Impact of oceanic asperities on the tectogenesis of modern convergent margins

Subduction
Oceanic asperities
Tectogenesis
Tectonic erosion
Underplating

Subduction
Aspérités océaniques
Tectogenèse
Érosion tectonique
Accrétion subcrustale

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ABSTRACT

This paper presents some of the implications of oceanic asperities in subduction zones, based on examples gathered during the world circumnavigation of R/V *Jean Charcot*. The study of these examples provides a new overview of active margin modelling in response to asperity subduction. It is concluded that both erosion and accretion may be governed by the oceanic plate even though frontal tectonic erosion is better documented because it is accessible to conventional surveys. Most of the time, erosion is due to the relaxation of the arc slope in the wake of asperity subduction.

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RÉSUMÉ

Rôle des aspérités de la croûte océanique dans la tectogenèse des marges convergentes

A partir des données géophysiques récoltées lors du Tour du monde du N/O Jean Charcot, nous présentons une première synthèse des effets produits par la subduction d'aspérités sur la structuration des marges convergentes. Les exemples de zones de subduction étudiées sur le pourtour de l'Océan Pacifique (Japon, Philippines, Nouvelles-Hébrides, Tonga-Kermadec et Amérique Centrale) ont permis de reconnaître quatre types d'effets : impact morphologique, érosion tectonique, déformation interne de la marge et accrétion subcrustale. Des liens étroits existent entre la morphologie de la plaque en subduction et la structure du rebord de la plaque chevauchante. L'érosion tectonique des marges actives est de mieux en mieux documentée et semble se produire principalement dans le sillage des aspérités en subduction. En revanche, l'accrétion subcrustale de lambeaux sédimentaires ou océaniques est soupçonnée dans plusieurs cas mais reste encore difficile à prouver.

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INTRODUCTION

From 1984 to 1987, seven R/V *Jean Charcot* cruises were devoted to the study of the subduction zones around the Pacific rim where numerous asperities of the oceanic plate are subducted. Chronologically, these cruises were (Fig. 1): Kaiko I off Japan (from June to August 1984); Pop II off Mindoro (November 1984); Nanhai off Luzon (March 1985); Seapso I off New Hebrides (October 1985); Seapso V off Tonga (January 1986); Seaperc off Peru (July 1986) and Seamat off Middle America (from June to July 1987). Some of them, like Kaiko I or Seapso I, were followed by *in situ* observations and monitoring from the *Nautile* submersible: the Kaiko II (from June to August 1985), Subpso I (March 1989) and Kaiko-Nankai (August-September 1989) *Nadir* cruises. The oceanic asperities can be fault scarps, seamounts, hot-spot chains, spreading ridges, aseismic ridges, continental platforms, oceanic plateaus or fracture zones.

We recognize four effects of subducting asperities on the tectogenesis of the margins:

- Morphological imprint;
- Tectonic erosion;
- Internal deformation of the margin;
- Underplating or accretion.

We shall use terms like *margin complex*, *continental* or *island arc margin*, *upper plate* or *wedge* instead of *accretionary prism* in the text because, in our opinion, this last term is not appropriate to the consuming margins that we describe. Among the discussed areas, it can only be used for the Nankai Trough.

MORPHOLOGICAL IMPRINT

When an oceanic asperity subducts, the margin adapts itself on the underthrusting topography even when the asperities are small fault scarps. Seabeam and single-channel seismic data recovered from R/V *Jean Charcot* surveys provide an excellent support for discussing this topic.

Oceanic faults

During Kaiko I cruise in the northern Japan Trench (Cadet *et al.*, 1987), we have shown that two sets of oceanic plate faults are reactivated beneath the continental margin, and that gravity sliding consequently developed in the upper plate along these oceanic directions. They are N-S trending horst and grabens, related to the bending of the oceanic plate when entering the subduction zone, on the one hand, and ancient normal faults set N 65° inherited from the original structure of the oceanic crust, on the other hand (Fig. 2). The N 65° fault set parallel to the oceanic magnetic lineations seems to be reactivated into vertical (or

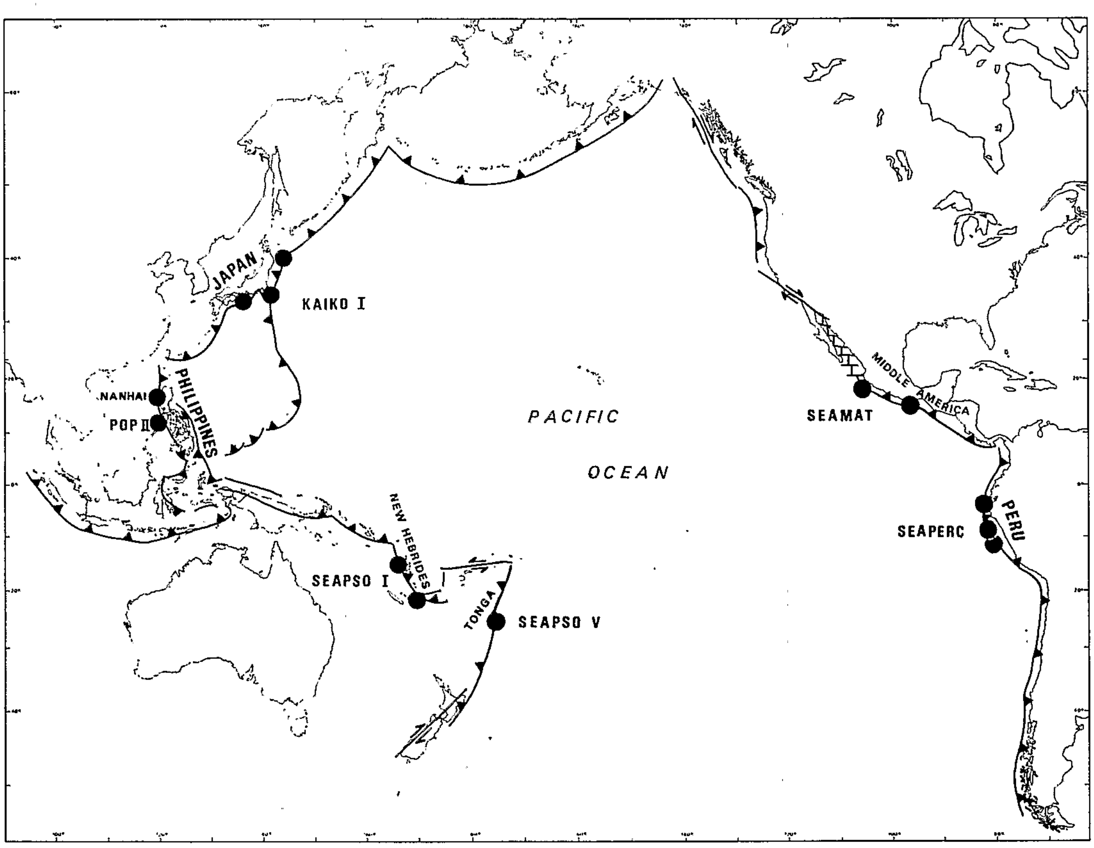

Figure 1

Location of the Pacific areas surveyed during the circumnavigation of R/V Jean Charcot and discussed in the text.
Localisation des zones reconnues lors du Tour du Monde du N/O Jean Charcot et discutées dans le texte.

reverse) faults with a major right-lateral component. Apparent vertical offset can reach 50 to 200 m and apparent lateral offset of a few kilometres can be checked along the trench axis for example (Fig. 2, Lallemand *et al.*, 1986). The N 65° lineaments can be traced 25 km landward of the trench axis at a point where the crustal thickness of the margin reaches 8 km. Thus, we can, at least partly, relate the N-S cliffs of the landward slope to the passage of the N-S oceanic normal fault scarps. This relation implies that the oceanic grabens are not entirely filled by slumps or turbidites. Alternatively, cliffs of the landward slope may be caused by oceanic faults that are reactivated below the margin, as shown by some focal mechanisms of earthquakes.

