma_z$. This is comparable to the K_0 value for consolidated clay as below.

When we introduce inelastic, plastic, or other style of elastic deformation, the pelagic sediments deposited on an ocean or trench floor are prone to flow or yield during consolidation. The value of K_0 (defined as σ_h/σ_z) during consolidation ($\sigma_h = \sigma_x = \sigma_y = K_0\sigma_z$) is thought to be 0.3 to 0.4 for sand, and may exceed 0.7 for clay (Jones, 1994; Karig and Morgan, 1994). In this case $\sigma_x = \sigma_y = 0.3\sigma_z$ to $0.7\sigma_z$. Before incorporation into the accretionary prism, in oceanic sediments, $\sigma_z > \sigma_x = \sigma_y$, that is for a normal fault regime if the condition is provided either for a normal fault or a vertical tensile fracture. In Fig. 2, we adopt that during consolidation of clay or mud, $\sigma_x = \sigma_y = 0.5\sigma_z$.

Stress state in the deformation front and rotation of principal axes of stress

When the sediments approach the trench due to plate convergence (in this case, subduction normal to the trench axis is assumed for simplicity), they began to undergo horizontal compression. The stress increases toward the thrust front until the elastic limit of the sediments is exceeded, with the result being coseismic thrust faulting along the plate boundary (decollement). We assume that the sediment deformation under plane strain conditions, because the strain in the y direction is zero ($\varepsilon_y = 0$). In this case, because the increase of σ_z resulting from increase of σ_x is small (Turcotte and Schubert, 1982, p. 110), we obtain $\sigma_y = \nu\ (\sigma_x + \sigma_z)$ (Jaeger and Cook, 1969, p. 107). Using the assumption that Poisson's ratio (ν) being 0.2 to 0.9, we obtain $\sigma_y = 0.2\ (\sigma_x + \sigma_z)$ to $0.9\ (\sigma_x + \sigma_z)$. We assume that one of the principal stress axes is vertical near the surface of the crust, because it is by definition a free surface. We assume that when σ_h increases to its maximum and exceeds the vertical (or overburden) stress, $\sigma_1 = \sigma_x$. The horizontal stress increase in the proto-thrust zone from the frontal thrust to the deformation front may be linear by stress relaxation after instantaneous response depending upon the rheological properties of the sediments.

In Fig. 2, we show a representative case of lateral change in stress magnitude for σ_x, σ_y and σ_z along the x-coordinate around the deformation front. We assume that for the state at rest, K_o consolidation occurs (K_o = 0.5), and for elastic response Poisson ratio (ν) is 0.5. In this case we also suggest that when the sediments are incorporated below the thrust front, the overburden at the trench lower slope increases incrementally, by small values, suggesting that σ_z increases gradually as subduction and accretion continue over time.

The indicated stress conditions continue to gradually change as horizontal stress increases linearly into the prism. The sediments could be deformed if the effective stress ($\sigma_{eff} = \sigma_n - p$; where p = pore-fluid pressure) is high enough for tensile or shear fracturing. The thrust front is determined to be where the largest detachment thrust fault (decollement) splays upward and reaches the seabed. The fault motion is thought to be transmitted from a much deeper seismic fault. This movement of the thrust block creates strong horizontal compression toward the trench. The splay place of the decollement must occur at a critical value of pore-fluid pressure in order to flow under thrust regime conditions as shown in Fig. 2 (asterisk). The sediments just outside this critical region may undergo a linear increase of stress under elastic conditions as mentioned above, and thus a linear increase is shown in Fig. 2.

In conclusion we understand that the three stress regimes may occur from the ocean-ward to prism-ward, first during stress at rest, or K_o consolidation, normal fault regime occurs. Then as the horizontal compression begins to increase linearly at the deformation front, the vertical stress σ_y may become intermediate with σ_x becoming maximum, then strike-slip fault regime occurs. Eventually horizontal compression prism-ward overcomes the intermediate another horizontal compression, then thrust fault regime occurs. The width of the strike-slip fault regime depends upon the quantities of K_o, and the horizontal stress σ_x transferred to the frontal thrust from landward.

Therefore in the subduction zone front, sediment entering the prism is under three different stress regimes which occur as in Fig. 2, depending upon the stress conditions.

