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Subduction and tectonics. Discussion on the results of the IPOD program in active margins

Subduction
Tectonics
Active margins
IPOD

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Marges actives
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ABSTRACT

Since the advent of plate tectonics the active margins of the oceans have been studied according to a model whose basis is a piling up of imbrications of oceanic material units, in front of the upper plate, forming a great tectonic accretionary prism. This model is broadly the same for all the authors ; it has been largely used for alpine-type or paleo-oceanic mountain chain, all around the world.

After more than a year of deep drillings on active margins, the IPOD program has given fundamental data making it necessary to reconsider previous models and their application to mountain chains.

The authors have directly taken part in the drillings on western and eastern Pacific active margins (Legs 60 and 67) and they have worked on the tectonics of alpine (paleo-oceanic) chains of the peri-mediterranean, peri-caribbean, and peripacific belts. They compare the geological data accumulated from these two direct sources. The tectonic constraints regime is specified and the consequences of the subduction are looked for. The notions of collision and obduction are discussed in relation to subduction and tectonics.

Finally, an analysis of the temporal evolution of active margins and of chains, shows the necessity of thinking in terms of superimposed tectonics.

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RÉSUMÉ

Subduction et tectonique. Réflexions à partir des résultats du programme IPOD sur les marges actives.

Depuis l'avènement de la tectonique des plaques, les marges actives des océans sont traitées selon un modèle dont la base, à quelques variantes près selon les auteurs, est un empilement d'imbrications d'unités à matériel océanique, au front de la plaque supérieure, en un important prisme d'accrétion tectonique. Ce modèle a été abondamment appliqué aux chaînes de montagnes de type alpin, ou paléo-océanique, tout autour du globe.

Après plus d'un an de forages profonds sur les marges actives, le programme IPOD a apporté des données essentielles qui obligent à reconsidérer, au moins en partie, les modèles antérieurs et leurs applications aux chaînes de montagnes.

Les auteurs ayant, d'une part participé directement aux forages sur les marges actives Ouest et Est Pacifique (Legs 60 et 67), d'autre part travaillé sur la tectonique des chaînes « alpines » (paléo-océaniques) périméditerranéennes, péricaraïbes, péripacifiques, confrontent les faits géologiques accumulés par ces deux sources directes. Le régime des contraintes tectoniques est précisé et les conséquences de la subduction sont recherchées. Les notions de collision et d'obduction sont discutées par rapport à la subduction et à la tectonique. Enfin, une analyse de l'évolution dans le temps des marges actives comme des chaînes, montre la nécessité de raisonner en terme de tectoniques superposées.

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INTRODUCTION

Since the birth of plate tectonics the active margins of the oceans have been dealt with from a quite simple model : the subduction of an oceanic lithosphere under another lithosphere determines oceanic materials units which pile up in the front of the upper plate forming an accretionary prism made of tectonic imbrications which lift up the margin and build up a range during the time of subduction.

This model results, on the one hand, from the theoretical constraints imposed by the general kinematics of the plates, and on the other hand, from the interpretation of marine data : bathymetry, seismic profiles, gravimetry (Sugimura, Uyeda, 1973 ; Karig, 1974 ; Karig, Sharman, 1975 ; Biju Duval *et al.*, 1979 ; Dickinson, Seely, 1979, etc.). The model of the accretionary prism was soon applied to mountain belts : western-american range, California, Oregon, Alaska (Ernst, 1970 ; Scholl, Marlow, 1974 ; Blake, Jones, 1974 ; Rangin, 1978, etc.), Alpine chains (Ernst, 1975 ; Boccaletti *et al.*, 1971), Caribbean chains, western Pacific belts, etc. (Dewey, Bird, 1970). The bibliography using now classic models is very large and the cited references are just an introduction. A complete bibliography can be found in the various articles of this volume.

Active margins only recently have been explored in a direct way by deep drilling in the framework of IPOD program (1977-1979). Unexpected results have been obtained and new problems have come up.

We propose to assemble the principal facts brought to the fore by the IPOD drillings carried out up to now. Then we shall compare the notions of subduction in the Oceans with the tectonics in the mountains, before trying to differentiate their roles in the evolution of orogenic belts. We shall base our investigations on data collected on earth — in the perimediterranean and pericaribbean ranges and the western-american Cordilleras — and on data collected at sea, having taken part in the Leg 60 (R. B., Mariana transect) and Leg 67 (J. A. Middle America Trench, Guatemalan transect). We shall stress the new problems and the difficulties of classic models more than on generally accepted conclusions.

IPOD DRILLINGS IN ACTIVE MARGINS : UPDATED CONCEPTIONS ; THE URGENT NEED TO KNOW MORE

Thanks to the IPOD/DSDP program, direct data obtained by deep drillings are available for the active margins of Japan (Legs 56 and 57), of the Shikoku basin (Leg 58), of the Philippine sea and the Marianas (Legs 59 and 60) and of Central America [Legs 66 and 67 (Fig. 1)].

Moreover, direct observations — in submersible — have been done by the HEAT group (Hellenic Arc and Trench) in the Hellenic Trench in the Eastern Mediterranean (Le Pichon *et al.*, 1979 *a* and *b*, and this volume).

Finally, detailed surveys — carried out by Seabeam (CNEXO, R/V jean Charcot) — have recently given a very precise bathymetry permitting a morpho-structural analysis of certain areas of the Middle America Trench and of the Hellenic Trench.

