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First in-situ observation at a major backthrust system of an active accretionary prism (eastern Nankai Trough – Japan)

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Key words. – Marine Geology, Subduction, Accretionary prism, Backthrust, Nankai Trough, Japan.

Abstract. – During the Kaiko-Nankai cruise, several dives were devoted to the exploration of a linear 2 000 m deep ridge (Yukie ridge) located at the trench-slope break of the Eastern Nankai accretionary wedge, off southwest Japan. This ridge is locally one of the two most active venting sites discovered across the prism. Based on the interpretation of seismic lines together with *in-situ* structural observations, we show that this ridge is basically an asymmetrical anticline related to the motion along a prominent backthrust (landward verging thrust fault). This backthrust evolves north-eastward to a 5 km wide deformation zone with dominant landward vergence. This backthrust system vanishes westward as Zenisu ridge vanishes too and is thus present only opposite the Zenisu intra-oceanic deformed zone. We thus propose to relate the development of the backthrust to the presence of an older compressional oceanic ridge buried below the prism. Surprisingly, no significant fluid venting is associated with the outcrop of the main backthrust whereas spectacular seeps (carbonate cementation and biological activity) were observed in a strike-slip zone crossing the Yukie anticlinal ridge but none on the northern slope.

Première observation par submersible du rétrochevauchement majeur d'un prisme d'accrétion (fosse de Nankai, Japon sud-ouest)

Mots clés. – Géologie marine, Subduction, Prisme d'accrétion, Rétrochevauchement, Fosse de Nankai, Japon.

Résumé. – Pendant la campagne KAIKO-NANKAI, une série de plongées du submersible Nautile a été consacrée à l'étude d'une ride linéaire (dite ride de Yukie) située à une profondeur de 2 000 m dans la partie orientale du prisme d'accrétion de Nankai (Japon sud-ouest). C'est sur cette ride que se trouve l'un des deux sites majeurs d'expulsion de fluides du prisme. A partir de profils sismiques et d'observations par submersible, nous montrons que cette structure est un anticlinal asymétrique lié au fonctionnement d'un important rétrochevauchement (faille inverse à vergence continentale). Ce rétrochevauchement évolue vers le nord-est en une zone complexe de déformation compressive où la vergence dominante reste continentale. Cette ride morphologique et le rétrochevauchement associé n'existent qu'en face du chevauchement intra-océanique de la ride de Zenisu. Nous proposons donc de relier les deux phénomènes par exemple par le passage sous le prisme d'une ride Paléo-Zenisu (similaire pour son origine mais formée antérieurement). Paradoxalement, les manifestations spectaculaires de sorties de fluides (activité biologique intense et concrétions carbonatées) ne sont pas situées sur le flanc nord de la ride où le rétrochevauchement affleure mais au sommet de l'anticlinal où une zone déformée qui a été interprétée en décrochement recoupe la structure.

VERSION FRANÇAISE ABRÉGÉE

Introduction

La campagne KAIKO-NANKAI du N/O « Le Nadir » qui s'est déroulée en Août 1989 avait pour objet l'étude des relations entre circulations de fluides et tectonique dans la partie orientale du prisme d'accrétion de Nankai produit par la subduction du bassin de Shikoku (plaque de la mer des Philippines) sous le Japon sud-ouest (fig. 1). Grâce à une étude préalable utilisant une caméra traînée près du fond, il a été montré que les manifestations d'expulsion de fluides se concentrent en deux sites tectoniquement actifs. Une série de 24 plongées du submersible Nautile a été consacrée à l'étude de ces deux sites. Le premier site correspond au sommet du premier anticlinal au front de déformation. Le site le plus interne qui fait l'objet de cette publication correspond à une ride linéaire (dite ride de Yukie, fig. 2) située à une profondeur de 2000 m.

Mise en évidence du rétrochevauchement

A partir de données de bathymétrie obtenues par sondeur multifaisceaux (fig. 3) et de profils sismiques multitraces (fig. 4), nous montrons que cette structure est un anticlinal asymétrique lié au fonctionnement d'un important rétrochevauchement (faille inverse à vergence continentale). Cette hypothèse est confirmée par des observations *in-situ* faites

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lors des plongées en submersible. En particulier, lors de la plongée n° 9, deux coupes à travers le flanc nord de cette ride ont permis de mettre en évidence des successions de plis métriques, à charnières en chevrons et dont l'asymétrie indique un cisaillement qui est en accord avec le mouvement de rétrochevauchement proposé (fig. 5, 6 et 8). Ces plis sont recoupés localement par une zone de cisaillement épaisse d'une dizaine de centimètres dont le mouvement a une composante inverse et dont la vergence est continentale. Une coupe plus au nord-est (localisée en figure 3) est obtenue en combinant les informations de 4 plongées (plongées 2, 5, 6 et 15). Elle confirme l'asymétrie générale de la ride de Yukie car des strates à fort pendage (fig. 7) ont été observées le long du flanc nord de la structure (voire même sub-verticales à la base). Nous interprétons les deux observations : couches très redressées dans la coupe orientale et distribution de la déformation en surface pour la coupe occidentale (fig. 7 et 9) comme des indices de propagation du rétrochevauchement profond qui n'affleure probablement pas en surface comme une faille unique. Le rétrochevauchement qui semble localisé en profondeur évolue vers le nord-est en une zone complexe dont l'expression de surface est une zone de déformation compressive nettement plus large (jusqu'à 4 kilomètres) où la vergence dominante reste continentale.

Origine du rétrochevauchement

La ride morphologique et le rétrochevauchement associé n'existent qu'en face du chevauchement intra-océanique de la ride de Zenisu. Cette dernière est liée au voisinage de la zone de collision d'Izu où l'arc volcanique d'Izu-Bonin, qui s'enfonce difficilement sous le Japon central, subit une déformation interne absorbant une fraction non négligeable de la vitesse de convergence. La ride de Zenisu est un chevauchement crustal actif immédiatement au sud de la fosse de Nankai qui absorbe le même type de déformation interne dans la portion océanique de la plaque. En nous appuyant sur l'observation d'une nouvelle ride chevauchante naissante 50 km au sud de Zenisu, nous proposons de relier le rétrochevauchement dans le prisme et les chevauchements intra-océaniques par le passage sous le prisme d'un relief allongé baptisé ride « Paléo-Zenisu » (similaire pour son origine mais formée antérieurement à la ride de Zenisu). Des expériences analogiques permettent de comparer nos observations à l'évolution d'un prisme de sable sous lequel s'enfonce une ride de socle [Lallemant *et al.*, 1992b] (et fig. 10).

Rétrochevauchement et expulsion de fluides

Paradoxalement, les manifestations spectaculaires de sorties de fluides (activité biologique intense et concrétions carbonatées) ne sont pas situées sur le flanc nord de la ride où le rétrochevauchement affleure presque mais au sommet de l'anticlinal où une zone déformée qui a été interprétée en décrochement recoupe la structure. Ceci est probablement à relier à la structure du rétrochevauchement en propagation dont l'expression profonde est un système de faille localisé alors que son expression de surface est distribuée principalement dans un style plicatif. Dans ce contexte, un décrochement connecté au rétrochevauchement profond fournit un conduit privilégié pour les fluides profonds du prisme.

