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Sediment deformation and fluid activity in the Nankai, Izu-Bonin and Japan forearc slopes and trenches

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A variety of sediment and crustal deformation, associated with fluid activity, has been observed in the present forearc slopes, trenches and ancient onland outcrops in the Japanese island arcs. The Nankai forearc represents a typical clastic-dominated accretionary prism where the expulsion of pore fluids from sediments seems to have occurred intermittently, through both channelized and diffusive mechanisms, some of which appears to be pulsed. Mud diapirs occur within the trench, near the toe and upper slope of the accretionary prism. The widespread development of a gas-hydrate phase boundary (bottom simulating reflector (BSR)) may indicate pervasive fluid advection throughout the prism. The Japan Trench forearc is characterized by tectono-gravity slope instability and collapse, resulting in zones of fluid escape along normal faults. No BSR is observed in the Japan forearc despite the presence of organic-rich sediments. The Izu-Bonin forearc, apparently unlike the Japan and Nankai Trench forearcs, contains recently discovered serpentinite diapirs in which there are blocks of basic-ultrabasic rocks, together with blueschist. Fossil *Calyptogena* beds in the Pliocene basins of the Izu Collision Zone provide good examples of fluid activity associated with venting in an ancient accretionary prism now exposed onland.

Contrasting tectonic processes in the three forearcs may be explained by differences in the plumbing systems and hydrogeologic characteristics of the forearc basements: dewatering sediments in the Nankai Trough prism; impermeable and consolidated sediments in the Japan Trench prism, and the very permeable pillow-lava-volcaniclastic complex of the Izu-Bonin Trench forearc.

1. Introduction

The Japanese arc–trench systems contain the Kuril, Japan, Nankai, Izu-Bonin (Izu-Ogasawara) and Ryukyu trenches (figure 1). Among these, the Japan, Nankai and Izu-Bonin forearc regions have been most intensively studied using a panoply of techniques from shallow and deep seismic profiling, earthquake studies, deep-sea drilling, sampling and submersible dives.

The forearc to the Nankai Trough is associated with the subduction of the Philippine Sea plate. Active sediment accretion and the formation of a classic thrust and fold belt characterizes this region (Nasu *et al.* 1982; Aoki *et al.* 1983; Moore *et al.* 1990). North of the present forearc of southern Japan, the geology charts a long

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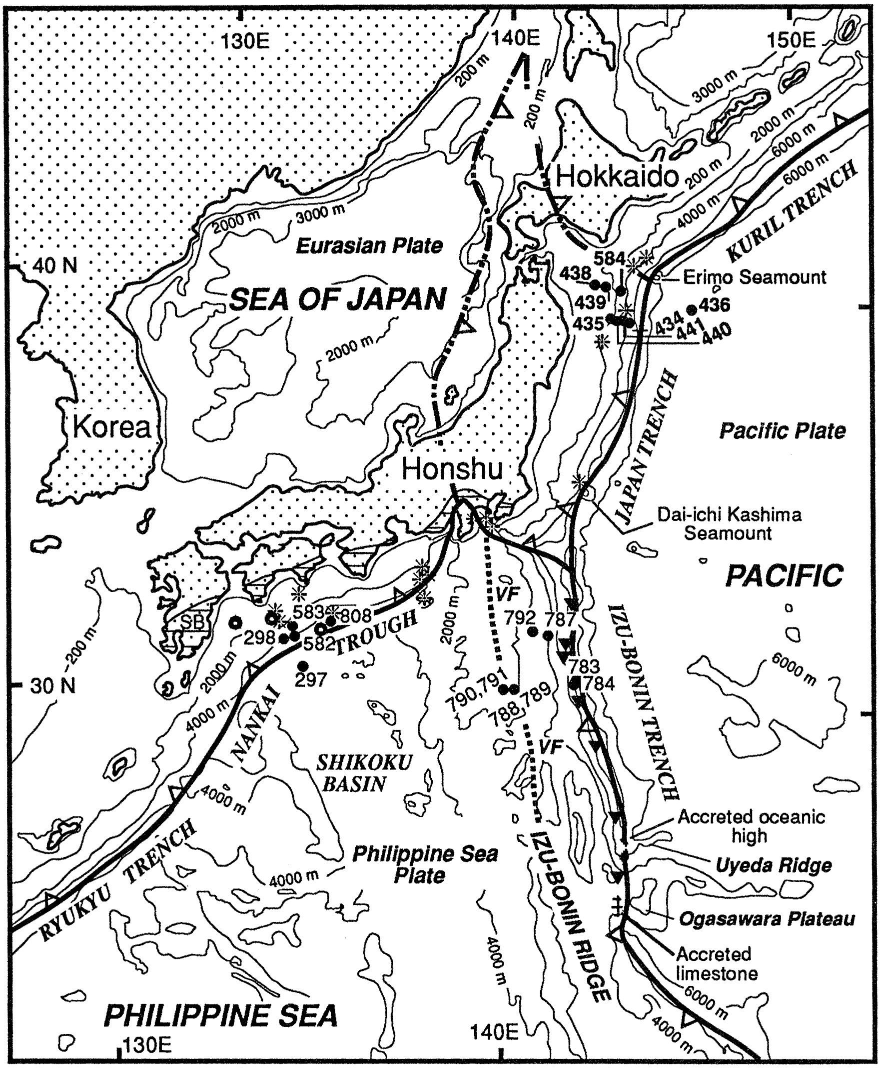

Figure 1. —△—, Japanese subduction zones; —...△..., plate boundaries; ●, IPOD drilling sites (DSDP and ODP); volcanic front of Izu-Bonin Arc (dash line labelled VF); $*$, probable fluid-venting-related biological communities; ▼, serpentinite diapirs; ○, location of selected mud volcanoes referred to in this paper. SB, Shimanto Belt.

history of subduction–accretion, at least since the Late Palaeozoic times (Taira *et al.* 1989).

The Japan Trench is the plate boundary where the Pacific plate is being subducted. The age of the Pacific plate here is about 130–140 Ma and comprises magnetic lineations trending ENE–WSW (Nakanishi *et al.* 1989). The forearc basement is interpreted as mainly Cretaceous accretionary prisms and to the more landward, a Cretaceous forearc basin (Yezo Basin, von Huene *et al.* 1982). The topography of the trench landward slope is characterized by large-scale gravity tectonics, including massive failure of the forearc slope (Cadet *et al.* 1987; von Huene & Culotta 1989).

The forearc to the Izu-Bonin Trench is associated with subduction of the slightly older Pacific plate where the oceanic crust ranges in age from 150–130 Ma (Nakanishi *et al.* 1989). The arc is mainly composed of a Cenozoic volcano–plutonic complex. The trench landward slope is characterized by two discrete slope segments separated by a terrace at water depths of 5–6 km (Honza & Tamaki 1985). Serpentinite diapirism is a prominent feature of this terrace (Fryer *et al.* 1985; Fryer & Fryer 1987).

The collision zone between the mainland southeastern central Japanese, or Honshu, arc and the Izu-Bonin arc records Neogene–Recent uplift and incremental accretion by crustal imbrication (Taira *et al.* 1989). The Neogene accreted material of the ancient Izu-Bonin forearc is exposed in Honshu, immediately north of the arc–arc collision zone. This collisional zone is called the Izu Collision Zone (ICZ).

There are various hydrogeological features associated with the three forearc regions and the ICZ. Although the type, coverage and quality of data from these modern forearc regions differs considerably, we believe that there are now sufficient data to critically review the hydrogeological features in relation to the morpho-tectonic aspects in these forearc regions.

Our approach in this paper is to firstly review the morpho-tectonics of the three forearcs and to describe the important hydrogeological aspects. The distribution of fluid-venting related biological communities and diapiric structures as surface manifestations of fluid flow provide one of the major ingredients in delineating recent to present flow paths. We then provide an overview of the heat flow, location of gas-hydrate (mainly methane-hydrate) related reflectors or bottom simulating reflector (BSR), and deep-sea drilling results as tools for evaluating fluid flow pathways. Finally, we assess the implications for the nature of fluid flow within the forearcs, particularly the accretionary prisms. We aim to show just how pervasive and important such processes are in generating forearc geology.

2. Nankai Trough forearc

(*a*) *Morpho-tectonics*

The Nankai Trough (figure 1) is the topographic expression of the plate boundary between the Philippine Sea plate and the Eurasian plate, with a convergence rate south of the island of Shikoku of about 3–4 cm a^{-1}, estimated by seismic slip data (Seno 1977), and 2–3 cm a^{-1} using geological constraints (Karig & Angevine 1986). The Philippine Sea plate in this region is composed of the Oligocene–Miocene Shikoku Basin (Kobayashi & Nakada 1978; Shih 1980; Chamot-Rooke *et al.* 1987). The Nankai Trough is relatively shallow (4.8 km maximum water depth) and filled by a 1–2 km thick pile of sediments (Le Pichon *et al.* 1987*a*, *b*).

There are basically two layers of sediments subducting below the forearc at the Nankai Trough: an upper turbiditic layer, and a lower hemipelagic stratigraphic succession (Kagami *et al.* 1986; Taira *et al.* 1991). The turbidites in Nankai Trough were supplied mainly from the Suruga Trough drainage area to the east, especially from the Fuji River (Taira & Niitsuma 1986). The sedimentation rate in the turbidite succession reached 2000 m Ma^{-1}, or more, comparable with present rates found in coastal-fluvial deposition around Japan. Taira & Niitsuma (1986) have shown that this enormous sediment flux, mainly from the Fuji River drainage basin to Nankai, occurred because of the arc–arc collision between the Izu-Bonin island arc and the Honshu (mainland Japanese) arc.