The horst and graben morphology developed across the plunging Pacific plate on the Tonga and Kermadec trenches seaward slopes (Fig. 1 and 3) probably constitutes the best example of extensional faulting induced by bending of the downgoing lithosphere. Multibeam mappings at different places in the Tonga trench area (Seapso V: Jean Charcot cruise and T. Washington transit) indicate that the bending-induced scarps are frequently up to more than 1 000 m and sometimes reach up to 1 500 m in vertical displacement (Pontoise *et al.*, 1986; Lonsdale, 1986; Pelletier and Dupont, this volume). Near the deepest part of the Tonga Trench (more than 9 500 m deep), these spectacular horsts and grabens trend N 15° to N-S. They are discontinuous along strike and interrupted by small transverse scarps that trend N 60°-70°. These transverse features probably correspond to the grain of the oceanic crust, because they parallel the magnetic lineations. The trench axis shows "en-échelon" basins almost parallel to the major scarps of the seaward slope and surrounded by steep slopes; the landward side being a straight scarp of

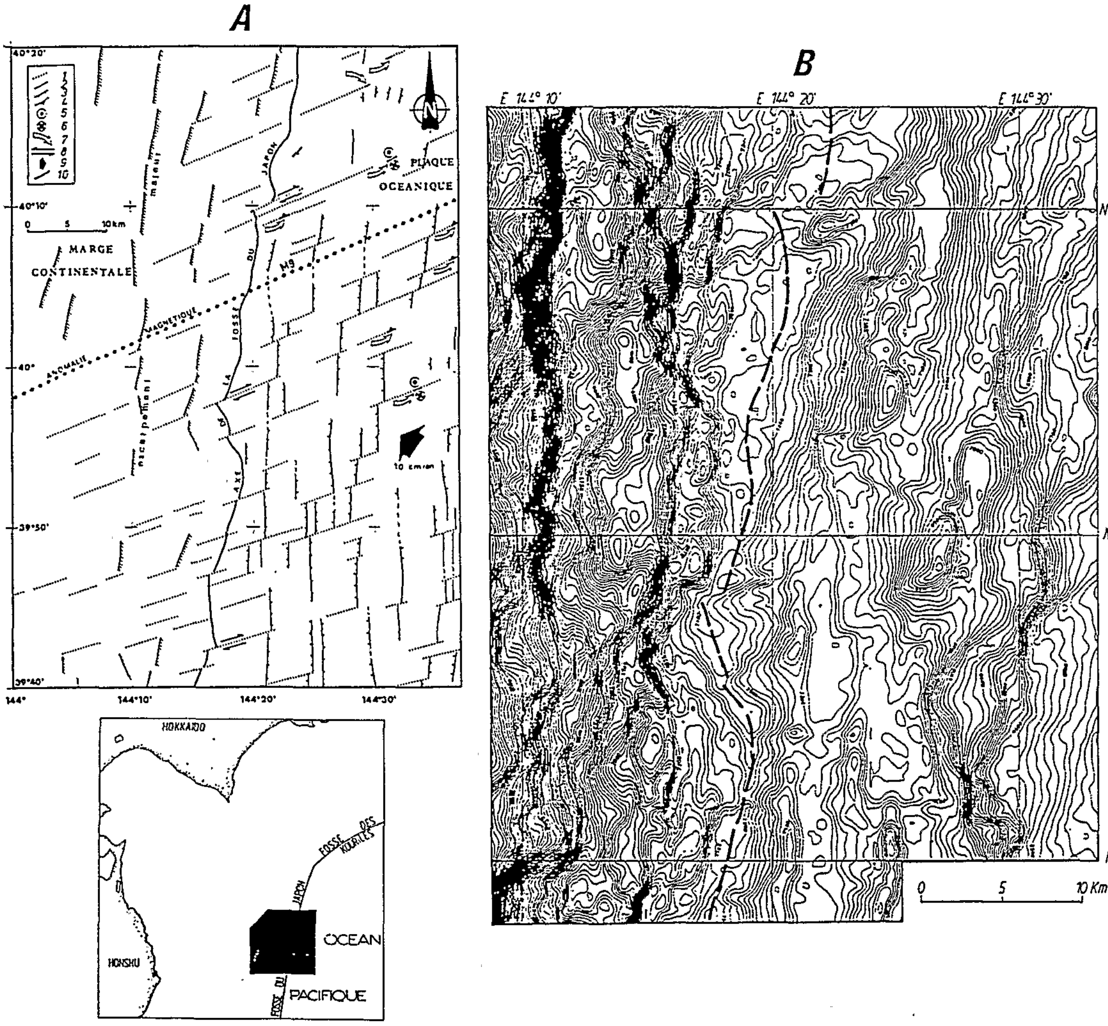

Figure 2

A- Structural map. 1 - Structural alignments or "lineaments" subparallel to oceanic magnetic lineations. 2 - Vertical faults. 3 - Normal faults. 4 - Apparent reverse faults on seismic profiles. 5 - Upfaulted block. 6 - Downfaulted block. 7 - Intersection point between N 65° lineaments and an E-W seismic profile. 8 - Fault with at least one important right-lateral component. 9 - Pacific plate motion relative to the Japanese plate (N 55°W). 10- Escarpments facing the trench axis (after Lallemand et al., *1986).*
B- Zoom on the Seabeam bathymetry of the Japan Trench showing a sector where some N 65° lineaments are aligned across the trench axis (in dotted lines). Isobaths each 20 m.
A- Carte structurale. 1- Alignements structuraux ou "linéaments" subparallèles aux linéations magnétiques. 2- Failles verticales. 3- Failles normales. 4- Failles d'aspect inverse sur les profils sismiques. 5- Bloc soulevé. 6- Bloc abaissé. 7- Intersection entre les linéaments N 65° et les profils sismiques E-W. 8- Faille ayant au moins un rejet dextre important. 9- Mouvement relatif de la plaque Pacifique par rapport à la plaque Japonaise (N 55°W). 10- Escarpements regardant la fosse d'après Lallemand *et al.*, 1986. B-Gros plan de la bathymétrie Seabeam de la fosse du Japon montrant un secteur où des linéaments N 65° traversent l'axe de la fosse (en pointillés). Intervalle entre les isobathes : 20 m

700-900 m height. Sills (or basement highs) between basins are observed where slightly oblique horsts and grabens or transverse structures enter into the subduction zone. The landward slope exhibits a stepped morphology suggesting a back-tilted fault-block tectonics. Scarps reach 200 to 800 m in height and strike N-S to N 15°, parallel to the trench and seaward slope major scarps. These data clearly suggest that the morphology of the lower landward slope is largely governed by the structures of the subducting plate (Lonsdale, 1986; Pelletier and Dupont, this volume). Possibly, as in the Japan Trench, structure, collapse and erosion of the Tonga landward slope is controlled by the passage underneath of these spectacular bending-induced scarps.

In the Manila Trench (Nanhai cruise), Pautot and Rangin (1989) noticed that the inherited fabric of the subducted oceanic crust had no major structural imprint on the landward slope fabric except the transform faults morphology which guides slightly the trend of the deformation front at the base of the landward slope.

Seamounts

The western Pacific plate supports many seamounts, some of them just beginning to subduct at trenches.

The Kaiko programme has studied several seamounts that are now at various stages of subduction in the Japan Trench (Fig. 4). The Daiichi Kashima seamount, approximately 60 km in diameter and 3.5 km in height, is partly subducted in the southern Japan Trench, resulting in a 7 km reentrant and several hundreds of metres of uplift of the continental margin. This produces a trough parallel to the trench and 20 km landward of it. The morphological imprint of the subducted part of the seamount on the margin is accommodated in three ways: the oceanic plate is depressed by more than 100 m due to the load of the seamount and the landward part of the seamount is down-faulted up to 1.7 km; the lower landward slope is uplifted in response to the local thickening of the toe of the prism; and the oversteepened lower slope collapses and the debris from mass-wasting subducts as suggested by the lack of filling in the trench (Lallemand *et al.*, 1989).