I. – INTRODUCTION

Most of the thickening within a typical accretionary wedge is obtained through a series of seaward-verging fold and thrust faults [Seely *et al.*, 1974]. However, landward vergence or backthrusting is a relatively common feature in the subduction related accretionary wedges and can even be the dominant structural fabric [Seely, 1977; Byrne and Hibbard, 1987]. A typical setting for significant backthrusting is the rear of the accretionary wedge at the boundary between the stabilized prism and the forearc basin. This has been described in the Indonesian forearc basins [Karig *et al.*, 1980], in the Barbados ridge [Westbrook, 1975; Speed and Torrin, 1989] and the Mediterranean ridge [Le Pichon *et al.*, 1982]. Silver and Reed [1988] review backthrusting in the accretionary complexes and correlate the presence of a major backthrust with the oceanward dip of the backstop, whereas landward dipping backstops are overlain by almost undeformed forearc basins. In the first case, the "Outer Arc High" or "Trench-Slope Break" [Karig and Sharman, 1975] coincides both with the aseismic front and the seaward edge of the crustal backstop. The landward flattening of the surface slope is then related to the landward increase in the basal strength [Byrne *et al.*, 1988].

Little is known about the deep geometry of the inner parts of the Nankai accretionary wedge but the most prominent fore-arc basins, Tosa basin and Muroto basin off Shikoku island and Kumano basin, off the Kii peninsula [Shiki and Misawa, 1982] do not show any significant backthrusting at their boundaries (fig. 1a and 1b). However, the structural

style of the prism shows significant alongstrike variations related to their taper angle [Le Pichon *et al.*, 1987a; Moore G. *et al.*, 1990], the taper angle has been defined as the dihedral angle of the accretionary wedge, i.e. the angle between the basal décollement and the surface slope [e.g. Davis *et al.*, 1983]. The largest change occurs near 137°30'E (fig. 1a) where the Tenryu canyon cuts through the deformation front of the prism. Westward of the canyon, the wedge has a moderate taper angle (8°) with a regular topographic slope, whereas the eastern area is more complex with an overall higher angle tapered prism (13°) with a well defined slope-break in the middle. In this eastern area (fig. 2), one can define a 5 km wide inner part of the wedge characterized by a steep topographic slope (15° enhanced by surface erosion locally up to 20° along the slump scars) in front of which an outer unit with very flat topographic surface (1.5°) is rapidly growing [Chamot-Rooke *et al.*, 1992]. The inner prism is bounded landward by a narrow linear feature followed from the Suruga trough inner wall eastward to the Tenryu canyon. From seismics and in-situ observation during Nautille dives, we interpret this elongated ridge as the surface expression of a major backthrust system. This backthrust system dies out just opposite the western edge of the Zenisu intra-oceanic compressive ridge [Le Pichon *et al.*, 1987b and 1987c, Lallemant *et al.*, 1989].

In this paper, we first present structural evidences for the existence of this backthrust system. We then try to understand why such a backthrust system is present east of Tenryu canyon. Finally, we discuss briefly the relationship of this backthrust system to the fluid circulation.

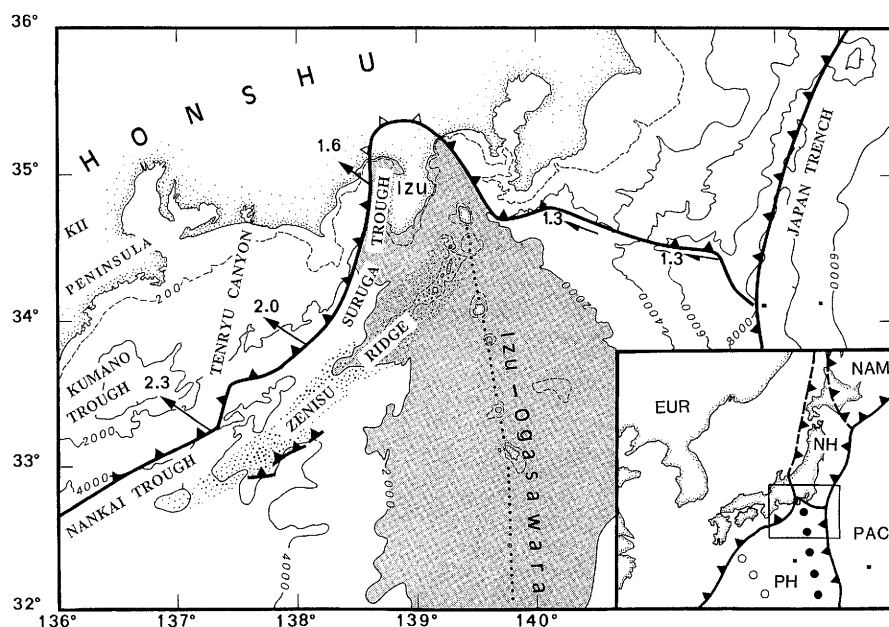


FIG. 1. - a : General location map of the studied area

Convergent plate boundaries are shown by bold lines with triangles (the triangles are on the upper plate). Arrows on the plate boundaries give the local linear plate convergence vector (motion is Philippine Sea plate versus Eurasian plate; values are in cm per year). The dotted area offshore localizes the compressional deformation belt of the Zenisu ridge and the shaded area shows the active volcanic arc related to the subduction of the Pacific plate. Bathymetric contours are expressed in meters. The inset shows the complex plate interactions in the area. EUR : Eurasian plate; PAC : Pacific plate; PH : Philippine Sea plate; NAM : North-American plate; NH : hypothetical North Honshu microplate. Solid circles shows the active volcanic arc, open circles correspond to the fossil Palau-Kyushu volcanic arc.

FIG. 1. - a : Carte de localisation du domaine d'étude

Les frontières de plaques (zones de subduction) sont représentées par des lignes épaisses avec des triangles vers la plaque supérieure. Les flèches le long de la frontière correspondent aux vitesses relatives linéaires des plaques deux à deux (valeurs en cm par an). Le figuré pointillé en mer représente la ceinture de déformation compressive intra-océanique de la ride de Zenisu et le grisé marque la localisation de l'arc volcanique lié à la subduction de la plaque Pacifique. Les contours bathymétriques sont en mètres. L'encart en bas à droite présente la situation géodynamique des plaques en présence (EUR : plaque Eurasiatique; PAC : plaque Pacifique; NAM : plaque Nord-Amérique; NH : microplaque Nord-Honshu).

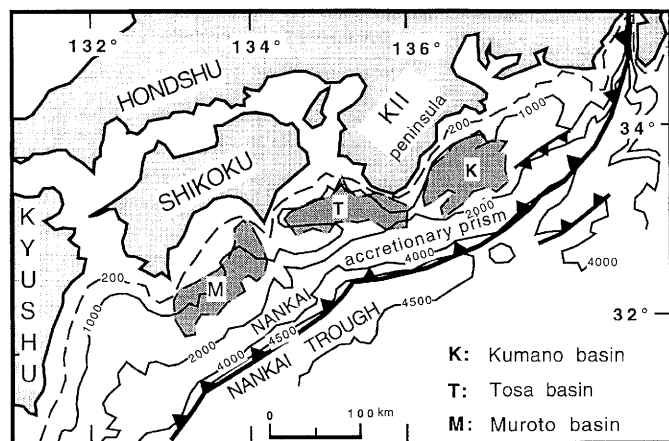


FIG. 1. - b : Simplified map of the Nankai accretionary prism with the main forearc basins (Muroto, Tosa and Kumano).

FIG. 1. - b : Carte simplifiée du prisme de Nankai montrant les trois principaux bassins d'avant-arc (Muroto, Tosa et Kumano).

II. - STRUCTURAL EVIDENCES FROM BATHYMETRY AND SEISMIC REFLECTION

Figure 2 is a structural map established on the basis of a Sea-Beam map and five multichannel seismic lines. Two main units are identified on it. The younger and outermost one results from the seaward propagation of a series of thrusts within the turbiditic trench fill. It is a low angle tapered wedge (the taper angle ranges from 3° to 4°) bounded to the south by a the frontal thrust (T1a around

4 020 m) and to the north by a major scarp (thrust T2a around 3 500 m at the base of the scarp). This unit, described by Chamot Rooke *et al.* [1992], narrows and finally dies out rapidly west of 137°50'E.