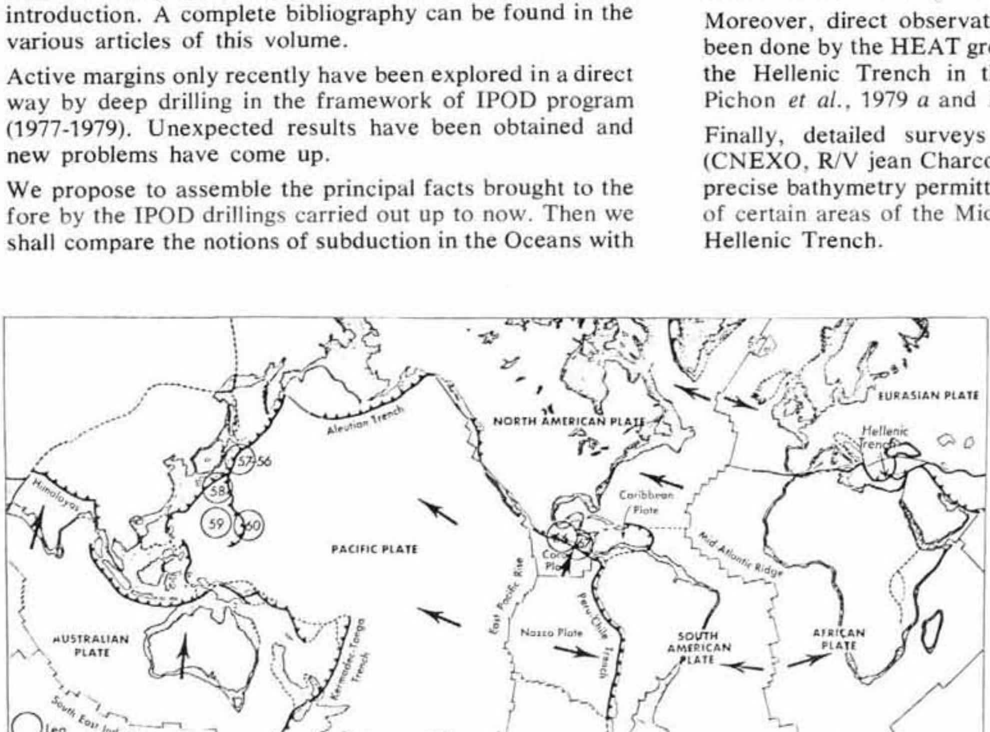

Figure 1

Location map of the IPOD drilling in Pacific active margins (Leg number).

Carte de localisation des campagnes de forage IPOD sur les marges actives du Pacifique (numéro du Leg).

What are the broadoutlines which arise after these studies (Fig. 2-7) ?

The present subduction in the Oceans is a fundamental geodynamic process, juste like the expansion of oceanic floor. It is the tectonic superposition, on the dimension of the lithosphere, of two plates along an active tectonic contact : the subduction zone is marked out by earthquakes, in a double-layered structure (Wadati-Benioff zones). The associated magmatism is significant in magnitude and its geochemistry, its petrography, its deposits, its mineralisations are quite typical.

However, one can notice that, up to the present day, the great tectonic contact of subduction areas has not yet been drilled : it is a major objective to be reached as soon as possible (for example at the level of the Middle America Trench [cf. Leg 67, Von Huene *et al.*, 1980 (Fig. 7) or at the foot of the Antillean Arc, objective of Leg 78A]. Direct data are required about the contact, the state of the constraints, the nature and the composition of the down-going plate, the possible modifications of the upper plate.

In the near future, we can hope to drill this major contact where it just slips under the upper plate. The Glomar Challenger can do it in some particular places and it is, a fortiori, within the capability of a ship like the Glomar Explorer.

However, is seems that only in the distant future will it be possible to drill deep enough to reach the subduction contact, where one expects the thermodynamic conditions to generate the blue schists facies metamorphis (30 km of depth correspond with a lithostatic pressure of 30 kilobars !). Unless, taking into account that tectonic overpressures may reduce the depth required by the mere consideration of the lithostatic pression. So, if most of the characteristics of the subduction have been observed — and so, demonstrated — or if they will be soon observed, on the contrary, the relationship between 'blue schists' and subduction will still remain a postulate for a long time... And we know the prominent role it plays in the interpretation of ranges.

The plunging oceanic plate bears its own tectonic history

Recent studies (drillings, Seabeam surveys have enabled us to assess the oceanic nature of the crust entering the subduction zone, to check the age of this crust, to study its sedimentary cover, to set up the main structures it takes on.

So, in front of the Middle America Trench (Fig. 4), the detailed Seabeam survey (Aubouin *et al.*, 1980 ; Renard *et al.*, 1980) shows a system of extensional faults and flexures determining a series of rectilinear N 130 to N 140 oriented spurs on the Cocos plate. These highs are oblique to the trench, but clearly parallel to magnetic anomalies in the site of Leg 66 (Fig. 5-6). Renard *et al.* (1980) think that this structuration is probably primeval ; it looks like the structuration on the Eastern Pacific Rise (Francheteau *et al.*, 1979 ; Cyamex Scientific Team, 1980). The down bending and the subsidence of the subducted plate preferentially brings about the rejuvenation of inherited faults.

In front of the Mariana Trench, the oceanic lithosphere is also cut by faults, oblique to the trench (Fig. 3) ; it is covered by a thin mantle of deep oceanic sediments marked by the great hiatus (from Upper Cretaceous to Pleistocene) which characterizes the sedimentary Cenozoic history of the Western Pacific (Hussong *et al.*, 1978 ; Blanchet, 1979 ; Blanchet *et al.*, 1979).

The nature, the structure, the sedimentary cover of the subducted oceanic plate characterize the geological evolution of the oceanic area which is concerned.

The Middle America Trench has been drilled down to its oceanic substratum which holds up a sedimentary series of the same nature and age as the Cocos plate series (Aubouin *et al.*, 1979 ; Von Huene *et al.*, 1980). The structures of the Cocos plate, examined with the Seabeam, plunge under the axis of the trench without contacting the inner slope of the trench and without modifying the structure of this slope (Fig. 5, 6). This confirms Heezen and Rawson's opinion (1977) : they thought that the active subduction area was note the foot of the slope but he axis of the trench.

Besides, at the level of Leg 66, a slight topographic feature revealed by the Seabeam survey, parallel to the axis of the

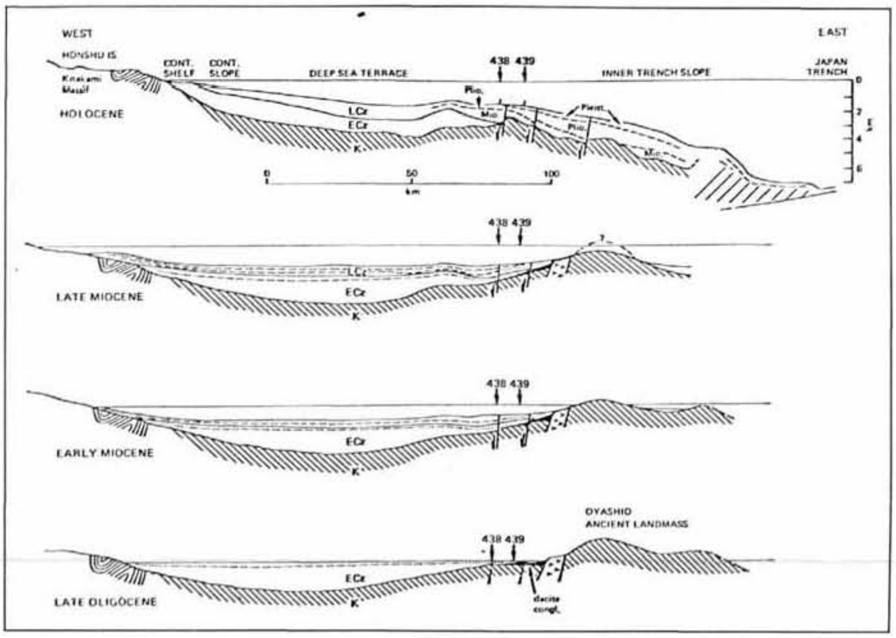

Figure 2

Leg 57 : Japan trench transect (after Von Huene et al., 1978). Diagrammatic history of Neogene subsidence on the inner slope of the Japan trench, based on Leg 57 sampling and JPDC multichannel records. K = Cretaceous ; ECz = early Cenozoic (Paleogene) ; LCz = Late Cenozoic (Neogene).

