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A summary of results from the IPOD transects across the Japan, Mariana, and Middle-America convergent margins

IPOD
Convergent margins
Japan
Mariana
Middle America

IPOD
Marges convergentes
Japon
Mariannes
Amérique Centrale

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ABSTRACT

Investigations of convergent margins along the IPOD transects support the concept of ocean floor spreading in back-arc basins and the concept of tectonically accreted sediment at the front of convergent margins. However, not all convergent margins have large accreted complexes, and other less frequently used concepts are required in the interpretations of these convergent margins. If the present rates of plate convergence are accepted, then much sediment that entered the trenches studied is presumably subducted rather than accreted. In some instances, the continental framework is truncated and somehow removed by tectonic erosion. Some convergent margins have subsided significantly during subduction. The crust above the Benioff zone appears to have been thinned by subcrustal erosion or the configuration of the Wadati-Benioff has changed. However, since only part of the subsidence can be explained by erosion, the change in thermal structure resulting from changing rates of subduction may be the major cause. To differentiate subduction-related processes commonly requires time-stratigraphic information from drill samples to make a kinematic reconstruction of the margin.

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RÉSUMÉ

Résumé des résultats des forages IPOD à travers les marges convergentes du Japon, des Mariannes et de l'Amérique centrale.

Les recherches sur les marges convergentes le long des transects IPOD confirment les concepts d'expansion océanique dans les bassins d'arrière-arc, et d'accrétion tectonique de sédiments au front de ces marges. Cependant, toutes les marges convergentes n'ont pas de grands complexes accrétés et l'on doit utiliser d'autres concepts moins classiques pour interpréter ces dernières. Si les taux actuels de convergence de plaques sont acceptés, on doit alors considérer que la majeure partie des sédiments arrivant dans les fosses étudiées est probablement subductée au lieu de s'accréter. Dans quelques cas, le bâti continental est tronqué et quelque peu enlevé par l'érosion tectonique. Quelques marges convergentes ont connu une importante subsidence durant la subduction. La croûte au-dessus du plan de Benioff semble avoir été amincie par érosion sous-crustale, à moins que la configuration de la zone de Wadati-Benioff ait changé. Cependant, on ne peut expliquer qu'une partie de la subsidence par l'érosion ; le changement dans la structure thermique résultant des taux variables de subduction peut en être la cause majeure. Pour reconnaître les processus dus à la subduction, il faut des données chronologiques et stratigraphiques obtenues à partir des forages, afin de faire une reconstruction cinématique de la marge.

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INTRODUCTION

The IPOD transects of geophysical data and drill cores across the Japan, Mariana and middle-America convergent margins expand knowledge of active margins into areas not touched by geophysical data alone. The combined modern geophysics and drill data provide a time-stratigraphic section from which the rates of tectonic and sedimentary processes can be estimated. Samples from beneath the ocean floor indicate the depth of past depositional environments and thus, by comparing their past and present position, some sense of vertical tectonism can be obtained in a geologic setting dominated by the horizontal motion of two convergent lithospheric plates.

The information provided by IPOD drilling on active margins supports many of the general concepts that the program was designed to test. The accretion of sediment at the front of the trench slope was persuasively supported by data from the Oaxaca transect (Moore *et al.*, 1979), but accreted deposits were not found everywhere. The development of back-arc basins by crustal spreading was convincingly confirmed (Klein *et al.*, 1978 ; Kroenke, Scott, 1978 ; Hussong *et al.*, 1978), and some insight was obtained as to the complexity of this process. Although new discoveries were expected, few anticipated their proportions. There is evidence along all transects that a large amount of sediment is subducted rather than accreted, that continental lithosphere may be subducted, and that lithofacies of the trench floor, trench slope, and shelf cannot be predicted with only simple models of sediment distribution. The information from each leg has been summarized at this colloquium by the scientific staffs of each of the IPOD active-margin legs. In this summary we can refer only to the preliminary results of the legs because many of the Initial Reports of the Deep Sea Drilling Project on IPOD active margin legs have not yet been published. We have extracted the main results from the IPOD active margins program in this summary of the first of three colloquia on active margins at the 26th International Geological Congress.

