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Structural geological evidence from ODP Leg 131 regarding fluid flow in the Nankai prism, Japan

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ABSTRACT

The fluid flow regime of accretionary prisms influences their morphology and dynamics, and is closely interrelated with deformation. For example, the Lesser Antilles prism shows drainage principally along channels provided by tectonic structures such as thrusts and the basal decollement. A similar behaviour has been suggested for the Nankai prism, and this was investigated during ODP Leg 131. Coring at site 808 penetrated the entire prism and underthrust sediments, and allowed detailed documentation of structures seen in the cores. However, neither the frontal thrust nor the decollement show any visible sign of channelised fluid flow. No veins, mineralised surfaces or clastic dykes were observed. The single clastic dyke seen within the prism appears unrelated to a deformation zone. On the other hand, small-scale structures such as faults and deformation bands are unusually numerous in the Nankai prism, and colour and diagenetic changes within them suggest that they may have acted as micro-conduits for drainage. Further contrasts with other prisms are shown by the sequence of deformation at Nankai and the relative paucity of deformation in the underthrust material.

Therefore, the tectonic and fluid flow regime at site 808 differs from the expected pattern. Marked increase in porosity immediately below the decollement hints at overpressuring in this zone, but the structures show no record of localised fluid activity. The structural geological observations throughout the Nankai prism are more consistent with bulk, pervasive dewatering, perhaps utilising the abundant deformation microstructures.

1. Introduction

Sediments that become incorporated in an accretionary prism lose large amounts of water, and the locations and efficiencies of the drainage routes are thought to have a major influence on the morphology and dynamics of the prisms [1]. The loss rates are especially great in the toe regions [2], where evidence has suggested that the dewatering paths closely interplay with deformation [3]. This is particularly true of the Lesser Antilles (Barbados) example: faults and the basal decollement act as conduits, and fluid pressures evolve in a complex way as deformation progresses [4]. Structures observed in recovered cores record histories of focused fluid flow and associated fluid pressure changes. Veins, for example, are common, and the mineralisation of scaly clay surfaces in the thrust and decollement zones indicates a close relationship between deformation and fluid movement [5]. The conceptual difference between such tectonically controlled channelised flow and a more diffuse, pervasive dewatering of a prism is illustrated in Fig. 1.

Reconnaissance observations have suggested that the Nankai prism, too, may show tectonic control on the dewatering pathways [6]. Elucidation of the possible association between deformation processes and hydrogeology at Nankai was the chief objective of ODP Leg 131. At site 808, core was obtained from the entire thickness of

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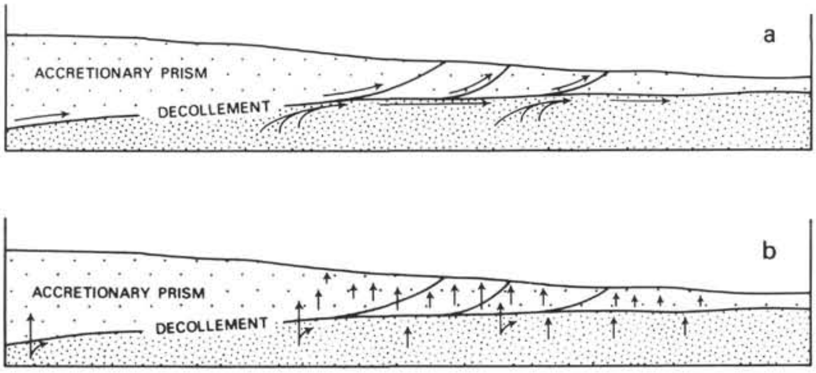

Fig. 1. Diagram to illustrate the conceptual difference between channelised fluid flow along (a) tectonic features and (b) pervasive, diffuse dewatering of an accretionary prism.

the prism toe and underthrust sediments down to the underlying ocean basement, and a comprehensive inventory was assembled of the deformation structures [7]. The setting of site 808 within the prism is outlined in Fig. 2. Details of the distribution and geometry of the structures will be presented elsewhere; the present contribution summarises the implications these structural observations have for understanding the fluid flow regime at Nankai.