The older unit, between T2a (3 500 m) and the major backthrust BT0 (2 300 m) has a poorly resolved internal structure due to the very steep topographic slope (> 15°) between the basal thrust T2a and the summit of the 2 000 m ridge immediately south of BT0. However, bathymetric and limited seismic evidence suggests the existence of at least two continuous landward dipping thrusts (T2b and T2c) outcropping on the southward facing slope. The unit narrows rapidly between 137°50'E and 137°53'E. Accordingly, the steepness of the southward facing slope is at least three times larger east of 137°53'E than west of 137°50'E. This is also where one observes massive erosional slump scars which have contributed to steepen the slope (fig. 2 and 3). Opposite the narrowest portion of the unit, two additional backthrusts [BT1 and BT2] outcrop north of BT0, forming a major 5 km wide backthrust zone identified in figure 2 and detailed in figure 3. This older unit can thus be described basically as a "pop-up" structure. Sediments sampled on its summit indicate that the transition from a depositional to an erosional stage occurred about 0,4 Ma. ago [Lallemand *et al.*, 1992a] dating either the formation of this structural unit or a major uplift event.

Figure 4a shows the upper part of the 6 channel reflection profile NK6 across the second unit in its narrowest portion where the backthrust system is best developed (location in fig. 3). The interpretation proposed in figure 4b is probably fairly reliable below the backthrust system whereas no decent interpretation can be drawn below the

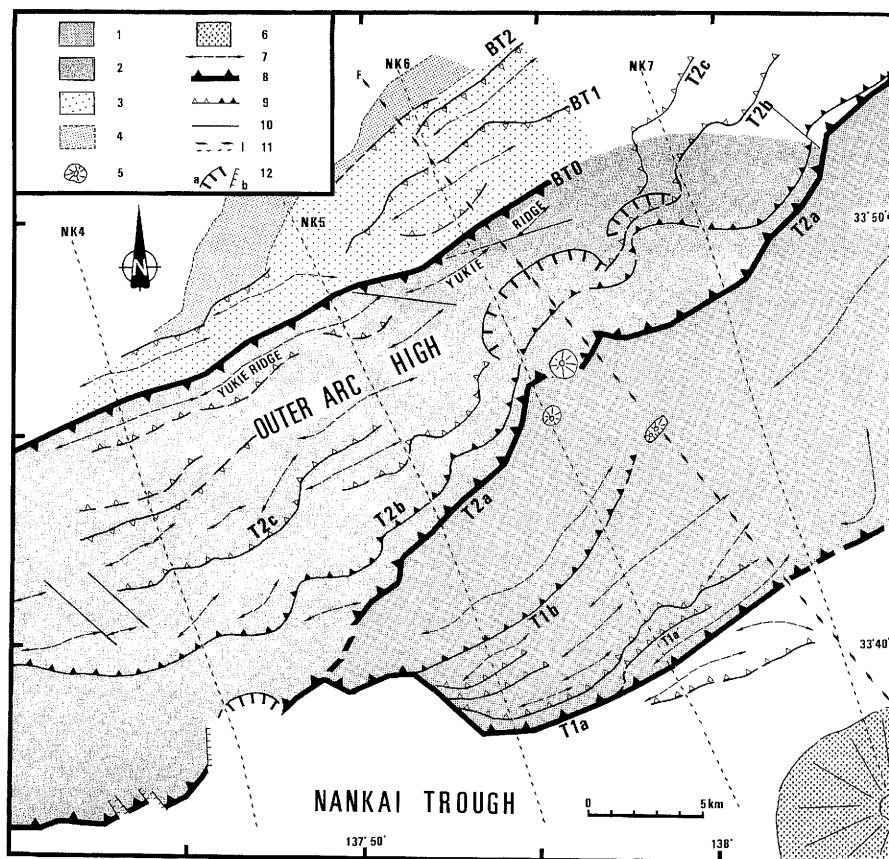
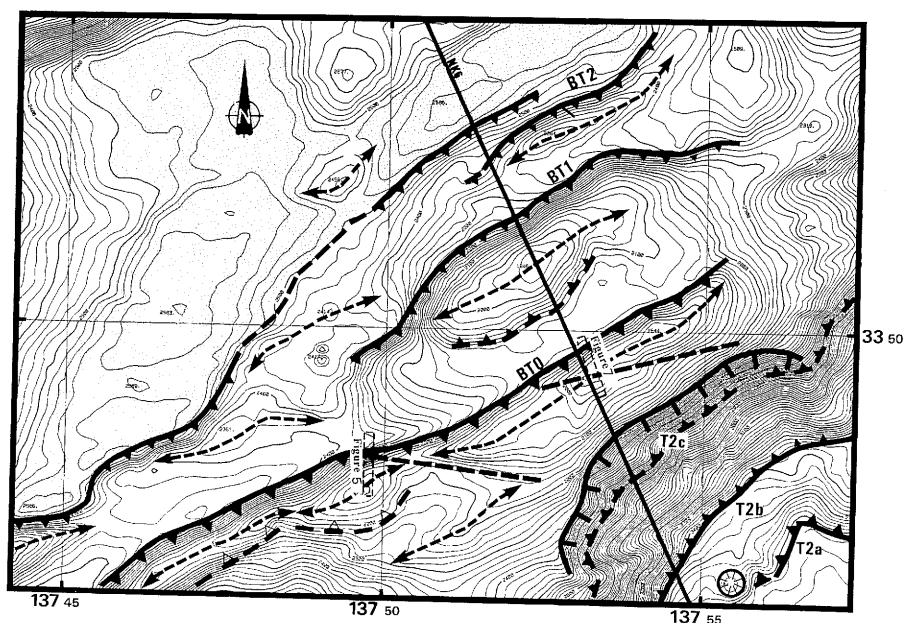


FIG. 2. — Structural map of the Kaiko-Nankai diving area, as located in figure 1.

1 : outer low angle tapered wedge unit. 2 : inner "pop-up" looking unit. 3 : domain of dominant active backthrusting. 4 : slope basin. 5 : mud diapirs. 6 : volcano of the Zenisu ridge. 7 : fold axis (anticline). 8 : major thrust. 9 : second order (b) and third order (a) thrusts. 10 : faults. 11 : seismic multichannel lines used to constrain the map (NK4 to NK7 are unpublished O.R.I. 6 channel lines, line F is from Kato *et al.* [1983]). 12 : erosional features, a : main slump scars; b : small canyons.

FIG. 2. — Schéma structural de la zone des plongées (campagne Kaiko-Nankai 1989) localisée en figure 1.

1 : domaine externe du prisme caractérisé par son angle critique faible. 2 : unité interne du prisme de structure "pop-up"; 3 : domaine des rétrochevauchements; 4 : bassin de pente; 5 : structures argilocinétiques; 6 : volcans de la ride de Zenisu; 7 : axes anticlinaux; 8 : chevauchements majeurs; 9 : chevauchements mineurs; 10 : failles; 11 : lignes sismiques utilisées pour contraindre le schéma (NK4 à NK7 : lignes non publiées de l'O.R.I., la ligne F est tirée de Kato *et al.* [1983]); 12 : structures érosives, a : cicatrices de slumps; b : petits canyons.