At the junction between the Japan and Kuril trenches, it has been also demonstrated by Lallemand and Chamot-Rooke (1986), mainly on the basis of its magnetic signature, that a subducting volcano is responsible for the 20 km reentrant of the landward slope. Inasmuch as the seamount is entirely buried below the lower landward slope, its size has been deduced from a 3-D magnetic model and corresponds to 30 km in diameter and 1.8 km in height, that is to say about 2500 km^3. The margin, formerly uplifted by 1.6 km above the top of the seamount, (corresponding to about 2000 km^3 of positive topographic anomaly), collapsed behind the trailing flank of the seamount producing an indentation (corresponding to about 500 km^3 of negative topographic anomaly) of the lower arc slope (see cross-section H-G on Fig. 4 and Fig. 5).

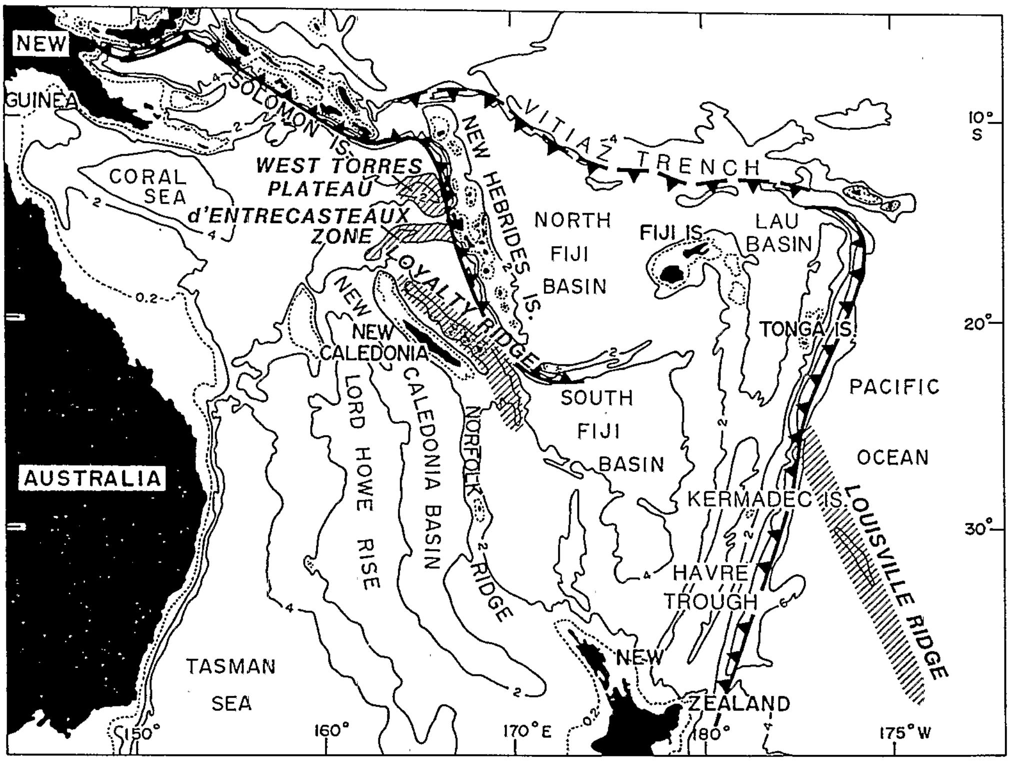

Figure 3

Structural sketch of the SW Pacific region showing the studied area. Isobaths each km (modified from Collot et al., 1987).

Schéma structural du Sud-Ouest Pacifique montrant la zone d'étude. Les isobathes sont contourées tous les km (modifié d'après Collot *et al.*, 1987).

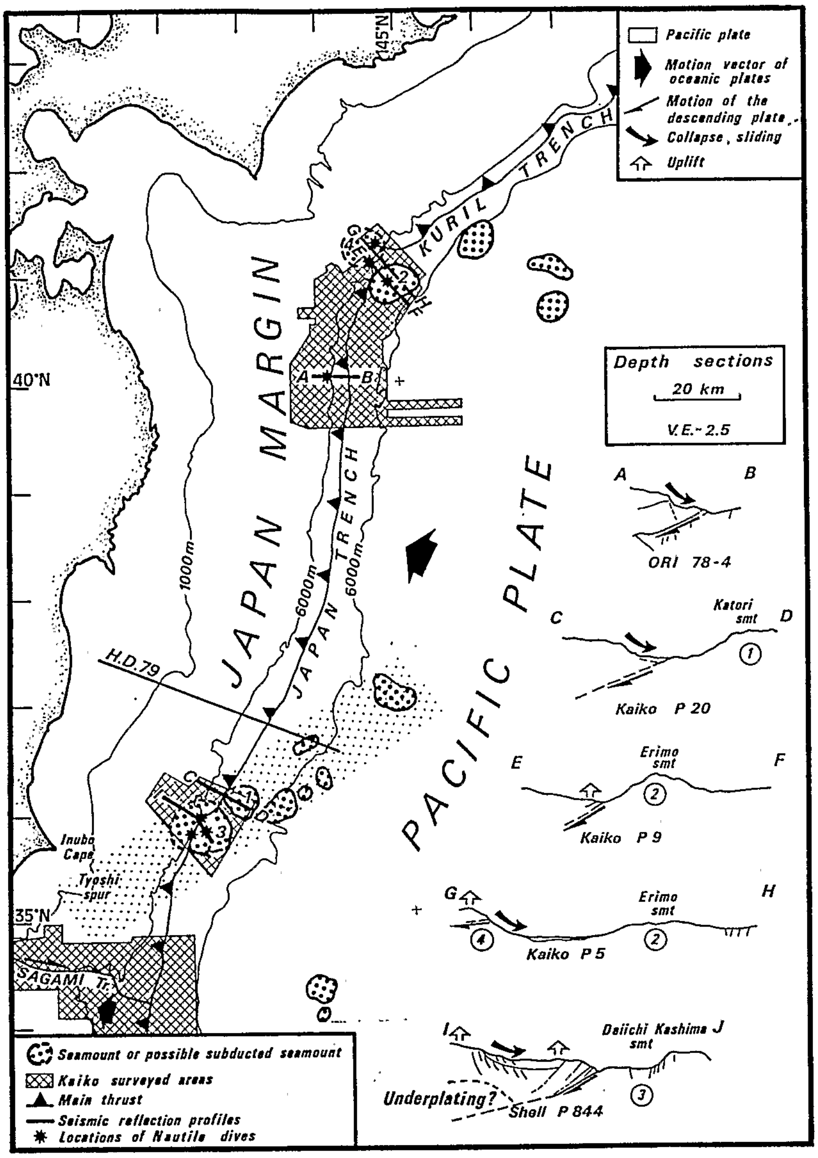

Figure 4

Locations of seamounts near the Japan Trench axis and simplified depth sections along some seismic lines at different stages of seamount subduction. Shaded band represents area of seamount chain subduction. Circled numbers refer to different seamounts plotted along the trench (after Lallemand and Le Pichon, 1987).

Localisation des monts sous-marins le long de la fosse du Japon et sections profondeurs simplifiées le long de quelques lignes sismiques à différents stades de subduction de monts sous-marins. La bande en grisé représente la projection sous le prisme de la chaine volcanique sous-marine. Les numéros cerclés renvoient aux monts sous-marins reportés sur la carte (d'après Lallemand et Le Pichon, 1987).

