

南海トラフ東部の付加プリズム末端部における 冷湧水現場の地質構造的状況

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1991年7月に「しんかい6500」による3回の潜航で行った地質構造的及び生物学的観察について報告する。潜航地点は、1989年のKAIKO-Nankai計画に基づく航海の間に調査された地域の東2.5kmにある東部南海付加プリズムの変形前面に位置している。この潜航の目的は、Kaiko-Nankai計画の潜航で得られた構造的解釈及び流体湧出と活断層間の関係を吟味することにあった。「しんかい」潜航は、1つの浅い分離断層が衝上前面上の斜面に露出していることを確認する新しい成果をもたらした。生物学的活動に関連した冷湧水は、両地点での衝上前面とは関係なかった。シロウリガイの群集は、すべて根が浅い小断層の上で見つかった。湧出口分布は流体が、この浅い小断層に沿いまだそれに根ざしている2つの衝上に沿って移動していることを示している。しかしながら、生物密集帯は、その断層露頭に限定されるのではなく、もっと幅広い帯状域を示している。断層が約50mよりも浅いとき、流体を通す効果が失われるものと結論される。

キーワード：南海トラフ、付加プリズム、冷湧水、分離断層、底棲生物群集

Tectonic Context of Venting Sites at the Toe the Eastern Nankai Accretionary Prism

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We present tectonic and biological observations made during three dives with the "Shinkai 6500" in July 1991. They are situated on the deformation front of the Eastern Nankai accretionary wedge, 2.5km east of a zone explored during the Kaiko-Nankai cruise in 1989. The purpose of the dives was to test the tectonic interpretation of Kaiko-Nankai dive and the relation between fluid seeps and active faults. The "Shinkai" dives brought new elements that confirm that a shallow detachment fault outcrops in the slope above the frontal thrust. No cold seep related biological activity was associated with the frontal thrust at both locations. All calyptogena colonies were found above the shallow detachment level. Vent repartition show that fluids are channelled along the shallow detachment and along two thrusts rooted in it. However, biologically active zones are not limited to the fault outcrops but define wider swaths. We conclude that

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faults lose their efficiency in channeling fluids when they are shallower than about 50m.

Key words: Nankai Trough, Accretionary prism, Cold seepage, Detachment fault, Benthic biological colony

1. Introduction

Overpressure of pore fluids in accretionary complexes generally induces channelized fluid flow along the décollement and the major thrust faults (Le Pichon et al., 1991; Moore and Vrolijk, 1992). These fluids have been imaged as polarity reversals in seismic profiles (Aoki et al., 1985; Bangs and Westbrook, 1991) or sampled during ODP drilling cruises (e.g. Moore et al., 1988). The presence of chemoautotrophic benthic biological communities is commonly interpreted as a tracer of active fluid flow out of the seabed (Suess et al., 1985; Le Pichon et al., 1987; Boulègue et al., 1987). In the case of the accretionary margins, these communities are frequently related to the outcrops of recently active thrust faults (Le Pichon et al., 1987 and 1991; Moore et al., 1990). Such venting systems have been intensively investigated in the Eastern Nankai Trough during the French-Japanese Kaiko-Nankai project (e.g., Kobayashi et al., 1992; Le Pichon et al., 1992) (Fig. 1). Henry et al. (1992) have inferred from in-situ thermal measurements that the Calyptogena benthic communities correspond to sites of focussed upward fluid flow with darcyan velocities as high as 100 m a^{-1} . These studies have also shown that the two most active venting sites are respectively located near the frontal thrust and close to the major backthrust.

There is an apparent paradox in the tectonic setting of the vents in the Eastern Nankai accretionary prism. The Tenryu Canyon venting sites observed during 1985 Kaiko cruise were clearly related to the outcrop of the eroded frontal thrust (Le Pichon et al., 1987), whereas within the Kaiko-Nankai sites, no seeps are related to the outcrop of the frontal thrust. Instead the most active seeps were found near the top of the first anticline (Le Pichon et al., 1992). Chamot-Rooke et al. (1992) have proposed that these vents are actually related to a shallow detachment whose outcrop is mappable as a bench with SeaBeam

bathymetry. However, the distance between the presumed shallow detachment outcrop and the frontal scarp is small there. The main purpose of the "Shinkai" dives 68, 69 and 70 was to test this hypothesis by investigating the tectonics and fluid activity along a section of the deformation front located about 2.5km east of the 1989 Kaiko-Nankai sites where the bench is better developed.