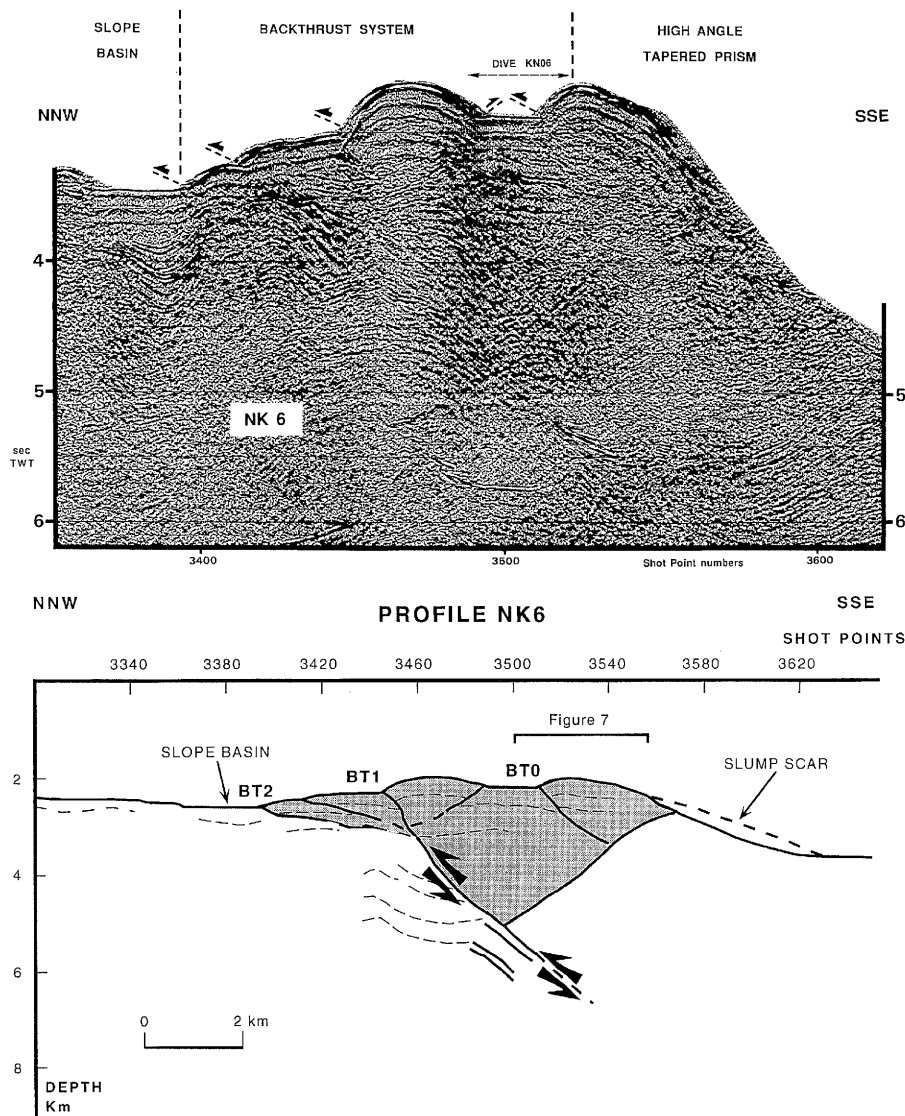


FIG. 4. — Seismic section NK6 across the backthrust system. The line is located in figures 2 and 3

a : time section with the position of the main thrusts outcrops.

b : line drawing of the same seismic section converted to depth using the time-depth empirical relationship of Le Pichon *et al.* [1987a].

FIG. 4. — Profil sismique NK6 à travers la zone de rétrochevauchement (localisation en figures 1 et 2); a : coupe en temps double avec localisation des failles majeures; b : pointé de la section sismique convertie en profondeur en utilisant la relation empirique de Le Pichon *et al.* [1987a].

steep slope of the slump scar. The two-way travel times were converted to depth using a time-depth relation obtained by averaging stacking velocities from Japanese multichannel seismic lines [Le Pichon *et al.*, 1987a]. Note that between BT0 and BT1, a second more northerly topographic ridge appears also to be bounded by a landward dipping thrust to the south and by a seaward dipping thrust BT1 to the north. Thus the structure suggests two asymmetrical pop-up structures limited to the north by a steep slope and to the south by a more gradual one. Below the basin between the two ridges, a series of reflectors dip at about 40° toward the south down to a depth of about 6 km. We relate these reflectors to a major backthrust at depth

from which near-surface backthrusts BT1 and BT2 originate. However, on this section, BT0 cannot be rooted directly in this deep backthrust and locally must be tectonically more limited. Our interpretation of the seismic line suggests that the shortening related to the backthrust is localized at depth along a single prominent fault whereas near the surface, the shortening is distributed over a 4 km wide area in a series of landward and seaward verging reverse faults. In the following section, we present structural field evidences obtained from the submersible near seismic line NK5 (at the eastern extremity of the complex backthrust zone) as well as near section NK6 showing that BT0 is indeed a backthrust.

FIG. 3. — Detailed Seabeam map of the backthrust system area with structural elements superimposed. Bold lines with triangles are thrusts. The bold dashed lines with arrows at their ends are anticlinal axes. The dotted area is a slope basin.

FIG. 3. — Carte bathymétrique Seabeam du système de rétrochevauchement dans la zone d'étude. Les chevauchements sont représentés par des lignes épaisses avec des triangles vers le compartiment supérieur. Les axes anticlinaux par des axes tiretés terminés par des flèches. Le domaine grisé correspond à un bassin de pente (bassin d'avant-arc réduit).

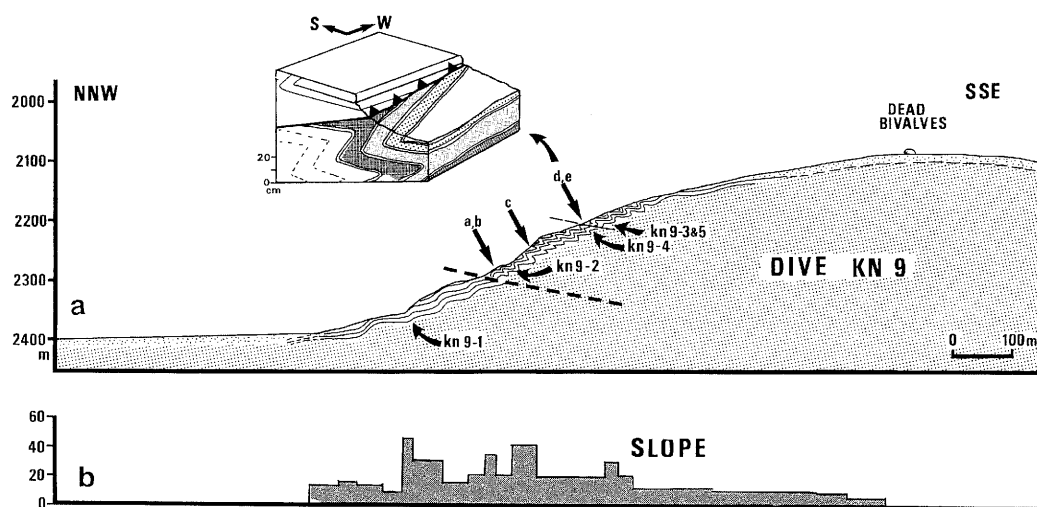


FIG. 5. — a : synthetic section of the dive KN09, showing the distribution of the tight overturned folds. The letters above the section refer to the pictures in figure 7. The sampling sites discussed in the text have been reported below the section. The inset shows the schematic interpretation of a sheared overturned fold as observed in pictures 8d and 8e.

b : Topographic slope (in degrees) corresponding to the dive KN09. The section is located in fig. 3.

FIG. 5. — a : coupe structurale synthétique de la plongée KN09 montrant la distribution des mini-plis déversés. Les lettres au dessus de la coupe localisent les photographies de la figure 8. Les sites d'échantillonnage discutés dans le texte sont localisés sous la coupe. b : pentes topographiques en degrés de la plongée KN09.

III. — TECTONIC EVIDENCES FROM DIVING OBSERVATIONS

Two dives were devoted to the structural study of the northern slope of the Yukie ridge (i.e. the northern boundary of tectonic second unit, see location in fig. 2). The geological observations are summarized in the two sections of figure 5 and 6 (located in fig. 3).