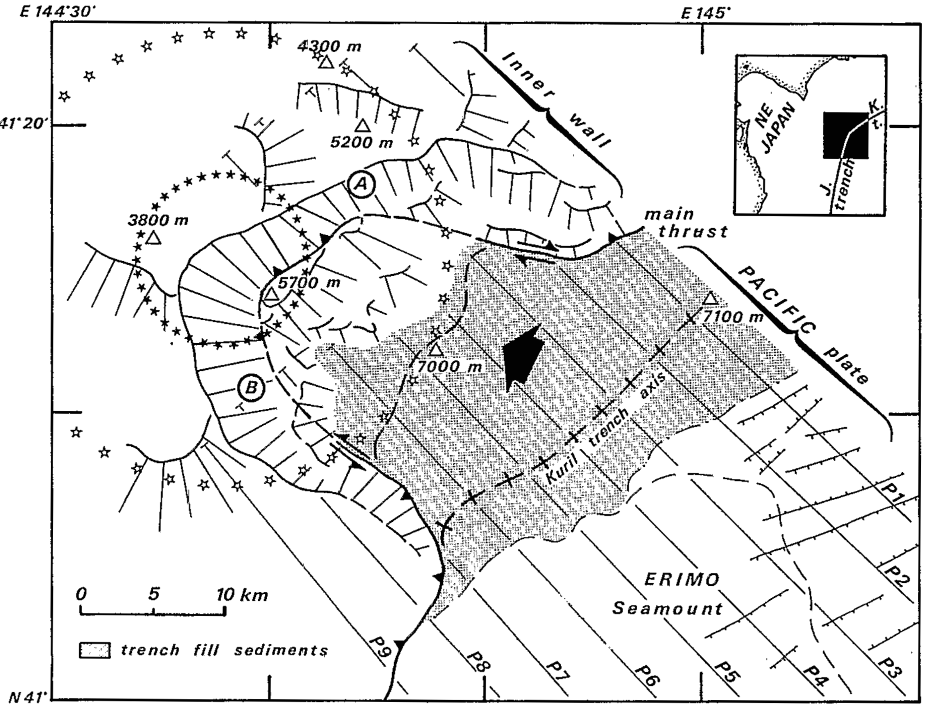

Figure 5

Structural map of the junction between the Japan and Kuril trenches. Dashed line at base of landward slope: deepest occurrence of the top of acoustic basement under turbidites. Solid stars: the top of volcano . Open stars : base of the seamount (at average depth of 7750 m, diameter 32 km). Both contours are entirely deduced from magnetic modelling after Lallemand and Chamot-Rooke, 1986. A and B are the locations of NAUTILE dives. Grey pattern : occurrence of trench fill. Curves with long barbs : cliffs. Straight lines with small barbs: oceanic normal faults. P1 to P9 : locations of single-channel seismic lines. Inset: J. trench = Japan Trench, K. t. = Kuril Trench.

Carte structurale de la jonction des fosses Japon et Kouriles. Pointillés à la base du mur interne : profondeur maximale de la croûte. Étoiles pleines : toit du volcan. Étoiles évidées : base du volcan subduit (profondeur moyenne: 7750 m, diamètre: 32 km). Ces contours sont entièrement déduits du modèle magnétique d'après Lallemand et Chamot-Rooke, 1986. A et B localisent les plongées du Nautile. Zone grisée : sédiments de remplissage de la fosse. Courbes avec de longues barbelures : escarpements. Droites avec de petites barbelures : failles normales océaniques. P1 à P9 : localisation des profils de sismique monotrace. Encart: J. trench = Fosse du Japon, K. t. = Fosse des Kouriles.

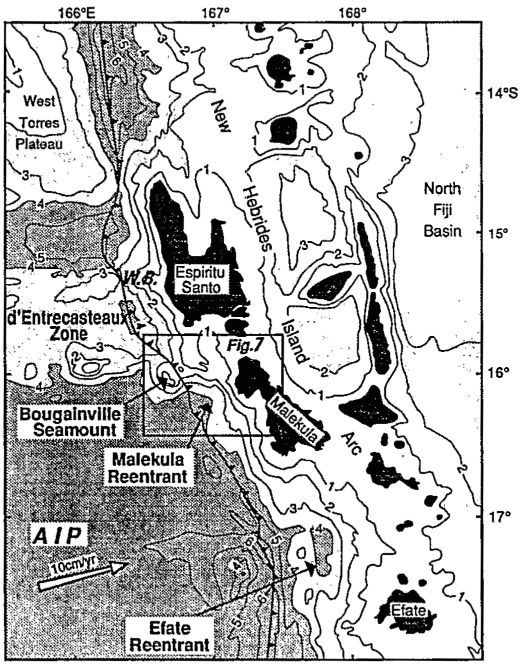

Figure 6

Central New-Hebrides island arc. AIP: Australia-India Plate. Barbed line shows the seafloor trace of the interplate decollement, barbs show downdip direction. Bathymetric contour interval is 1 km. W.B. = Wousi Bank. Location of fig. 7 (after Collot and Fisher, 1989).

Arc insulaire des Nouvelles-Hébrides centrales. AIP: Plaque Indo-australienne. La ligne avec les triangles souligne la trace sur les fonds marins du décollement interplaque, les triangles montrant la direction d'enfoncement. Les contours bathymétriques sont reportés tous les km. W.B. = Banc de Wousi. Localisation de la Fig. 7 (d'après Collot et Fisher, 1989).

Part of the missing slope material is sedimented in the trench, as suggested by the unusual trench fill thickness reaching locally 700 m (Lallemand, 1987) and the rest might be subducted.

Lallemand and Le Pichon (1987) considered that the Japan Trench margin evolved as a homogeneous wedge of deformable, noncohesive Coulomb material during seamount subduction, and show that the application of the Davis, Suppe and Dahlen model (1983) could account for the observed deformation. Their model predicted that the first consequence of seamount subduction is a compressive thickening of the toe of the wedge above the advancing flank of the seamount because of the oversteepening of the rigid base of the wedge; this agrees with our observations in the Daiichi Kashima area. This thickening shifts landward across the wedge with the advancing flank of the seamount. Erosion dominates the wedge above the trailing flank of the seamount because of the corresponding understeepening of the rigid base of the wedge. A reentrant is thus created in the toe of the wedge; it is largest when the oceanic flank of the seamount coincides with the base of the landward slope. At this time, the trench will probably have an abnormally large amount of sediments, as illustrated at the junction between the Japan and Kuril trenches (Fig. 5). After the subduction of the seamount, the edge of the wedge should progressively move back to its initial location, because no significant reentrants along the Japan Trench margin have been observed, despite the probable past subduction of seamounts.

In the New-Hebrides Trench off Esperitu Santo (Vanuatu), the Bougainville seamount is now at the same stage of subduction as the Daiichi Kashima seamount in the Japan Trench (Fig. 6). Furthermore, its size is similar to that of Kashima. The area was surveyed by R/V *Jean Charcot* during the Seapso I cruise and the following observations were made: no clear normal faulting affects the seamount, the margin is uplifted above the advancing flank of the seamount and the margin presents a 10 km reentrant (Daniel *et al.*, 1986). Immediately south of this seamount lies the deep subcircular Malekula reentrant in the lower arc slope (Fig.7). Its proximity as well as the similarity in morphology between this reentrant and that at the junction between Japan and Kuril trenches suggest that it is also formed by the collision of a seamount with the arc (Collot and Fisher, 1989). No clear magnetic signature proves that a seamount is subducting, but a strong and nearly circular uplift of the northern end of Malekula island (30 to 40 km landward of the reentrant along the direction of plate convergence) has been recorded. Consequently, it is probable that a subducted seamount forms an asperity and caused both the recent uplift and the recent reentrant. Using Seabeam data, Collot and Fisher (1989) propose that after formation of the reentrant, two styles of deformation cooperate to restore the arc slope: one involves collapse of the slope rocks surrounding the reentrant; the other includes the formation of a new accretionary wedge across the mouth of the reentrant (Fig. 7). These authors suggest that such a restoration process could lead to formation of a subcircular forearc basin; such a basin may be exemplified by the basin ensconced in the Efate reentrant (Fig. 6).