THE DEVELOPMENT OF BACK-ARC BASINS BY SEA-FLOOR SPREADING

Karig (1971) proposed that back-arc basins in the Philippine Sea (for example, the Mariana Trough) formed by spreading of ocean crust, and the results of *Glomar Challenger* drilling on Leg 31 are generally consistent with the spreading hypothesis (Karig, 1975). There has always been a question of how back-arc spreading was related to plate convergence and subduction.

In the complex Diato Ridge and Basin province of the northern Philippine Sea, back-arc spreading simultaneous with arc magmatism was confirmed by the studies of the scientific staff on Leg 58 (Klein *et al.*, 1980). Some former magmatic ridges are now subsided remnant arcs ; the basins presently contain volcanic rock formed during arc and post-arc volcanism. The evolution of this complex area can now be interpreted within the constraints of a broad multidisciplinary set of data. It includes about 35° northward migration and 55° rotation of a back-arc basin and subsequent periods when parts of the basin were subducted. The remaining questions concern the symmetry of the spreading that formed the west Philippine Basin and the ultimate age of its crust.

The staff of Leg 59, working farther south, concluded from a sequence of basement ages that back-arc spreading in the south part of the west Philippine Basin may have been simultaneous with volcanism along the Palau-Kyushu Ridge. Initial spreading and arc volcanism were followed by subsequent episodes of spreading and volcanism along the Mariana Ridge and Arc. The staffs of Legs 59 and 60 documented more thoroughly than before that new volcanic arcs developed sequentially, leaving behind a series of remnant volcanic ridges and associated back-arc basins. Although the back-arc basin crust appears to develop simultaneous with island-arc volcanism during long periods, there is some indication that for short periods one process occurs without the other. Therefore it is still not clear how mechanisms generating back-arc magma and the associated tensional forces are associated with converging lithospheric plates.

MAGMATIC ROCKS IN THE FORE-ARC REGION

Along the Japan and Mariana transects, arc-related volcanic and intrusive rocks were recovered at sites near the trench slope, far seaward of the presently active arc (Fig. 1). Off Japan, the recovered island-arc rocks are of rhyolitic to dacitic composition and from intrusive and extrusive environments (Fujioka, 1980). Refraction data (Nagumo *et al.*, 1980) indicate that another igneous body occurs nearby, and other plutons are suggested by low-amplitude magnetic anomalies (Oshima *et al.*, 1975). The crystallization age of these rocks determined by isotopic dating is 22-24 MY, which may be about the same age as the initial volcanism along the present arc (Yanagasawa *et al.*, 1980). Where these rocks occur, the upper surface of the subducting ocean lithosphere is shallow, and if the present temperature gradient measured downhole is extended to the base of the upper plate, the temperature is about one-quarter of that needed to produce island-arc magma (Fig. 1).

In the Mariana transect, arc-related volcanic and plutonic rock was recovered by dredging from as far seaward as the lower slope of the trench (Dietrich *et al.*, 1978). The dredged and drilled Eocene and Oligocene rocks are some of the oldest of the Mariana Arc (Hussong *et al.*, 1978). The altered state and their low melting temperatures indicate

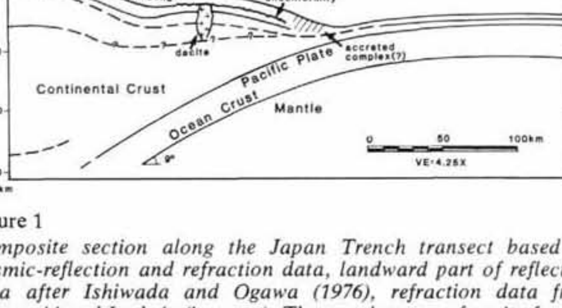

Figure 1

Composite section along the Japan Trench transect based on seismic-reflection and refraction data, landward part of reflection data after Ishiwada and Ogawa (1976), refraction data from Murauchi and Ludwig (in press). The angular unconformity formed by subaerial erosion in the late Paleogene and Neogene is indicated by a wavey line. The accreted complex is inferred from seismic data ; only overlying slope sediment was drilled. Dacite and associated island-arc rock was recovered at site 439 ; numbers refer to sites drilled on Legs 56 and 57.

