TECTONO-SEDIMENTARY SETTINGS OF SEEP BIOLOGICAL COMMUNITIES—A SYNTHESIS FROM THE JAPANESE SUBDUCTION ZONES—

Kantaro FUJIOKA and Asahiko Taira

Ocean Research Institute, University of Tokyo, 1-15-1 Minamidai, Nakano, Tokyo 164, Japan

Abstract. Submarine seepage-related biological communities have been discovered along Japanese subduction zones, mostly through campaigns by the submersibles “Nautil” (the Kaiko Project), “Shinkai 2000” and ROV “Dolphin 3K”. Observation of the modes of occurrence of deep-sea seep communities, which are characterized by the giant clam Calyptogena and the tube worm Lamellibrachia, suggests that they have common features. Such communities live on coarse substrates, often associated with erosional features, although the tectonic setting of each community varies from the fault zone within a trench’s landward slope, to the toe of a landward slope (plate boundary) and an intra-oceanic plate deformation zone. The occurrences are genetically classified into four types of association: fault scarp and talus, submarine canyon and talus, fan valley and turbidite, and slide escarpment and talus associations. Such tectono-sedimentary settings are common not only in convergent margins but in other deep sea environments, suggesting the possibility of a wide occurrence of seep communities in many parts of the world’s oceans.

1. Introduction

Subduction of an oceanic plate at a convergent margin causes a very active tectonic regime, in which fluids in rocks and sediments seem to play a key role in the structural evolution and mechanical behavior of the material composing the landward slope of the subduction zones (e.g. Von Huene and Lee, 1982).

During the Japan-France Kaiko Project (see Kaiko II Research Group, 1987), several deep-sea animal communities were discovered and carefully observed through the French submersible “Nautil” (Le Pichon et al., 1987b; Pautot et al., 1987; Cadet et al., 1987) (Fig. 1). These animal communities were considered to be closely related to the seepage of deep-seated fluids in their ecological environments (Ohta and Laubier, 1987; Boulegue et al., 1987) similar to other examples documented previously (Paull et al., 1984; Suess et al., 1986).

The findings of the Kaiko Project triggered the study of such communities and their related hydrogeologic frameworks in Japanese subduction zones. Among these, an extensive study of seep communities in the Sagami Trough region, utilizing the manned submersible “Shinkai 2000” and the unmanned submersible “Dolphin 3K” produced a large amount of data and many insights into seepage-related communities (e.g. Hashimoto et al., 1987; Ohta et al., 1987). At the same time, deep-sea photography and detailed studies of heat flow and seismic characteristics were conducted at the Nankai Trough region by the
Fig. 1. Submarine topography and locations of seep communities described in this paper.
R/V Hakuho-Maru in order to study the relationship between the area's structural type, physical properties and hydrogeology (TAIRA et al., 1988).

The study of modern examples has resulted in the reconsideration of fossil communities on land, some of them now identified as possible ancient equivalents of seepage-related animal communities (e.g. MATSUSHIMA and NIITSUMA, 1986).

The purpose of this paper is to review these recent findings and to try to relate the occurrence of deep-sea animal communities to a simple tectono-sedimentary context. We emphasize the importance of submarine erosion and the sedimentation of coarse-grained clastics in the occurrence of animal communities (FUJIOKA and TAIRA, 1987). The areas we examine are: the Nankai Trough region, the arc-arc collision zone between the Izu-Ogasawara and the Honshu arcs, and the Japan Trench region. First, we present a simple model for tectono-sedimentary settings of seepage-related animal communities. Then, we describe several communities in various regions as case studies for these models.

2. Tectono-Sedimentary Settings of Seep Community

The nutrients of seep-related communities are variable, but hydrogen sulphide and hydrocarbons seem to be the main sources of nutrients utilized by bacteria as bases for the food chain (e.g. CAVANAUGH, 1983; SUESS et al., 1986). This indicates that fluid sources in the sea floor are widely distributed. Especially where sediments containing a certain amount of organic matter have accumulated, nutrient-rich fluids should eventually be produced through diagenetic processes. Therefore, the occurrence of a seep community is not a matter of fluid source, but a matter of how the fluid can seep and be effectively sustained at the sea-floor surface. Here we stress the importance of erosional processes to expose conduits for fluid to reach the surface, and the sedimentation of coarse-grained sediments for aquifer production. The setting of submarine seepage zones is in many ways similar to that of oases on land, which develop at alluvial fan fringes. The model we have in mind is simple: to produce a large-scale or widely distributed community field, the following four settings are favorable (see Fig. 2).