Leg 57 : Coupe de la Fosse du Japon (d'après Von Huene *et al.*, 1978).
Schéma illustrant la subsidence néogène du mur interne de la Fosse du Japon, basé sur les résultats du Leg 57 et sur les enregistrements sismiques multitraces du JPDC. K = Crétacé ; ECz = Tertiaire inférieur (Paléogène) ; LCz = Tertiaire supérieur (Néogène).

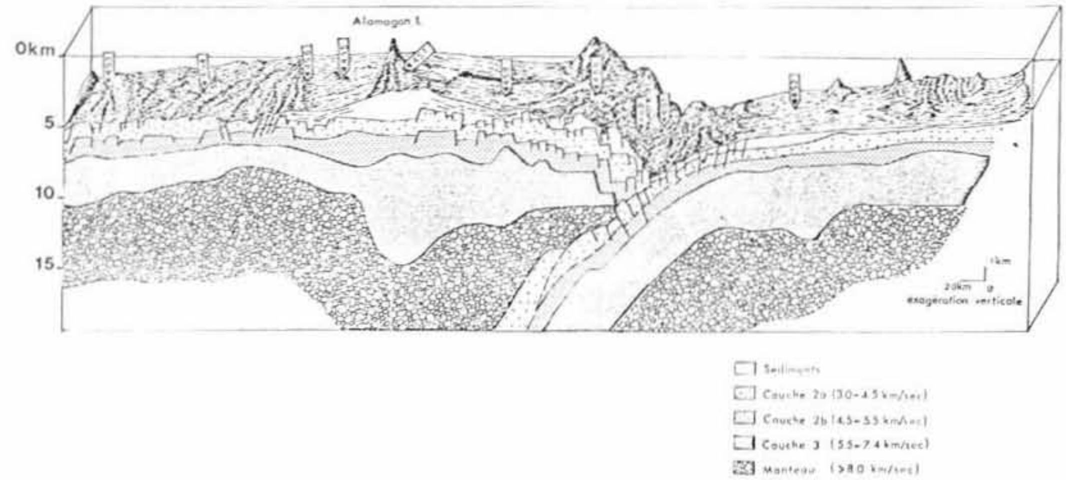

Figure 3

Leg 60 : Mariana transect (after Hussong et al., 1978). Physiographic diagram and crustal structure across the Mariana trench and arc, and the Mariana trough, with Leg 60 site locations shown.

Leg 60 : Coupe des Mariannes (d'après Hussong *et al.*, 1978). Schéma d'organisation et structure de la croûte le long d'une coupe de la fosse de l'arc et du bassin des Mariannes : la position des sites de forage du Leg 60 est indiquée.

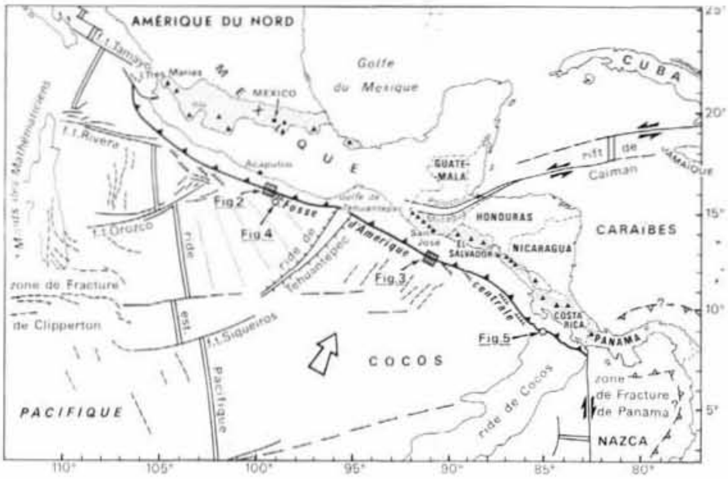

Figure 4

Structural diagram of Middle America Trench (after Renard et al., 1980).

Cadre structural de la Fosse d'Amérique centrale (d'après Renard *et al.*, 1980).

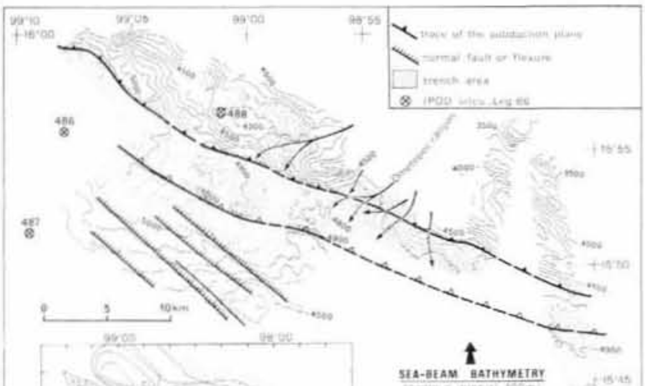

Figure 5

Leg 66 — Diagrammatic Seabeam map and regional magnetic anomalies (after Renard et al., 1980).

Leg 66 : Carte Seabeam schématique et anomalies magnétiques régionales (d'après Renard *et al.*, 1980).