This kind of structure may not be exceptional. A detailed structural study of the ODP area on the Barbados wedge based on deep towed side scan sonar images and 3.5kHz sounder profiles revealed the existence of surficial deformation within the frontal imbricate above a shallow detachment (Lallemant et al., 1990). There is no direct evidence for fluid venting in this area, but high surface heat flow (Foucher et al., 1989) and a transient thermal regime in ODP Hole 676 (Fisher and Hounslow, 1989) are attributed to the expulsion of fluid from the décollement. The region of highest heat flow, and the temperature and methane anomalies in the drill hole correlate better with the shallow detachment and minor faults connected to it than with the frontal thrust (Lallemant et al., 1990).

2. Structural background

The tectonic structure of the area at the kilometer scale is known from the Sea-beam map and a 6-channel stacked seismic section from ORI (NKT5, see location on Fig. 2) (Lallemant et al., 1990; Chamot-Rooke et al., 1992). Two recently accreted imbricates are bound by thrusts T1a and T1b. Thrust T2a limits another tectonic unit to the north, which is more deformed and backthrust over what has been considered as the current backstop of the accretionary wedge (Le Pichon et al., 1992). Section NKT5 displays continuous sedimentary reflectors at depth within the first thrust unit whereas the upper sequence is deformed through folding and thrusting

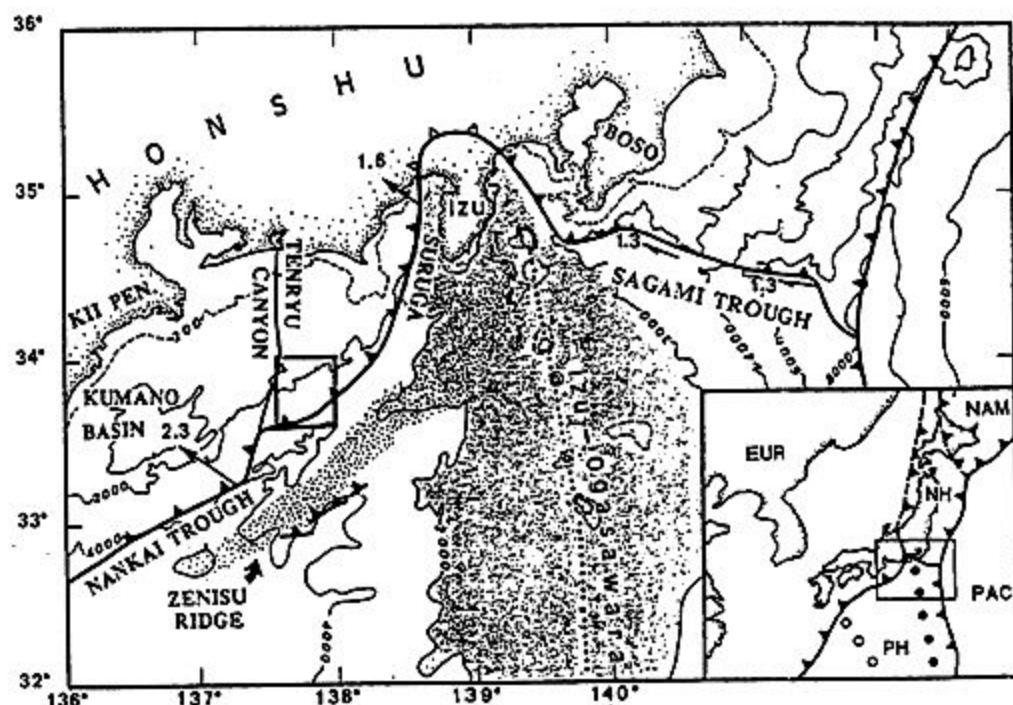


Fig. 1 General location map of the studied area (Le Pichon et al., 1992). Convergent plate boundaries are shown with barbed lines (barbs on the upper plate). Arrows on the plate boundaries give the local linear plate convergence vector (values are in centimetres per year). The stippled area offshore is the compressional deformation belt of the Zenisu Ridge and the shaded areas show the active volcanic arc related to subduction of the Pacific plate. Bathymetric contours are in metres. The inset shows the complex plate interactions in the area. EUR=Eurasian plate; PAC=Pacific plate; PH=Philippine Sea plate; NAM= North America plate; NH=hypothetical North Honshu microplate.