During the SEAMAT cruise (Fig. 1), which occurred along the Middle America Trench, a topographic high

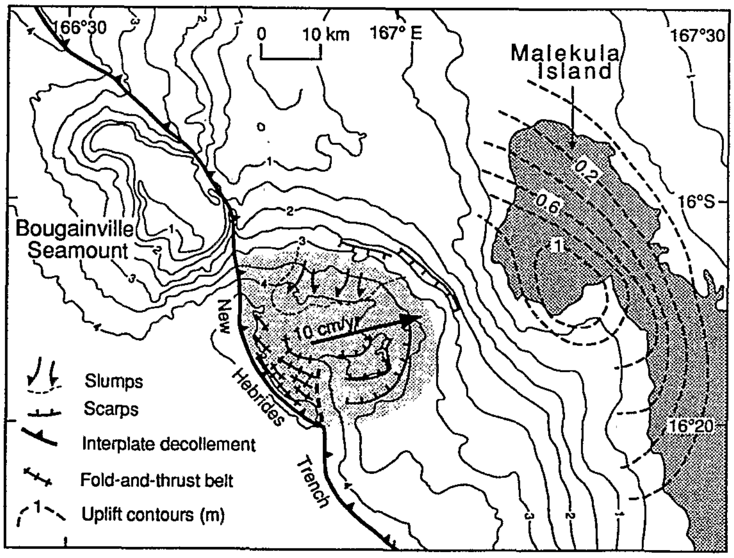

Figure 7

Structural interpretation of the morphology of the Malekula reentrant, which is outlined by the box in figure 6. Contours on Malekula island are derived from coral terraces and show the magnitude of uplift during the 1965 earthquake. The Malekula reentrant and the area of maximum uplift are aligned along the plate convergence vector. Bathymetric contour interval is 500 m (after Collot and Fisher, 1989).

Interprétation structurale de la morphologie du rentrant de Malekula, défini par une boîte dans la Figure 6. Les contours sur l'île de Malekula sont déduits des terrasses coralliennes et montrent l'amplitude du soulèvement lors du séisme de 1965. Le rentrant de Malekula et la zone de soulèvement maximal sont alignés parallèlement au vecteur convergence. L'intervalle entre les contours bathymétriques est de 500 m (d'après Collot et Fisher, 1989).

observed at the base of the landward slope just north of the junction of the trench with the Tehuantepec ridge was interpreted as an uplift related to the passage of a volcano in the subduction zone. As a matter of fact, this prominent feature is located in the continuation of a volcanic chain lying on the oceanic crust (Seamat cruise report, unpublished).

Ridges

Generally, sublinear ridges creep laterally along subduction zones because they trend obliquely to the plate convergence vector and the trench axis.

During Kaiko I (first phase, 1984), the junction between the Nankai Trough and the Ryukyu Trench was surveyed (Le Pichon *et al.*, 1987; Fig. 8). It is marked by subduction of the NNW-SSE Kyushu-Palau ridge which is a remnant volcanic island arc, inactive since 28 My (Karig, 1971). The northernmost extremity of the ridge is topographically less pronounced than further south; it is approximately 20 km wide, and 500 m high. The trend of the Nankai Trough in this area is NE-SW and the subduction vector is oriented N 310° so that the ridge is creeping slowly southwestward along the subduction zone. The ridge appears to act as an indenter on the margin generating a 30 km reentrant, the tip of the indenter being at present situated under the upper accretionary prism. The general bathymetric map confirms that subduction of the ridge does not produce collision effects similar to those induced by the Izu-Bonin ridge. The main reasons are probably that this ridge is much narrower, deeper and colder than the Izu-Bonin ridge. However, the quite peculiar configuration of the margin (Fig. 8) shows an asymmetric indenting effect. The asymmetry is obviously related to the present obliquity of the morphological axis with respect to the N 310° subduction vector.

The Nanhai cruise took place at the junction between the extinct *South China Sea spreading ridge* and the Manila Trench off Luzon (Pautot and Rangin, 1989). Seamounts (e.g. Scarborough seamount chain) are present westward all along the spreading axis. They are 30-40 km in diameter and 1.5 to 3 km in height, and they might have been injected in the rift structure after cessation of spreading (Taylor and Hayes, 1980) during the Late Miocene. The N 310° trending convergence between the South China Sea oceanic plate and the Luzon Arc along the N-S Manila Trench suggests that the ridge creeps slowly southward along the subduction zone (Fig. 9). The double curvature of the trench is interpreted as a

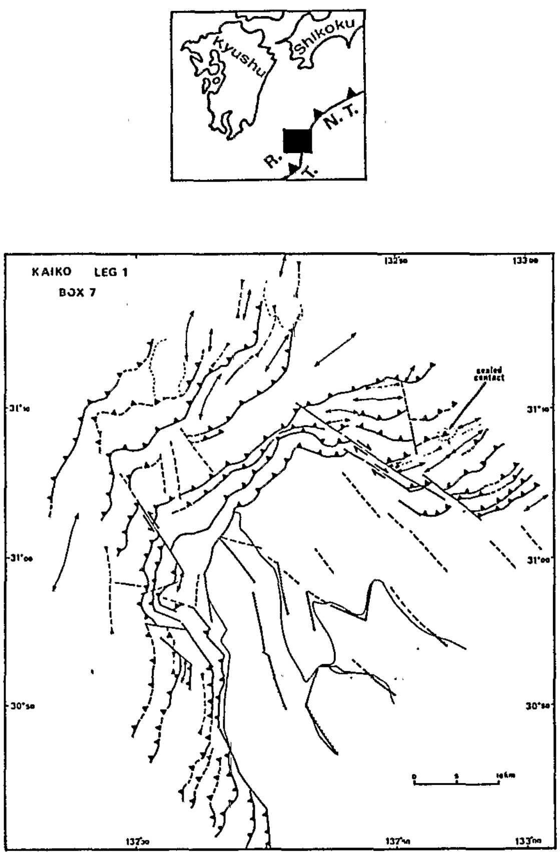

Figure 8

Structural sketch map of the surveyed area at the junction between the Kyushu-Palau ridge and the Nankai Trough. R.T. = Ryukyu Trench; N.T. = Nankai Trough (after Le Pichon et al., 1987).
Schéma structural de la zone reconnue à la jonction entre la ride Palau-Kyushu et la fosse de Nankai. R.T. = Fosse de Ryukyu; N.T. = Fosse de Nankai (d'après Le Pichon et al., 1987).

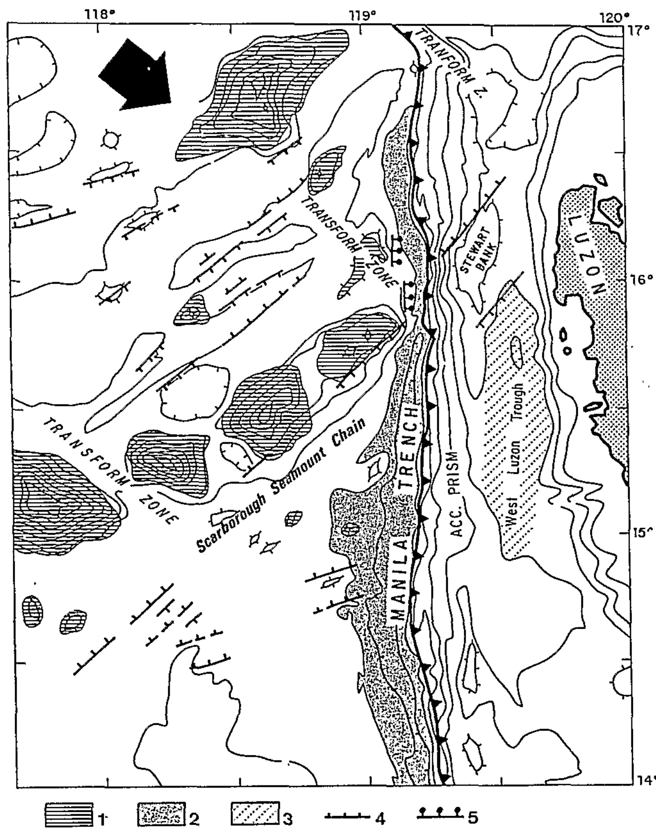

Figure 9

Interpretative sketch map of the Manila Trench surveyed area at the junction between the Scarborough chain and the trench. Main features are plotted combining multibeam and single-channel seismic data. 1= seamounts; 2= trench fill; 3= forearc basin; 4= normal fault related to the spreading history of the South China Sea; 5= normal fault near the trench and related to flexure of lower plate. Isobaths each 500 m (Pautot and Rangin, 1989).
Schéma interprétatif de la zone reconnue de la fosse de Manille à la jonction entre la chaîne Scarborough et la fosse. Les traits principaux sont reportés et déduits du Seabeam et de la sismique monotrace. 1 = monts sous-marins ; 2 = sédiments de remplissage de la fosse ; 3 = Bassin avant-arc ; 4 = Faille normale liée à l'expansion de la Mer de Chine du Sud ; 5 = Faille normale près de la fosse et liée à la flexure de la plaque en subduction. Les isobathes sont tous les 500 m (Pautot et Rangin, 1989).