Examples

A strike-slip fault regime has not often been recognized in the subduction zones under the sea, except for some large scale dislocation of the ocean topography (Goldfinger *et al.*, 1996). The present accretionary prism areas or trench lower slope areas are in general under a thrust fault regime, where $\sigma_x = \sigma_1$ but σ_y is σ_2 with $\sigma_z = \sigma_3$. In this case, where the strike-slip fault is dominant just before the thrust fault tectonics in the subduction zone fronts has not been widely known. However, recent submersible and ROVs observation in the trench axes near the Japanese trenches, many examples of such fractures dominated near the trench, where methane seepages sustain *Calyptogena* or other chemosynthetic biocommunities in an en echelon fracture pattern (Figs. 3 to 10) (Ogawa *et al.*, 1996a, b; Ogawa *et al.*, 1997, 1999; Asada, 2000MS). Similar examples are known from off the West Coast of the United States (Orange *et al.*, 1999).

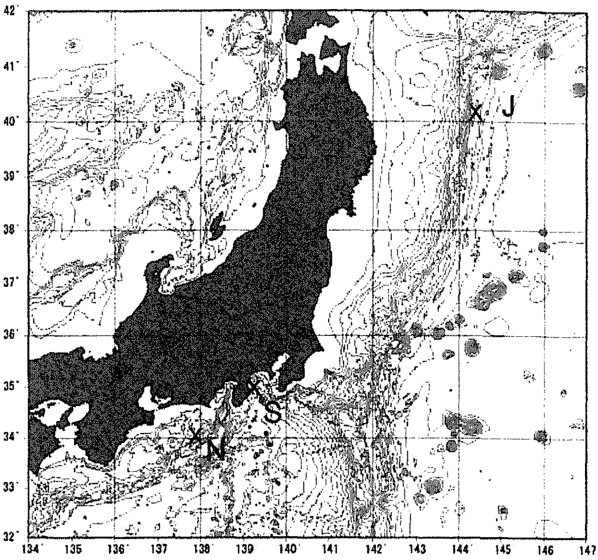
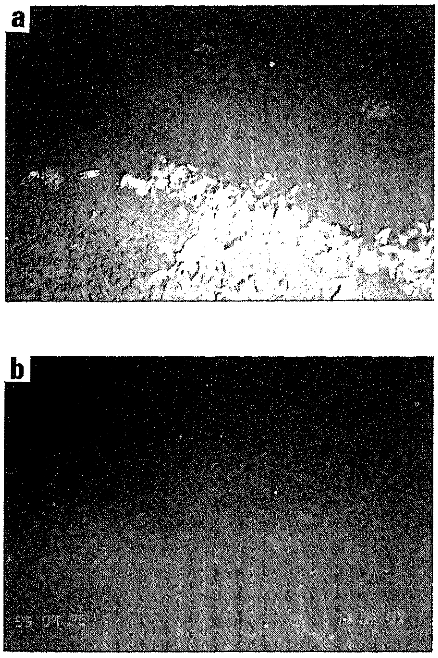


Fig. 3 Index map of the representative occurrences of systematic lineaments of *Calyptogena* communities from the Japanese trenches. J: northern Japan trench landward slope at the Sanriku escarpment, S: western Sagami Bay off Hatsushima, N: eastern Nankai trough off Omaezaki.

In the Japan trench, Sagami trough and east Nankai trough areas (Fig. 3), at the foots or slope toes of the active trench faults such animal communities occur, and the zones of such communities parallel outcropping thrust faults. Each comminity is very well oriented with a narrow zone of several tens of centimeters wide and several meters long (Figs. 4 to 10). In many cases they form an en echelon pattern, or diamond pattern. We proposed that these orientations indicate existence of a strike-slip fault regime close to the thrust fault realm (Ogawa *et al.*, 1996b). The fracture pattern is compatible with a large scale stress system resulting of the oblique subduction system of each area (Fig.



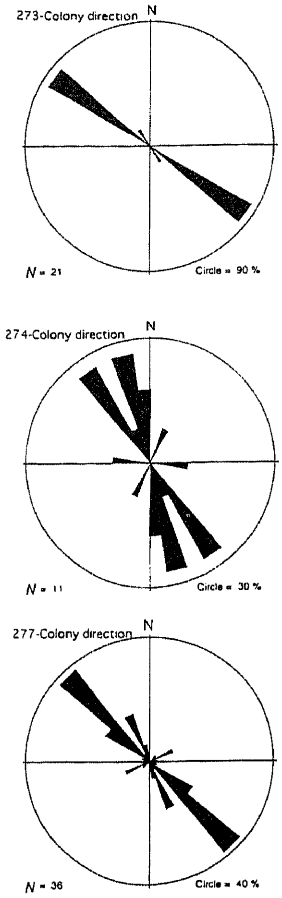


Fig. 4 Example of shear fracture-based systematic lineaments of *Calyptogena* communities at the Sanriku Escarpment foot in the northern Japan trench. Left: Photos from the submersible *Shinkai 6500* dive 6K#277. Conjugate shear fractures are recognized in a, and en echelon fractures in b. Direction of camera is approximately to N30°E in both a and b. The width of the scene is approximately 5 meters in a, and 10 meters in b. Right: Rose diagrams from the *Shinkai 6500* dives 6K#273, 273, and 277. Adopted from Ogawa *et al.*, 1996a.