2.1 Fault scarp and talus cone associations

Faults apparently provide an effective way for deep-seated fluids to escape. Surface manifestations of faults are often associated with fault scarps, where gravity failure and erosion produce talus cones; these then provide materials of various sizes to form aquifers for venting fluids.

2.2 Submarine canyon and talus associations

Submarine canyon formation by tectonism, gravity collapse and turbidity currents can expose deeper sedimentary sections which provide conduits for diagenetic fluid to escape to the surface. Again, talus cones or canyon floor deposits can compose aquifers.

2.3 Fan valley and turbidite associations

Similar to submarine canyons, fan valleys and channels on submarine fans produce conduits for fluid. The source of the fluid may not be deep-seated; as submarine fan sediments are often rich in organic materials, enough biogenic methane can be provided to the surface to maintain a seep community. Turbidite and debris flow deposits should serve as permeable layers suitable for aquifer formation.
2.4 *Slide escarpment and talus associations*

Large submarine slides are also capable of exposing deeper sedimentary sections and allowing a formation’s fluids to escape to the surface. Again, similar to fault scarp and talus associations, coarse debris derived from the escarpment creates an aquifer.

We suggest that the seep animal communities found around Japan can be classified as one of the above associations or a combination thereof. In the next section, we describe details of these communities, the type of associations and related tectonic settings.
3. *Seep Communities in the Nankai Trough Region*

3.1 *Tectonic framework*

The Nankai Trough forearc region is characterized by the tectonic mode of sediment-accretion: thick trench filling by turbidites, well-developed accretionary prism and forearc basins.

The turbidites in the Nankai Trough have been supplied from the Suruga Trough region, mainly from the fan-delta of the Fuji River, through an axial main channel (TAIRA and NIITSUMA, 1985; SHIMAMURA, 1988). The turbidites are very coarse-grained in the proximal area and grade to fine-grained, mainly fine sand to silt size in DSDP Site 582, off western Shikoku Island (TAIRA and NIITSUMA, 1985).

The accretionary prism developed in the Nankai Trough region displays one of the best-developed thrust-fold belt type structures. The structure of the Nankai accretionary prism has been classified into three zones based on the style of the thrust belt: the proto-thrust, imbricate thrust and late thrust zones (multi-decollement zone) (KAGAMI et al., 1983; KAGAMI, 1985; TAIRA, 1985).

The development of these structures seems to be closely related to the stratigraphy of the subducting sediments (Fig. 3). At the trench, seismic stratigraphy shows three distinctive layers: a horizontally layered upper sequence, a slightly inclined, lower transparent sequence and the acoustic basement. The results of DSDP Legs 31 and 87 (KARIG et al., 1975; KAGAMI et al., 1985) showed that the upper two layers correspond to the upper turbidite layer and the lower hemipelagic layer, respectively. The acoustic basement is considered to be the oceanic crust of the Oligo-Miocene Shikoku Basin. There is a highly reflective horizon within the hemipelagic layer, which has been interpreted as a Pliocene sandy layer. This sandy layer is considered to be over-pressured and to serve as a main detachment surface (decolllement); the decollement zone can be traced as far as 35 km from the proto-thrust zone.

The hydrogeology framework can be inferred from three main sources of data at the Nankai Trough: heat flow, acoustic impedance log and animal communities.

The heat flow transect of the Nankai Trough region (KINOSHITA, 1987 MS) indicates the following hydrogeologic implications (see Fig. 3A).

a. There is a general landward decrease of the heat flow value.

b. A sharp rise of heat flow is recognized at the toe of the deformation front.

c. Fluctuation of the heat flow value is a characteristic feature of the landward slope.