2. Structures in the Nankai prism

At site 808, small-scale tectonic structures are common. They vary in appearance from planar kink-like features termed here deformation bands (Fig. 3a), following Karig and Lundberg [8], through narrower shear zones to undulating small faults (Fig. 3b). These and the major structures are summarised below in order of increasing depth. The small-scale structures are first encountered at 260 m below the sea floor (mbsf). The faults are discontinuous, very narrow, dark-coloured zones that rarely extend in length for more than a few centimetres. The deformation bands are markedly more planar, and deflect the host material in zones reaching up to 0.5 cm in width. Like the faults, the bands are dark in colour, and comprise material that seems to be a darkened variation of the host rock. Structures of

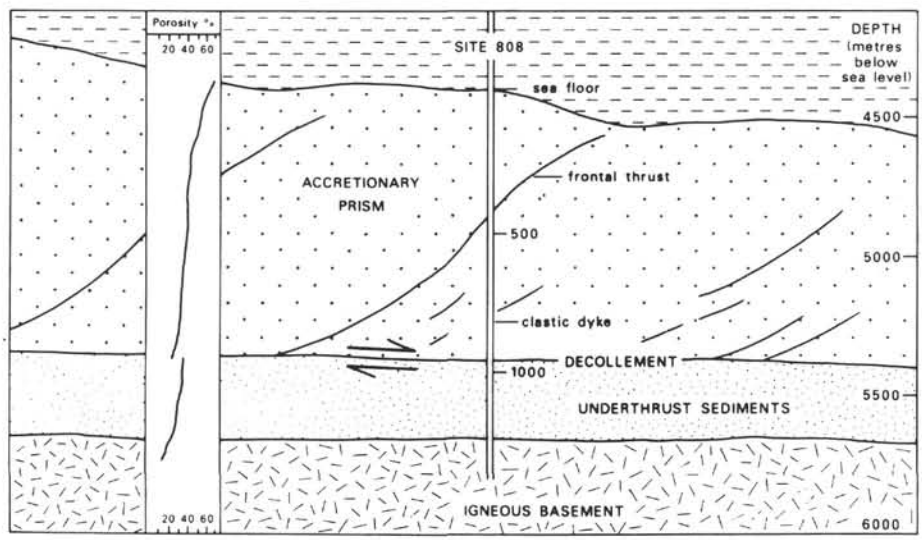

Fig. 2. Diagrammatic cross section to show the setting of site 808 within the Nankai prism and some of the features encountered. The inset illustrates approximate porosity values (note the abrupt increase at the decollement).