that they were formed in the presence of abundant water. Perhaps this water was derived from the dehydration of the lower plate during subduction (Anderson *et al.*, 1976) as suggested to us by J. Natland (written comm.).

The position of ancient arc-related rocks, much closer to the trench than the presently active arc, suggests that the depth to the top of the subducting oceanic lithosphere was once deeper or that the base of the continent may formerly have been farther seaward unless forearc magmas are produced by some other process than the melting of subducted materials.

SUBDUCTION ACCRETION

Prior to drilling, multichannel seismic-reflection records were interpreted as showing tectonic accretion related to subduction, or subduction accretion, off Japan and Middle America. The clearest pre-drilling geophysical evidence was from the middle-America Trench transect off Oaxaca (Shipley *et al.*, 1980). Seismic data from this area show a sequence of strong landward dipping reflectors below a thin layer of reflections paralleling the seafloor (Fig. 2). Drilling at three sites on Leg 66 indicates that the age at the top of the landward-dipping reflectors progresses from Pleistocene at the foot of the trench slope to upper Miocene near the middle of the slope. This age progression is evidence for the stacking of thrust slices of material from the subducting ocean crust (Moore *et al.*, 1979). However, despite the increase of deformation with depth observed in every core, no major faults were recognized from repeated ages or the physical character of cored sediment (Moore *et al.*, 1979). Penetration (maximum 542 m) was less than expected and perhaps deeper drilling would have provided evidence of the thrust faults interpreted from the seismic records and dating of cores.

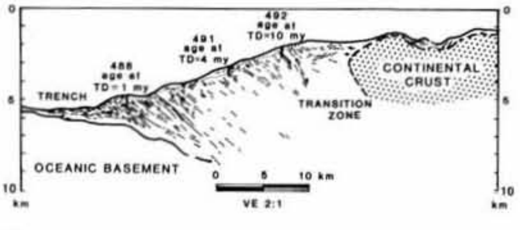

Figure 2

Composite section along the Middle America Trench transect off Oaxaca, Mexico, showing landward-dipping reflections and the truncated continental framework. At the bottom of hole 492 the sediment is about 12 MY old whereas at the bottom of hole 488 it is of Quaternary age. From Moore et al., *1979.*

Off Japan, the Marianas and Guatemala small-scale deformation increases rapidly with depth in slope sediment but no accreted subduction complex or major thrust faults were recognized in the core ; however, drilling probably did not penetrate deeply into the section inferred from seismic data to be an accreted sequence. On the Japan Trench transect an interval of repeated ages at the bottom of hole 434 could signify thrust faulting, slumping, or possibly environmental changes recorded by the microfossil flora. Thus, an imbricate thrust sequence might have been penetrated but this interpretation is not unequivocal.

Sediment recovered from the landward slopes of the trench on all transects is mainly hemipelagic mud and interbedded thin volcanic ash. No pelagic sediment characteristic of the deep ocean basin was recovered. This observation does not in itself rule out the possibility that offscraped oceanic material was recovered because thick hemipelagic sediment was recovered in holes as much as 20 km seaward of, and 2,000 m above, the trench floor of the Middle America and Japan Trenches. If only the top of the deep ocean section and trench floor deposits are accreted (Moore, 1975) they would be difficult to distinguish from sections deposited on the landward slope of the trench. Nonetheless, benthic foraminiferal faunas on the Japan and Guatemala landward slopes seem to indicate that only slope deposits were penetrated because they contain a mixture of transported forms and not the faunal assemblages found at trench depths.