Figure 5 shows a tectonic section obtained during Nautilie dive KN09 (S. Lallemand, observer) on the northern flank of the Yukie ridge, in a place where the northern slope (up to 25°) is the steepest of the whole area. The dive began in a flat lying basin without any significant outcrop. The base of the steep slope at 2 350 m is characterized by sub-horizontal mudstone layers interbedded with thin [thickness less than 10 cm] silty layers. The tectonic style of the base of this cliff is a series of stratal undulations whose steepest dips are about parallel to the topographic slope. From 2 270 m up to 2 130 m, a significant erosion along the slope reveals that the alternations of thin muddy and silty layers are strongly folded (bottom photographs in figures 8a to 8c, located in fig. 5). The folds are typical chevron folds with very tight angular hinges (the typical distance between successive hinges being about 50 cm). The folds are asymmetrical and overturned with a short reversed limb dipping about 70° to 80° southward whereas the long normal limb are subhorizontal to gently dipping (about 20°) northward (see examples in fig. 8c). The folds have a constant axis azimuth around N080°E. Note that this direction is slightly oblique to the axis of the Yukie ridge and to the present-day slope. A well defined shear zone outcrops at 2 205 m (bottom photographs in figures 8d and 8e, located in fig. 5) and cuts the reversed limb of an overturned fold (fig. 8d and inset of fig. 5). Are these folding related to the tectonics or are they simply a consequence of a gravity gliding down the slope? We favour the first hypothesis based on the following observations :

- the intensity of folding is maximum in the middle of the section whereas the base of the cliff with similar slope angles shows only long wavelength undulations;

- at least one sharply defined subhorizontal shear zone cuts through the folds;

- above the basal folds at 2 270 m (fig. 8a and 8b), most of the folds have a consistent chevron shape (fig. 8c), suggesting a coherent shear in a semi-consolidated sediment;

- the fold axes are slightly oblique to the direction of the present day slope (see distribution in fig. 6);

- there is a gradual change of the bed attitudes between the strongly folded strata of the mid-slope to the subhorizontal layers of the upper slope, whereas in the gravity gliding hypothesis, there should be a scar at the top of the strongly deformed section.

Figure 7 is a synthetic tectonic section of the Yukie ridge near the seismic line NK6, based mostly on dives KN06 (J.T. Iiyama, observer) and KN15 (J.P. Cadet, observer), the seeps and biological manifestations of fluid outflow are simplified from figure 5 in Lallemand *et al.* [1992b]. The very base of the northern slope of the Yukie ridge is a muddy slope covered locally with fresh blocks of semi-consolidated mudstones. The first outcrop occurred at 2 100 m showing overturned massive mudstone beds dipping about 70° to 80° toward the south. From this depth up to 2 030 m, the bedding of the massive layers (frequently thicker than 50 cm) is slightly steeper (30° to 40°) than the slope (25°), as one can see on the bottom photograph of figure 8f, and becomes flat again from 2 130 m to the top of the ridge. No evidence has been found for significant shortening within this forelimb of the Yukie ridge anticline. Several outcrops on the southern part of the section reveal that the layers are conformable to the slope there. We refer as "chaotic zone" the part of the section where the beds are disturbed and frequently tilted. This area has been interpreted by Lallemand *et al.* [1992a] as a possible right-lateral strike slip zone crossing the axis of the anticline and along which the seeps seem to be concentrated. Although both figure 5 ("western section") and figure 6 ("eastern section") are consistent with an asymmetrical anticlinal structure, the structural style of the northern slope of Yukie ridge along the eastern section is quite different from the western section, probably in relation with the difference in thickness of the sedimentary layers (10 cm to few tens of centimetres in the western section versus 50 cm to 1 m in the eastern section).

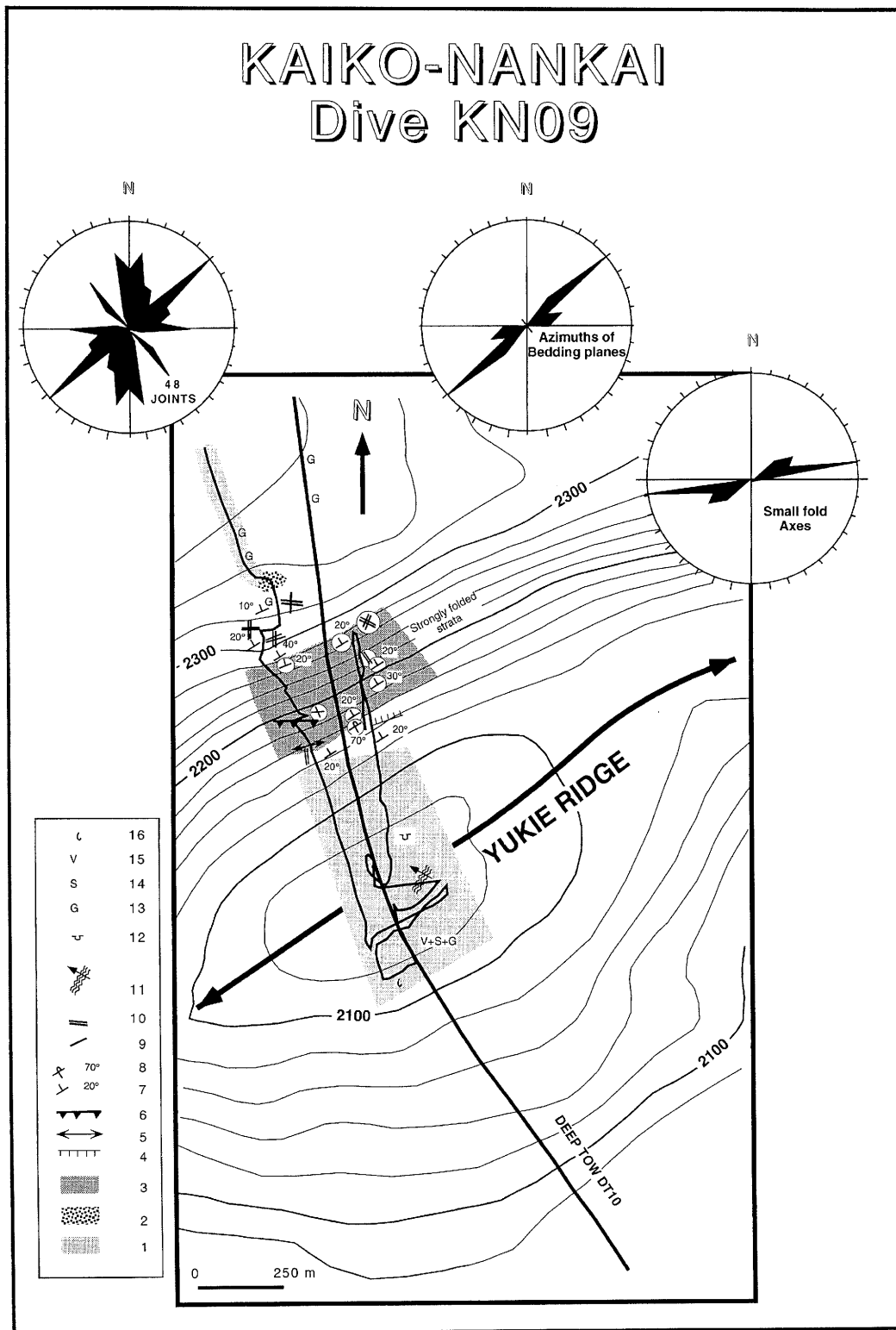


FIG. 6. – Dive KN06 track on a Seabeam bathymetry framework. The directions of bedding azimuths, metric folds and joints are also drawn. 1 : pelagic sediments; 2 : talus; 3 : outcropping folded stratas; 4 : scarps; 5 : anticlinal axes; 6 : reverse faults; 7 : bedding attitude; 8 : bedding attitude (overturned beds); 9 : minor joints; 10 : first-order joints; 11 : ripples with the current direction; 12 : concretion; 13 : galathea crabs; 14 : bivalves “*Solemyia*”; 15 : vestimentiferan worms; 16 : bivalves “*Calyplogena*”.