The structure of the forearc to the Nankai Trough can be summarized as a trench

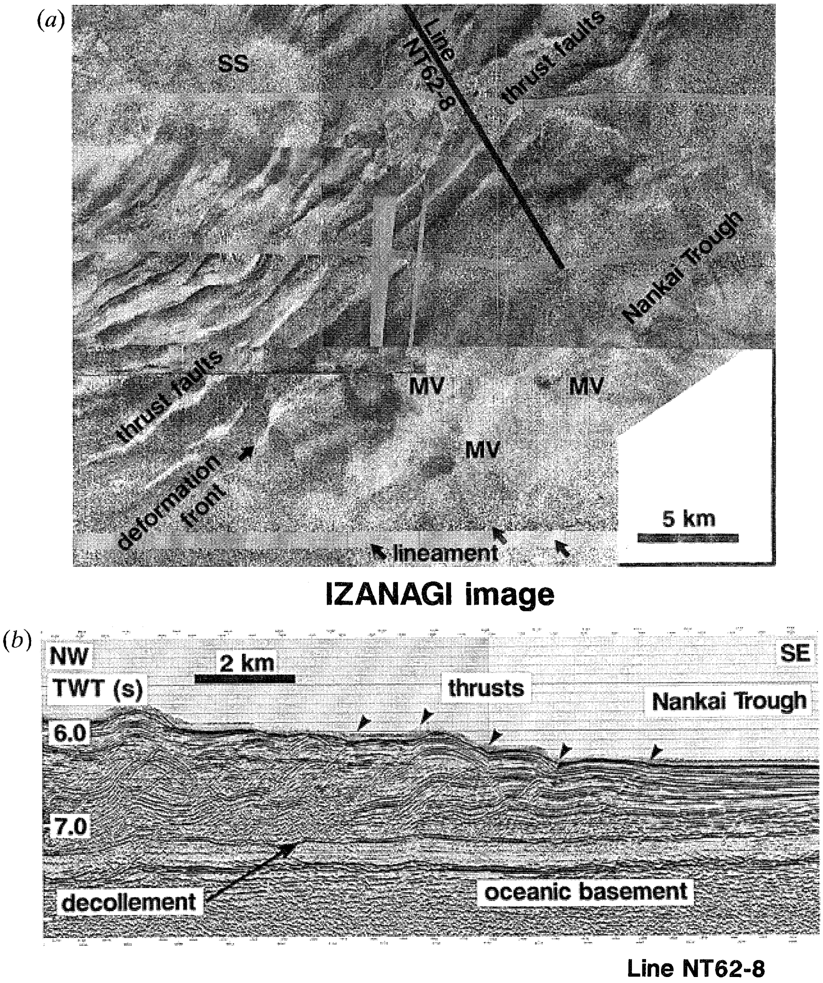

Figure 2. (*a*) IZANAGI sidescan seafloor image of the Nankai forearc near toe of accretionary prism at ODP Leg 131, Site. MV, mud volcano; SS, submarine slide. Lower slope thrusts intersecting seafloor visible. Lineations on outer trench slope. Site survey seismic line marked. (*b*) The seismic line NT62-8 shown in (*a*).

landward slope, comprising an active accretionary prism partly covered by slope basins, a trench-slope break and forearc basins. Deformation of the trench sediments initiates a 'proto-thrust zone', where progressive thickening of the trench wedge can be observed on seismic reflection profiles (Moore *et al.* 1989) as well as core analysis (Karig & Lundberg 1990). In 3.5 kHz sub-bottom profiling records, faults are predominantly high-angle reverse faults with spacing on a scale of about 0.5–1 km and with vertical offsets of 5–20 m.

The frontal thrust zone shows a series of regularly spaced active thrusts spaced at 1–2 km apart (figure 2), and with landward dips that converge to a detachment zone (decollement) which, in some seismic lines, can be traced to about 30 km landward from the trench area (Moore *et al.* 1990). The decollement zone occurs at a particular horizon in the upper Shikoku Basin hemipelagic stratigraphy, but appears unrelated to any obvious lithological change (Taira *et al.* 1991).

Farther landward, the internal image of the accretionary prism is marked by a loss of the typical seismic signal and, instead, the presence of vague landward-dipping reflectors. The decollement seems to change elevation to a lower level and the detachment of the hemipelagic layer from the oceanic basement appears to occur at 4.5 s TWT below the sea floor (Ashi 1991). Normal faults perpendicular, as well as oblique, to the frontal thrust trend begin to develop in this zone, suggesting a possible change in the relative magnitude of the principal stress direction. Taira *et al.* (1988) interpreted this zone to coincide with the transition from frontal accretion to underplating.

Landward of the active accretionary prism, a structural high, the trench-slope break, composed of deformed slope basin sediments and older accretionary prism material, occurs typically at water depths of 0.5–1.5 km. To the arcward side of the trench-slope break, forearc basins are developed with 1–2 km thickness of Neogene sedimentary successions (Okamura 1990), underlain by older accretionary prism material, referred to as the Shimanto Belt (Taira *et al.* 1988).

(*b*) *Hydrogeologic features*

Fluid-venting related biological communities have been observed at several locations along the Nankai forearc through submersible dives, deep-sea photography and dredging. The best studied areas are located in the eastern Nankai Trough where Kaiko and Kaiko–Nankai expeditions revealed the extensive distribution of biological communities (Le Pichon *et al.* 1987*c*). They occur basically in two regions: the frontal part of the accretionary prism, and the upper trench landward slope, and we suggest that both these regions are zones of preferred fluid venting in the accretionary prism.

The frontal part of the accretionary prism seems to be a zone of preferred fluid expulsion (Brown & Westbrook 1988; Moore *et al.* 1988; Moore *et al.* 1990), and they have been interpreted as sites of rapid tectonic dewatering and/or associated with fluid flow from the decollement (Moore *et al.* 1990). Henry *et al.* (1989) showed that the inferred rate of fluid flow associated with the biological communities is large and suggest that fluid venting is rapid (100 m a^{-1}) and transient.

In the upper slope region, several locations are identified as sites of fluid venting, including both the eastern and western Nankai Trough regions (Okamura *et al.* 1986). The presence of biological communities in these regions appears to be associated with zones of active faulting and erosion. As the biological communities generally prefer coarse-grained substrata for growth, wherever turbidity currents and/or deep semi-permanent currents, like the Kuroshio current, have eroded or winnowed out a sandy seafloor, there exists a greater propensity for the establishment of such communities. We also suspect a possible link between gas-hydrate development at many of these sites (see below).

Other evidence for fluid migration in the Nankai forearc has been obtained from the distribution of mud volcanoes revealed by IZANAGI sidescan sonar. The region mapped by IZANAGI sidescan is located in the western Nankai Trough, including the ODP Leg 131 sites (figure 2). Some volcanoes have diameters up to 2 km and relief above the surrounding sea floor of 200 m. The mud volcanoes occur in three areas: (*a*) trench floor adjacent to the toe of the accretionary prism, with an alignment at high angles to the deformation front, interpreted as associated with wrench faults in the prism but controlled by basement structures (Ashi 1991); (*b*) upper trench landward slope, and (*c*) at the base of the landward slope of the forearc basins. The mud volcanoes in the upper slope region occur within a large sediment slide approximately 20 × 30 km. The sediment slide was a consequence of seismo-tsunamigenic thrust faulting in this region of the prism (Ando 1975). The relationship between sediment sliding and mud diapirism remains unclear, but we suggest that many slides are possibly related to the presence of the extensive, shallow, BSR development.

The nature of the fluid pathways within the accretionary prism has been constrained by surface heat flow measurements, the distribution of BSRs, and drilling results from various DSDP and ODP sites.

Studies of the thermal structure of the prism, based on surface heat flow measurements (Kinoshita & Yamano 1985; Yamano *et al.* 1988; Taira *et al.* 1988*b*), and the location of the BSR (Yamano *et al.* 1982; Ashi 1991), indicate that anomalously high heat flow occurs at the toe of the prism which deviates from the predicted trend based on conductive flux of heat from the oceanic crust. In the Nankai prism, the BSR shows several features (Ashi 1991): (1) the seaward limit of the BSR lies near the toe of the prism, generally only a few thrust-sheet packages landward of the frontal thrust; (2) the BSR does not extend through to the undeformed slope-basin successions; (3) the BSR is well developed in the upper slope region extending through the deformed slope and older accretionary prism deposits, and (4) the BSR is not detected in the forearc basins. The common occurrence of the BSR in the accretionary prism also suggests the widespread advection of fluids throughout much of the forearc.

Hyndman *et al.* (1991) proposed a new mechanism for the formation of gas-hydrate in which, essentially, the gas-hydrate forms by the percolation of methane undersaturated fluid, in contrast to previously suggested processes involving generation from a gas-saturated fluid (Miller 1974). The observed distribution of the BSR in the Nankai accretionary prism, undeformed slope basins and forearc basins, suggests that locally the volume of fluid migration has not been substantial enough to form a gas-hydrate layer, due to fast rates of sediment accumulation and/or low permeability.