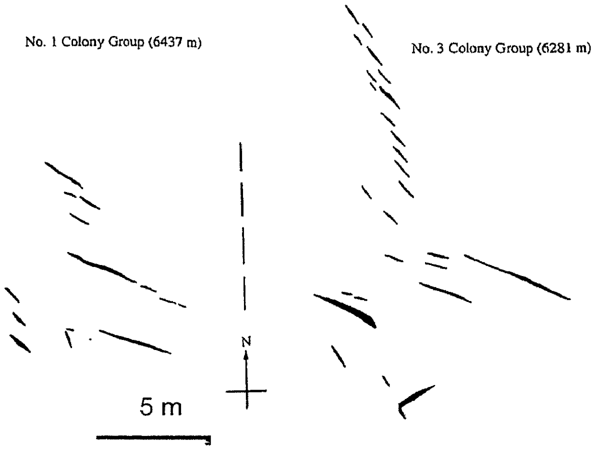


Fig. 5 Sketch maps of the *Calyptogena* communities at the Sanriku Escarpment, northern Japan trench, No. 1 colony group on the left, and No. 3 group on the right (Based on the video data of the submersible *Shinkai 6500* dive 6K#277. Adopted from Ogawa *et al.*, 1996a).

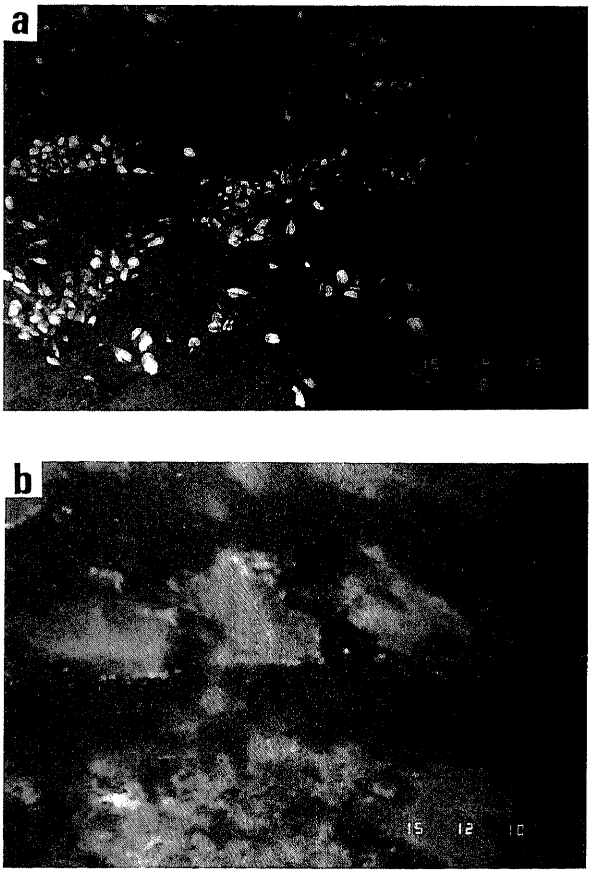


Fig. 6 Example of conjugate shear fracture-based systematic lineaments of *Calyptogena* communities at the West Sagami Bay fault foot off Hatsushima Island, Sagami Bay (Ogawa *et al.*, 1997, 1999). Direction of camera is approximately to N30°E in a and to N50°W in b. The width of the scene is approximately 5 meters in both a and b. By Shinkai 2000 dive 2K#940.

11-above). However, as shown above, even under normal convergence conditions, such a fracture pattern of strike-slip fault regime is also possible (Fig. 11-below).

On the other hand, the on land examples for the strike-slip fault systems close to the thrust front are rare, because such on-going stress products are not easy to be recognized nor preserved. In recent years, we have found several examples in the on land Miocene–Pliocene accretionary prism to the south of Tokyo, central Japan, where early stage deformation, just after sedimentation, are preserved (Hanamura and Ogawa, 1993; Yamamoto *et al.*, 2000). Figure 12 indicates the conjugate pattern of fractures of injected sandy/pebbly sediments which indicate strike-slip faulting. En echelon patterns are also known. Figure 11 is another example of such a stress regime. This faulting and fracturing took place under high-fluid pressure conditions, and the material was then incorporated into an accretionary prism by third faulting.