FIG. 6. – Carte structurale simplifiée de la plongée KN09 sur fond de bathymétrie multifaisceaux. 1 : drapage de sédiments pélagiques; 2 : talus; 3 : affleurement de couches plissées; 4 : escarpements; 5 : axes anticlinaux; 6 : faille inverse; 7 : pendage des couches; 8 : pendages inverses; 9 : joints mineurs; 10 : joints majeurs; 11 : rides de courants avec direction du courant; 12 : concrétion; 13 : galathées; 14 : bivalves “*Solemyia*”; 15 : vestimentifères; 16 : bivalves “*Calyplogena*”.

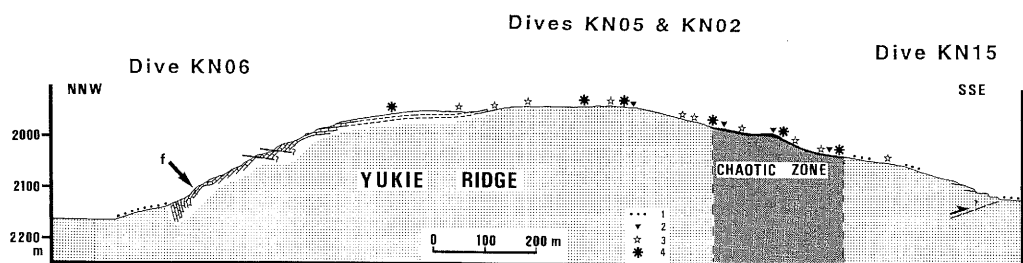
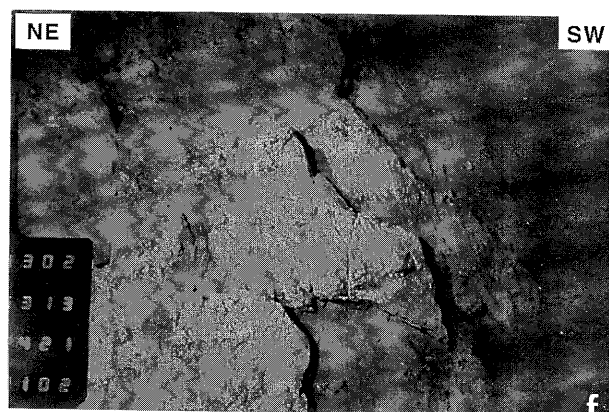
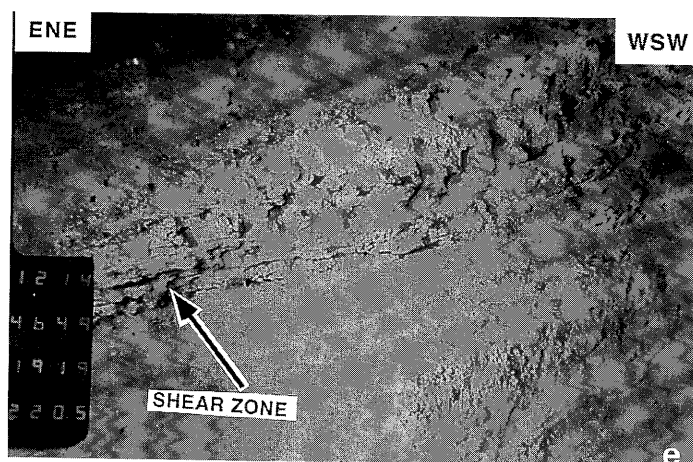
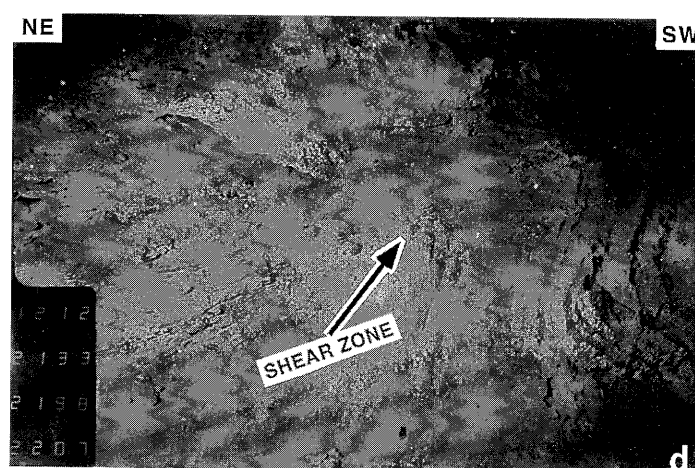
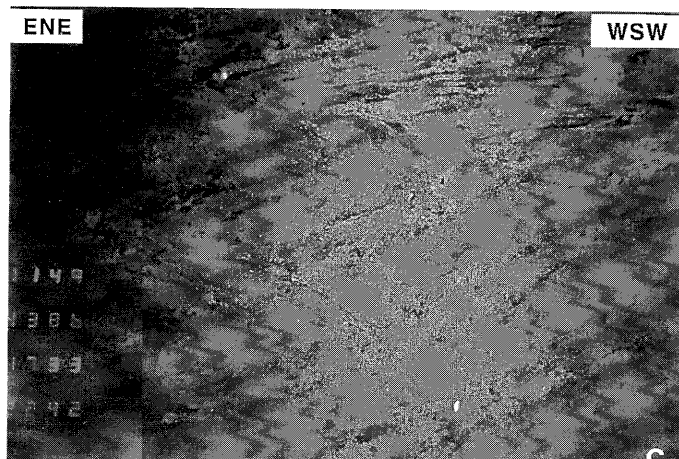
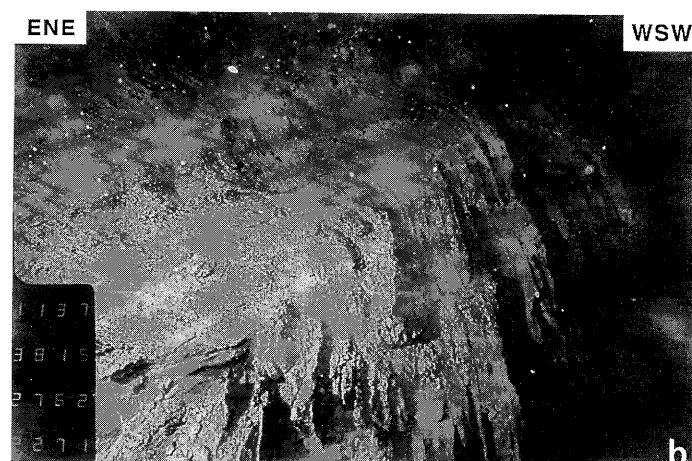
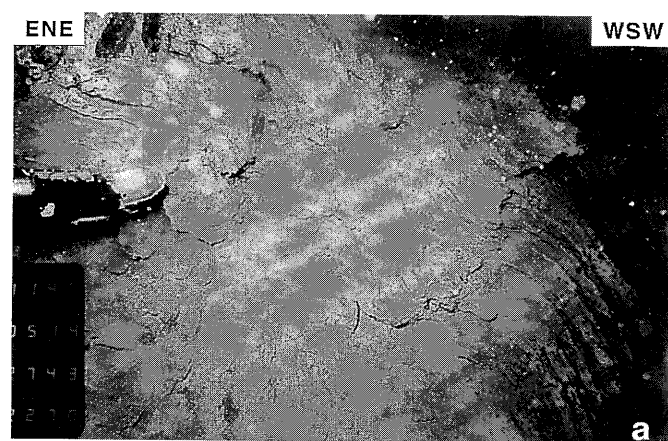


FIG. 7. – Synthetic section of the eastern part of the Yukie ridge as deduced from Kaiko-Nankai dives KN02, KN05, KN06 and KN15. 1 : erratic blocs; 2 : vestimentiferan tube worms; 3 : dead clam shells; 4 : living colonies of *Calyptogenia* clams.