In the Nankai prism, in the upper slope region there is a well-developed shallow gas-hydrate phase boundary approximately 200 m below the seafloor (mBSF) which, potentially, could be a source for fluid venting. Sediment sliding and faulting in this region may trigger accelerated rates of fluid migration to release trapped fluid beneath the gas-hydrate phase boundary. The distribution of vent-related bio-communities and mud diapirs (volcanoes) in this region may be related to the development of the shallow BSR.

ODP Leg 131 drilling at Site 808 penetrated 1327 m of stratigraphy below the toe of the prism, from the upper 20 m thick slope veneer, through the frontal thrust and decollement, to the *ca.* 15 Ma subducting oceanic basement (figure 3). Shipboard results show no unequivocal mineralogical or geochemical reason for present active, concentrated, fluid flow within the sedimentary column, even at the thrust front and the decollement, the latter being within monotonous hemipelagic sediments of the palaeo-Shikoku Basin, although there is a slightly more carbonate-rich interval from within the decollement (960 mBSF) to about 25 m below (1000 mBSF). There are some geochemical anomalies associated with the decollement, such as a chloride anomaly in the pore fluids (figure 3), but there is no observable mineralization that could be ascribed to channelized or diffusive fluid flow within the prism, for example calcite-filled microstructures. There is, however, a broad low-chloride pore-water zone below 550 mBSF (figure 3). The start of the chloride anomaly appears to coincide exactly

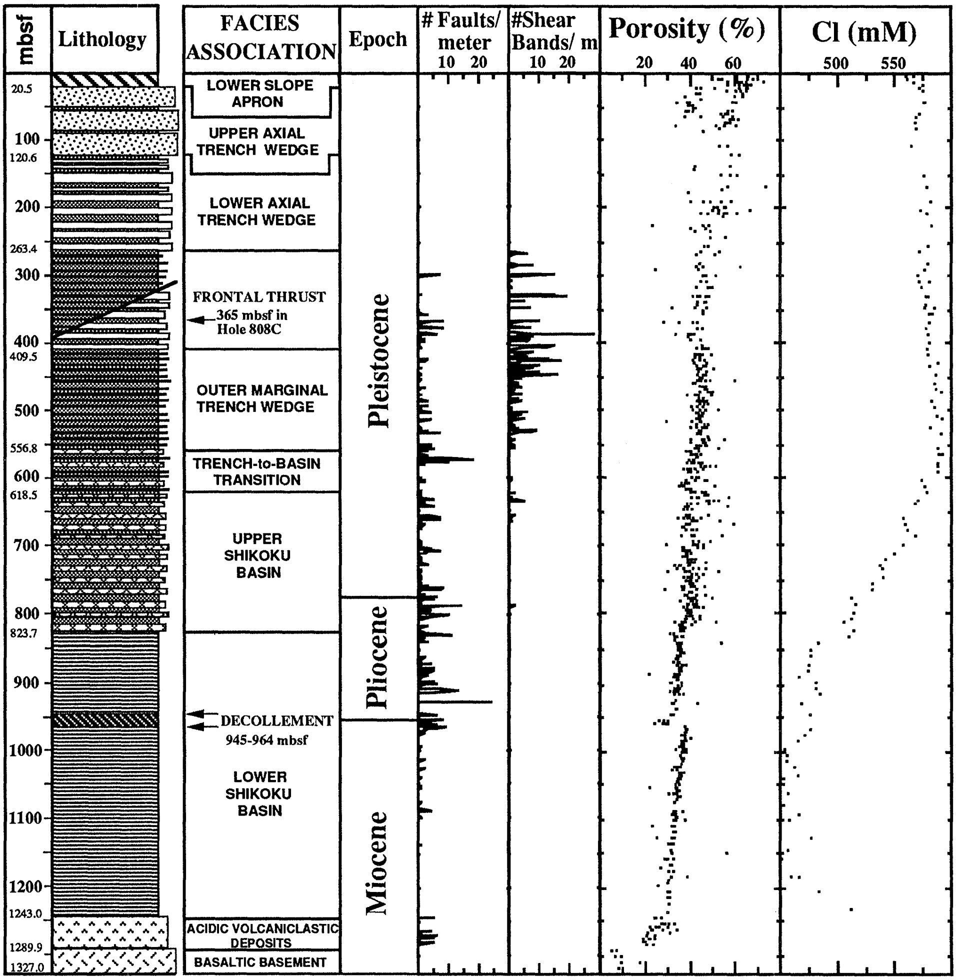

Figure 3. ODP Leg 131 results (from Shipboard Scientific Party, ODP Leg 131, 1990).

with the onset of the illitization of smectite at about 530 mbsf, therefore at least some component of the chloride anomaly could be due to the release of clay mineral bound water during early diagenesis. The overall magnitude of the anomaly, however, would require at least some pulse of deeper fluid flow in the past. Thus the results from ODP Leg 131 contrast with the enhanced methane concentration and low-chloride spike detected in pore fluids from the decollement and fault zone in the Barbados accretionary prism (Moore *et al.* 1988). The origin of the low-chloride fluid remains enigmatic.

There is a sharp contrast in the intensity of deformation above and below the decollement. Sediments above the decollement are intensely deformed, whereas below there is virtually no deformation. The porosity data (figure 3) suggest that the decollement is an overpressured zone separating normally consolidated from underlying underconsolidated muddy sediments. Permissible interpretations of the ODP Leg 131 data-set are: (*a*) fluid flow is pulsed and channelized; or (*b*) there is present channelized fluid flow along the decollement, but the shipboard measurements were unable to detect this and the fluids have not produced any clearly visible mineralization, for reasons that we do not yet understand. In addition, the BSR and the actual presence of an overpressured decollement demand continuous diffusive flow throughout the accretionary prism. The decollement is overpressured and also acts as a seal to inhibit the dewatering of underthrust sediments. The mechanism by which the decollement maintains both the characteristics of an overpressured zone and seal at the same time remains unclear.

3. Japan Trench forearc

(*a*) *Morpho-tectonics*

The Japan Trench (figure 1) is 7–8 km deep and sediment starved, except in the area of the trench triple junction where sediments are supplied from the ICZ (Taira *et al.* 1989). The trench seaward slope is characterized by well-developed half-graben structures on the subducting oceanic plate (Kaiko 1 Research Group 1986; Cadet *et al.* 1987). The trench landward slope is steep, with a mean slope angle of 7°, commonly forming a steeper upper slope with benched topography. From the coastline of the subaerial forearc massif to the trench-slope break at a depth of 2.5 km, there is a broad 150 km wide terrace underlain by a Cenozoic succession (forearc basin, about 2 km thick) (Nasu *et al.* 1979).

Seismic profiles from the forearc basins to the upper trench landward slope are characterized by landward-dipping reflectors which are unconformably overlain by a latest Palaeogene to Neogene sedimentary succession in which normal faults predominate (Nasu *et al.* 1979). IPOD results and industrial drilling showed that the landward-dipping reflectors correlate with Cretaceous sedimentary rocks (von Huene *et al.* 1982) which probably equate with the Yezo-Sorachi Belt of Hokkaido (ophiolitic forearc basin sequence). The seaward portion of the basement rocks below the trench-slope break to trench landward slope region may represent late Cretaceous to early Palaeogene accretionary prism material (Hidaka Belt). The unconformable contact between the sedimentary cover and subjacent landward-dipping reflectors generally cannot be traced seaward beyond the region of the trench landward slope. The lower portion of the trench landward slope is characterized by discontinuous, high-frequency reflections. Below the trench landward slope, a detachment surface (decollement) can be traced for about 15 km landward (Nasu *et al.* 1979). Extensive horst and graben features are developed on the subducting oceanic plate and are partly to completely covered by sediment slides and debris from the trench landward slope (von Huene & Culotta 1989).

IPOD drilling at Sites 438 and 439, from the forearc terrace, recovered a Pleistocene to Lower Miocene sequence of interbedded mudstone, diatomaceous mudstone and siltstone above a succession of sandy turbidities (von Huene *et al.* 1982). Below the latter deposits, Oligocene shallow-marine sandstones and volcanic breccias occur above an unconformity dated at about 40 Ma, and below which there are Cretaceous claystones. DSDP sites in the lower and mid-slope region are dominated by Quaternary to Middle Miocene mudstones, some of which are diatomaceous (von Huene *et al.* 1982).

SeaBeam topographic mapping shows that the trench landward slope of the Japan Trench is dominated by large-scale gravity collapse (Cadet *et al.* 1987*a*). The topography is characterized by steep concave scours, large blocks of slope material and a debris apron on the trench floor. The most spectacular examples are associated with seamount subduction. Near the junction of the Japan and Kuril Trenches, the Cretaceous Erimo Seamount, part of a seamount chain, is approaching the trench axis. The inner trench wall in this area shows signs of seamount indentation and gravity failure (Cadet *et al.* 1987; Fujioka & Taira 1989). A large embayment with enormous scours is observed to the north of the Erimo Seamount. Yamasaki & Okamura (1988) investigated this area further using magnetic anomalies, and suggested that a seamount of about the same size as Erimo Seamount is buried beneath the irregular topography partly created by slope failure. Southeast of Erimo Seamount, the inner wall of the Japan Trench comprises a series of crescent-shaped escarpments, and an intervening hummocky terrain, with lobate topography at the trench. Fujioka & Taira (1989) interpreted these features as the expression of a large submarine landslide complex. The slide, 50 × 40 km, probably resulted from seamount subduction in which oversteepened escarpments eventually collapsed.