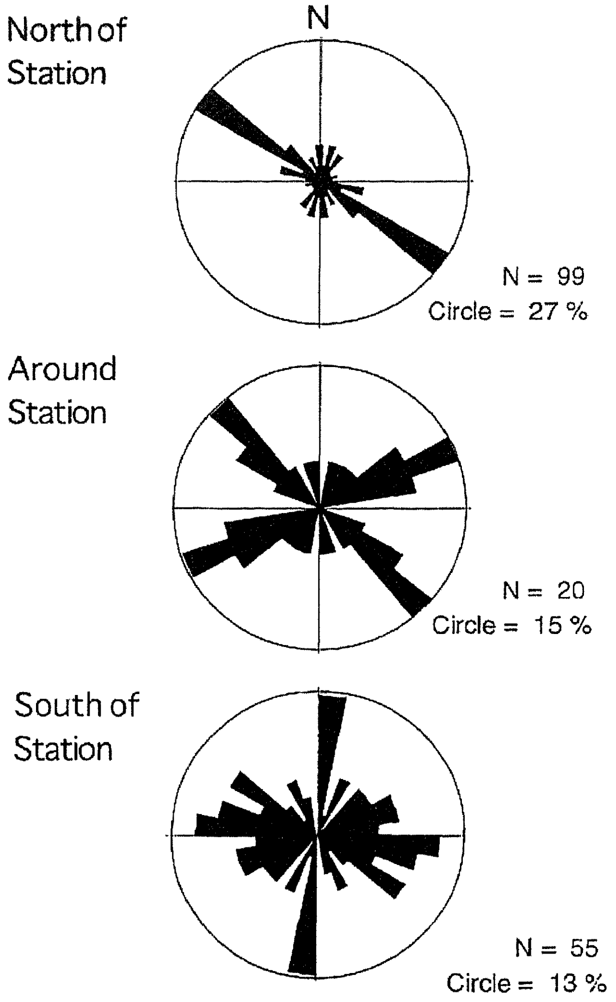
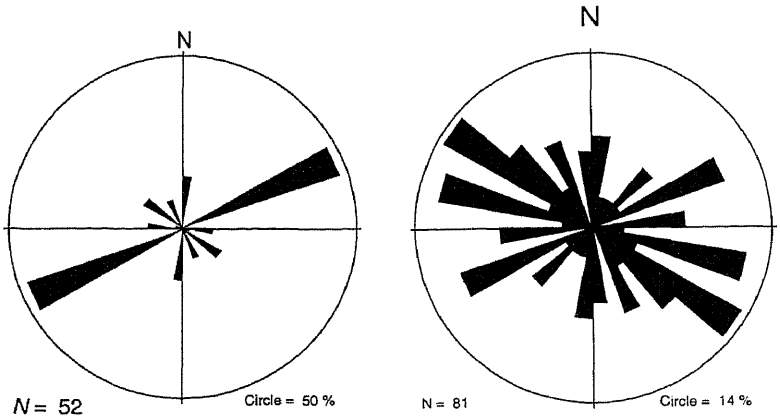


Fig. 7 Rose diagrams of lineaments of *Calyptogena* communities at the West Sagami Bay fault foot off Hatsushima Island (Based on all the available video data of the submersible *Shinkai 2000* dives. Adopted from Asada, 2000MS). Between each area, dominant direction patterns are different, but in most cases two directions are dominant. See also Figs. 8 and 9.



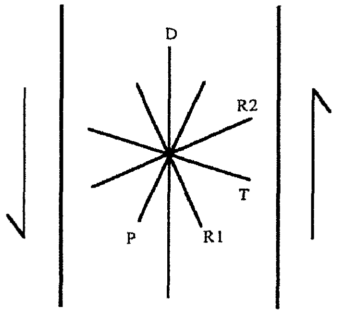


Fig. 8 Rose diagrams of lineaments of *Calyptogena* communities in the north of the station at the West Sagami Bay fault foot off Hatsushima Island (Based on the video data of the submersible *Shinkai 2000* dives 2K#940, on the north of the Hatsushima station (left; Ogawa *et al.*, 1997) and 2K#1051, to the north of the station (right; Ogawa *et al.*, 1999). Attention if the interpretation is assumed as in some cases synthetic Riedel shears, in another case antithetic ones, and occasionally P-shears may be dominant, under left-lateral strike-slip fault regime (Dresen, 1991). Actually around this site, left-lateral component-bearing convergence occurs.