result of the indentation sweeping of the ridge. The subducted axial seamount chain characterized by a strong relief has left a clear impact in the fore-arc area. The most evident of these structures is the Stewart Bank, which can be traced 50-60 km eastward on the landward slope of the trench. The fore-arc basin is clearly interrupted in front of the ridge (Fig. 9) and two distinct subbasins are known: the West and North Luzon Troughs. The first of these is not yet affected by the ridge subduction, while the second (extending north of 18°N, out of the Fig. 9) is characterized by an irregular topography. Between these two basins lies a broad structural high corresponding to the Stewart Bank.

The curvilinear d'Entrecasteaux Zone is at present subducting below the New Hebrides island arc. It is a 80 km wide submarine complex of ridges and seamounts that extends from the northern New Caledonia ridge to the Central New Hebrides (Fig. 6), and comprises two east-trending ridges 2 to 4 km high: the North d'Entrecasteaux ridge and the South d'Entrecasteaux chain (Collot *et al.*, 1985). The convergence between the Australia-India plate and the Pacific plate supporting the island arc occurs approximately along a N80° direction. The E-W d'Entrecasteaux Zone being slightly oblique to the plate convergence, it creeps slowly northward parallel to the trench at an average rate of about 2.5 cm/yr. Unlike the indentation created in the Nankai margin by the Palau-Kyushu ridge, no indentation is recognized in the New Hebrides margin in front of the North d'Entrecasteaux ridge (Collot and Fisher, in press). However, the major feature of slope morphology in the central part of the "collision" zone is the broad protrusion that cuts transversely across the slope and culminates in the Wousi Bank, which almost reaches sea level. This strongly uplifted area (1500-2500 m) is clearly due to the passage of the crest of the North d'Entrecasteaux ridge.

The N 155° Louisville Ridge, a Late Cretaceous and Cenozoic hot-spot chain of guyots and seamounts, obliquely enters the N 20° Tonga-Kermadec subduction zone at 26°S, causing a major sill which marks geographically the transition between the Tonga and Kermadec Trenches (Fig. 10). Extinct volcanoes of the Louisville ridge are distributed along a 75 km-wide band (Lonsdale, 1988). The northernmost occurrence of the ridge before subduction is the Osbourn guyot which is 30 km in width at its base and 3 km in height, culminating at 1900 m water depth. Taking into account the convergence motion between the Pacific-plate and the Tonga-Kermadec arc-platelet, the ridge swept the Tonga Trench (Dupont, 1979) and creeps rapidly southward along the Kermadec Trench at a minimum rate of 10 cm/yr (Pelletier and Dupont, this volume). Several large-scale drastic changes occur west of the ridge-trench junction (Fig. 10):

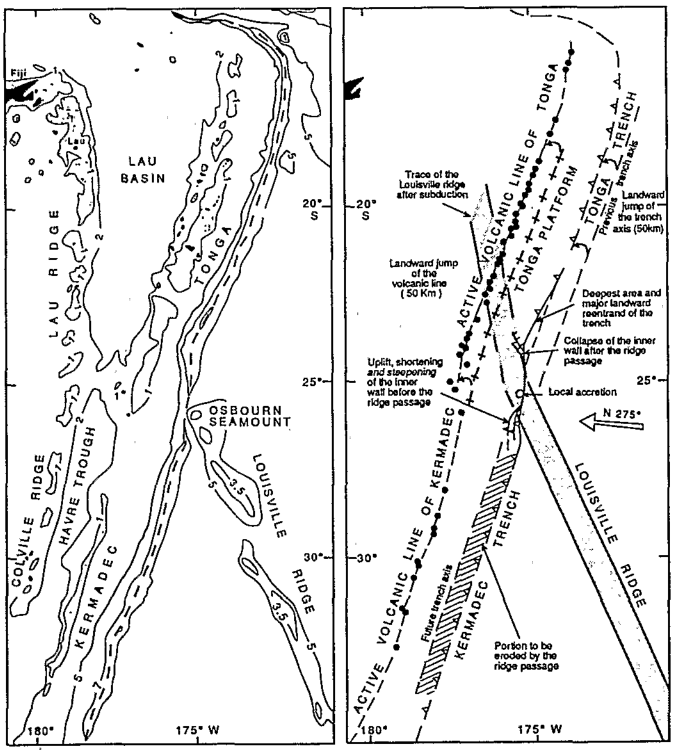

Figure 10

Simplified bathymetric and structural maps of the Tonga-Kermadec island arc system, illustrating the effects of the Louisville ridge subduction. Depths are in km. Full circles are emerged and submerged volcanoes identified from bathymetry or single channel seismic data. Projection of the previously subducted portion of the ridge assuming a N 155° trend is shown. Convergence motion at the Louisville ridge-trench intersection is from Pelletier and Louat(1989), (adapted from Pelletier and Dupont, this volume).

Cartes bathymétrique et structurale simplifiées du système d'arc insulaire Tonga-Kermadec illustrant les effets de la subduction de la ride de Louisville. Les profondeurs sont en km. Les cercles pleins correspondent aux monts sous-marins émergés et immergés identifiés à partir de la bathymétrie et des profils sismiques monotraces. La projection de la partie déjà subduite de la ride N 155° est reportée. Le mouvement relatif des plaques au niveau de l'intersection ride-fosse est tiré de Pelletier et Louat (1989), (adapté de Pelletier et Dupont, ce volume).

- The trench presents a segment that strikes N-S and links the N 20°-parallel Tonga and Kermadec Trenches, resulting in a misalignement and a 50 km offset between the trenches;
- The Tonga Platform located between the active arc and the trench disappears southward and is replaced by the Kermadec ridge including active volcanoes and a seaward sloping fore-arc basin;
- The Tonga active volcanic arc is also misaligned and offset landward with respect to the Kermadec volcanic island chain;
- The back-arc domain is short and presents a major sill between the Lau Basin and the Havre Troughs. Moreover, both rates of convergence at the trench and back-arc opening increase drastically north of the ridge-trench junction (Pelletier and Louat, 1989).

The Louisville ridge-trench intersection was surveyed during the Seapso V cruise (Pontoise *et al.*, 1986; Pelletier and Dupont, this volume). South of the intersection, where the flank of the ridge arrives at the subduction zone, the Kermadec Trench shallows and migrates westward due to a change in trend from N 20° to N-S. This landward shift observed in the restricted Seabeam survey is 17 km, but reaches 50 km from the end of the N 20° Kermadec Trench to the junction point. Simultaneously, the landward slope of the trench axis steepens, shortens and uplifts (1 500 m) due to the landward dipping thrust faults created in response to the advancing ridge. As mentioned above at the intersection, the trench is marked by a major sill reaching 5 500 m in depth, 3 500 m above the mean depth of the Tonga and Kermadec Trenches. This sill occurs just west of a small satellite seamount of the Osbourn guyot, that partly clogs the trench. In front and in the extension of the ridge, although a small hill could be an offscraped volcano at the base of the landward slope, major elongated hills (reaching 2 600 m water depth) and depressions are likely parts of the landward slope locally uplifted and collapsed over the relief of the subducted ridge. North of the junction, immediately after the eastern flank of the ridge entered the subduction zone, the trench is abnormally deepened by more than 10 000 m and the trench axis shows an arcward virgation. The landward slope deepens rapidly northward, has a stepped morphology and is affected by collapse and mass-wasting along two normal-fault sets, one parallel to the trench and the seaward slope bending-induced scarps and the other transverse to the trench.