Taking 110 mW/m² as a theoretical basal heat flow value from the oceanic crust, it was found that the heat flow value observed at the trench was higher than the general trend. It was suggested that this anomalous heat flow trend is due to fluid circulation. The high peak at the deformation front could be related to a concentrated seepage along the fault. At the landward slope, the fluctuation pattern of the heat flow seems to correspond to the structure of the prism: high at the fault zone and low in between. Therefore, a cell of upwelling and downwelling circulation within the prism has been proposed (TAIRA et al., in press).

Acoustic impedance is the parameter which reflects the seismic characteristics of a formation, and is defined by:

\[
\text{Acoustic Impedance} = \text{Bulk Density} \times \text{Seismic Velocity}.
\]

Air-gun seismic reflection data obtained during the R/V Hakuho-Maru cruise KH86-5 were analyzed for the acoustic impedance log using an inversion method (NISHIYAMA, in press).
The results of the analysis indicate that there is a widely developed overpressurized zone within the trench and accretionary prism of the Nankai Trough (see Fig. 3B).

A seismic velocity (P wave) analysis obtained through ocean bottom seismometers indicates that the velocity maintains 3.1 to 3.5 km/sec, at the base of the prism from the toe to as much as 50 km landward, at about 5 km sub-bottom depth (Nishizawa et al., personal communication). This velocity at the base of the prism is much slower than at the forearc of the Japan Trench, where the velocity reaches 5 km/sec (Suyehiro et al., 1985). This suggests that there is a “low-velocity zone” which is probably related to the development of wide areas of over-pressurized horizon. This over-pressurized zone acts as a pumping mechanism to support a wide distribution of animal communities in the Nankai Trough region (Taira et al., in press).
3.2 *Seep animal communities*

During the Japan-France Kaiko Project, seepage-related animal communities, mainly composed of clams (*Calyptragenia*) and tube worms were found through observations using the submersible “Nautil” in the region of the Tenryu deep-sea fan. *Calyptragenia* and tube worms have also been found in the landward slope region of the island of Shikoku by means of dredging, photography by the R/V Hakuho-Maru (TAIRA et al., in press) and the submersible “Shinkai 2000” (OKAMURA et al., 1986), in water depths ranging from 700 m to 4700 m (Fig. 4). Because observation data are limited for these latter communities, their detailed natures are not known. Therefore, we concentrate our description only on the Tenryu community.

The seep community found at the mouth of the Tenryu Submarine Canyon is an example of the fan valley and turbidite association type. It is situated in a fan-valley of the Tenryu Fan a few hundred meters wide, near the main thrust of the toe of the Nankai accretionary prism (LE PICHON et al., 1987a) (Fig. 5). A tectonic fold within the valley was partly eroded and a series of small fault scarps was observed. The orientation of the faults and the axes of fold indicate a NW-SE compression (Fig. 6). Figure 8 is a sketch map of the Tenryu Community. The seep community shows an elongated distribution, about 80 meters long, along a NE-SW trending reverse fault. It is composed of a condensed population of *Calyptragenia*, tube worms and other animals (Fig. 8). Temperature and methane anomalies and isotopic evidence indicate the seepage of deep-seated fluids (BOULEGUE et al., 1987; DRON et al., 1987) through fractures exposed by erosion from turbidity currents. The substrate of the community is composed of a few centimeters of mud at the surface with granular to very coarse-grained sand underneath. At the dense clam colony, the coarse-grained sediments are stirred-up and make a homogenized sedimentary substrate. We emphasize that permeable coarse-grained sediment is an important factor in producing percolating fluids for organisms to use.

4. *Seep Communities at the Arc-Arc Collision Zone*

4.1 *Tectonic framework*

The northward motion of the Philippine Sea Plate causes collision of the Izu-Bonin arc with the Honshu arc, where active tectonism has operated since the middle Miocene time (Fig. 10) (TAIRA et al., in press).