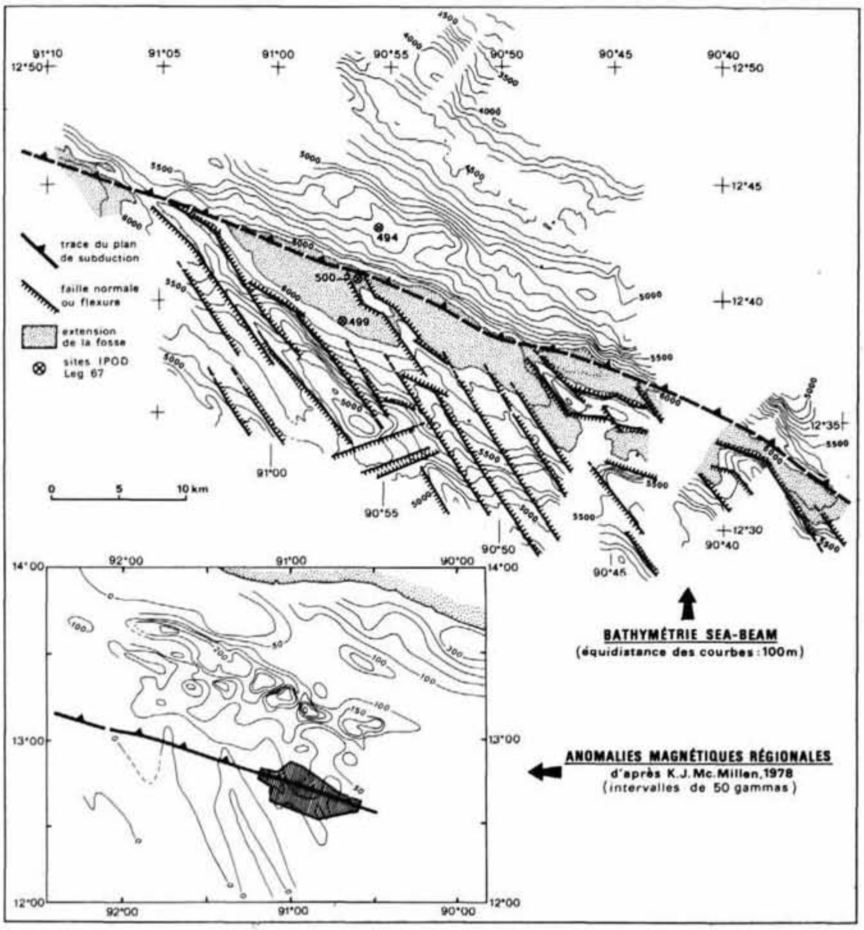

Figure 6

Leg 67 — Diagrammatic Seabeam map and regional magnetic anomalies (after Renard et al., 1980).

Carte Seabeam schématique et anomalies magnétiques régionales (d'après Renard *et al.*, 1980).

trench (and not to the structuration fo the outer slope) could be the mark of the subduction itself.

So, the trench looks like a series of lozenge-shaped basins separated by small ridges which correspond to the beginning of the horsts of the Cocos plate.

Finally, we must note that — up to the foot of the inner slope — no compressive deformation was observed.

The inner wall of the trenches and the arc-trench realm have been drilled off Japan (Von Huene *et al.*, 1978 ; Fig. 2), off Marianas (Hussong *et al.*, 1978 and this volume ; Fig. 3), Mexico (Moore *et al.*, 1979, and Watkins *et al.*, this volume ; Fig. 4-5), and Guatemala (Von Huene *et al.*, 1980 and this volume ; Fig. 4, 6, 7) ; they have been observed in submersible in the Hellenic trench (Le Pichon *et al.*, this volume).

The drillings have reached the Upper Cretaceous off Guatemala and the Middle Eocene off the Marianas and various levels of the Tertiary to upper Createaceous in the Japan trench after having gone through complete sequences in which the normal and continuous stratigraphic succession can be described with the very precision of nannofossils.

The facts, observed by drillings and in submersible differ slightly from the prediction of standard models. They are described in detail elsewhere in this volume.

We mention that as for the cited active margins :

— up to now, no tectonic repetitions in the sequences corresponding to imbrication of tectonic units of a prism were observed ;

— the sequences, drilled at the foot of the inner wall off Guatemala (Leg 67), are much older (Upper Cretaceous) than the sediments which cover the oceanic crust in the nearby trench ; this contradicts the progressive accretion of more and more recent terrains ;

— the tectonic regime is a generalized and active extension, and not a compression (at least since the Neogene). This can be observed with submersible in the Hellenic trench (Le Pichon *et al.*, 1979 *a* and *b*) in the drillings (especially Leg 60), in the Seabeam surveys (Middle America), in the seismic profiles (Leg 60), so this can be observed at several scales (Blanchet, 1979) ;

— a differential active subsidence and not an uplifting — is revealed in the Japan trench, in the Mariana and the Guatemala trenches. It goes with an uplifting of the island arcs (The Mariana arc, Guam, Tinian, the Egean Arc — Crete) ; this also contradicts the idea of progressive accretion ;

— the eruptive basement, when it is reached (Legs 57, 60, 67) is not from oceanic type, even in the so-called 'intra-oceanic' system of the Marianas wich is set up on a basement of calc-alcaline lavas and of arc-tholeiites (bronzite-andesites, "boninites"). Everything occurs as if the arrangement of active margins, which is observed now, was born in Neogene and superposed on prior tectonic evolutions, paleogene and older but having their own logic.

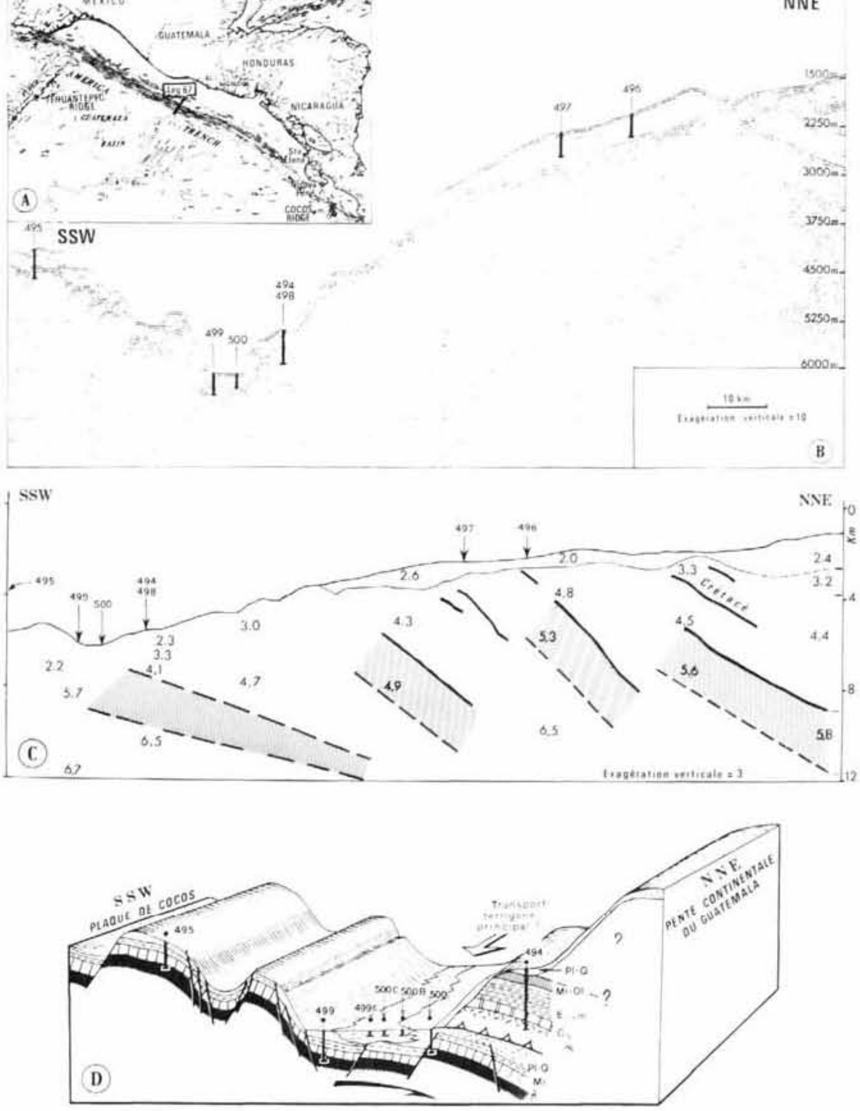

Figure 7

(after Aubouin et al., 1980).
A. Location of the Leg 67 transect ;
B. UTMI Multichanel seismic profile (Ladd et al., *1978) ; drilled site locations are indicated ;*
C. Geological interpretation of the B profile ;
D. Conceptual diagram for Leg 67 transect.