Deformation of shallow sediment on the landward slope by microfracturing was commonly observed beginning at a depth of about 200 m and continuing to more than 600 m. Microfracturing may be a dominant mode of tectonic deformation under the trench slope. There is evidence for geopressured sections from the logging in holes on the lower slope of the trench off Japan (von Huene *et al.*, 1978 ; Arthur *et al.*, 1980). We speculate that : 1) perhaps the greatest dislocations within some underthrust margins are concentrated along narrow zones that are saturated with overpressured water ; 2) that the absence of teleseismic earthquakes at the seaward end of the Benioff zone is explained by water lubricated faults and abundant microfracturing ; and 3) that a small frictional resistance along lubricated faults could explain terranes that are coherent on a large scale despite the thousands of kilometers of oceanic crust that have been subducted.

SEDIMENT SUBDUCTION

Soft sediment entering a subduction zone is commonly presumed to be scraped off the more competent ocean crust and to be mechanically attached to the margin's existing framework. Some authors argue that sediment may be entrained in graben of the ocean plate that is subducted beneath the landward slope of the trench (Lister, 1971 ; Hilde, Sharman, 1978 ; Schweller, Kulm, 1978). Accretion of oceanic sediment was studied along the active margin

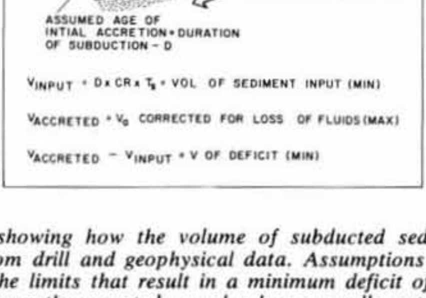

Figure 3

Diagram showing how the volume of subducted sediment was derived from drill and geophysical data. Assumptions have been made at the limits that result in a minimum deficit of sediment. Drilling above the accreted complex has generally not penetrated into, or very far into, the accretion complex, which is commonly inferred from landward-dipping reflections in seismic data.

transects by comparing the potential input, as estimated from sediment thickness on the ocean crust and convergence rates, with the corresponding sediment volume of the accreted body at the front of the subduction zone. In all cases the volume of accreted sediment was inferred from interpretation of seismic records and its age was limited from drilling (Fig. 3). Despite the inability of the *Glomar Challenger* to drill completely through the landward dipping sediment sections and recover the oldest sediment in a subduction complex, the oldest rocks penetrated at sites on the lower slope of the trench can be used as the minimum age of the accreted subduction complex (Fig. 3). This procedure would give the largest possible volume of sediment scraped off the ocean crust in a given time, to compare with the smallest volume of sediment contributed from the oceanic plate ; the calculations produce results in an estimate of the maximum amount of sediment that has been accreted. Such an estimate on the Japan Trench transect indicates that during the past 6 MY only about 20 % of the sediment input has been accreted and the rest is presumably subducted. Off Guatemala there is virtually no sediment younger than Cretaceous at the foot of the trench slope requiring a period of no accretion or removal of the previously accreted sediment. Along the Mariana Trench most of the rocks are igneous, and any sediment scraped from the ocean crust is rare. Even along the Oaxaca margin, where subduction accretion is best demonstrated, a maximum of 66 % of the incoming sediment is estimated to be accreted. The imprecision of these estimates is insufficient to affect significantly the large amount of sediment subducted.

Watkins, Moore and their colleagues (this volume) suggest that off Oaxaca much of the sediment passing beneath the front of the margin is accreted by being attached to the underside of the accretionary mass. The evidence for this process, which they term underplating, is that the wedging of successively accreted thrust slices to uplift and tilt strata landward occurs only at the very toe of the trench slope. Yet the paleontological evidence shows uplift of the whole slope. Underplating of subducted sediment is one explanation of the uplift.