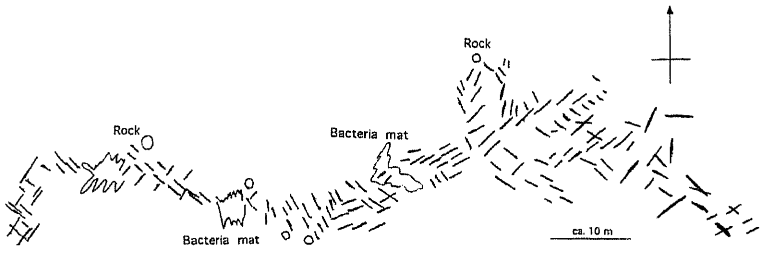
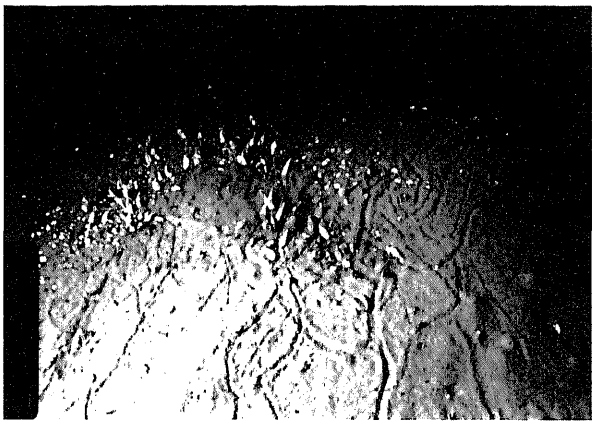
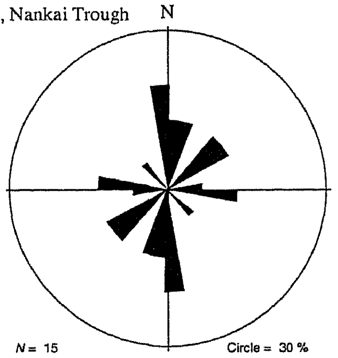


Fig. 9 Map view of *Calyptogena* community pattern at the West Sagami Bay fault foot, 200 m south of the Hatsushima station. View from the submersible *Shinkai 2000* dive 2K#940, drawn by Y. O.



Colony direction
B-2 site, Nankai Trough



Fracture pattern under right-lateral slip component regime

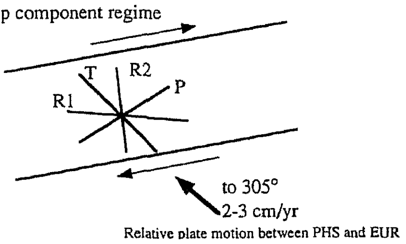
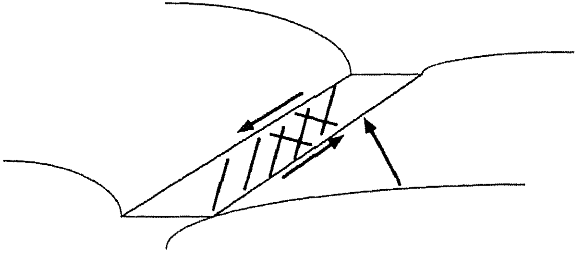


Fig. 10 Photo of *Calyptogena* communities on the trench landward slope of the East Nankai trough from the submersible *Nautile* during KAIKO-Nankai project, looking toward N, and rose diagram of the lineament of communities obtained by ROV *KAIKO*, dive 45, and its interpretation. In this case too, three types of Riedel shears similar to Fig. 7 are recognized under the plausible right-lateral component-bearing convergence.

En echelon and conjugate shear fractures as Riedel shears in a strike-slip sliver by oblique subduction



Conjugate shear fractures due to strike-slip stress regime (This paper)

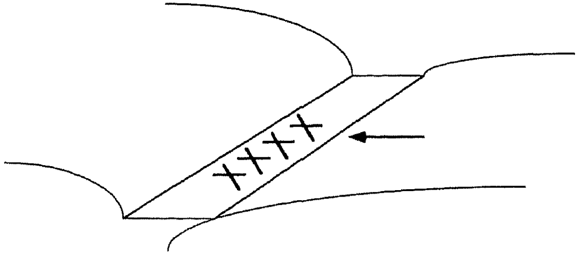


Fig. 11 Two models for conjugate or en echelon shear fractures under strike-slip fault regime in subduction front of forearc sliver model in which strike-slip regime is the result of the partitioning of strike-slip component of oblique subduction (above), and stress transfer model (shown in this paper) in which superficial part of the ocean floor sediments suffers strike-slip fault regime by stress transfer from the thrust front (below). See text in detail.