(d'après Aubouin *et al.*, 1980).
A. Situation du Leg 67.
B. Profil sismique multitrace (Ladd *et al.*, 1978) ; la situation des sites forés est indiquée.
C. Interprétation géologique du profil B.
D. Schéma interprétatif pour la coupe du Leg 67.

The problem of the tectonic accretionary prism, created by subduction arises

It is also the problem of its premanency, postulated in the models in order to structure and uplift the mountain chains.

In the examples studied until now, when subduction undoubtedly works in its present position (that is to say since the Neogene) no tectonic repetitions have been observed. There is no compression but extension, the inner walls of the trenches are not uplifted but subsided and the foot of the inner wall is much older, its nature is not the same as the nature of the sediments which arrive into the trench. Moreover, on the transect of Legs 57, 60, 67 there is no sufficient room for an accretionary prism which would have the volume predicted by the models, though the subduction could have been significant (10 cm/year, 100 km/M.Y., in the place of Leg 67 in the Middle America Trench).

In the Middle America trench (Leg 66), some of the reflectors deeping eastward on the seismic profiles were interpreted as the overthrusting planes of an accretionary prism, before the leg have been gone through by the IPOD drillings : in fact, these are coarse sand layers in a more silty sequence. This stresses the fact that indirect geophysic data must be cautiously interpreted and that it is necessary to have a direct geological control as for the oceanic bedrocks just as for the emerged outcrops on land.

In the same part of Middle America trench, the grading of coarse terrigenous facies — from Neogene — (these facies being increasingly older when going up the slope) was considered as an indirect argument in favor of the existence of an accretionary prism (Moore *et al.*, 1979, and Watkins *et al.*, this volume) : every coarse level is sedimented in the trench, then it is accreted and uplifted. But, no tectonic contact has been gone through and everything is based on the fact that the deposit of all the coarse turbidites occurs in the trench.

The Seabeam surveys in the Middle America Trench (Renard *et al.*, 1980) show sedimentary basins, terraced along the inner wall ; a branche of submarine canyon opens into every basin. So, terrigenous sediments can settle directly on the terraced basins just like it was predicted (Karig *et al.*, 1978). This limits, all the more, the indirect interpretation based on the distribution of terrigenous facies. Moreover, the first indications deducted from the repartition of glauconite — a good indicator of shallow sedimentation — suggests a subsidence of the Mexican continental margin since — and while — the Neogene, and not an uplifting.

But we must strongly underline that active margins are just beginning to be studied by direct methods and that the observed facts are necessarily limited to the explored regions. What about the Caribbean (the Antillean Arc — the Barbados Ridge) in the Aleutian, in Indonesia, where the interpretation of indirect data seems to indicate a well structured accretionary prism ? Time will tell and we must consider that an accretionary prism may occur in some trenches, depending on various parameters : deeping of the Benioff zone, age of the subducting plate convergence rate, sedimentary thickness, tectonic framework...

Several remarks can be made as hypothesis for new scientific works :

a) the present framework observed at the level of subduction zones seems young or very young ; the structural morphology seems to take place or to become more marked in the Mio-Plio-Quaternary. The Middle America trench was probably born in the beginning of Pliocene. During this evolution the tectonic regime is tensional with strong systems of normal faults going with a subsidence characterized everywhere in the studied area ;

b) this neotectonic regime creates the present arrangement and is superposed on to an island arc or a continental border which has been structured all along prior tectonic phases that can be seen on land : the Miocene, Paleogene, Upper Cretaceous (Laramian), Middle Cretaceous, Upper Jurassic (Nevadian) phases.

This neotectonic regime may have no connection with prior structures. In its northern half the Middle America Trench cuts southern Mexican structures with a 45° angle. The Japan Trench is oblique to Hokkaïdo Island structures which are back up to it (the Hokkaïdo nappes are thrusted westward, towards Asia). The neotectonics of present trenches has not necessarely genetic relationship which the tectonic of the mountain chains or of the Cordilleras edged by these trenches ;

c) the inner wall of the trench (whose structural morphology is neotectonic) is composed of the superposed tectonics of the continent or of the arc along which it runs. These tectonics have their own structures, folds, overthursts, nappes. The most recent of these tectonic deformations can be contemporary with the subduction.

So, it is necessary to carefully distinguish the superposed tectonics at the level of active margins before trying to determine the relations of cause and effect between subduction and structures.

It is possible that some features on the seismic profils are structures or tectonic contacts (overthrust) older than subduction. So, this latter has not originated them. Thus, a future submersion of the Californian range would give a margin with as many potential eastward-deeping reflectors as pre-Upper-Eocene overthrusting contacts, which can be observed on land (Roure, 1979). Thus, tomorrow, a submersion of Crete would show a profil of accretionary prism-type discontinuities truncated by normal neogene faults. The present aspect summarizes all the tectonic marks of the past.

Like in the Middle America Trench, the Costa Rican tectonic belt (Nicoya-Santa Elena) go in the inner wall (Leg 67), at the foot of which a sedimentary sequence similar in logic and age has been drilled. A strong positive magnetic anomaly on the continental shelf lines up on to Nicoya Peninsula structures which are pre-Campanian in age (Ladd *et al.*, 1978). Are the eastward — deeping seismic reflectors the pre-Neogene overthrusting planes of the chain which outcrop on land ? or, are these reflectors the great lithologic break of its sequence ? The same remark can be made about Oregon and Alaska profiles : samples of Upper Cretaceous age have been collected there by dredgings (Von Huene *et al.*, 1978).