SUBDUCTION EROSION

Tectonic erosion, which is the retreat or subsidence of a margin through removal of material from a landward slope of the trench, can be caused either by strike-slip faulting or by subduction erosion. Subduction erosion (Scholl *et al.*, 1980) is a term equivalent to consumption (Kulm *et al.*, 1977), to some uses of tectonic erosion (Karig *et al.*, 1978), or just simply erosion (Hussong *et al.*, 1976). Subduction erosion can occur either at the leading edge of a margin, thus leaving a truncated margin, or along the subsurface base of the lithosphere above the Benioff zone, thus causing subsidence as the overlying crust is thinned. Subduction erosion has been suggested infrequently in the last few decades (e.g. Hussong *et al.*, 1976 ; Kulm *et al.*, 1977 ; Scholl *et al.*, 1981). However, arc magmatism in the present forearc area, evidence of massive subsidence in the forearc and trench slope areas during subduction, and abrupt truncation of the continental framework on the landward slope of the trench all suggest that some trench slopes have periods of retreat.

Subsidence dominates the Neogene tectonic history of the forearc area off Japan, and net subsidence rather than uplift dominates Neogene vertical movement in the Mariana forearc area. Off Oaxaca, the shelf first subsided 2 to 3 km, and then rose during the latest episode of subduction accretion to the present depths of 1 to 1.5 km. Off Guatemala, subsidence since early Miocene time was indicated by the study of benthic fauna in the Neogene slope sediment, and either subsidence or a large rise in sea level are reported from the Guatemalan shelf (Seely, 1979). If subsidence of the margin involves some isostacy, thinning of low-density continental crust and replacement with higher density oceanic crust would seem to be required. An alternative mechanism, reported by Langseth and his colleagues, accomplishes subsidence by changes in the rate of subduction with its consequent change in thermal conditions to provide cooler rock of greater density. Such exchanges of less dense for denser crust would probably occur at the crustal contact formed by the present subduction zone.

The subsided paleolandmass off Japan had a Miocene Pacific shoreline that is now beneath the landward slope of the trench within 20 km of the present trench axis. A reconstruction of the margin with a shoreline within 20 km of the trench axis requires that the axis was formerly further east and suggests that during the Neogene it retreated west relative to Honshu by erosion of the trench slope. Off Oaxaca, subduction accretion began about 10 MY ago against a truncated margin of Paleozoic and older cratonic rock. Here the truncation may have been caused by strike-slip faulting. Off Guatemala, truncation by subduction erosion is perhaps the most attractive of three explanations for the Cretaceous section recovered by drilling at the foot of the slope. Truncated margins are common, but the type of tectonic erosion that has caused truncation is not always clear. Considerable evidence exists for subduction erosion, especially off Japan (von Huene *et al.*, 1978 ; Murauchi, Ludwig, 1980 ; Langseth *et al.*, 1981, this volume).

Perhaps the concept of subduction erosion has been applied infrequently by geoscientists because it requires processes that seem unlikely, such as stuffing young rock beneath older rock of greater density or large-scale abrasion of the continental framework. The concept of tectonic erosion by lateral faulting has been more frequently invoked to explain truncated margins, and indeed it is much less difficult to imagine (see, for instance, Karig, 1974). However, if the plate convergence vector at some of the margins truncated in the past 10 MY has not changed appreciably, then the lateral component of fault motion, and hence the lateral transport of crustal fragments, should be small. Near the Japan and Guatemala transects the Neogene crustal fragments missing from the foot of the margin have not been located in adjacent seismic records for hundreds of kilometers along strike. Therefore, subduction erosion deserves consideration as one cause of structural truncation at underthrust margins despite the present conceptual problems.