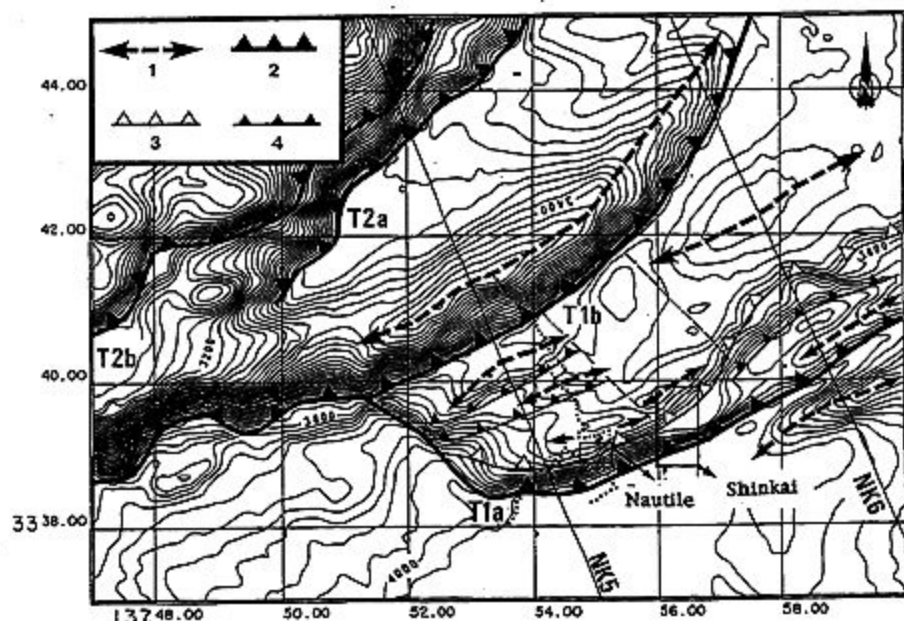


Fig. 2 Detailed Seabeam map and structural interpretation at the toe of Eastern Nankai accretionary prism (from Chamot-Rooke et al., 1992). 1: anticline axes; 2: major thrusts; 3: shallow detachment fault outcrop; 4: minor thrusts. The two boxes indicate the respective areas of Nautile dives during Kaiko-Nankai cruise and of "Shinkai 6500" dives 68, 69 and 70.

above a detachment fault (Fig. 3). This shortening probably accommodates the progression of the tip of the second imbricate along fault T1b. Observation of strata dips during Kaiko-Nankai dives showed that a narrow bench at depth 3,840m, near the top of the slope associated with the frontal thrust, is the outcrop of a low angle fault zone. This bench was thus interpreted as the outcrop of the shallow detachment fault (Chamot-Rooke et al., 1992). However, the correlation made between this bench and the thrust scarp that can be followed on the sea-beam map east of the Kaiko-Nankai dive sites needed to be checked. For this reason the "Shinkai" dives were done at a location 2.5 kilometers to the east where a 600m wide plateau separates the lower slope from the slope attributed to the shallow detachment fault outcrop.

3. Structural interpretation of the dives

3. 1 Description of the dives

The frontal thrust system was explored along two N 330° oriented transects 250m apart (dive 68 to the east and dive 69 to the west) (Fig. 4). The trench shows a flat silty-muddy heavily burrowed bottom. The frontal thrust (probably around 4,010m) is concealed by a steep (20° to 30° dipping) and tectonically active talus made of angular blocks of mudstone, where rock avalanches cut gullies along the line of maximum slope. The boundary between the talus

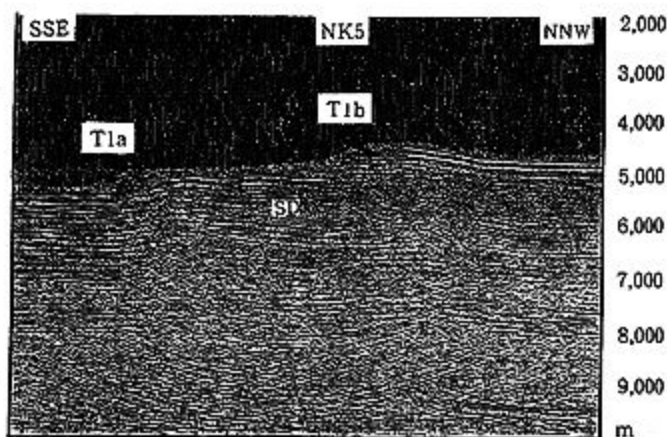


Fig. 3 Detail of the 6 channel O.R.I. seismic line NK5 at the toe of the prism. (deconvolved and post-stack depth migrated time section).

and the outcropping beds corresponds to a slope break at 3,970m. Upslope, two major series of scarps are present on both transects (they are located respectively between 3,970 and 3,940m and between 3,900 and 3,880m) and correspond apparently to thick mudstone layers. The layers crop out almost continuously up to 3,840m. They are more or less conformable to the slope with small undulations (with a wavelength of about 10m). Dive 69 ended up on a bench at 3,960m where the first clam colonies were found.