FIG. 7. – Coupe structurale simplifiée de la partie orientale de la ride de Yukie et localisation des manifestations de sorties de fluides d'après les plongées KN02, KN05, KN06 et KN15. 1 : blocs erratiques; 2 : vestimentifères; 3 : coquilles de *Calyptogenia*; 4 : colonies vivantes de *Calyptogenia*.



Five sedimentary samples have been taken along the western section (see location in fig. 5) and dated based on relatively well preserved microfossils and nannofossils (determinations by G. Glaçon and C. Müller). All the samples are Pleistocene in age and younger than 0.78 Ma. Samples KN9-2 and KN9-4 are in the range 0.35 to 0.78 Ma, whereas KN9-3 and KN95 are dated between 0.23 and 0.46 Ma. The most probable interpretation is that the entire outcropping sequence has an age around 0.4 Ma, which is in good agreement with the ages in the eastern section discussed in more detail by Lallemand *et al.* [1992a].

Considering that the small-scale chevron-type folds are not related to gravity sliding along the slope, and consistently with the seismic lines, we can interpret these folds as the expression of fore-limb thickening above a blind (propagating) thrust. We draw in figure 9 a cartoon illustrating very crudely how the forelimb thickening can account for the distribution of the shear deformation localized at depth along a single thrust plane. A more geometrical but similar model has been developed by Suppe and Medwedeff [1990] in the theory of fault propagating folds with fixed axial surfaces.

IV. - POSSIBLE ORIGIN OF THE BACKTHRUST SYSTEM

We noted earlier that the backthrust system described in this paper abruptly ends to the west at the longitude of Tenryu canyon. This is also the longitude at where Zenisu ridge ends (see fig. 1). The Zenisu ridge has been shown to be a tectonic feature produced by intra-oceanic shortening. This roughly N-S shortening is expressed as prominent landward (NW) dipping crustal thrusts [Le Pichon *et al.*, 1987b and 1987c; Lallemand *et al.*, 1989] resulting in a rapid uplift of an asymmetrical ridge with a steep faulted scarp to the south and a gentler slope to the north. The vertical throw on the fault scarp is of the order of 2 to 4 km and the increase of the basement slope toward the trench is of the order of 2° to 3°. It is thus reasonable to investigate whether the formation of the backthrust can be related to the presence of Zenisu ridge opposite to it.

Zenisu ridge thrusting is related to the nearby collision of the Izu-Bonin active volcanic arc with the Japanese continental block. A smaller comparable compressive ridge parallel to Zenisu exists 45 km to the south [Lallemand *et al.*, 1989]. The compressive horizontal force developed at the Izu collision zone is thus responsible for the nearby deformation of the oceanic plate [Huchon, 1985] into a series of crustal-scale fold and thrust systems [Chamot-Rooke and Le Pichon, 1989; Lallemand *et al.*, 1989]. As this collision has existed since at least Pliocene [Huchon, 1985; Soh, 1986], we can assume that successive ridges have been formed in a steady state process of lithospheric buckling with about a 50 km wavelength [Chamot-Rooke, 1988] since at least 5 Ma. A small ophiolitic body accreted to the Japanese margin has been described in the Miura peninsula and interpreted as a Miocene compressive oceanic ridge [Soh *et al.*, 1991]. Accordingly, a former compressive ridge (similar to the present-day Zenisu ridge) could now be present below the accretionary wedge under the second tectonic unit investigated in this paper. This

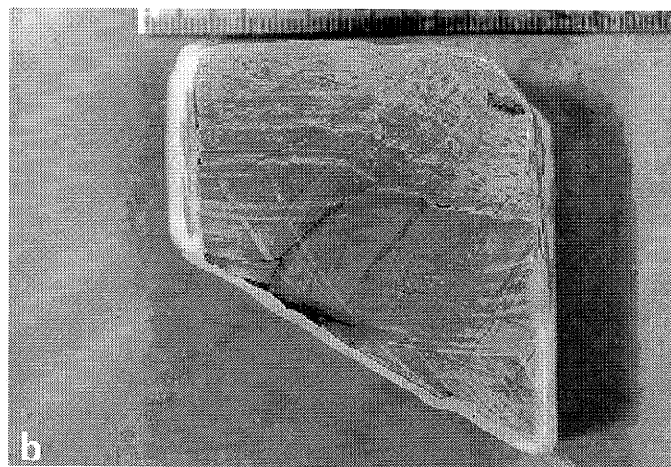
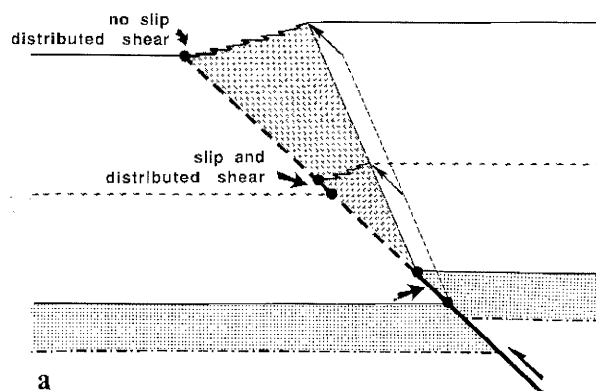


FIG. 9. - Model of distribution of the shear deformation above a blind ("propagating") thrust. a : the wedge-shaped and shaded area is the domain of bed shortening expressed as kink folds observed during dive KN09. b : natural example of a shear band showing this kind of distribution (core from the central Nankai accretionary prism, O.D.P. Leg 131, picture by T. Byrne).

FIG. 9. - Modèle de distribution de la déformation associée à un chevauchement aveugle (en propagation). a : distribution du glissement (slip) et de la déformation cisailante des couches (shear); b : un exemple de ce type de déformation à l'échelle centimétrique dans un échantillon du leg ODP 131 dans la partie centrale du prisme de Nankai (photo : T. Byrne).

is the hypothesis developed by Lallemand *et al.* [1992b]. The presence of a basement ridge might be the cause of a significant change in the topographic slope causing pop-up structures to develop within the upper thrust slices as described in figure 10.

Note however that physical properties of the wedge material such as cohesion can control the presence or the absence of major backthrust systems cutting through the stack of forward thrust imbricates, as shown by the squeeze-box modelling of Coulomb thrust wedges carried out by G. Mu-lugeta [1988]. In these experiments, Coulomb materials are shortened in front of a vertical rigid buttress and back-thrusts appear for significantly cohesive material in rela-

FIG. 8. - Nautilé pictures of the backthrust area

- a : dive KN 9. First encountered small-scale fold in the silt-mud alternations (depth : 2 270 m).
- b : dive KN 9. Same location as 7-a.
- c : dive KN 9. Typical eroded hinges of the tight overturned folds in the silt-mud alternations (2 250 m).
- d : dive KN 9. Shear zone cutting an overturned fold (2 207 m).
- e : dive KN 9. Detail of the same shear plane (2 207 m).
- f : dive KN 6. Strongly dipping beds on the BT0 steep slope (2 100 m).

FIG. 8. - Photographies prises du sous-marin Nautilé dans la région du r trochevauchement (plong es KN09 (a-e) et KN06 (f)). a et b : pli m trique rencontr    la base de la section d form e (prof. 2 270 m); c : charni res  rod es de mini-plis en chevrons dans les alternances de silts et d'argilites (prof. 2 250 m); d et e : plan de cisaillement recoupant obliquement les syst mes de plis (prof. 2 207 m); f : couches   fort pendage de la base du r trochevauchement BT0 (prof. 2 100 m).