Concluding remarks

We proposed that strike-slip fault (or stress) regimes are common at subduction zone fronts, and even if in narrow zones, are widespread in some island arc regions. Such stress regimes include; the state for a normal fault, the state for a strike-slip fault, then finally for a thrust fault. The state of stress is composite in origin, and in each case the cause of a certain stress field is complicated. However, at least in the subduction front area, horizontal compression with vertical intermediate compressional axis exists around the deformation front. Chemosynthetic biocommunity distribution

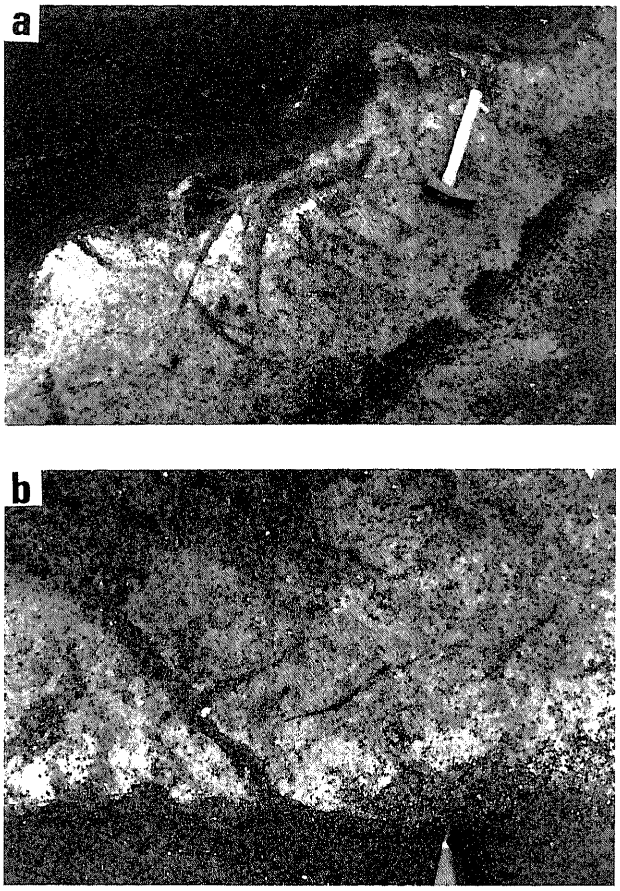


Fig. 12 Example of outcrop of the late Miocene Miura accretionary prism, Hamamoroiso, Miura Peninsula. Note that liquefied sandy or pebbly injection makes along en echelon and conjugate fractures on the bedding plane, suggesting horizontal compressional stress for strike-slip regime. Acute side of the hammer indicates north. After Ogawa *et al.* (2006).

in Japanese trench areas show good examples of strike-slip fault regime in the subduction zone front.

However, there are complications. The stress regime is basically not so simple as treated in this paper. The stress transfer from landward to seaward is not linear, unlike the simple assumption in this paper that the elastic strain prevails instantaneously during an earthquake. The stress might transfer in ways depending upon the rheological response of the sediments in front of the thrust front. The viscosity response may be of the prime importance. Another problem is that the stress axes are not always vertical or horizontal, but in the sediments around the thrust or deformation front, they may rotate obliquely, and gradually change from vertical to horizontal. We have not discussed these problems in detail in this paper, but should consider based on critical numerical analysis and actual observation or measuring of stress or strain.

The last and most important problem is that when we discuss the soft sediment deformations, for example in the sediments incorporating to the subduction zone, pore-fluid pressure has a most important role, but in this paper it was not treated in detail. Differential stress, *q*, is not affected by the quantity of pore-fluid pressure, because in any case the *q* value has no component of pore-fluid pressure. However, when the fracture or intrusion occurs the pore-fluid pressure quantity or so called the effective pressure should be considered for fracturing condition. We need to evaluate the timing and conditions for such phenomena by the quantity of pore-fluid pressure.

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References

Asada, M., 2000MS, *Relation between tectonics and distribution of chemosyntheitic animal communities off Hatsushima, Sagami Bay*: Bachelor Thesis, College of Natural Science, University of Tsukuba, 44 pp.

Ashi, J. and Taira, A., 1992, Structure of the Nankai accretionary prism as revealed from IZANAGI sidescan imagenary and multichannel seismic reflection profiling: *Island Arc*, **1**, 104–115.

Behrmann, J. H., 1991, Conditions for hydrofracture and the fluid permeability of accretionary wedges: *Earth and Planetary Science Letters*, **107**, 550–558.