The plateau is found at 3,840 to 3,830m, which is the same depth found for the thrust outcrop further to the west. Soft undulations form two parallel highs two hundred meters apart. The plateau then deepens northward. Outcropping strata were found only

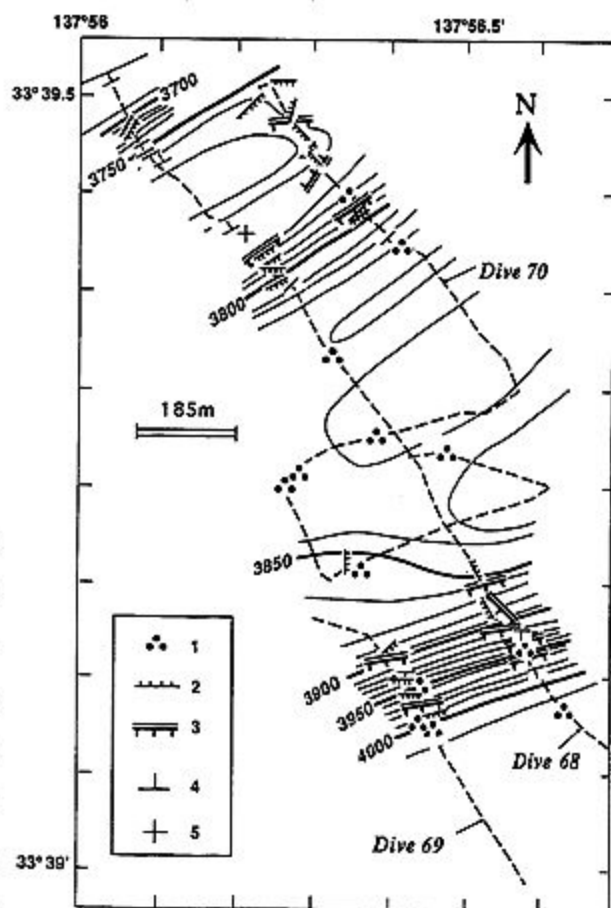


Fig. 4 Tectonic observations from the "Shinkai 6500" dives at the toe of eastern Nankai accretionary wedge (location in Fig. 2): 1: blocks; 2: small scarps ≤ 1 m; 3: scarps ≥ 1 m; 4: bedding planes dip direction; 5: horizontal bedding.

in one location. Occasionally a few scattered mudstone blocks were observed. There is little erosion and strata are most probably conformable with the topography.

The upper slope is made of two 80m high scarps. The base of the first is hidden by a talus. Above, outcropping strata observed during dive 68 are almost conformable with the slope. This is not as clear for dive 70, but on both transects a 10m high cliff of thin layered sediment terminates the steep part of the slope.

The 200m wide bench between the two scarps has a different aspect along the two dives. The strata dips measured along dive 68 define an anticlinal ridge that is followed by a shallow flat valley. Dive 70 crosses a 10m deep valley limited by two cliffs, and finds many outcrops with random strikes, the strata being subhorizontal. We assume heavy erosion in the part of the valley crossed by dive 70 whereas the part crossed by dive 68 was filled by the debris.

The uppermost ridge is also an anticline. Strata outcropping on its southern slope are conformable except at its very base, where outcropping strata dipping northward are observed. These latter strata probably lie below the thrust outcrop.

3. 2 Structural map and cross-section

As often during submersible dives, the thrusts could not be observed directly because either the thrusts were hidden by talus or erosion was not strong enough to provide good outcrops. However, topography and strata dips suggest that all three major slopes are indeed thrust scarps (Fig. 5). There is a good correlation between the depth observations of scarps made during the different dives and most of the differences can be attributed to erosion. The structure can thus be illustrated by a single balanced cross section (Fig. 6). The dip of the shallow detachment fault is assumed to be the same as that of the continuous reflectors from seismic profile NKT5. It is also assumed that the sedimentary unit above the shallow detachment thickens eastward, so that its surface would be horizontal in the absence of deformation. Seismic profiles NKT5 and NKT6 show that the thickening of this unit is largely non tectonic and

that it can be considered to have originated as a piggyback basin (Chamot-Rooke et al., 1992). The chosen detachment dip of 1.5° may be too high or the sedimentary thickening chosen too small, as some adjustments were needed in the construction of the section. As a consequence a duplex had to be inserted below the northern anticline. Also, the surface of the plateau had to be eroded, which was not observed. However, we consider this balanced cross-section to be a reasonable interpretation of the structure observed. The shallow detachment has been prolonged almost to the edge of the plateau although no fault outcrop was observed there. We suppose that the undulations of the surface of the plateau resulted from folding (possibly involving a blind thrust) above the detachment.