One of the principal conclusions from a study of the Japan Trench forearc is that the lower portion of the trench landward slope is mechanically very weak and, therefore, subject to frequent massive gravity failure.

(*b*) *Hydrologic features*

In the Japan Trench forearc, a number of fluid-venting related bio-communities have been observed, mainly consisting of the giant clam *Calyptogena*, suggesting pervasive fluid venting from the inner trench landward slope and forearc terrace.

Observations from submersible dives show that the trench landward slopes comprise highly sheared mudstones and talus breccias forming a step-like topography (Pautot *et al.* 1987; Cadet *et al.* 1987*b*; Kaiko II Research Group 1987; Lallemant 1989). Vent-related bio-communities are commonly located on the coarse-grained talus veneer and on sheared mudstones associated with normal faulting (Fujioka & Taira 1989; Henry *et al.* 1989).

Recently, several specimens of *Calyptogena* and other vent-related clams, have been obtained by beam trawling from the seafloor of the upper terrace in water depths of *ca.* 1730 m. Although there is no direct visual observation, the existence of fluid-seepage has been suggested from the same area (Ohta 1990, personal communication), this area being within part of a canyon system with a large embayment along the margin of a probable large normal fault block on an anticlinal ridge. Inspection of the nearest seismic profiles to this area, *ca.* 50 km to the north and to the south, reveal that the deep-sea terrace at depths of 1500–2000 km generally coincides with an anticlinal ridge in which intensely faulted Miocene–Pliocene sediments are recorded. The origin of the venting fluids remains uncertain.

Mud diapirism has not been identified in the Japan Trench forearc. This is probably due to the lack of suitable sidescan sonar imaging of the area.

Two lines of evidence exist to constrain the internal fluid pathways in the Japan Trench forearc, i.e. heat flow and drilling data There are relatively few heat flow measurements (less than 20) available for the entire Japan Trench forearc (Yamano & Uyeda 1988). It is therefore premature to infer any systematic variation of heat flow in this region unlike in the case of the Nankai Trough forearc. To date, however, the heat flow data suggest: (1) in contrast to the Nankai prism, no heat flow maxima occurs at the toe of the landward slope of the prism, and (2) heat flow values appear much lower than for Nankai, being about 30 mW m^2.

The downhole temperature measurements at IPOD Site 440 revealed non-linear thermal profiles, from which Burch & Langseth (1981) suggested a vertical fluid flux of approximately 1.4 cm a^{-1}. As no further augmentation of data has been made in this area, these data seem to be the only indication of possible fluid advection in the Japan Trench forearc.

There is no gas hydrate related BSR identified in the Japan Trench forearc despite the presence of organic-rich diatomaceous sediments.

Drilling cores from IPOD sites in the forearc basin and upper trench landward slope yielded abundant evidence of small-scale deformation structures, particularly from the diatomaceous mudstones and include post-depositional veins, healed fractures and microfaults (von Huene 1980; Carson *et al.* 1982). Beneath the forearc basin, these small-scale structures occur only at depths greater than 620 m (Miocene) associated with a zone of normal faulting. Beneath the landward slope of the trench, however, they occur at depths shallower than 250 m (Pliocene). Bulk densities in the landward trench sites indicate a zone of over-pressure at *ca.* 200–700 MBSF. Carson *et al.* (1982) interpreted this zone as associated with tectonic dewatering of the underlying sediments and the upward migration of fluids resulting in an excess pressure horizon above. Such advection of fluids should provide favourable conditions for the development of a gas-hydrate phase boundary. No BSR, however, has been detected to date in the Japan Trench forearc. The reasons for this are unclear, but it may be that there is only about 1 km of unconsolidated sediments (above the Cretaceous basement) which may not generate sufficient gas hydrate to replenish any potential incipient hydrate layer. Pressure–temperature conditions may also be inadequate. In the Peru forearc, a BSR is documented from a comparable geotectonic setting to that in the Japan Trench forearc, in an area dominated by large normal faults (von Huene *et al.* 1988). We speculate that the BSR is absent because there is not sufficient pervasive advection of fluids in the Japan Trench forearc compared with many other forearcs. Further detailed study is required to resolve this problem.

4. Izu-Bonin Trench forearc

(*a*) *Morpho-tectonics*

The evolution of the Izu-Bonin arc system started with the initiation of westward subduction of the Pacific Plate in the early–middle-Eocene (Uyeda & Ben-Avraham 1972). An episode of Middle Oligocene to early Miocene rifting and seafloor spreading generated the Shikoku Basin and divided the arc in two, with the present Izu-Bonin arc and the remnant, submerged, Kyushu-Palau Ridge. The present incipient rifting of the Izu-Ogasawara arc commenced in the late Pliocene to early Pleistocene.

The present configuration of the Izu-Bonin arc comprises, from east to west, a 7–9 km deep prominent trench, forearc region including a trench landward slope, an outer-arc high, a volcanic arc, an active backarc rift, and the Shikoku marginal basin (Honza & Tomaki 1985) (figure 1). The forearc basin is filled by volcaniclastic and hemipelagic sediments banked behind the outer-arc high. In the southern part of the Izu-Bonin forearc, the outer-arc high is called the Ogasawara Ridge and includes the Ogasawara Islands where the forearc basement, Eocene volcanics and shallow-marine limestones, are exposed (Hanzawa 1947). Several mature dendritic submarine canyon systems have developed across the Izu-Bonin forearc basins to the trench. These canyons have incised as much as 1.5 km into the surrounding sedimentary successions (Taylor & Smoot 1984). The Izu-Bonin forearc thus shows more canyon-eroded morphology than either the Nankai Trough or Japan Trench forearcs.

The lower trench landward slope of the Izu-Bonin Trench is characterized by the offscraping of an oceanic high. SeaBeam mapping by the hydrographic department of the Japanese Maritime Safety Agency (Iwabuchi *et al.* 1988) of the Uyeda Ridge (Smoot & Heflner 1986), shows a linear, E–W trending, topographic high about 150 km in length, 18 km wide, and with a maximum elevation of 4.2 km, to the north of the Ogasawara Plateau. The ridge is being subducted at the Izu-Bonin Trench where water depths are in excess of 9 km. At the toe of the landward wall, there is a prominent 8 × 4 km high at about 5 km landward from the trench axis. This topographic feature is oblique to the linear and smooth N–S trending cliff line of the trench landward slope. It also shows a continuous magnetic anomaly from the ocean side and no associated gravity anomaly, suggesting that this portion is a continuation of the oceanic crust. Iwabuchi *et al.* (1988) interpreted the linear high as a probable offscraped segment of the Uyeda Ridge at the toe of the inner trench wall.

Part of the Ogasawara Plateau is subducting at the southern Izu-Bonin Trench: a prominent structural high occurs in the toe of the trench landward slope at this boundary, as the rectangular-shaped, 50 × 20 km, Hahajima Seamount, with about 2 km of relief from the surrounding oceanic floor. Dredge samples from this seamount are ultramafics. To the southeast of this seamount, there is a steep, N–S trending, cliff interpreted as the toe of the trench landward slope. At a depth of 3.3 km, which is about 1 km above the trench axis, a deep-tow survey by JAMSTEC (Momma *et al.* 1990) revealed exposures of white-coloured rocks, which upon dredging were shown to include late Cretaceous (Turonian) nannofossil limestones. Micritic limestones of this age have not previously been recorded from the Izu-Bonin forearc, but they are comparable with the limestones that veneer the Ogasawara Plateau. It seems likely that at least part of this steep trench landward slope may comprise accreted Ogasawara Plateau crust.

The above evidence leads us to speculate that at least part of the forearc crust to the Izu-Bonin arc consists of accreted oceanic material from the Pacific plate. This, then, suggests different types of accretionary processes operate in the Izu-Bonin Trench forearc compared to the Nankai Trough and Japan Trench forearcs.

(*b*) *Hydrogeologic features*

On the mid-slope bench of the trench landward slope of the Izu-Bonin Trench to the Mariana Trench, there are a number of serpentinite seamounts ranging from 5 km to more than 20 km in diameter, and from several hundred to more than 1400 m in height (Ishii 1985). These seamounts are spaced at intervals of 15–60 km along the bench situated less than 50 km from the trench axis.

Two sites on ODP Leg 125 were drilled on the forearc seamounts within the Izu-Bonin forearc (Torishima Seamount), and three sites into Conical Seamount in the Mariana forearc. Primary mantle material was recovered as predominantly highly depleted, tectonized, harzburgite which has experienced medium-grade metamorphism. The associated fluids contain significant amounts of hydrocarbons, with methane concentrations of up to 400 $\mu l\ l^{-1}$ of sediments.

One of the major findings from ODP Leg 125 is the recovery of blueschist facies metamorphic rocks from the Conical Seamount of the Mariana Trench (Maekawa *et al.* 1991). Conical Seamount is situated about 30 km above the subducting slab, and the blueschist metamorphism probably occurred at *ca.* 150–250 °C and 4–6 kbar (0.4–0.6 GPa) (13–18 km deep).