In the Sagami Trough region, a very oblique subduction of the Izu-Bonin arc is inferred (Fig. 10). The trough receives coarse terrigenous clastics along its axial part, but the slopes of both sides of the trough are dominated by volcanogenic materials. Active faulting at both sides of the trench produces a complex tectonic framework. The landward slope is composed of an accretionary prism showing a fault-bounded, steplike topography (KATO et al., 1983). The NW-SE trend of the ridge, a manifestation of faults and folds, is dissected by NE-SW canyons (FUJIOKA and FURUTA, 1986). Several seep-communities are recognized at the foot of one such chain of the ridge, called the Okinoyama Bank, at a depth of about 1100 m (Fig. 10).

At the other side of the trough (the western oceanic side), a seep community also occurs off Hatsushima Island to the southeast (HASHIMOTO et al., 1987); the setting can be interpreted as an intra-subducting plate deformation zone (Fig. 10), intersecting with the volcanic front of the Izu-Ogasawara Arc (FUJIOKA et al., in press). Both these communities belong to fault scarp-talus associations.

The intraplate deformation on the seaward side is represented by a topographic expression called the Zenisu Ridge, a NE-SW trending topographic high, the southern
Fig. 5. Seabeam map of the Tenryu Community site and other diving sites of the Kaiko Project. The Tenryu Community was discovered during dive KD-3 and later visited during dive KD-5. A seep community was also found during dive KD-6 (after Kaiko II Research Group, 1987).
Fig. 6. Orientation of fault and fold axis observed during Kaiko dive KD-3 (left) and a model for tectonic interpretation (right).

Fig. 7. Sketch of the Tenryu Community. The temperature shown was measured by thermister probe at 10 cm below the surface. A: the location of Holothurian found during dive KD-3; B: the location of Holothurian on dive KD-5 (four days later).
Fig. 8. Photos of Tenyu Community. A: scattered dead shells of Calyprionacea. B: Holothurian and water sampler. C: Sampling sediment. D: Sampling by net.
margin of which is bounded by a major thrust fault. According to seismic profiling surveys, the Zenisu Ridge is composed of the tilted and uplifted Shikoku Basin oceanic crust (Le Pichon et al., 1987a). Dives made during the KAIKO Project revealed the exposure of lower Miocene to Oligocene siltstone, which can be correlated to the Shikoku Basin hemipelagic layer. Also, a Calyptogena seep colony was found, suggesting active fluid seepage along the thrust fault zone (Fig. 10).

The geology on land indicates that an accretion of oceanic crust and island arc mass, together with trench-fill clastics, has taken place since the middle Miocene time. This can be explained by the successive stepping out of the plate boundary migrating to the south and the accretion of island arc material with a trough-fill clastic sequence (Taira et al., in press). To the north of this zone, there is a series of forearc basin sediments in which a few locations of ancient Calyptogena occurrences are known. The most prominent one is found in the Ikego Formation of the Miura Peninsula (Matsushima and Niitsuma, 1986) which can be interpreted as old submarine canyon fill deposits.

These lines of evidence indicate that at the Izu-collision zone, fluid seepage occurs in a very wide area, both landward and seaward of the subduction-collision zone. We discuss further details of these communities in the next section.

4.2 Seep communities
A. The Hatsushima communities

The Hatsushima Communities are located to the southeast of Hatsushima Island to the east of the Izu Peninsula, and were found during dives with the submersible “Shinkai 2000” (Sugiura and Egawa, 1985). The communities have been investigated, mainly by submersible, several times and their nature described (Hashimoto et al., 1987; Ohta et al., 1987). The communities lie on the eastern slope of the Izu Peninsula at water depths ranging from 800 m to 1200 m, and consist mainly of Calyptogena, tube worms, crabs and other organisms. Figure 11 is a topographic map around the Hatsushima Communities. An abrupt topographic break runs approximately N30E, at water depths around 700 m to 800 m, forming a chain of steep cliffs grading to a gentle slope as far as the axis of the Sagami Trough. Active faults have been inferred along this cliff. The abrupt topographic change is considered to a surface manifestation of the thrust plane of the Izu-Toho line proposed by Ishibashi (1978). The distribution of the communities shows a linear trend almost parallel to the extension of the Izu-Toho line from 34°57'N to 35°01'N (Figs. 11 and 12). Sediments which cover the communities are coarse volcanogenic materials. We interpret that these
communities are an example of the fault scarp and talus association type. The source of fluid for this community is not known; however, there is a possibility of a hot spring-related hydrogeologic framework.