3. 3 Azimuthal distribution of joints

The statistical distribution of joint strikes observed during dive 68 is shown on Fig. 5. The preci-

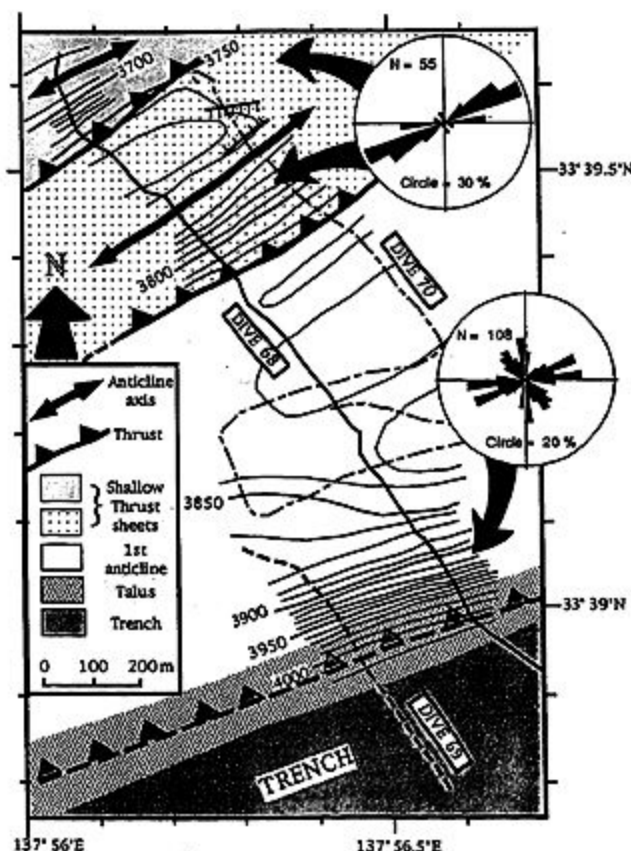


Fig. 5 Synthetic structural map of the "Shinkai" dives area.

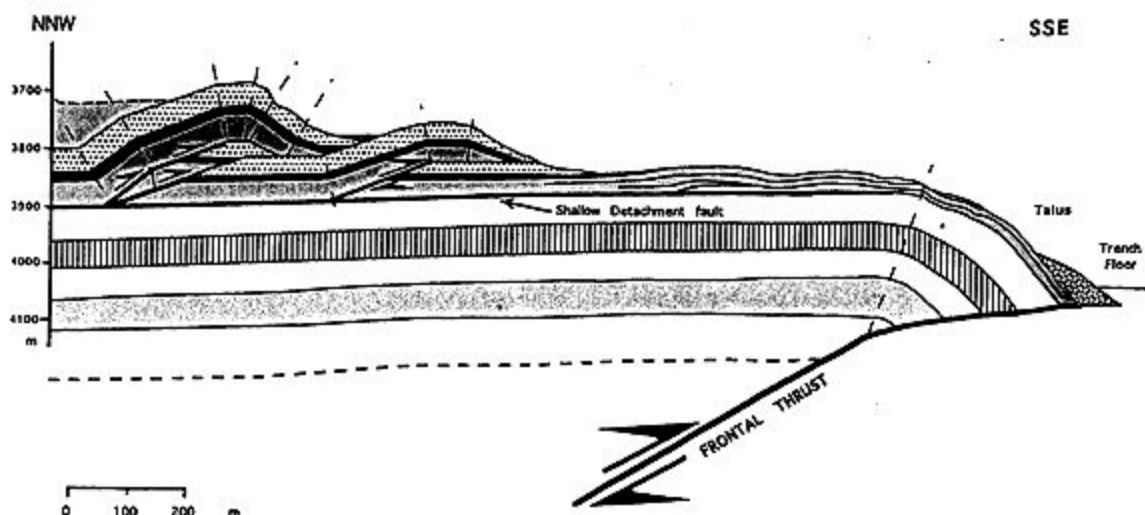


Fig. 6 Balanced cross-section along the track of "Shinkai" dive 68 based on the estimated bedding dips and according to our hypothesis of a shallow detachment fault plane.

sion of the strike determinations from the video images is about ten degrees and we have accordingly used classes of ten degrees. One observation corresponds to the presence of joints of the corresponding class on one outcrop, and thus may correspond to several joints. The reason for this choice is that a direct count of the number of joints would tend to give more weight to thin strata, which have a smaller joint spacing, while strike measurements on the longer joints in thicker strata are usually more precise.