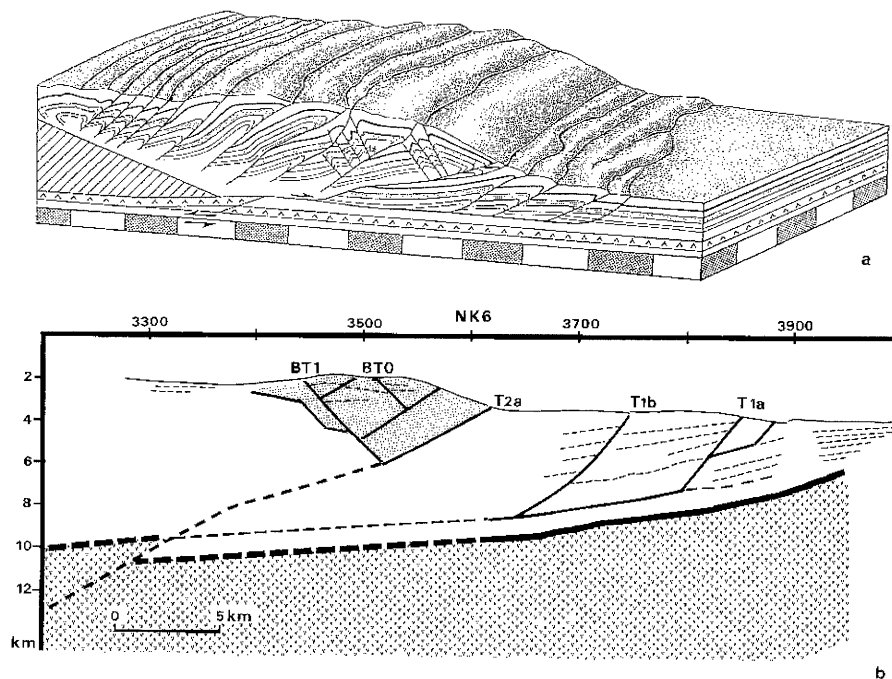


FIG. 10. – “Paleo-Zenisu ridge” subduction model for the origin of the backthrust system

a : line drawing of a “sand-box” experiment carried out by Lallemand *et al.* [1992b], showing the consequences of the subduction of a compressional relief under the prism. The relief is designed to mimic the Zenisu ridge thrust system [Lallemand *et al.*, 1989].

b : Interpretation of the seismic line NK6 as related to the subduction of an older compressional oceanic relief. The deep part of the section with dashed lines is extrapolated according to the sand-box experiment.

FIG. 10. – Modèle de subduction d’une “paléo-Ride de Zenisu” comme origine du système de rétrochevauchement. a : schéma d’une expérience analogique réalisée par Lallemand *et al.* [1992b], montrant l’effet de la subduction d’un relief de socle comparable à la ride de Zenisu sous le prisme. b : interprétation de la ligne sismique NK6 dans la même hypothèse de la subduction d’un relief de socle. La partie profonde de la section, en lignes tiretées, est extrapolée par comparaison avec le modèle analogique.

tively high angle tapered wedge. The second and most important parameter controlling the development of a backthrust at the rear of the wedge is the friction along the basal décollement [Malavieille *et al.*, 1991, Byrne *et al.*, 1993]. A high basal friction favours the development of a backthrust even in case of a landward dipping. On the other hand, a wedge with a seaward dipping backstop but with a low basal friction shows a poorly developed backthrust system. As stressed by Byrne *et al.* [1993]: “A detailed picture of an underlying backstop cannot be determined from surface information alone”.

V. – POSSIBLE RELATIONSHIPS BETWEEN THE FLUID CIRCULATIONS AND THE BACKTHRUST SYSTEM

Significant venting activity has been observed along the outcrop of a prominent backthrust of the Oregon active margin [Moore J.C. *et al.*, 1990]. In the same Kaiko-Nankai area, Chamot-Rooke *et al.* [1992] have shown that near the deformation front, the venting sites are related to a channelized flow through the major fault zones. It seems thus reasonable to investigate how closely the fluid seeps and the fault pattern are related in our backthrust domain.

Although we have carefully investigated both the BT0 outcrop zone and the summit of the anticline along the seismic section NK5, we have not found any clear evidence for active fluid seeps. The only indication for possible fluid outflow was a small cluster of living vestimentiferan tube worms together with a few dead *Calyptogena* and solemyid bivalves found at the very top of the ridge.

Along section NK6 (fig. 7), no evidence for seep was found along the outcrop of backthrust BT0. A single well defined seep was found on the top edge of the backthrust

scarp. But most of the seeps, whether active or fossil, were found along a roughly linear, 300 m wide band oriented approximately N070°E to E-W. Chaotic structures have been interpreted as indicating a concentration of tectonic activity. Sedimentary beds outcropping within this band are often broken and tilted up to the vertical. Lallemand *et al.* [1992a] propose that this tectonic feature is the surface expression of a strike-slip fault which could probably be right lateral, based on the N315°E overall shortening direction.

Finally, no seeps were found on the southern slope of the second unit where several thrust outcrops are known from seismics and multibeam bathymetry (e.g. T2b and T2c, see fig. 2) as well as from the field observation by submersible [fig. 2 and 5 in Lallemand *et al.*, 1992a]. Moreover, during one dive devoted to one of the mud volcanoes of this area (fig. 2), no active venting activity was found.

The presence of a significant amount of methane in the fluids sampled [Gamo *et al.*, 1992; Boulègue *et al.*, 1990] and the composition of the concretions made out of methane in the seep area [Sakai *et al.*, 1992] indicate that at least part of the fluids come from a depth of several hundred meters and possibly more. The problem then is to understand why the fluid seeps are mostly found along the supposed strike-slip fault outcrop zone. The interpretation we have given of the BT0 backthrust outcrop as a blind fault can explain why no significant fluid seeps out there. This is because the deformation in the outcrop area is distributed over more than 150 meters mostly through folding and consequently no significant increase in permeability may be expected there.

On the other hand, a vertical strike-slip fault may result in the formation of an increased permeability vertical zone rooted on a deeper reverse fault possibly connected to the

deep décollement. Behrman [1992] has shown that wrench faults and normal faults can show associated hydrofractures and permeability increases to greater depths than thrust faults. Unfortunately, a lack of reliable information about deep geometry of the fault system prevents us from speculating further on the deep piping system and does not give a credible explanation for the absence of fluid seeps along the frontal thrusts.

VI. – CONCLUSION

We have shown that a backthrust system characterizes the accretionary wedge east of Tenryu canyon opposite Zenisu intraoceanic compressive ridge. We propose to relate the formation of this backthrust system to this context by the presence of a fossil compressive ridge buried under the prism.

We have shown further that the backthrust system is the northern boundary of an asymmetrical large scale pop-up structure made of sedimentary material last deposited about 400 000 years ago. A detailed submersible survey of the southernmost backthrust (BT0 in fig. 2) shows well defined chevron type folds and reverse faults over a width of 150 meters. This is interpreted as the progressive deformation above a blind thrust. The backthrust movement which is located along a plane resolved on the seismic line at depth becomes progressively distributed through folding over a

significant width in the near-surface area.

Finally, we showed that no significant fluid seeps were found neither at the outcrop of the backthrust nor at the outcrop of seaward verging thrusts bounding the pop-up structure, although erosion is very active there. On the other hand, abundant seeps are present along the outcrop of a probable strike-slip fault zone slightly crossing obliquely the axis of the Yukie ridge anticline. We propose that this fault may be rooted at depth to the deep piping system and short circuit the shallower thrusts although we have no good evidences on the fault system at depth.

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