An *Alvin* diving survey revealed the presence of chemical chimneys associated with fluid venting (Fryer *et al.* 1990). These chimneys are made of carbonate, calcite and aragonite, together with silicate (a new Mg-silicate) (Haggerty 1985). Fryer *et al.* (1990) considered that a biogenic source in the Mariana forearc is unlikely to have been responsible for producing these chimneys. Instead, they suggest that methane was generated at depth beneath the forearc wedge, possibly by the interaction between mantle material and water from the subducting slab, including both sediment-hosted water and slab-hosted water.

Thermally, the forearc region is characterized by an arcward increasing trend in heat flow ranging from 20 to 100 mW m^{-2}. Heat flow values greater than 50 mW m^{-2} pose a problem in accounting for the thermal structure of the forearc region: the forearc temperatures become too high at the appropriate depths for generating blueschist metamorphism. Although the heat flow measurements from the Izu-Bonin forearc are rather few in number to satisfactorily resolve this paradox, we discuss some possible solutions in a later section of this paper.

ODP Legs 125 and 126 (Fryer *et al.* 1990; Taylor *et al.* 1990) encountered abundant dark vein-like structures in the sediments, typically 3–5 cm long, subvertical to bedding, in some cases S-shaped, and with bifurcating terminations. Sediment dykes and other fluidization structures were also reported from the forearc sediments. Some vein structure occurs at depths of less than 50 m below the seafloor, suggesting a phase of early fluid migration. Recently, Kimura *et al.* (1989) documented vein structure farther south from within 50 cm of the seafloor, in unconsolidated volcaniclastic muds, near the junction of the Mariana and Yap Trenches. The vein structure occurs widely throughout the accreted forearc sediments exposed in onland sections. The role of vein structure in fluid migration and expulsion is not yet fully understood, but their abundance suggests that vein structure may be an important indication of early porosity reduction processes within some forearcs. Vein structure is discussed further in a later section.

5. Fluid activity in the arc-arc Izu Collision Zone

The Izu Collision Zone (ICZ) encompasses the region of Neogene-Recent arc-arc collision between the mainland Japanese, or Honshu, arc and the Izu-Bonin island arc immediately west of the trench–trench–trench triple junction off SE Japan (figure 4). The present collision boundary extends from west to east through the Suruga Trough, below Mt Fuji, and through Sagami Trough to the triple junction area.

Reconstructing plate boundaries around the ICZ suggests that accretion of successive segments of the Izu-Bonin (Izu-Ogasawara) arc crust has occurred by crustal delamination and incremental accretion (Taira *et al.* 1989; Soh *et al.* 1991).

The Miura Group (Eto *et al.* 1987) ranges from late Miocene–Pliocene (10–3 Ma) and comprises deep shelf to basinal sediments, mainly as scoriaceous to pumiceous volcaniclastics derived from the Izu-Bonin arc. These sediments, now exposed onland, represent part of the Neogene accretionary complex resulting from arc–arc collision in the ICZ. The sediments accumulated in relatively short-lived foreland basins, filled by overall coarsening and shallowing upward sequences developed along the major basin-bounding thrust faults. The basin fills tend to become younger in age from north to south, interpreted as a consequence of the incremental migration of the plate boundary caused by the incorporation of segments of the Izu-Bonin arc onto the Honshu arc (Taira *et al.* 1988).

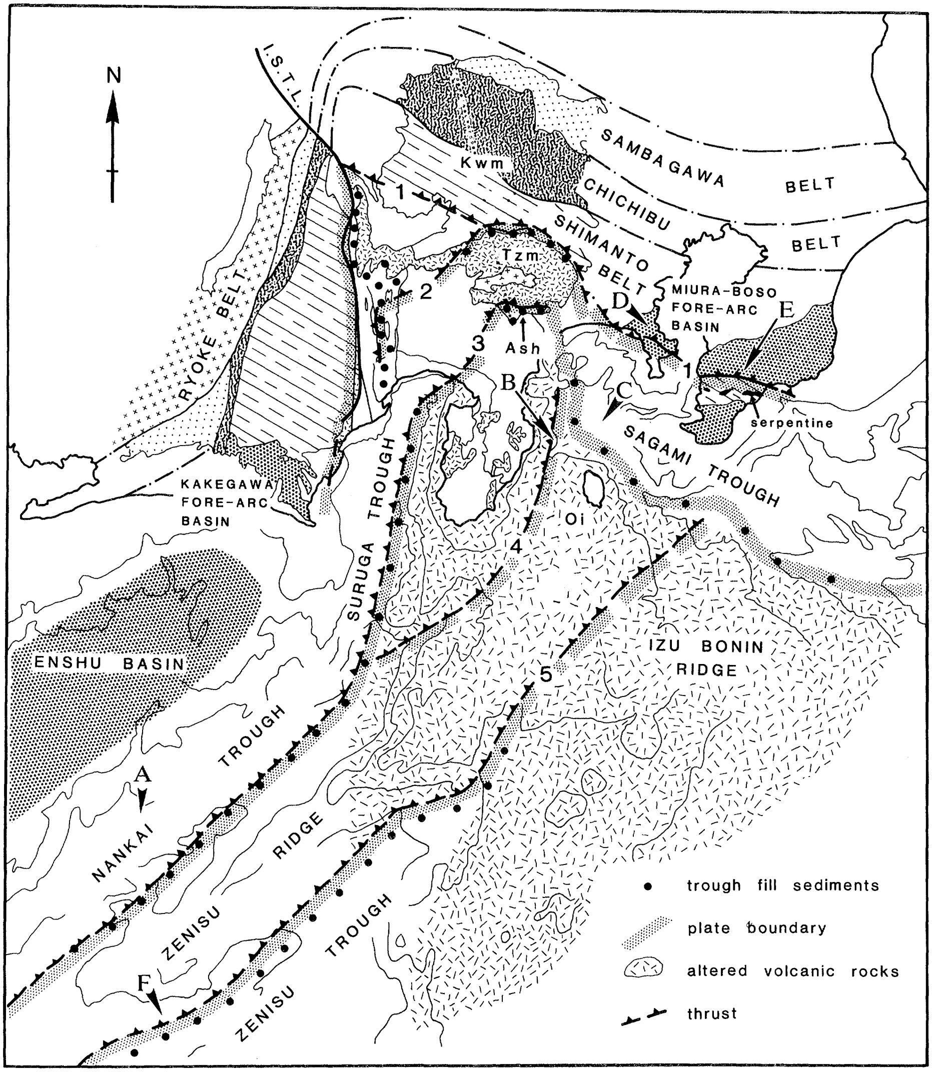

Figure 4. Tectonic framework of the Izu collision zone and location of related seep communities. A, Tenryu Community; B, Hatsushima Community; C, Okinoyama Community; D, Ikego Formation; E, Kurotaki Formation; F, Community at the Zenisu Ridge. Arrow to bottom-right is the direction of plate motion. Nos 1–5 refer to successive plate boundaries caused by the incremental accretion of Izu-Bonin are segments; 4 and 5 are incipient plate boundaries. Oi, Oshima Islands.

The main purpose of introducing the ICZ here is to discuss recent offshore fluid venting along the Sagami Trough and fossil fluid activity in the Miura Group.

(*a*) *Fluid venting in the Sagami Trough*

In the Sagami Trough, a collisional plate boundary between the forearc segment of the Izu-Bonin arc and Honshu arc, several fluid-vent-related bio-communities have been identified (figure 4) (Ishii *et al.* 1988; Hashimoto *et al.* 1989). The bio-communities occur in three tectonic zones: (1) Hatsushima zone of the Izu Bonin arc; (2) along the frontal thrust of the accretionary prism (Sagami accretionary prism) in

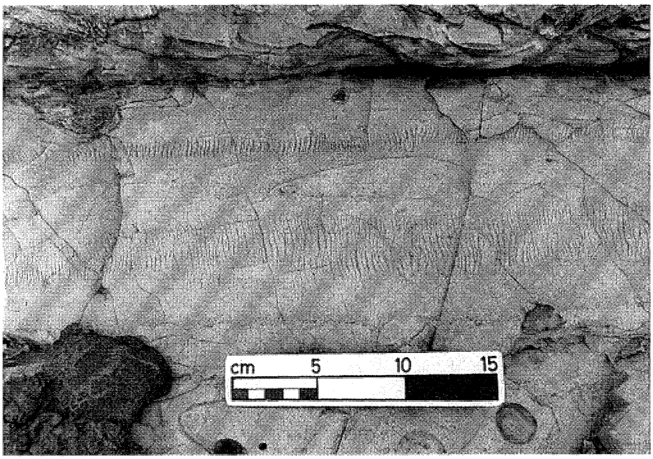

Figure 5. Vein structure, Miocene–Pliocene Misaki Formation, Miura Peninsula, SE Japan. These structures represent the earliest post-depositional expression of pore-fluid activity which generates a systematic fabric in muddy lithologies.

which the forearc sediments of the Izu-Bonin arc and trough-fill sediments have been accreted, and (3) the landward margin of the mid-slope terrace and head of submarine canyons.

The Hatsushima fluid-venting zone is situated along the base of the N–S trending fault scarp to the east of Izu peninsula. Submersible dives have located dense populations of *Calyptogena* communities (Hashimoto *et al.* 1989), and by the remote operating vehicle *Dolphine* 3K (Hattori 1989). Kinoshita & Yamano (1990) measured very high heat flow, up to more than 190 mW m^{-2}, and showed that these values occur close to the volcanic front, and suggests that this unique area is a fluid venting site. Furthermore, this data shows that volcanic heat sources must influence fluid circulation.