In the lower slope roughly orthogonal jointing is observed. Four families appear to be defined. It is not clear that this is justified or if they should perhaps instead be grouped in just two families (NNE-SSW and ESE-WNW). Of the four possible families families two are strictly orthogonal (N80-90 & N170-180) and the two others are respectively N60-70 and a wider distribution at N120-150.

The direction of slip determined for the Tonankai 1947 earthquake in 1944 is N305°-310° (Kanamori, 1972; Ando, 1975). These authors have assumed that the direction of slip of this very large earthquake is also the direction of plate convergence in the area. Lallemant et al. (1993) determined the dimensionless stress tensor by inversion of slickenlined fault data from ODP site 808. This drill hole is situated on the toe of the Western Nankai

accretionary wedge, and penetrated the frontal thrust and the decollement. There is an excellent agreement between the 308° to 315° direction of convergence computed for this site from different kinematic models and the direction of compression below the frontal thrust which is $310^{\circ} \pm 10^{\circ}$. Assuming this is also the case in the area of the dives, joints of strike N120-150 are compatible with the probable direction of σ_1 in the trench.

In this context, the N80-90 and the N170-180 could be shear joints. However the absence of significant relative movement makes it difficult to distinguish shear joints from tensional joints unless the principal directions of stress can be determined independently from slickenlined faults (e.g. Bergerat et al., 1991).

The strike of the frontal thrust being locally N70, N 60-70 joints could be extensional and related to slope instability of anticlinal folding.

On the upper slope, almost all joint are N50 to 70, parallel to the strike of the upper thrusts and the associated anticlines. This can also be due to a surficial tensional stress. The absence of the orthogonal direction suggests that these sediments do not have the same stress history as those from the lower slope which were deposited in the trench. This is not surprising if the upper unit was deposited later within a piggyback basin.

4. Biological communities and venting activity

Since the first in situ observation of biological communities related to cold seeps on the Oregon accretionary margin (Suess et al., 1985), the occurrence of such cold-seeps benthic biotae have been widely reported in active accretionary margins (e.g. Le Pichon et al., 1987; Faugeres et al., 1987; Le Pichon et al., 1990) as well as in active erosional margins (Cadet et al., 1987; Fiala-Medioni et al., 1992). Quantitative estimates of the fluid outflow through the colonies have been obtained with benthic chambers in the Oregon margin (Carson et al., 1990) or in the eastern Nankai Trough with detailed in-situ temperature gradient measurements (Henry et al., 1992). These studies lead to the conclusion that the benthic communities are the site of focussed upward flow with darcian velocities from 10 to 100m yr⁻¹.

4. 1 Types of colonies

Contrasting with the hydrothermal vents of the mid-oceanic ridges, the cold seeps communities gather several different species of bivalves (e.g. Okutani and Metivier, 1986). In the Eastern Nankai Trough, several types of colonies have been defined on the basis of the sizes and densities of the bivalves (Sibuet et al., 1990; Henry et al., 1992). Bivalves of less than 5cm in length are considered as small, those of length 5-10cm, medium and those of more than 10 cm length large. The benthic communities observed during the "Shinkai 6500" dives 68 to 70 fall into three types. According to Sibuet et al. (1990), the "type A" colonies are large (up to 2m in diameter), very dense (up to 1,000 individuals/m²) colonies with all three sizes of elongated bivalves (clams from genus *Calyptogena*) (from 5cm to 15-25cm); the "type C" colonies are composed of large half buried clams (*Calyptogena*) at low density (30 ind./m²) frequently associated with "white patches" considered to be bacterial mats (Henry et al., 1992) or carbonate deposits (Gamo et al., 1992). Finally, the "type E" colonies have been described as small (less than 50cm diameter) but dense colonies (200 ind./m²) of small rounded bivalves which belong to other members of

the Vesicomidae family (Sibuet et al., 1990). During the three Shinkai dives, many colonies of small individuals were found and labelled "type E", some of it being much denser (up to 1,000 ind./m²) than the standard "type E" defined from Kaiko-Nankai dives. Density is however difficult to estimate as zooms on these colonies show that many individuals are almost completely buried.