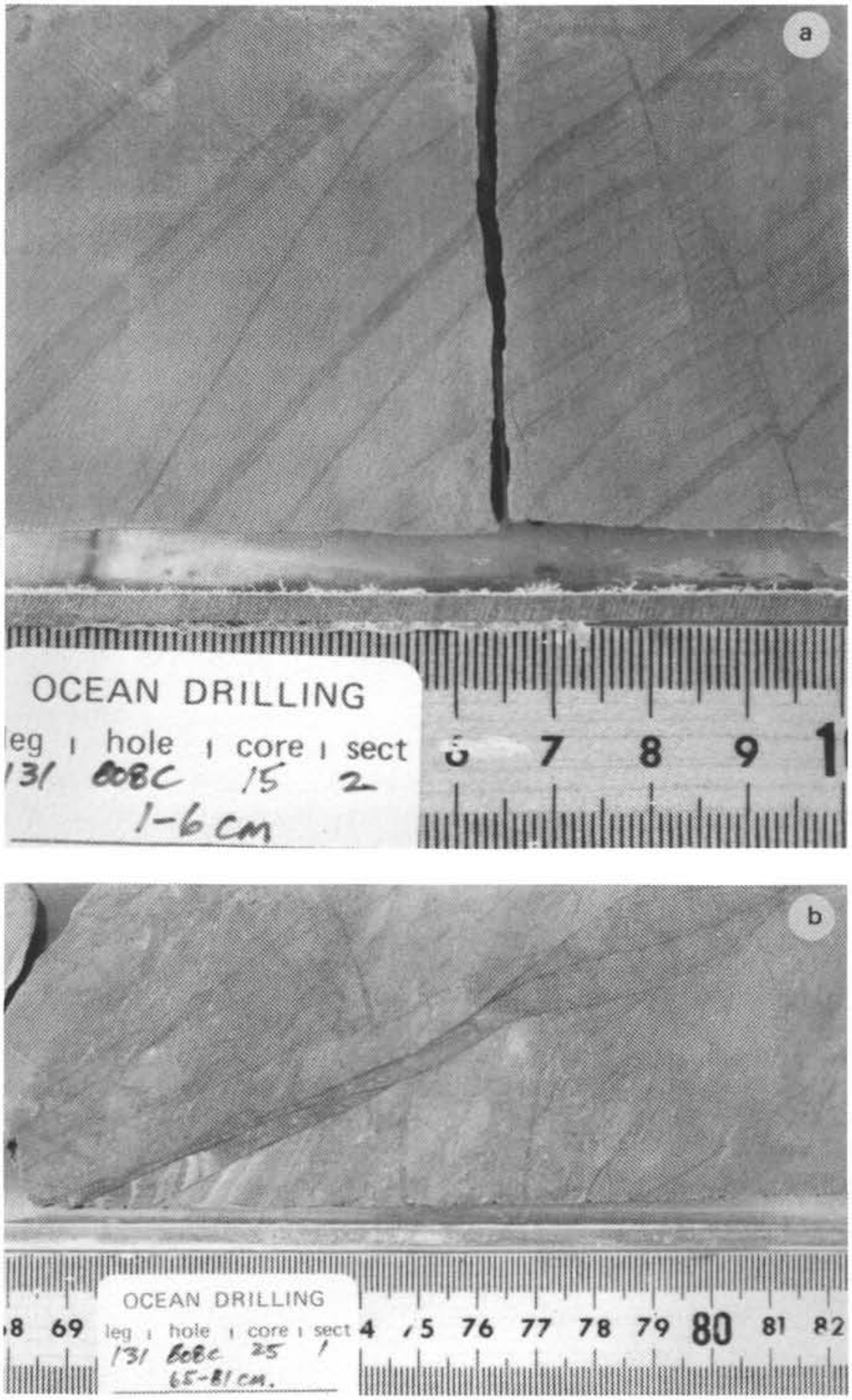

Fig. 3. Representative illustrations of two of the main types of structures seen in the cores from site 808. (a) Deformation bands. (b) Small faults.

appearance intermediate between the faults and deformation bands are termed here shear zones. Experimentally produced zones of shear similar to these show a loss of porosity of several percent, yet at the same time an increase in permeability along the structure [9]. Although examples from Leg 87 show no mineralogical change within the bands [10], preliminary examination of the deformation bands from site 808 reveals some weak diagenetic alteration, and shipboard XRD analysis indicates the presence of gregite. Mineral growth along somewhat similar structures in other environments has been inferred to indicate enhanced fluid flow along the zones [11]. The Nankai prism seems to be unusually rich in these small-scale features. If each structure is acting as a micro-conduit, the cumulative contribution to drainage could be considerable.

The frontal thrust zone of the Nankai prism reveals a tectonic history different from that recorded at Barbados. The 26 m thick thrust zone is defined by the following: steepening and overturning of bedding into an inclined fold pair; markedly increased frequency of small faults and deformation bands; and zones of brecciation and scaly fabric. Some of the faults comprise conspicuously dark material up to 3 mm across, which preliminary investigation reveals to contain significant amounts of pyrite. The deformation bands in the prism show a consistent geometric relationship with bedding, and this is maintained by the rotated beds of the thrust zone, indicating that the bands formed before the folding of bedding. Beds and deformation bands are crosscut by faults and by the breccia and scaly fabrics. Therefore, a sequence of ductile failure followed by buckling and brittle fracture is indicated. All this contrasts with the Barbados prism, where folds overprint scaly fabrics and thrusts [12]. Such tectonic differences between the two prisms could connote differences in dewatering behaviour.

The breccias in the thrust zone consist largely of fragments of the host silty clay up to 2 cm across, trapezoidal in shape where they occur between oblique fracture sets, and in places elongate. Where the elongation is marked, the fragments form zones resembling scaly clays, commonly oriented sub-parallel to bedding. There is little sign of the disorganised, ramifying patterns commonly associated with hydraulic fracture in fault zones, and no veining has been observed. Apart from pyrite concentration in the small faults, there is no indication that fluids travelled preferentially along the thrust zone. The 309 m of slip deduced for the amount of transport accomplished in the thrust zone may have been aided by elevated fluid pressures, but there is no supporting structural evidence.

Below the frontal thrust, a fissility is conspicuous. Fissility is present in the cores as shallow as 70 mbsf, but at depths of about 700 mbsf its effects are very noticeable, producing discrete, planar fractures in a bedding-parallel orientation, typically with a spacing of several centimetres. The structure presumably reflects an increasing phyllosilicate alignment with depth, and this will affect the permeability characteristics of the sediment. Laboratory-generated clay sediments can show three orders of magnitude in permeability variation depending on whether the measurement is made parallel or perpendicular to bedding [9]. If dewatering at site 808 is chiefly pervasive rather than dominated by channelling along tectonic conduits, this must be incorporated in hydrogeological models of the prism.

The deformation bands continue to be significant to a depth of 560 mbsf, below which conditions appear to have been inappropriate for successful formation. Faults, however, are found throughout the recovered section of the prism. Their nature and geometry vary with depth, and their distribution is noticeably heterogeneous. High concentrations coincide locally with somewhat steepened bedding and zones of brecciation, perhaps representing incipient or failed zones of focused strain. However, none of these structures record any fluid activity. No veins or other sign of mineral deposition have been observed.

Around 650 mbsf there are several narrow horizons of indistinct vein structure, broadly similar to those recorded elsewhere [13]. The "vein" material appears slightly darker but otherwise little different from the host rock, and displacements across the structures are negligible. Although structures such as these have been interpreted as reflecting high fluid pressures [14] or dewatering channels [15], we follow the inference [13,16] of slow, local fluid movement in zones of tensile failure. These structures have not been found elsewhere at site 808.