Brown, K. M. and Westbrook, G. K., 1987, The tectonic fabric of the Barbados Ridge accretionary complex: *Marine and Ptroleum Geology*, **4**, 71–81.

Chamot-Rooke, N., Lallemant, S. J., Le Pichon, X., Henry, P., Sibuet, M., Boulegue, J., Foucher, J.-P., Furuta, T., Gamo, T., Glacon, G., Kobayashi, K., Kuramoto, S., Ogawa, Y., Schultheiss, P., Segawa, J., Takeuchi, A., Tarits, P. andTokuyama, H., 1992, Tectonic context of fluid venting at the toe of the eastern Nankai accretionary prism: Evidence for a shallow detachment fault: *Earth and Planetary Science Letters*, **109**, 319–332.

Dresen, G., 1991, Stress distribution and the orientation of Riedel shears: *Tectonophysics*, **188**, 239–247.

Fujioka, K. and Taira, A., 1989, Tectono-sedimentary settings of seep biological communities: A synthesis from the Japanese subduction zones: In *Sedimentary facies in the active plate margin*. ed. by A. Taira and F. Masuda, TERRAPUB, Tokyo, 577–602.

Gamo, T., Ishibashi, J., Shitashima, K., Kinoshita, M., Watanabe, M., Nakayama, E., Sohrin, Y., Kim, E., Masuzawa, T. and Fujioka, K., 1988, Anomalies of bottom CH_4 and trace metal concentrations associated with high heat flow at the *Calyptogena* community off Hatsu-shima Island, Sagami Bay, Japan: A preliminary report of *Tansei Maru* KT-88-1 cruise Leg-1. *Geochemical Journal*, **22**, 215–230.

Goldfinger, C., Kulm, LV. D., Yeats, R. S., Hummon, C., Huftile, G. J., Niem, A. R. and McNeil, L. C., 1996, Oblique strike-slip faulting of the Cascadia submarine forearc: The Daisy Bank fault zone off central Oregon: In: Bebout, G. E., Scholl, D. W., Kirby, S. H. and Platt, J. P. (eds.) *Subduction – Top to bottom. Geophysical Monograph* **96**, 65–74, American Geophyscial Union.

Hanamura, Y. and Ogawa, Y., 1993, Layer parallel faults, duplexes, imbricate thrusts, and vein structures of the Miura Group: Keys to understanding the Izu forearc sediment accretion to the Honshu forearc: *IslandArc*, **3**, 126–141.

Hashimoto, J., Ohta, S., Tanaka, T., Hotta, H., Matsuzawa, S. and Sakai, H., 1989, Deep-sea communities dominated by the giant clam, *Calyptogena soyoae*, along the slope foot of Hatsushima Island, Sagami Bay, central Japan: *Palaeogeography Palaeoclimatology Palaeoecology*, **71**, 179–192.

Jaeger, J. C. and Cook, N. G. W., 1969, *Fundamentals of Rock Mechanics*: Methuen and Company, London, 513 pp.

Jones, M., 1994, Mechanical principles of sediment deformation: In Maltman, A. J. (ed.) *The geological deformation of sediments*. Chapman & Hall, London, 37–71.

Karig, D. and Morgan, J., 1994, Tectonic deformation: stress paths and strain histories: In Maltman, A. J. (ed.) *The geological deformation of sediments*. Chapman & Hall, London, 167–204.

Kobayashi, K., 2002, Tectonic significance of the cold seepage zones in the eastern Nankai accretionary wedge – An outline of the 15 years KAIKO Projects –: *Marine Geology*, **187**, 3–30.

Kulm, L. D., Suess, E., Moore, J. C., Carson, B., Lewis, B. T., Ritger, S. D., Kadko, D. C., Thornburg, T. M., Embley, R. W., Rugh, W. D., Massoth, G. J., Langseth, M. G., Cochrane, G. R. and Scamman, R. L., 1985, Oregon subduction zone: venting, fauna and carbonates: *Science*, **231**, 561–566.

Masuzawa, T., Handa, H., Kitagawa, H. and Kusakabe, M., 1992, Sulfate reduction using methane in sediments beneath a bathyal "cold seep" giant clam community off Hatsushima Island, Sagami Bay, Japan: *Earth and Planetary Science Letters*, **110**, 39–50.

Matsuda, T. and Kinugasa, Y., 1991, Active faults in Japan: *Episode*, **14**, 199–204.