The highest flow rates (100m/a) were obtained in type A colonies. However, arguments based on chemistry (Dron et al., 1987) and on temperature and surface heat flow measurements (Henry et al., 1992; Le Pichon et al., 1991) show that fluids flowing through these colonies are mixed with sea-water. On the contrary fluid flowing through white patches and type C colonies have the highest methane content (Gamo et al., 1992), but the flow rates are too low to cause a measurable thermal anomaly. Type E colonies have intermediate flow rates, of the order of 10m/a where measurable. The repartition of the colonies in the Kaiko-Nankai area lead to the following scheme for fluid circulation (Henry et al., 1992). The fluids come into the venting zone along the shallow décollement. A small amount stays fairly concentrated and feed white patches and type E and C clam colonies at its outcrop. The rest of it escapes upward through the sediments and get mixed with sea-water, possibly by convection driven by salinity contrast. It feeds clusters of type A colonies and also type E colonies.

4. 2 Spatial distribution of the benthic communities

No evidence of venting activity has been found in the lower section (below 3,910m) along the forelimb of the anticline related to the frontal thrust. Conversely, vent-related benthic communities are widely distributed in the upper section between 3,860 m and 3,680m. Despite a certain scattering, the colonies are not randomly distributed but tend to cluster (Fig. 7). In both dives 68 and 69, the deepest venting manifestation is of the same kind (a white patch) and appears at the same depth (3,910m) suggesting thus a stratigraphic venting origin. The first clam colonies appear at a slope break at 3,860m

depth. They are small type E colonies, not particularly dense. The biological activity is much more important on the plateau. As on the bench marking the shallow detachment outcrop in the Kaiko-Nankai area, white patches with associated type C colonies are found, as well as type E colonies. However, type E colonies appear to be denser and more spread out. A concentration of these is found at 3,830 to 3,840m depth on the top of the first undulation, close to the edge of the plateau. Two clusters of type A colonies have also been identified further northward on top of the second undulation.

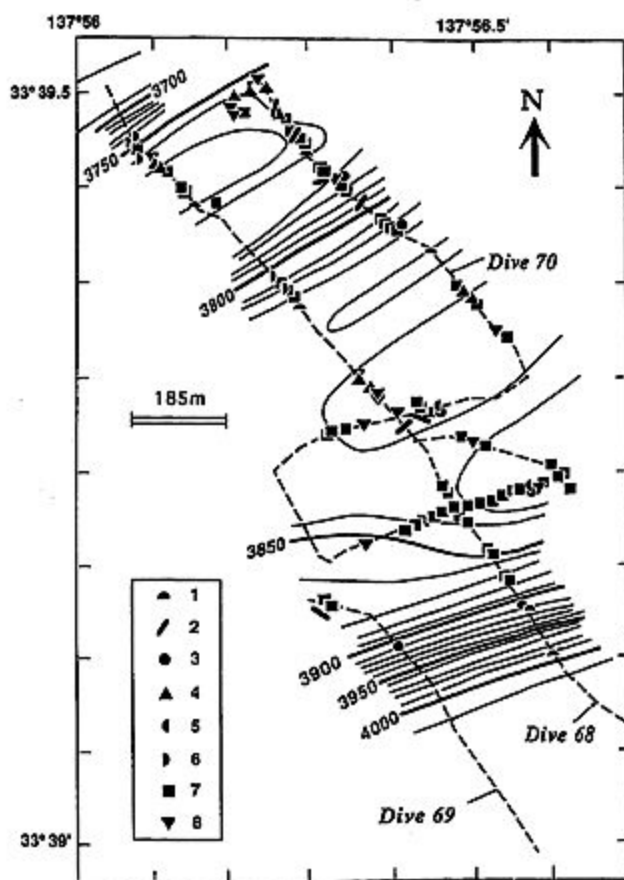


Fig. 7 Biological observations from the "Shinkai 6500" dives at the toe of eastern Nankai accretionary wedge; 1: dead clams; 2: linear clam colony, symbol orientation gives the strike of the colony; 3: white patches (bacterial mats?). Symbols 4 to 8 refers to different types of colonies; 4: type A; 5: type C; 6: type D (= dispersed clams); 7: type E; 8: unknown type. Symbols may represent clusters of colonies. They are representative of whether a particular type of colony is present, but not of the size of the population.

In the Kaiko-Nankai area, all the type A colonies were found on the summital plateau, above 3,790m. The corresponding location in the zone of the "Shinkai" dive would thus be the bench at 3,770m depth, with an important difference: a thrust outcrops there (Fig. 8). Some biological activity (type E colonies and small white patches) is associated with the first of the two upper thrusts. But the most active area appears to be the upper bench. There, dense type E colonies are found in the valley whereas large type A colonies are found near the base of the slope, where the second upper thrust supposedly outcrops. Many of the colonies observed in this area are associated with strata outcrops, suggesting that at least in the last meters of sediment, fluid tends to flow along more permeable strata rather than along faults. The zone of type E activity is wider along dive 70 where outcrops are more frequent. However, dense type E activity is also present in the bottom of the valley along dive 68, indicating that the blanket of recent sediment does not prevent fluid venting.