At 813 mbsf, deep within the prism (Fig. 2), there occurs the only visible evidence anywhere at site 808 for overpressuring—a clastic dyke. It is a 2 cm wide band of medium-grained, grey quartz sand injected into a dark grey silty clay host. The structure dips 45° towards the northwest (after palaeomagnetic orientation correction). No appropriate source material is seen in the core. Although a lone occurrence, it is possible that further examples form an extensive horizontal zone of dykes, of which only one happened to be penetrated by the drill bit. However, this interval bears no relation to any known deformation feature. It is 150 m above the basal decollement, does not coincide with any of the zones of increased fault frequency in the prism, and has no correlative on the seismic trace. The suggestion is that this localised zone of overpressuring played no significant part in the tectonic and hydrogeological history of the prism.

The basal decollement of the Nankai prism was encountered at site 808 at a depth of 945 m, marked by the top of a well-developed breccia/scaly fabric zone. These textures dominate to a depth of 964 m, at which depth there is an equally abrupt lower boundary to the deformation. As viewed in the recovered cores, the decollement therefore occupies an interval of approximately 19 m. The largest fragments preserved in the zone, up to 5 cm across, tend to have a trapezoidal or rhomboidal shape suggesting their generation between systematic fractures. Smaller pieces show similar shapes, although in places they are more elongate and slightly shiny, approaching a scaly clay in character. There is nothing in the appearance of the zone to suggest that fluids have played a role more significant here than elsewhere in the prism. In particular, there are no signs of mineral deposition, on clast surfaces or in veins. The abundance of fractures in the core as it is now seen gives the material a very loose, open appearance, but it is possible that at depth this clay–silt material was much more coherent and poorly permeable.

There is a marked porosity increase immediately below the decollement (Fig. 1; [7]), which prompts various scenarios for the tectonic and hydrogeologic history of the decollement zone. For example, it could have acted as a seal in order to preserve the observed elevated porosities of the footwall, or alternatively it may have been an overpressured fluid conduit that decoupled the materials above and below and allowed them to undergo different stress-related drainage histories (Karig et al., in prep.). However, such hypotheses are little constrained by the structural observations: there is no visible supporting evidence for the decollement zone having been overpressured or having acted as a fluid conduit.

Whether or not overpressuring was involved, it does seem that the stress regime of the prism was effectively decoupled from the underthrust material, because the latter shows remarkably little deformation. The few faults that were observed are minor, and probably very early in origin. Some appear to be synsedimentary. Ironically, in the lower plate there are clear records of fluid movements, such as dewatering veinlets below some of the ash layers at 1250 mbsf, and the abundant mineralised fractures and veins in the basalts of the ocean basement. However, these shed no light on the interplay between tectonics and hydrogeology in the overlying prism.

3. Contrasts with other prisms

The structural style at site 808 of the Nankai complex appears to differ from that seen in other prisms. As mentioned earlier, the sequence of ductile and brittle deformation modes apparent at Nankai differs from that inferred from the Lesser Antilles structures. Deformation bands are a conspicuous deformation feature of the Nankai prism but, apart from a record from the Aleutian Trench [13], are not found elsewhere. The frequency of faults documented from one of the most intensely deformed parts of the Lesser Antilles margin, Leg 110 site 671 [4], is roughly 10% of that recorded at Nankai site 808. Conversely, the underthrust sediments at Barbados show considerable deformation, including significant development of scaly clay, whereas there is an abrupt loss of deformation below the Nankai decollement zone. Because fluids are an important influence on deformation style, these contrasts in structural geology suggest that the hydrogeological regime at Nankai is significantly different.

The kinds of structures commonly taken as registers of fluid activity are veins and other mineralised fractures, and clastic dykes. The example of the last feature at Nankai is isolated from known deformation structures, suggesting little interaction between the overpressuring that provoked it and the tectonism. Mud-filled veins are abundant in the Peru margin [17] and are known from locations such as Japan, Marianas, and Guatemala, together with several onland sites [13]. At Nankai site 808, they are feebly developed and occur at only one horizon, occupying a total interval of less than 10 cm. Mineralisation is known from several sites in the Barbados prism; the formation of veins of rhodochrosite and "zeolite" in the deformation zones, together with other mineral changes, was cited to "attest to fluid flow along these surfaces" [4, p. 589]. In contrast, no veins or macroscopic signs of mineralisation were observed anywhere in the sediments recovered from the Nankai prism at site 808.

The structural geological manifestations of fluid flow in the Nankai prism are feebly developed and show little relationship with the deformation of the complex. Drainage of the accreting sediments may have been channelised, overpressuring may have been important, but the structures preserve no record of such phenomena. The structural geological register is more consistent with the dewatering of the Nankai prism having been largely accomplished by bulk, pervasive fluid flow, to which the wealth of microstructures may have significantly contributed.

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