TECTONIC EROSION

Most of the margins registering asperities subduction are characterized by tectonic erosion. Active tectonic erosion means a loss by faulting, slumping and dragging of continental or arc material at the front of the margins. We will only emphasize the role of the subduction of asperities on tectonic erosion.

Von Huene and Lallemand (1990) have estimated the magnitude of frontal erosion along the northern Japan and Peru margins superior to 50 and 27 km respectively during the last 20 Ma. Including subcrustal erosion, this provides minimal estimated rates of erosion through a cross-section of the Japan and Peru trenches of 50 and 27 km^2/Ma respectively. The erosion rate reached 44 km^2/Ma during the last 8 Ma. Von Huene and Lallemand noticed that one agent of such erosion is the subduction of asperities on the subducting lower plate. Rather than abrading, the positive topographic features break up the base of the slope by elevating and oversteepening it to a condition of general gravity failure. The disaggregated slump debris are transported down the subduction zone on the descending plate, as the absence of a significant trench fill suggests.

Tectonic erosion related to ridge subduction has been proposed along the Tonga-Kermadec Trench (Pelletier, 1989; Pelletier and Dupont, this volume). As discussed above, the Tonga volcanic island chain and trench are shifted 50 km to the west with respect to the Kermadec system (Fig. 10). Consequently, the distance between the trench and the summit of the arc (now inactive) shortens and the landward trench slope steepens from Kermadec to Tonga. Because these changes suggest a disappearance of a lower part of the landward slope and occur at the latitude of the Louisville ridge-trench intersection, it could be concluded that the ridge erodes during its oblique passage a part of the front of the upper plate and is easily subducted - excepted some portions locally and temporarily accreted - under the Tonga-Kermadec margins (Pelletier, 1989; Pelletier and Dupont, this volume). Erosion occurs before and after the ridge passage following different processes. South of the junction, the base of the arc margin is shortened and eroded by underthrusting; indeed, the Tonga platform and the shifts of the trench and the volcanic island chain already exist immediately north of a line parallel to the convergence motion and crossing the ridge-trench intersection (Fig. 10). The landward flank of the ridge seems to abrade the cumbersome part of the landward slope before underthrusting the margin. North of the junction, the landward slope collapses and debris from mass-wasting subducts (Pelletier and Dupont, this volume); indeed, the deepest part and the largest reentrant of the Tonga Trench occur just north of the intersection between the trench and the eastern flank of the ridge, and probably result from an accelerated erosion due to the relaxation of the slope in the wake of the ridge subduction. The size of the eroded part between the Kermadec and Tonga margins and consequently the 50 km westward retreat of the trench and volcanic arc are a function of the dip of the lower trench slope and of the height of the facing ridge.

South of the North d'Entrecasteaux ridge, Collot and Fisher (1989b) and Fisher *et al.* (in press), describe a vigorous erosion of the arc slope along large normal faults accompanied by numerous slump masses due to the relaxation of the arc slope in the wake of the ridge. The area of the "collision" zone that is affected by tectonic erosion and mass-wasting is about twice as large as the width of the ridge and the authors estimate the time required to heal the morphologic disturbances caused by the ridge subduction in the order of 0.8 Ma.

INTERNAL DEFORMATION OF THE MARGIN

We can now examine the tectogenesis of the margin in terms of internal deformation. Seismic reflection data interpretations and *in situ* observations by submersible give information for this.

Because in the Coulomb wedge model, the critical topographic slope changes much slower than the dip of the rigid base, the dramatic changes in dip of the subducting plate that accompany the subduction of a seamount induce a characteristic sequence of tectonic events, which Lallemand and Le Pichon (1987) have identified in the Japan Trench. As the subducted seamount progresses below the wedge, a zone of shortening and thickening that overlies the landward flank of the seamount progresses at the same velocity; this zone is followed by a zone of erosion and slumping that overlies the trailing flank of the seamount.

The shortening of lower trench slopes in "collision" zones can reach several tens of kilometres mainly as a function of the size of the subducting body. Concerning seamounts, we observe a 7 to 10 km reentrant in front of Daiichi Kashima and Bougainville seamounts, which are partly engaged in the subduction zone. Reentrants observed in the immediate wake of subducted seamounts, at the junction between Japan and Kuril trenches and south of Bougainville, have typically a diameter of 20 km. The indentations related to the impingement of large scale ridges are of the order of several tens of kilometres (50 km in front of the Louisville Ridge for example).

Such a shortening is accommodated along thrust faults within the lower trench slope and creates a consequent thickening of the prism during the subduction of the positive feature (see the amplitude of uplift in the previous section, from a few hundreds of metres to a few kilometres) and then a relaxation by mass-wasting.

As a matter of fact, two prominent thrusts are recognized along the P-844 Shell multichannel seismic line in front of the Daiichi Kashima seamount (Lallemand *et al.*, 1989). They crop out 8 to 9 km landward of the trench axis and separate an area of extensional deformation on the slope from a frontal wedge under compressive deformation (see cross-section I-J on Fig. 4). The frontal wedge material is deformed by imbricated thrusting and folding. This seismic interpretation was confirmed during *Nautile* dives (Kaiko II cruise; Pautot *et al.*, 1987). The stepped morphology in the lower part of the slope might well correspond to thrusting; small-scale folding of Pleistocene layers, with an axis parallel to the trench, was observed along the cross-section. These layers also exhibit a pseudocleavage (closely spaced joints) along mainly transverse directions, parallel to the local vector of plate convergence.

Two dives went to the rim of the reentrant, located in the northernmost Japan Trench (Fig. 5), due to the recent collision with a seamount, revealed a fractured and deformed volcano-detritic sequence affected by normal faults parallel to the trench (gravity sliding above the trailing flank of the subducted seamount) and a pseudocleavage parallel to the subduction vector like that previously mentioned.

Shortening and thickening of the New Hebrides margin complex were also observed in front of the Bougainville seamount, where multichannel seismic data (Fisher *et al.*, 1986; Collot and Fisher, 1988) indicate that west-verging thrust faults and folds deform the accretionary complex. Structural directions transverse to the arc slope were also reported in the same area (Daniel *et al.*, 1986). During the Subpso I cruise, *Nautile* dives were conducted in this collision zone, and will provide some new data.

Ridge subduction can cause deformation even across the entire width of the island arc. This is exemplified with the d'Entrecasteaux Zone which seems responsible for the compressive deformation recorded across the Central New-Hebrides Arc just in front of the subducted part of the ridge (Collot *et al.*, 1985; Daniel *et al.*, 1989).

A particularly interesting case of convergence between a continental platform (seaward slope) and a margin was studied during Pop II cruise off Mindoro (Philippines) (Rangin *et al.*, 1988). Both South China Sea basin and North Palawan continental block subduct at the southern Manila Trench (Fig. 11).
When the oceanic crust is subducted, a simple accretionary prism-fore-arc basin pattern is developed. Conversely, where the continental margin of this basin is subducted, internal deformation is randomly distributed through the major part of the fore-arc area which is fragmented into various crustal microblocks. In the "collision" zone, the upper part of the landward slope is characterized by structures which are oblique to the general trend of the deformation front, most of the folds trending N-S. Important thrust fault and strike-slip fault zones delineate distinct crustal microblocks present in the fore-arc area. These microblocks are also affected by internal deformation.

UNDERPLATING OR ACCRETION

In the following discussion, underplating does not refer to any magmatism, but rather to subcrustal offscrapping process.