On the contrary one can note that many compressive structures marking the Plio-Quaternary have no connection with a characterized subduction context : the Los Angeles basin, the Northern-eastern margin of Venezuela or, even more, in a collision context, in Iran, India... ;

d) subduction and compression, subduction and accretionary prism may not be systematically connected. On the contrary, it is necessary to wonder wether on both sides of the major lithospheric overthrust shown by the Benioff zone the two plates, yet structured by their prior own evolution, essentially react in an extensive regime, the down going plate falling into the subduction zone while the upper plate follows this dipping by tensional faulting and subsidence ;

e) but it is possible that an accretionary prism might be built up by subduction in now unexplored regions. To be certain of that we must base our investigations on direct data — such as drillings and submersible observations — analyzing the superposed tectonics of these regions. Any other approach would leave doubts : the structures (fold and overthrusting) of an inner wall are not necessarily generated by the subduction in the trench. Intra-plates tectonic deformations can occur there or elsewhere, and only the knowledge of regional tectonics can guide the interpretation.

PRESENT AND OLD ACTIVE MARGINS : (PALEO) SUBDUCTION AND TECTONICS IN MOUNTAIN CHAINS

Since 1968, the plate-tectonic theory has been creating new concepts about the mountain building. A significant number of models has been published about all the chains in the world to make the goedynamic evolution visible by using plate-tectonics.

This profusion of conceptions has been generally positive ; but the wrong side of this success is that unavoidable suppositions and hasty simplifications conceal the complex reality ; and when only indirect large-scale data are taken into account, it leads very often to an explanation for a geological problem posed in another dimension.

Considering that :
— ophiolites characterize old oceanic crust ;
— subduction builds up a tectonic accretionary prism ;
— subduction carries lithosphere materials down to significant depth, it can be inferred that the chains with ophiolites (« paleo-oceanic ») first take the shape of tectonic accretionary prism ; if the process stops then, they are generally

called « subduction chains », if the process ends with the collision between two continents, they are generally called « collision chains ». In both cases, subduction is thought to have genrated the blue schist facies (high pressure metamorphism).

Today, to be accurate, one can only use clearly demonstrated data for present subduction to explain old subductions. So, we know precisely the seismic characteristics of present subductions : the evidence of a major tectonic contact at the foot of the trench has been demonstrated by the great difference of the series in the trench and in the continental margin (Leg 67) ; the spatial connection with andesitic volcanism is obvious when one studies the locations of volcanism in the western parts of Americas, with the break from Middle America to Oregon at the level of the transform zone of California. We can even hope, in the near future, the drilling of the subduction contact (see above, p. 285).

But, in the near future, we will probably be unable of drilling into the depths where blue schists formation is supposed to take place : this latter is connected to subduction according to the interpretation of paleosubduction zones. There is no actualistic reference to high pressure metamorphism : its connection with paleosubductions is based on a pure geologic argumentation.

So, present subduction markers which can be used to think about the past are only the strong calcalcaline magmatism and the tectonic contact of a vulcanized and granitized continental margin overthrusted upon oceanic sediments lying on oceanic crust. But, calcalcaline magmatism and also the continent-ocean contact can be found in other contexts (which are not paleosubduction).

We can sum up by a quick overview on some examples of chains :

In the Mediterranean alpine domain

Tectonic belts result from collision, as the mere chronology shows (Fig. 8). So, we must look for subduction in older stages of their history (e.g. Jurassic). The tectonic framework, reveals that the major collision with continental blocks occurs in the late Jurassic in the Hellenides and the Dinarides (Aubouin *et al.*, 1970 ; Aubouin, 1976 ; Blanchet, 1974) and may be in others parts of the Alpine belt. The paleosubduction is older than the collision (Fig. 9).

In the locations (such as the Egean Arc) where a subduction is active today, all the structures, prior to the neotectonic, result from the collision with a continental block in Mesozoic and early cenozoic time ; at the basis of the pile of nappes resulting from the collision there are series with continental basement (Aubouin, 1977). Everywhere in the domain born of the Tethys, the collisions play the essential role ; the subductions precede or follow them. It is not in the Tethyan domain that the tectonic role of subduction will be easily and convincingly determined.

The Californian domain, apparently more favourable, does not suggest better conclusions : there is an early collision with continental fragments, these collisions being associated or not with the great translations revealed by paleomagnetism (Jones *et al.*, 1977).

The chain, as it can be observed in California (Bailey *et al.*, 1970) as it extends southward in southern California (Jones, *et al.*, 1976 ; Gastill *et al.*, 1975 ; Rangin, 1978) and in the North in Oregon (Roure, 1980) results from many superposed tectonics since the Jurassic, the most recent event reworking all the previous structures.

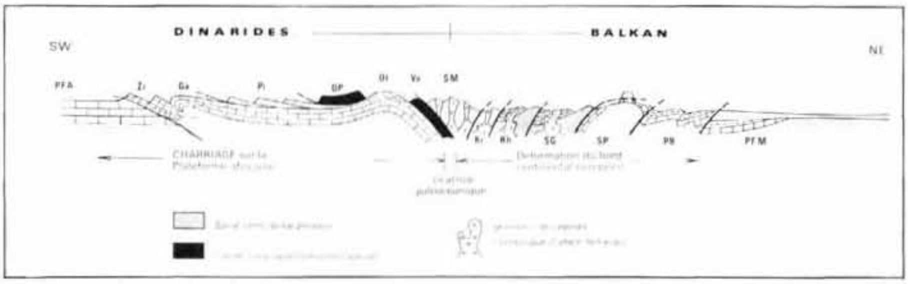

Figure 8

Cross section of the Dinarides and Balkan alpine chains (after Aubouin (1977)).

Coupe de la chaîne alpine des Dinarides aux Balkans (d'après Aubouin, 1977).

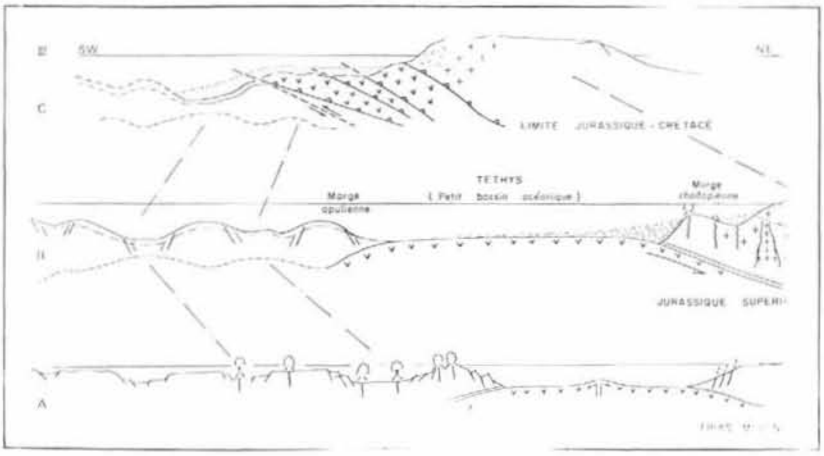

Figure 9

A paleo-oceanographic model for the Dinaric Alps (after Blanchet, 1977).

Modèle paléo-océanographique pour un secteur des Alpes Dinariques (d'après Blanchet, 1977).