Mikada, H., Ienaga, M., Goto, T. and Kasaya, T., 2006, Current research status and meaning of fluid pressure monitoring at the Nankai Trough: *Journal of Geography, Tokyo Geographical Society*, **115**, 367–382.

Moore, G. F., Shipley, T., Karig, D. and Taira, A., 1990, Structural geometry at the toe of the Nankai accretionary prism from MVS and ESP data: *Journal of Geophysical Research*, **95**, 8753–8765.

Moore, J. C. and Byrne, T., 1987, Thickening of fault zones: A mechanism of melange formation in accreting sediments: *Geology*, **15**, 1040–1043.

Moore, J. C., Brown, K. M., Horath, F., Cochrane, G., MacKay, M. and Moore, G. F., 1991, Plumbing accretionary prisms: effects of permeability variations. *Philosophical Transactions of the Royal Society of London, Series A*, **335**, 275–288.

Moore, J. C., Orange, D. L. and Kulm, L. D., 1990, Interrelationship of fluid venting and structural evolution: Alvin observations from the frontal accretionary prism, Oregon: *Journal of Geophysical Research*, **95**, 8795–8808.

Ogawa, Y., Fujikura, K., Iwabuchi, Y., Kaiho, Y., Izumi, N., Inoue, A., Nogi, Y., Taira, K., Kikuma, T., Lee, I. T., Kodera, T., Nagai, S., Okano, H., Ikegami, A., Fujioka, K. and Kuwano, T., 1996a, Dive report of "Shinkai 6500" 1995 cruise at the northern Japan trench landward slope (dives 272–277): *JAMSTEC Journal of Deep Sea Research*, **12**, 1–22.

Ogawa, Y., Fujioka, K., Fujikura, K. and Iwabuchi, Y., 1996b, *En echelon* patterns of *Calyptogena* colonies in the Japan Trench: *Geology*, **24**, 807–810.

Ogawa, Y., Fujiwara, Y., Hunt, J. C., Iwase, R., Kaneko, H., Kawamura, K., Kitazato, H., Kobayashi, H., Koizumi, K., Kubota, S., Nishida, S., Otsuka, T., Shimanaga, M., Takaki, Y., Tsuchida, S., Tsuchiya, M., Uematsu, K., Yamamoto, T., Hashimoto, J. and Segawa, J., 1997, Preliminary report of "*Shinkai 2000*" May 1997 Sagami Bay Mission – Dives 939 –945: *JAMSTEC Journal of Deep Sea Research*, **13**, 353–373.

Ogawa, Y., Iwase, R., Kanazawa, T., Kaneko, H., Kawakami, S., Kawamura, K., Koyama, S., Kobayashi, H., Maki, Y., Sakai, S., Takaki, Y. and Asada, M., 1999, Preliminary report of "*Shinkai 2000*" Sagami Bay Mission, NT98-12 Leg 1 – Dives 1047–1051: *JAMSTEC Journal of Deep Sea Research*, **15-II**, 135–144.

Ogawa, Y. and Kobayashi, K., 1993, Mud ridge on the crest of the outer swell off Japan Trench: *Marine Geology*, **111**, 1–6.

Ogawa, Y., Tanaka, K. and Suzuki, K., 2006, Interpretation of some geologic atructures of unconsolidated or partially consolidated sediments: *Journal of Geography of Tokyo Geographical Society*, **115**, 326–352.

Ohta, S. and Laubier, L., 1987, Deep biological communities in the subduction zone of Japan from bottom photographs taken during "*Nautile*" dives in the Kaiko project: *Earth and Planetary Science Letters*, **83**, 329–342.

Orange, D. L., Greene, H. G., Reed, D., martin, J. B., McHugh, C. M., Ryan, W. B. F., Maher, N., Stakes, D. and Barry, J., 1999, Widespread fluid expulsion on a translational continental margin: Mud volcanoes, fault zones, headless canyons, and organic-rich substrate in Monterey Bay, California: *Geological Society of America Bulletin*, **111**, 992–1009.

Turcotte, D. L. and Schubert, G., 1982, *Geodynamics: Applications of continuum physics to geological problems*: John Wiley and Sons, New York, 450 pp.

Westbrook, G. K. and Smith, M. J., 1983, Long decollements and mud volcanoes: Evidence from the Barbados Ridge Complex for the role of high pore-fluid pressure in the development of an accretionary complex: *Geology*, **11**, 279–283.

Yamamoto, Y., Ohta, Y. and Ogawa, Y., 2000, Implication for the two-stage layer-parallel faults in the context of Izu forearc collision zone – Examples from the Miura accretionary prism, central Japan: *Tectonophysics*, **325**, 133–144.