5. Conclusion

The in-situ tectonic observations made during the "Shinkai 6500" dives 68 to 70 are consistent with the tectonic model proposed by Chamot-Rooke et al. (1992). The repartition of the biological activity confirms that venting is related to the shallow detachment fault. The general pattern is the same in both areas. White patches and colonies of large clams occur only in the deepest section, and closest to the shallow detachment, while the densest and largest *Calyptogena* colonies (type A) form in clusters on flat surfaces, at least 30 meters above the shallow décollement. Type E colonies are found everywhere in the active zone, but tend to be denser and larger near the edge of the plateau and on the upper bench than elsewhere in the Shinkai dive area and than in the Kaiko-Nankai area. Although vent repartition indicates that the shallow detachment channels the fluids into the area, surface venting is only loosely related with the active thrusts, as in the Kaiko-Nankai area. An active band of 100 to 200m must be

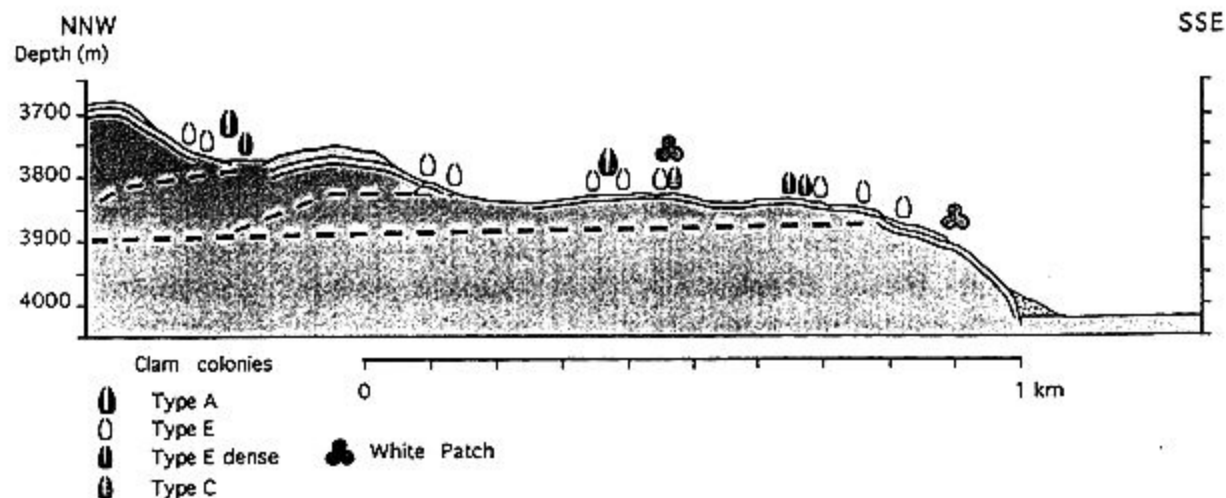


Fig. 8 Interpreted section along the track of the "Shinkai 6500" dive 68 showing the relation between biological observations and structure.

associated with each of the two upper thrusts, and the activity on the plateau could not be related directly with tectonic structures. This implies that faults are able to channel fluid but that they seem to lose this ability when they come closer than about 50m from the surface. Flow then spreads out along permeable strata and escapes through joints.

A possible explanation of this behavior is that the permeability contrast between the sediment and the fault decreases near the surface. It is known that clayey sediment permeability tends to increase near the surface, especially if the surface sediment is poorly consolidated (permeability changes two orders of magnitude between surface and 200m depth in ODP hole 671 at the toe of Barbados wedge; Taylor and Leonard, 1990). On the contrary, fault permeability may not increase near the surface because increase of permeability in faults is generally associated with dilatant behavior, which requires overconsolidated or cemented sediments (Moore et al., 1990).

But the spreading of the fluid flow near the surface can also be explained without assuming a change in the physical properties of either fault or sediment near the surface. If the sediment is heterogeneous enough and cut by fractures or joints, one can assume that clusters of connected conduits of high permeability exist (for example one or two orders of

magnitude higher than the bulk permeability), but that these clusters do not span through the whole system. In such a case, a fault can channel the fluid flow across the system in a sense that it connects the clusters. On approaching the surface, fluids flowing along the fault will invade the first cluster connected to the surface having the same hydraulic conductance as the fault itself and get lost. If this is the case, the distribution of venting sites would simply tell us that the characteristic sizes of this connected cluster is several tens of meters of thickness and 100 or 200m of horizontal spread.

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