The major compressive phases (often with overthrusting and nappes) are Upper Jurassic (as shown by the disconformity of the Lower Cretaceous in Baja-California and the age, about 150 m.y., of the blue schists reworked as exotic blocks in the mélange in California) ; Lower to Middle Cretaceous (as shown by the disconformity of Campanian Maestrichtian in Oregon) Upper Cretaceous — Lower Eocene or even younger (as proved by the age of youngest unit of the western most Franciscan).

Today, the basal contacts of the westward overthrust nappes are late contacts ; in no way they can represent the simple primeval contacts of an accretionary prism. This is the case of high pressure facies units which are overthrusted on sedimentary units much younger than the age of their metamorphism : whatever the point of view from which the contact is looked at may be, it cannot be a subduction.

When the superposed tectonics have been made out, one can propose a geodynamic model such as in southern California (Rangin, 1978) where one can recognize (Fig. 10) :

— a paleo-oceanic evolution from Upper Triassic to Jurassic. A small oceanic basin (ophiolites, radiolarites) is bordered, to the East, by an active island arc whose outcroping volcanic materials and volcanodetritic sedimentary consequences are known. In such an epoch an eastdipping subduction might explain this magmatism ;

— a period of collision beginning in Upper Jurassic ; H.P. metamorphism dates back to Lower Cretaceous (so it is diachronous with the subduction) ;

— from the Middle Cretaceous, hypercollision generates overthrusting which form most of the contacts which can be seen today ;

— a neogene cutting up into horsts and grabens and the Plio-Quaternary opening of the Baja California Gulf are superimposed to prior tectonics.

Thus, this example enables to differenciate (paleo)-subduction (Upper Trias, Jurassic) and tectonics (polyphased from Upper Jurassic to Paleogene) before the reworking of the whole structure by a neotectonic phenomenon.

The Caribbean domain where the conditions for a pure collision do not seem to be realized today was nevertheless the area where collision took place in the Upper Jurassic when, for the first time ophiolitic nappes were set up (before being reworked later).

The geodynamic model, recently proposed (Beck *et al.*, 1979 ; Stéphan *et al.*, 1980 ; Bellizzia *et al.*, 1980) emphasizes the paleo-oceanic and tectonic stages of evolution.

Taking into account the present arrangement of the chain, it has been necessary to backtrack the tectonic framework (Fig. 11) and to replace the tectonic, magmatic and metamorphic events since Jurassic, according to a timing imposed by the facts.

The paleo-oceanographic stage is Lower to Middle Jurassic and there is no clear evidence of subduction. Suture, obduction and collision took place in an early phase during Upper Jurassic — Eocretaceous. H.P. metamorphism is considered to be Eocretaceous and, seems to be contemporaneous with obduction and collision, rather than with subduction.

Many hypercollision phases took place in Upper Cretaceous and in Tertiary ; additionally there were tensional periods and megafolding.

Tectonics, from obduction and suture (Upper Jurassic) until present day is permanent ; the role of subduction at the moment of the oceanic spreading is not yet fixed. Once more, the tectonic contacts cannot represent the simple primeval contacts tied with a subduction.

EVOLUTION : FROM OCEANS TO MOUNTAINS, AND THEN TO THE OPENING OF NEW OCEANS

One can make out the superposition of many temporal stages in the building up of a paleo-oceanic chain between its continental edges.

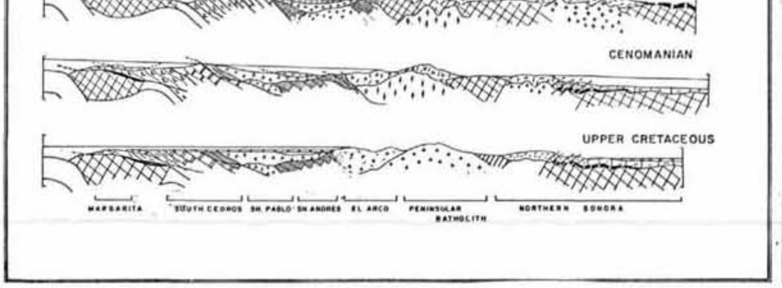

Figure 10

Geodynamic model for the jurassic-cretaceous evolution of Baja-California (after Rangin, 1978).
Modèle géodynamique pour l'évolution jurassique et crétacée de la Basse Californie, Mexique (d'après Rangin, 1978).

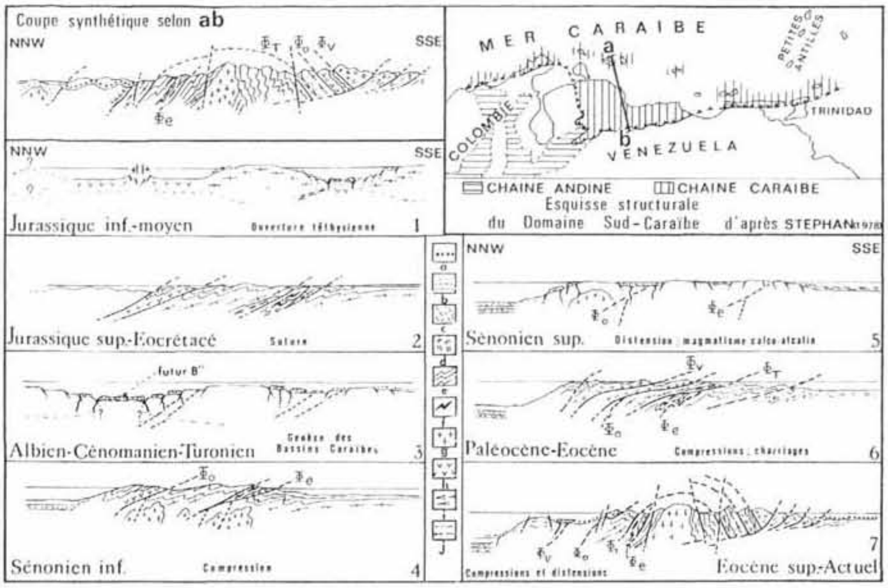

Figure 11

Geodynamic Model for the South Caribbean belt in Venezuela (after Bellizzia et al., 1980).

1. *Jurassic (Lower to Middle) : oceanic opening of the Tethys.*
2. *Upper Jurassic — Lowermost Cretaceous : suture, obduction, collision.*
3. *Albien to Turonian : Opening of the caribbean basins ; Paleo-oceanographic reorganisation.*
4. *Lower Senonian : Compression.*
5. *Upper Senonian : Extension ; calcalcaline magmatism.*
6. *Paleocene — Eocene : Compression ; overthrusts.*
7. *Upper Eocene — to Present : compressions and extensions : thrusting, megafolding, faulting.*
8. *Diagrammatic cross section ab (9).*
9. *Structural diagram from the South Caribbean (after Stephan et al.,* 1978).