The fluid-venting-related bio-communities in the Sagami accretionary prism provide an important comparison with the Nankai accretionary prism farther west. In both prism sites, fluid venting is apparently related to: (1) thrust faults and the hinge regions of anticlines, and (2) canyon systems, again probably linked to tectonic features. In the Sagami Trough, the two fluid-venting sites are located either on anticlinal ridges or along thrust faults, both constituting the wall of a submarine canyon. This setting is similar to ones found in the Kaiko–Nankai sites. Dredge samples from the mid-slope show clam colonies on a thrust fault eroded by a submarine canyon. These morpho-tectonic settings indicate that fluid venting is currently taking place along active thrust faults in the Sagami Trough.

(*b*) *Fossil fluid activity in the Miura Group, SE Japan*

Evidence for fluid activity in the Miocene–Pliocene Miura Group, SE Japan, is grouped into two different types: (1) fossil *Calyptogena* beds in comparable tectonic positions compared to those from the present Sagami Trough, and (2) vein structures, sediment injections and related phenomena in the palaeo-Izu-Bonin forearc sediments developed prior to, and during, accretion of the ‘Miura block’ onto the Honshu arc.

On Miura peninsula, the deep-marine volcanic sandstones and conglomerates of the Ikego Formation, deposited in upper bathyal depths (inferred from benthic foraminifera), contains a giant clam colony of *Calyptogena* (Niitsuma *et al.* 1989). Our onland fieldwork indicates localized concentration of these clams, many of which are preserved in life position, suggesting their preservation close to fossil fluid-venting sites. Abundant evidence of sediment dykes and injection-related brecciation, suggests the possibility of high pore-pressure within the dewatering and lithifying sedimentary pile. Locally, there is extensive cementation, some of which developed in the shape of circular conduits and chimneys, reminiscent of the modern fluid-venting chimneys found in the Japanese forearcs. Calcite cements obtained from the shell-bearing volcanic conglomerates, within the Ikego Formation, have extremely light carbon isotopic ratios ($\delta^{13}C = -19.7‰ - 49.2‰$), suggesting an origin from biogenic methane due to fluid seepage. Detailed mapping shows that the *Calyptogena* colony in the Ikego Formation probably formed on fault-related talus (chaotic) deposits along a canyon wall trending NNW–SSE. The reconstructed sedimentary environment suggests that this onland ancient setting is similar to the mid-slope site in the Sagami accretionary prism.

Vein structure is abundant in the Miura Group (figure 5). The vein structure is generally restricted to layer-parallel zones 1–10 cm thick, in which individual veins are approximately equidistant, ranging from 1–30 mm apart (Pickering *et al.* 1990). They tend to be planar and typically up to 0.1–2.0 mm in width in the central parts. There are, however, several generations of vein structure, with later sets tending to be larger and more widely spaced, even with sigmoidal geometries.

In general, the vein structure in the Miura Group predates virtually all of the faulting, although there are a few rare cases where the vein structure may cut layer-parallel thrusts, which may also be very early structures. Vein structure occurs within blocks of sediment caught up in early, chaotic, sediment slide deposits. Our unpublished X-ray tomographic analysis of such vein structure suggests that the veins apparently contain more dense interiors than the surrounding material and host sediments, indicating that they represent a porosity reduction. Such data suggest that the vein structure formed early in the deformational history of the dewatering sediments, and probably at rather shallow depths of burial.

Vein structure has been recognized from various forearc trench-slope settings from DSDP and ODP sites (see summary by Lundberg & Moore 1986). Recently, Kimura (1989) documented vein structure from within a few metres of the seafloor in unconsolidated volcaniclastic muds near the junction of the Mariana and Yap Trenches. Drilling in the Mariana and Izu-Bonin forearcs also revealed the shallow occurrence of vein structure, from within 100 MBSF (Fryer *et al.* 1990; Taylor *et al.* 1990).

There have been many interpretations of vein structure (Knipe 1986; Lundberg & Moore 1986). Cowan (1982), who was the first to describe vein structure from the Middle American Trench, interpreted it as extensional fractures. Knipe (1986) interpreted the structure as forming in response to gravity-induced downslope failure of sediment. Knipe (1986) also noted the possibility that veins may develop or be modified to a sigmoidal geometry as a result of shear parallel to bedding in unconsolidated slope sediments (cf. Kimura *et al.* 1989). Pickering *et al.* (1990) interpreted vein structure in the Miura Group as forming in an extensional setting under gravity-controlled creep processes.

The evidence for a porosity reduction within the vein structures suggests that they provided effective and pervasive fluid expulsion conduits. Although the overall significance of vein structure in the consolidation history of forearc sediments

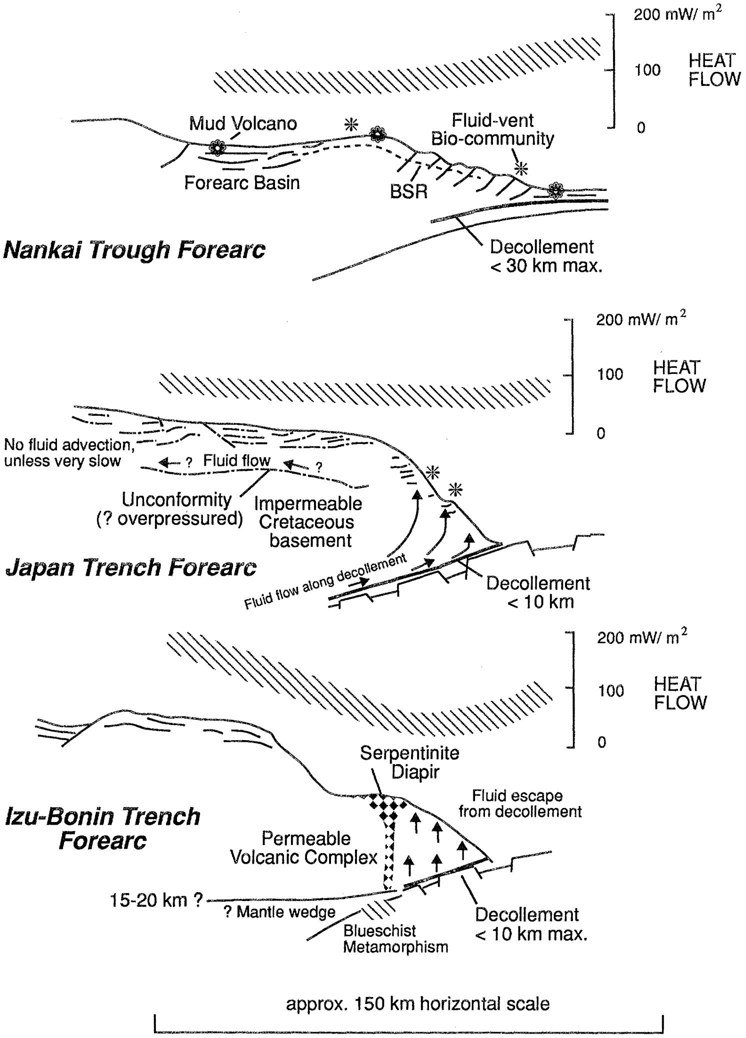

Figure 6. Synthesis of forearc structure and hydrogeologic features in the Nankai, Japan and Izu-Bonin Trench forearcs. Schematic only.

remains uncertain, their abundance and orientation within the Miura Group suggests that they acted as important local conduits for fluid flow in certain finer-grained lithologies.

7. Discussion

The three forearc regions described in this paper show a wide variety of tectonic style and fluid activity which is summarized in figure 6 and table 1. The three fundamental questions to address are: (1) the source of the various fluids in forearcs; (2) the hydrogeologic framework and fluid pathways (mechanisms of fluid migration, circulation patterns, fluid fluxes, etc.), and (3) the relationships between tectonics, diagenesis-metamorphism and fluid circulation. Although we stand a considerable distance away from solving all these problems, we can assess at least some of the important implications bearing on these problems from the available data.

Table 1. *Comparison of morpho-tectonics and hydrogeology*

	Nankai	Japan	Izu-Bonin
trench sediments and tectonics (subduction rate)	1–2 km thick turbididites and hemipelagites, no horst and graben on outer swell (3 cm a^{-1})	500 m pelagites and hemipelagites, horst and graben (10 cm a^{-1})	500 m thick pelagites and ashes, horst and graben (6 cm a^{-1})
shape of trench landward slope	single slope or gentle lower slope and steep upper slope	very steep lower slope and gentle upper slope	steep lower slope and gentle upper slope
tectonics of trench landward slope	sediment accretion	gravity failure	partial accretion of oceanic highs
forearc rocks	accretionary prism (mostly turbidites and hemipelagites)	Cretaceous sedimentary rocks overlain by Cenozoic sequence	Eo–Oligocene volcanic complex overlain by Neogene volcaniclastics
vent-related biological communities	occur at the toe region and upper slope	occur at the lower trench landward slope and trench-slope break	not known
diapiric features	mud volcanoes at the toe region, upper slope and forearc basin	not known	serpentinite diapirs at the mid-slope bench
bottom simulating reflectors	well developed in the trench landward slope	no development	no development
heat flow	landward decrease (200–500 mW m^{-2}) high at the toe	uniform (20–50 mW m^{-2})	landward increase (20–80 mW m^{-2})
vein structure	not known	present	present
hydrogeologic interpretation	concentrated flow at the toe and upper slope; slow advection in entire prism; overpressured decollement	overpressured decollement with forward fluid flow; overpressured lower slope	less overpressured decollement; slow advection through forearc basement; migration of deep-seated fluids through serpentinite diapir

(*a*) *Fluid sources*

In subduction settings, fluid sources include the subducting slab and sediments, accreted and subcreted sediments, cover sequences, basement magma-related fluids and meteoric water. At present, we cannot quantify the relative amounts of fluid generated by these sources at different levels in the forearcs. The following discussion of fluid sources, therefore, tends to be related to the amounts of sediments being subducted.