Many arguments, involving gravity anomalies, morphology or seismic interpretations, were used by Pautot and Rangin (1989) for proposing that Stewart Bank (Fig. 9) is a piece of the subducted Scarborough Seamount Chain which has protruded through the fore-arc of Manila Trench in very recent time. This can be interpreted as the result of underplating of ridge fragments which uplifted the fore-arc during slowing or recent cessation of subduction. Both uplifting and slivering of the oceanic crust fringing the Stewart Bank indicate that it is also thrust faulted at its base and in the process of being incorporated by underplating to the landward slope of the trench. Traces of more advanced accreted stages could be found northward in the Vigan High area (located just out of the upper right limit of Fig. 9 in the extension of the subducting ridge), where the ridge has already swept the landward slope of the trench.

The Wousi Bank protrusion observed a little southward of the extension of the North d'Entrecasteaux ridge below the New Hebrides margin (Fig. 6) suggests a similar interpretation inasmuch as magnetic anomalies which outline the subducted ridge are offset right-laterally (Collot and Fisher, in press).

Accretion of parts of the Louisville guyot-chain and its surrounding apron has been documented along the Tonga landward trench slope near the present-day ridge-trench junction. Morphology, seismic interpretation and magnetic anomalies suggest that a small dome-shaped hill, located just west of the sill of the trench in front of the satellite seamount of the Osbourn guyot, is possibly a volcano from the ridge accreted at the foot of the landward slope (Pelletier and Dupont, this volume). Immediately north of the junction point, the morphological characteristics of the trench and landward slope suggest a development of a small accretionary prism where the Louisville turbidite apron is being subducted (Lonsdale, 1986). In this area, latest cretaceous pelagic sediment recovered by a dredge haul indicate that some of the Louisville chain has been accreted to the lower trench slope (Scholl *et al.*, 1987). However, accretion appears limited in size and momentaneous (1 to 2 Ma) since collapse and mass-wasting occur subsequently in the wake of the ridge subduction.

Underplating is required to explain the profound morphological changes from Kermadec to Tonga, especially the presence of the Tonga Platform in a high position. Underplating of Louisville Ridge fragments, though likely, has not yet been definitively proved. In contrast, underplating of arc-slope rocks eroded in front of the underthrusted ridge seems at least partly responsible for the presence of the high-standing Tonga platform that is developed north of the latitude of the present-day ridge-trench junction, and already exists south of the supposed position of the subducted ridge beneath the Tonga margin (Fig. 10) (Pelletier and Dupont, this volume).

There are also some arguments in the southern Japan Trench for underplating (Lallemand *et al.*, 1989). The Daiichi Kashima Seamount belongs to an extinct

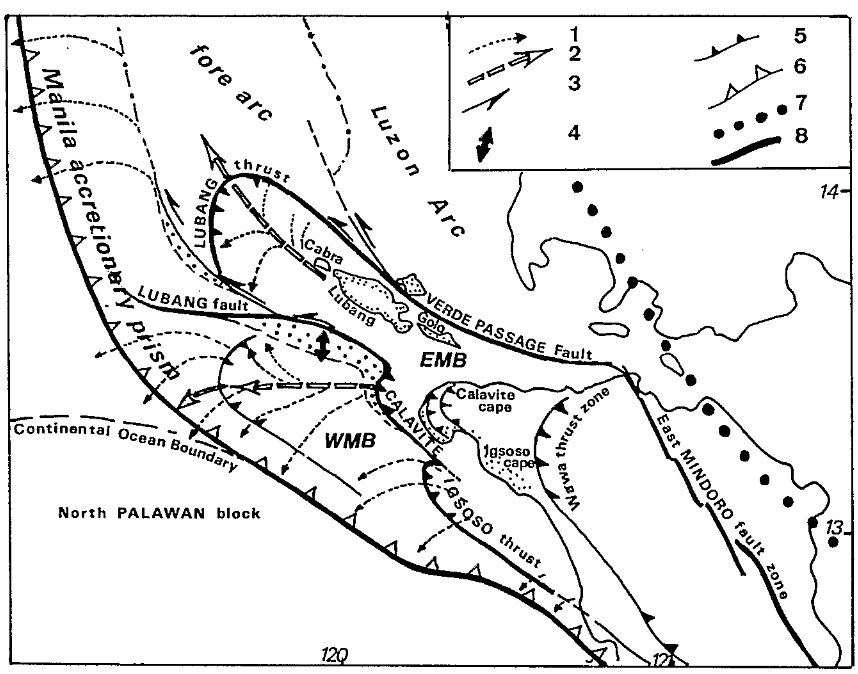

Figure 11

Interpretation of the southern tip of the Manila trench. WMB = West Mindoro Block; EMB = East Mindoro Block; 1 = stress trajectory; 2 = hypothetical motion of the EMB and the WMB; 3 = sense of motion of strike-slip fault; 4 = extension direction in Lubang Basin; 5 = thrust fault; 6 = deformation front of the Manila Trench; 7 - axis of the Luzon volcanic arc; 8 = boundary of major blocks (WMB and EMB) after Rangin et al., *1988.*
Interprétation de la terminaison méridionale de la fosse de Manille. WMB = Bloc Ouest Mindoro ; EMB = Bloc Est Mindoro ; 1 = trajectoires des contraintes ; 2 = Mouvements hypothétiques de EMB et WMB ; 3 = sens du mouvement le long des décrochements ; 4 = direction d'extension dans le bassin de Lubang ; 5 = chevauchement ; 6 = Front de déformation de la fosse de Manille ; 7 = axe de l'arc volcanique de Luzon ; 8 = frontière entre les principaux blocs (WMB et EMB) d'après Rangin *et al.*, 1988.

volcanic chain oriented ENE-WSW and other seamounts may have preceded the Daiichi Kashima. A knoll located landward of it (clearly evidenced on the Seabeam map at the western end of cross-section I-J on Fig. 4) is bounded by two pronounced headless canyons perpendicular to the trench. One small canyon cuts across the front of the knoll and appears to predate the development of the knoll itself, thus indicating a recent uplift. A swarm of small earthquakes below the knoll was related to the subduction of a seamount (Kikuchi and Sudo, 1985). The P 844 multichannel seismic line crosses this area and shows a zone of poor reflections below which we can follow rather easily to the decollement (Fig. 4, cross-section I-J). All the above features might be explained by underplating of a part of a seamount. Subcrustal accretion could have produced the uplift of the knoll, the oversteepening of the slope, and the resulting listric faults, in the wake of the accreted seamount in front of the Kashima, compensating the mass excess.

In Mindoro Island, the Middle Miocene boundary between the North Palawan block (Eurasian plate), and the Mindoro block to the east, is outlined by obducted Middle Oligocene ophiolites (Rangin *et al.*, 1985), interpreted as a jammed fragment of the south China Sea oceanic crust between the North Palawan and Luzon convergent terranes (Fig. 11). This suture zone is presently inactive attesting to a rapid rearrangement of the suture zones within the collision area (Rangin *et al.*, 1988).

The Zenisu ridge off the northern Nankai Trough may correspond to an incipient accretion of a portion of the oceanic crust to the margin (Lallemant *et al.*, 1989). There exists geological evidence for a repetitive southward jump of the plate boundary during the Neogene, leading to successive block accretions and a future jump of the plate boundary to the south could be responsible for the accretion of the Zenisu ridge to the Japanese margin as an ophiolitic body. At present, this is the mere speculation because it is not already engaged in the subduction zone.

CONCLUSION

The review of the different structural contexts where oceanic asperities subduct in trenches allows us to draw some general conclusions.

- During subduction, at least the lower slope of the continental or island-arc margin, models itself on the oceanic topography even if the irregularities are small-amplitude fault scarps.
- A compressive thickening of the toe of the margin is observed above the advancing flank of a subducting seamount and collapse occurs above the trailing flank.
- Loss of continental or island-arc material is at least partly due to the relaxation of the arc slope in the wake of the asperity followed by the debris subduction. Some observations show that loss of upper plate material seems also due to the abrading (or downward forcing) of the deep margin complex in front of the asperity subduction. Thus, the subduction of positive features would be one of the major components of frontal tectonic erosion.
- Transverse faulting or jointing of the lower slope material in collision zones seems common among to the different situations.
- Underplating or subcrustal accretion of ridges or seamounts to the upper plate is proposed for most regions studied, but very difficult to prove.

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