Modèle géodynamique pour la chaîne Sud Caraïbe au Vénézuéla (d'après Bellizzia *et al.*, 1980).

The stage of the oceanic (paleo-oceanic) basin

For Alpine chains the oceanic history is as old as Triassico-Jurassic (200-140 m.y.). The markers are ophiolites which may represent the former oceanic crust (Allègre *et al.*, 1973 ; Coleman, 1977 and Rocci, 1980). Sometimes there is a large ocean, sometimes there are small oceanic basins, marginal basins, with continental margins, passive and active.

The setting up and the evolution of paleosubductions must be looked for in such a stage. The markers are calcalcaline magmatism on continental margins or arc, and volcanoclastic sequences in sedimentary series. They can be studied mainly in the chains where inner zones and back-lands out-crop (California, Dinaro-Hellenides, Southern Asia). If an accretionary prism is built up by subduction, it must be looked for in such a stage, as well. But such a prism has problably not lasted until now without changing. This, because of superposed tectonics, because of superposed metamorphisms and of hypercollision processes characterizing inner zones.

Moreover, is not there a fundamental difference between the great ocean subductions (which are in fact particular cases of opening having succeeded) and small oceanic basin subductions ? We think that marginal basins and small oceanic basins could be the real models we can apply to the paleo-oceanic zones of the chains (Blanchet, 1977 ; Le Pichon, Blanchet, 1978). They are the only ones which can generate a pile of nappes (including elements of oceanic crust) by collision between a continent and an island arc which limits these blocks. Whereas the fate of the large ocean is probably to disappear in the permanent subduction, like in the Andes Cordillera (approximately since 20 m.y. : Le Pichon, Blanchet, 1978).

Thus the Pacific is a key domain for understanding the chains with its two types of arrangement :

— in the western Pacific the overthrusts are towards the continent like in the periaustralian ophiolitic crown (Aubouin *et al.*, 1977 *a*) ; in the continuation of the Tethys they might provide a model for the Alpine chains derived from the Tethys. This type can also be found from Hokkaïdo to Sakhaline in the North-West and in Taïwan in the Centre.

— in the North Eastern Pacific, the overthrusts — at least the recent ones — are toward the Pacific like in Baja California, California and Oregon.

We can note that the continental facing systems are situated in the close vicinity of the continental masses, or separeted from them by seas originated from pure extension (like Tasman sea, for example) and always limited on the oceanic side by other marginal basins and not the subduction of the Pacific : the Pacific itself is never drifted towards the continent.

What are, for example, the temporal evolution of south China Sea and of the Manila Trench ? What is the spatial transition from the South China sea-Manila Trench-Philippine system to Taïwan and Ryu-Kyu ? This is a key-area in the globe to better understanding the formation of chains (R. Blanchet, 1977).

The end of the oceanic evolution

The first tectonics take place when the whole system get a compressive regime ; the oceanic crust is sliced up in large units which are overthrusted on the continental margin (tethian or alpine-type collisions), or on island arcs with continental basement (Californian type collision) ; the **overthrust of ophiolites** is, at a chaine-scale, the great early tectonic phase which generates in the basins, sedimentary sequences with blocks (mélanges, olistoliths, " séries à blocs") by reworking the ophiolite sequences of the overthrusted units (diabase-radiolarites formation, in the Dinarides-Hellenides, mélange in California, some of the " schistes lustrés " units in the Alps, series with blocks in the Caribbean chain). This overthrust of Ophiolites was called obduction (Coleman, 1971). If we want to use the word "obduction", it is to mean an oceanic overthrust or charriage due to the collision of a continent with a block that have stopped a previous subduction. this word can also be used simply to mean overthrust or "charriage" of ophiolites.

After the suturation (the oceanic suturation can occur as many times as the number of oceanic spaces to be sutured) the **collision** goes on, and by many compressive phases, slices up the oceanic series, the margins (their basins and their floors) into units overthrusted twice, three times or more, and piled up by flat shearing or by " décollement ".

A flat crustal shearing of great magnitude generally reworks the belt during hypercollision, generating the most apparent horizontal contacts. The most spectacular **hypercollision** result is the Himalaya (Mattauer, 1975) ; the eastern Alps are another example. But this phenomenon is quite general (Aubouin *et al.*, 1977 *b;* Aubouin, 1980).

Finally, wide folds or swells set up in the late phase, frequently generating the most evident characteristic features of the chains ; it is the case in the Alpine chaines originated from the Tethys where — except in the Himalaya cf. supra — the highest summits are always situated on such swellings.

The chain may be reworked by tensional tectonics creating basins, crustal thinning (Basin and Range, pannonic Basin, circum alpine fault system). Some of them may succede particularly well and generate new small oceanic basins (the Gulf of California, the western Mediterranean). Such an evolution may have happened in various epochs : thus, the setting up of the Caribbean basin in Middle Cretaceous (about 110 m.y. BP), after the subductions and collisions of the late Jurassic and of the Lower Cretaceous, has certain similarities with the formation of the Mediterranean sea.

CONCLUSION

The IPOD program has enabled us to get direct data on active margins, for the first time. The drillings have provided new facts which are yet partly obscure but that must be taken into account before any generalisation. If there is a tectonic accretionary prism on the drilled margins it is necessarily more limited than on the classic models. It seems that on these drilled margins the general regime resulting from subduction is extension and not compression, subsidence and not uplifting. The subduction seems to be the fundamental geodynamic phenomena, at the dimension of the lithosphere, marked by the overthrusting of one plate on another one. Secondary phenomena result from subduction : such as the subsidence of the margin in extensive regime, making the trench look like a graben. According to our present knowledge, the formation of an accretionary prism does not seem compatible with these data, in the drilled areas ; each plate has its own deformations, its superposed tectonics and its geologic evolution. When studying active margins we must systematically carry out research in regional tectonics on the arcs and at the same time on the continental borders.

As regards mountain belts, chains such as California, the Alps, the Caribbean, for example, were soon compared with accretionary prism model (precisely taken up in the Pacific). When analyzing superposed tectonics, we can determine the role of each tectonic phase in the formation of the belt before the role of paleosubductions can be considered. The observed tectonic contacts are generally late and, thus, they cannot be compared with the possible early contacts of accretionary prisms resulting from subduction. It is more and more admited that blueschists are in several chains, synchronous with tectonic phases, necessarily younger than the possible paleosubductions. So, we cannot take the tectonic accretionary prisms of the chains as a reference to justify their existence in the oceans.

And, *vice versa*, this paper can be a program for further research, not an established conclusion. We must develop research in present day oceans, on active margins, especially on the large areas which are not yet drilled and in the more complex small oceanic basins (marginal basins in the western Pacific and in the eastern Mediterranean).

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