It is possible to estimate the volume of sediments that are incorporated into the subduction zone in the three forearc regions discussed in this paper. The parameters used are: (1) the thickness of sediments incorporated into the subduction zone, and (2) the rate of subduction. In the Nankai forearc, the mean thickness of sediments is about 1000 m, including trench wedge and hemipelagites. The rate of subduction off Shikoku is about 3 cm a^{-1}. In the Japan Trench, the estimate is not so simple due to the development of horst and graben structure. We estimate a mean vertical displacement of graben blocks of about 300 m, based on seismic profiles (Kaiko I Research Group 1986). The thickness of the pelagic and hemipelagic cover on the Pacific seafloor is about 600 m. Because the horsts and grabens are about equally developed, the mean thickness of sediments subducted is *ca.* 750 m, assuming that the graben are filled by debris at the trench. The subduction rate is *ca.* 10 cm a^{-1}. In the Izu-Bonin forearc, the sediment thickness on the oceanic crust is about 400 m. The mean displacement of normal fault is similar to those in the Japan Trench, i.e. *ca.* 300 m. This gives a mean sediment thickness of 550 m of sediment that potentially can be subducted. The subduction rate is 6 cm a^{-1}. These estimates, although they are first approximations and ignore the porosity variations, suggest that the annual rate of sediment being subducted in the three forearcs, expressed in cubic metres per metre width are as follows:

Nankai: 30 m^3, *Japan*: 75 m^3, *Izu-Bonin*: 33 m^3.

These values show that the volumes are the same order of magnitude in the three forearcs: the greater value for the Japan Trench forearc possibly indicates that it receives more water than the other forearcs. The sediment volumes involved in the Japan Trench and Izu-Bonin Trench forearcs, where sediments are subducted directly underneath the trench landward slope without frontal accretion, are roughly comparable with, or probably larger than, that for the Nankai accretionary prism in which frontal accretion is a major process. These contrasting accretionary processes of predominantly frontal accretion (Nankai) and subcretion (Japan and Izu-Bonin) should provide very different mechanisms for sediment dewatering and fluid migration paths.

One of the very important sources of fluids in the accretionary complex is the release of loosely, and more tightly, bound structural water from sediments, especially clay minerals, during compaction and early diagenesis. The general decrease in porosity with depth, as seen in ODP Leg 131 Site 808 (figure 3), provides an indication of the volumes of trapped seawater that are released during the early phases of compaction when primary porosity is lost. The illitization of smectites, for example, will release relatively large volumes of low-chloride fluids. In ODP Leg 131 Site 808 near the toe of the Nankai accretionary prism, the decollement is at a temperature of about 110 °C, which is well within the smectite–illite transformation field, therefore a component of the low-chloride anomaly probably owes its origin to this early diagenetic mineralogical change, from about 530 MBSF.

Among the possible fluid sources, geochemical data suggest that magma-related fluids are probably relatively insignificant in the case of the Japanese forearcs. An input from meteoric water may be important, as for example is the case in the Peru margin, but little is known of its significance in the Japanese forearcs.

(b) *Fluid Pathways*

The Japanese forearcs and trenches exhibit considerable evidence for diffusive and channelized, focused, fluid flow and venting. There are three different modes of fluid migration in forearcs: (1) diffusive advection through porous media; (2) channelized flow in some permeable conduits, and (3) migration of fluids related to host material transfer such as diaprism. Again, the relative importance of these mechanisms and temporal nature (transient against steady-state), remains unclear in the three forearcs. We suggest that the fluid pathways will, to a large extent, be controlled by the nature of the forearc basement and the volume of subducted sediments.

Probably, the best evidence for diffusive fluid flow is the presence of a BSR. The widespread distribution of a BSR in the Nankai Trough forearc suggests that fluid migration occurs throughout most of the landward trench slope region. The absence of a BSR in the Japan and Izu-Bonin Trench forearcs does not preclude fluid migration throughout the landward slope. However, we suggest the possibility of very different fluid circulation patterns in the lower landward slope region of the Japan and Izu-Bonin forearcs.

The Japan Trench forearc is underlain by Cretaceous accretionary prism and forearc sediments. The outcrops of equivalent rocks in Hokkaido suggests that the concealed prism is composed of highly consolidated and impermeable rocks, mainly of deformed flysch deposits. Such strata may act as an impermeable seal on any subducted water-rich sediments: the reason why there is no BSR in the Japan Trench forearc may be a consequence of insufficient water being supplied to the overlying sediments to cause pervasive fluid advection. As pointed out by von Huene & Culotta (1989), the existence of a long and continuous seismic image of the decollement in the Japan Trench forearc suggests an overpressured zone. Thus, the decollement with an upper seal, should be a conduit for fluid flow. As there is insufficient material to accrete above the decollement, no internal deformation related to accretion occurs. Instead, the forward migration of fluids should produce an overpressured toe in the lower landward slope. This may be the reason why the lower trench slope is so weak in the Japan Trench prism, which is subject to repeated sediment mass failure.

In the Izu-Bonin arc, the basement of the trench landward slope is mainly composed of Eocene–Oligocene volcanic rocks, including volcaniclastics, hyaloclastic breccias, and pillow and sheet lavas (Taylor *et al.* 1990); locally, there is accreted oceanic material. We believe that the Izu-Bonin forearc has essentially achieved a steady state, with neither voluminous accretion nor major gravity tectonics to modify the volume of the forearc. Furthermore, it is reasonable to assume that the Izu-Bonin forearc basement comprises very permeable materials. In such a setting, subducted sediments would be expected to dewater rapidly. We therefore speculate that in the Izu-Bonin forearc, a water-saturated decollement is even less likely to develop than in the Japan Trench forearc. As material in the Izu-Bonin forearc is generally permeable, massive sediment failure, as slides, is uncommon. A corollary of these arguments is that the decollement in the Izu-Bonin forearc has a greater frictional resistance compared with that in the Nankai and Japan Trench forearcs. The absence of a BSR in the Izu-Bonin forearc may be due to lithologic control: organic-poor volcaniclastic rocks, which may explain why the accretion of an oceanic high is taking place at the Izu-Bonin forearc.

(*c*) *Implications for forearc seismicity and thermal structure*

The foregoing discussion leads to two broad implications for the deeper seismicity and thermal conditions in the forearcs.

It is a striking feature of subduction zones in general that there is virtually no seismic activity along the subduction zone to depths of 20–30 km (Yoshii 1979; Fukao 1979). Such seismically quiet zones suggest that the zone is subject to smaller frictional effects due to the presence of fluids (Shimamoto 1985). As suggested earlier in this paper, the amount of subducted fluids may, at least in part, be a function of the rate of dewatering at the shallow part of the prism, at depths of about 5 km. The linkage between shallow dewatering processes and the availability of fluids from greater depths is unclear. It is therefore important to investigate the width and depth of the aseismic slip zone in relation to the shallow level processes operating towards the toe region of a prism. Very little data is currently available on this topic.

Reck (1987) pointed out that heat flow in the Japan Trench forearc is apparently too high to produce blueschist metamorphism at depth. He suggested that the high heat flux in the forearc is a manifestation of extensive fluid migration to the surface.

The calculated temperature at a depth of 30 km in the three forearc case studies is: 600 °C in Nankai, 300 °C in the Japan Trench forearc, and 700 °C in the Izu-Bonin forearc (Uyeda *et al.*, unpublished data). Although the surface heat flow measurements in the forearcs are too few to make any conclusive statement, these temperatures suggest that Reck's hypothesis may be valid. The recent recovery of blueschist from the Izu-Bonin forearc suggests that blueschist metamorphism is probably taking place at depth. The Izu-Bonin forearc, therefore, could provide a unique opportunity to investigate the role of fluid migration linked to blueschist metamorphism, i.e. the question of the depths from which fluid migration in the forearc can affect the thermal structure of the subduction zone. To date, the temperature of subduction zones is primary determined by the age of oceanic lithosphere and calculations of shear heating along the slip zones, whereas the energy transfer by fluid flux has not been fully evaluated.

8. Conclusions

In this paper, we have stressed the pervasiveness of fluid activity in the Nankai Trough, Japan and Izu-Bonin Trench forearcs, and shown that the fluid flux can play an important role in shallow to deep level tectonics, and the thermal structure of the forearc regions. We have reviewed a variety of fluid activity in three, morpho-tectonically, contrasting forearcs.

The main morpho-tectonic characteristics of the Nankai Trough, Japan Trench, and Izu-Bonin Trench forearcs are:

1. The Nankai Trough forearc is an accretionary system dominated by frontal accretion, and with a long history of development as a fold-thrust belt.
2. The Japan Trench forearc is predominantly erosional, mainly by slope failure and sliding, and has a pronounced subsidence history. The basement of the trench landward slope is composed of Cretaceous consolidated sediments.
3. The Izu-Bonin Trench forearc appears to be more stable than the other two forearcs, with evidence of local oceanic crustal accretion. The basement is composed of an older lava-volcaniclastic complex.