B. Okinoyama Communities

Clam communities were identified along the western foot of the Okinoyama Bank, a ridge of accretionary complex, at depths of 900 m to 1100 m (Hattori, personal communication). Figure 13 shows the slope topography just near the slope break at the western foot of the bank chain. The communities’ substrate is covered with coarse sand.
Fig. 11. Submarine topography and location of Hatsushima Community (after Hashimoto et al., 1987).
mixed with gravels with a muddy matrix (HASHIMOTO et al., 1987). The Okinoyama communities can be considered examples of the fault scarp and talus association type.

5. **Seep Communities in the Japan Trench-Kuril Trench Regions**

5.1 **Tectonic framework**

The Japan Trench is characterized by a different tectonic regime than the Nankai Trough region. The topographic, seismic and geologic evidence indicates that the Japan Trench landward slope displays only a small number of accretionary prisms, if any. Large-scale gravity-induced failure is a dominant feature of the slope (CADET et al., 1987a) (Fig. 14). The subducting oceanic plate is Cretaceous in age, much older than the Oligo-Miocene Shikoku Basin at the Nankai Trough. At the outer slope of the trench, the oceanic crust is faulted into remarkable horst and graben structures. The northern Japan Trench exhibits a gigantic scarp with a mean slope of about 10°. The seismic evidence indicates that there is
an enormous truncation of strata at this scarp (Fig. 15), suggesting possible large-scale gravity failure along this steep cliff.

Dives by the “Nautil”revealed the existence of clam communities along this scarp, especially on the terrace topography where coarse-grained sediments composing talus cones are present. This suggests that slide escarpment and talus association seep communities occur in the Japan Trench landward slope.

Seamount chains on the Pacific sea floor have been subducted at the Japan Trench, and two prominent mounts are presently at the trench axis: the Dai-ichi Kashima Seamount and the Erimo Seamount. The subduction of such seamounts seems to play a major role in the tectonics and topographic evolution, as well as the hydrogeology, of the landward slope.

The Dai-ichi Kashima Seamount is a Cretaceous seamount now at a critical stage of subduction. The western half of the seamount is dissected by a normal fault and is being subducted under the landward slope of the Japan Trench (Fig. 16). The landward slope exhibits an elevated topography due to the subducting topographic high, which is at the same time highly fractured (KAITO II RESEARCH GROUP, 1987). A clam community was found on the landward slope near the toe.
A similar example of seamount subduction is found at the junction between the Japan and Kuril Trenches, where the Cretaceous Erimo seamount is about to traverse the trench axis. A spectacular embayment is observed to the north of the Erimo Seamount, associated with a magnetic anomaly (Fig. 17). This topography was identified as an indentation marking a subducted seamount by Taira and Fujoka (1985) and Cadet et al. (1987a). There is also an unusual topography to the south of the Erimo Seamount which we suspect to be a feature of a gigantic submarine landslide (see Fig. 14). This interpretation is drawn from the fact that there is a series of crescent-shaped escarpments to landward, hummock
Fig. 15. Seismic profile and dive sites of the Kaiko Project at the Miyako Community. Arrow on the seismic profile indicates the location of the community. ODP drill sites are also shown.
Fig. 16. Seismic profile and dive sites at the Dai-ichi Kashima Seamount. Arrow on the map indicates location of the community.
Fig. 17. Seismic profile and dive sites at the Erimo Seamount-Kuril Trench region. Arrow on the map indicates location of the community.

topography in the middle and lobate topography at the trench, all topographic indications of a landslide complex. We believe this landslide, about 50 km across, was caused by successive events of seamount subduction. Subduction of a seamount produces a steep escarpment which is unstable, eventually collapses and slides back to the trench (Fig. 14C).

A dive by "Nautil" along the gigantic escarpment to the north of the Erimo Seamount revealed that there are scattered clam communities.
The tectono-sedimentary settings of the Japan Trench seep communities are summarized in Fig. 18.

5.2 Seep communities

A. The Kashima Community

The Kashima Community was found during a transect dive from the Dai-ichi Kashima Seamount via the Japan Trench and its forearc region. At 5700 m, several dead clam shells were found, and then at depths of 5640 m, a living clam community was found (PAUTOT et al., 1987). The community is situated on a gentle thrust plain at the foot of a steep cliff in the landward toe of the Japan Trench, near the Dai-ichi Kashima Seamount (FUJIOKA and TAIRA, 1987) (Fig. 18). A temperature anomaly about 0.3°C higher than that of the ambient sea water was measured with a thermistor probe. Sediments associated with the community were collected by an Ekman type sampler and identified as coarse-grained sediments rich in organic matter. The community consists of clams, Holothurians in Figs. 7 and 8, gastropods and other organisms (Fig. 19).

We suspect that fluid circulation along the mega-shear zone is responsible for this community. In the lower part of the shear zone, coarse debris makes up large talus cones, which may be too active to maintain a stable substrate for a community to be established. At the upper part of the shear zone, from a transition to fractured mudstone, there are vertical cracks, small gullies and coarse-grained sediments, all of which provide a favorable setting for a seep community to be maintained. The Kashima community, therefore, can be classified as a combination of the fault scarp and slide escarpment and talus associations.

B. The Miyako Community

Seep communities, probably the deepest ever identified in the history of ocean research, were discovered in the Japan Trench forearc at a depth of 5900 m (Fig. 18). The communities are located on a steep, gigantic cliff of about 1500 m elevational difference. Data on the community are summarized in Fig. 18.

The section exposed on the cliff is composed of alternating zones of highly sheared and disrupted mudstone and relatively coherent zones of structurally undisturbed mudstone. The sequence is considered to be from the Plio-Miocene age. Abundant evidence for gravity failure, quite fresh in appearance, was identified. The seep communities were found on a step terrace where coarse debris derived from the upper cliff forms talus deposits (Fig. 19). We interpret that this community is a typical example of the slide escarpment and talus association type.

C. The Kuril Community

Scattered clam communities were identified during KA IKO dives (Fig. 18). The dives revealed that the section exposed along the gigantic cliff is composed of pervasively sheared mudstone with volcanic ash intercalations. Structural disruption is very severe, including layer parallel extension, normal faulting and low angle slip planes.

The communities observed were all small, with several clams clustered on small benches of the escarpment (Fig. 21). The route taken in the dives went along a cliff too steep to maintain substantial animal communities. Rather, some of the patchy communities observed possibly indicate direct vents from the shear zone, exposed to the surface by gravity failure.

6. Conclusion

Convergent plate margins provide a wealth of opportunity for volcanogenic and squeezed formation fluids to escape to the sea floor. Tectonic settings favorable for venting
Fig. 18. Tectono-sedimentary framework of the seep communities in the Japan—Kuril Trench regions. A: Kashima Community. B: Miyako Community. C: Kuril Community.
include: faults on landward slopes, plate boundary toe regions and intra-oceanic deformation zones. The fluid sources have not been identified for each case, but speculation allows that diagenetic and magma-heated fluids (hot springs) seem to be two main sources of fluid at convergent margins.

Submarine erosion is a key element for seep community establishment. Erosion keeps the fluid conduits open and, at the same time, provides a permeable substrate enabling animals to use the percolating fluids.

Four main types of tectono-sedimentary settings for seep communities have been established in this study: fault scarp and talus associations, submarine canyon and talus associations, fan valley and turbidite associations and slide escarpment and talus associa-
Fig. 20. Photos of the Miyako Community. A: Sampling of the community. Note the remnant of uneroded substrate at the center-top. B: Sampling by net.

sections.

We propose that such tectono-sedimentary settings of seep communities are not restricted to convergent margins; rather, they can exist just about anywhere on the sea floor. Thus, seep communities can be far more common biological features of the sea floor than previously thought.

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Fig. 21. Photo of the Kuril Community. Note very coarse substrate.

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