We suggest that the fluid pathways and permeability variations within these three forearcs are quite different. In the Nankai forearc, concentrated fluid expulsion occurs at the toe of the prism and upper trench landward slope; the rest of the prism is dominated by slow fluid advection as sediments gradually dewater. In the Japan Trench forearc, concentrated fluid flows occur in relation to normal faulting, and there appears to be no pervasive advection from depth. The decollement could be water-saturated and subject to relatively lower frictional forces. The forward migration of fluids along the decollement produces overpressuring at the lower trench landward slope, which triggers massive sediment failure. In the Izu-Bonin forearc, slow fluid advection may occur throughout the permeable forearc basement. The decollement, however, may not be water-saturated. The rapid loss of water from the decollement, through permeable arc-basement, could explain the reason for the accretion of oceanic highs in the Izu-Bonin forearc, and also provide an explanation for the relatively steep lower trench landward slope, assuming the Coulomb wedge model (Davis *et al.* 1983) is applicable.

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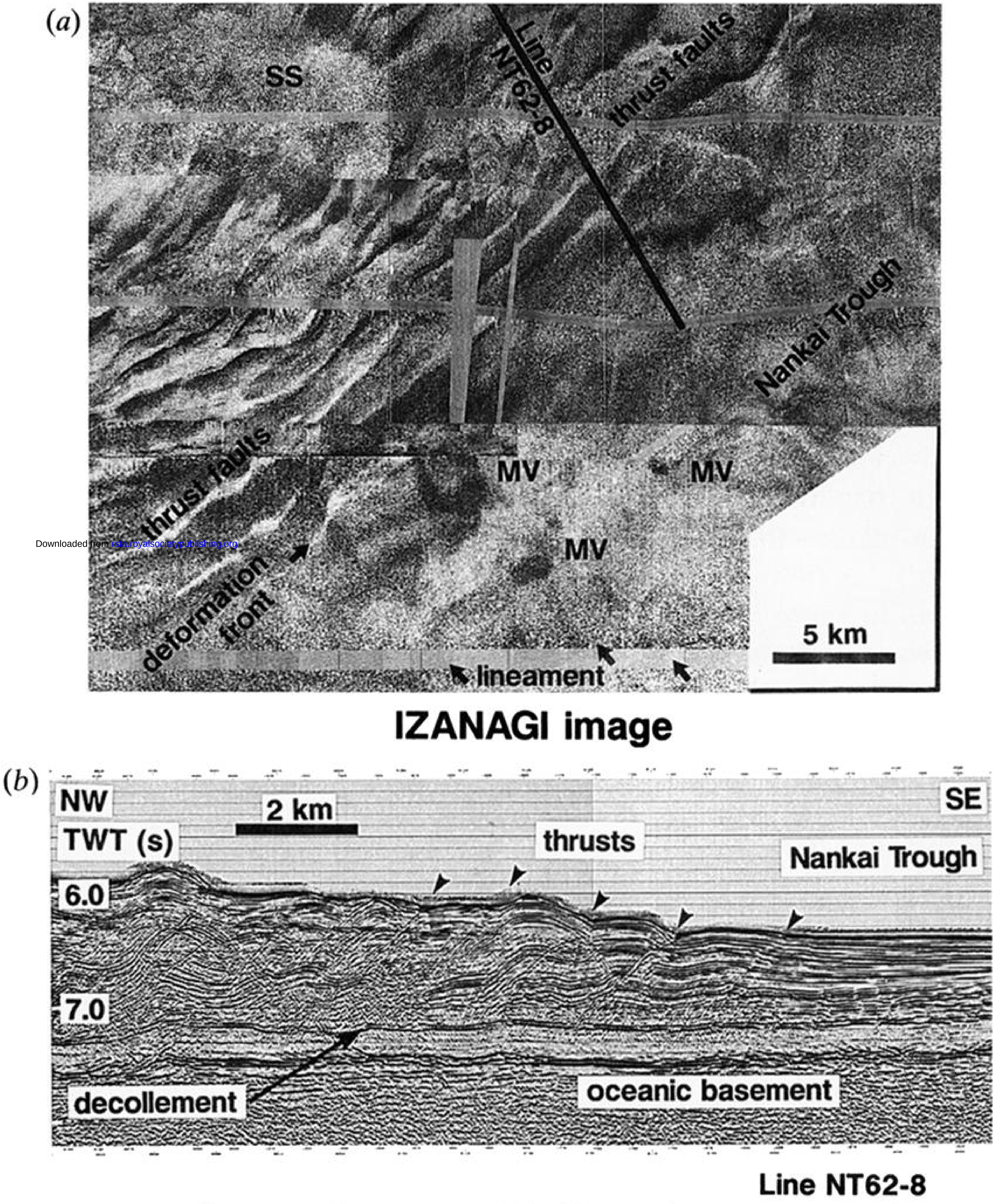
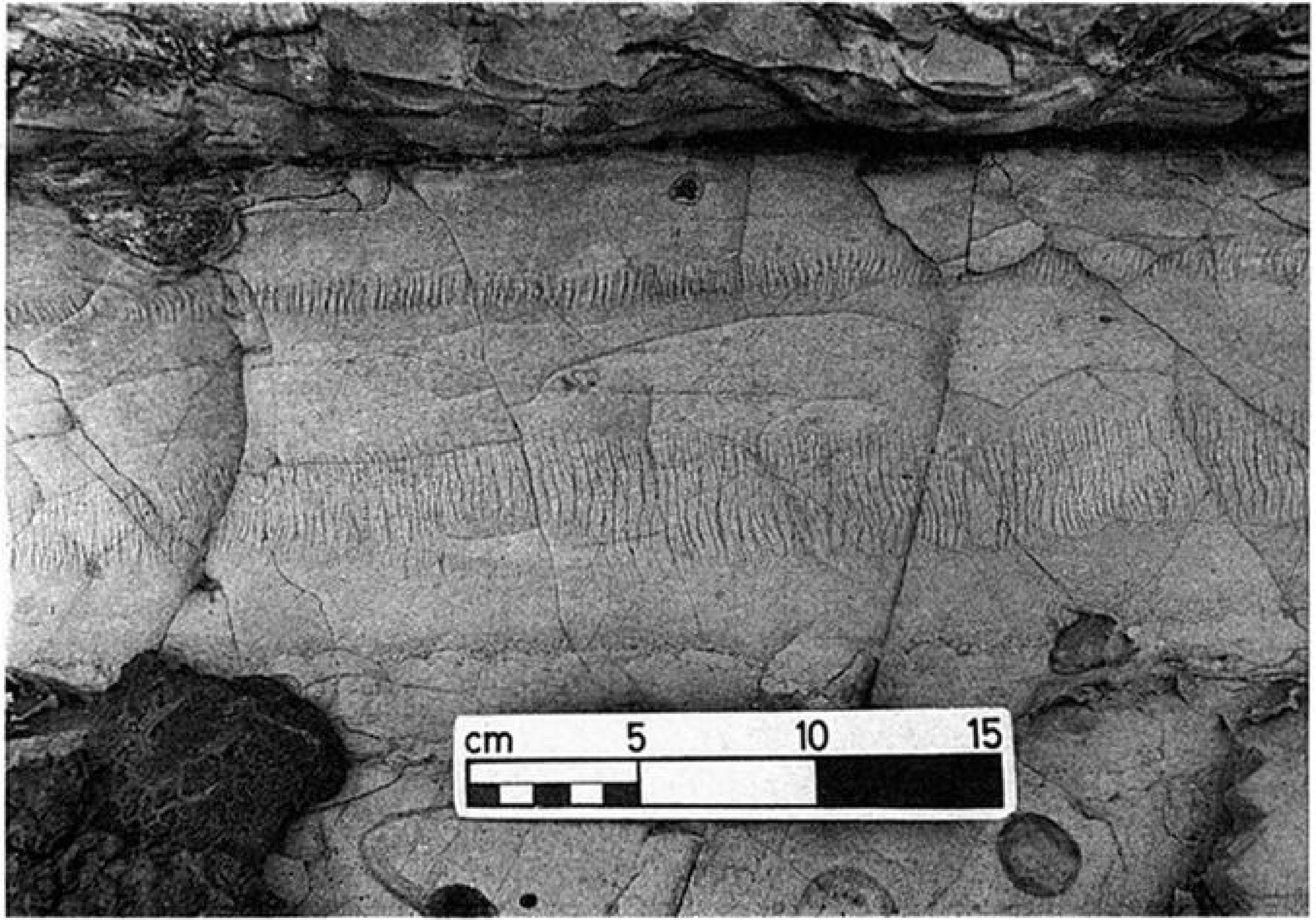


igure 2. (*a*) IZANAGI sidescan seafloor image of the Nankai forearc near toe of accretionary prism t ODP Leg 131, Site. MV, mud volcano; SS, submarine slide. Lower slope thrusts intersecting eafloor visible. Lineations on outer trench slope. Site survey seismic line marked. (*b*) The seismic ne NT62-8 shown in (*a*).



igure 5. Vein structure, Miocene–Pliocene Misaki Formation, Miura Peninsula, SE Japan. These ructures represent the earliest post-depositional expression of pore-fluid activity which generates systematic fabric in muddy lithologies.