SEDIMENT FACIES DISTRIBUTION

Most of the sediment recovered by DSDP drilling in deep-water forearc areas and trench slopes is hemipelagic silt and clay rich in volcanic ash (including sites on Legs 18, 19, and 31). Clean sand in discrete beds is a relatively minor constituent in the core material recovered ; however, it is also more difficult to recover than silt and clay. On the middle America transect off Oaxaca, caving sand stopped drilling in the trench and on the trench lower slope. On the middle America transect off Guatemala the trench fill (sampled in nine holes) is predominently silt and clay. It is also in the Aleutian Trench off Kodiak (Kulm *et al.*, 1973). Conventional sampling (piston coring and dredging) of the shallow strata along the Japan Trench margin, the Aleutian Trench margin, and the middle America Trench margin has produced mainly silt and clay similar to that in the DSDP core. Off Oaxaca near a major canyon across the margin, a significant amount of sand was recovered in piston cores, and along the other canyons coarse sediment was cored or dredged. Thus, although sand is perhaps underrepresented in recovered material because it impeded the drilling or coring, hemipelagic silt and clay are the main materials recovered from the trench and lower slope, a conclusion also confirmed by downhole logging.

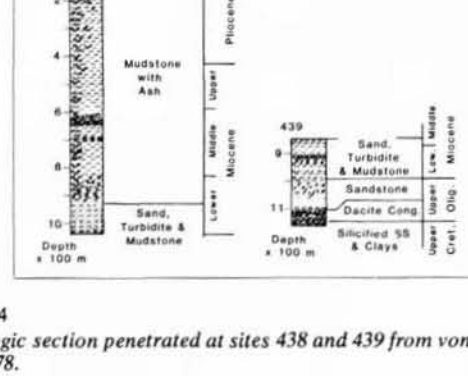

Figure 4
Lithologic section penetrated at sites 438 and 439 from von Huene et al., *1978.*

Hemipelagic sediment like that deposited on continental arc-trench systems is also deposited beyond the trench in the deep ocean basin. The hemipelagic sections seaward of the trenches are generally of late Miocene age, although near the Aleutian Trench (site 178) and Kamchatka Trench (site 192), the deepest hemipelagic material is of early or perhaps middle Miocene age. When the sites of deposition are restored to their position in Miocene time by applying global plate motion history, these sites were apparently several hundreds of kilometers out to sea when they received terrigenous sediment. One consequence of the thick hemipelagic sediment far out on the ocean plate is that considerably more hemipelagic sediment is available to be accreted than if the whole oceanic section were typical pelagic ooze. This may be one explanation for the sparse oceanic sediment in some ancient deposits that are interpreted as tectonically accreted complexes. From the cores and surface samples, it appears that in modern trenches only very subtle lithologic differences distinguish environments of the shelf, slope, trench, and perhaps even the trench seaward slope. The contrast of muddy sediment sampled from modern trenches with sandy sediment from presumed ancient analogues is puzzling.

Biofacies are the best indicator of paleodepth ; however, those interpretations of paleodepth referenced to oceanographic depth boundaries such as the carbonate compensation depth are difficult to project back in time. The depths of the carbonate compensation depth have fluctuated in the past, especially along margins.

The number of cores and other samples is obviously insufficient to clearly show the small lithofacies differences between depth environment along a modern convergent margin. Underwood *et al.* (1980) conclude that modern trench floor, slope basin, and slope deposits can range from fan complexes through hemipelagic and pelagic deposits. A similar conclusion results from all DSDP studies except the Oaxaca transect. Off the Japan and Middle America Trenches coarse- to fine-grained sediment is transported in channels from near shore across the margin and ultimately to the trench (Arthur *et al.*, 1980 ; Moore *et al.*, 1980). This bypassing of the shelf produces the similarity of lithologies across the margin. The similarity of lithofacies is consistent with observations of morpho-tectonic and sedimentary features. The morphologies and structures in seismic records across any part of the Japan margin reveal slump, channel, overbank, ponded, draped, and fan deposits, only in different relative proportions (von Huene, Arthur, in press). There are no definite links between the sedimentary structures seen in geophysical records and the corresponding sedimentary facies associations ; however, the trend of one should be reflected in the other. We speculate that no single type of facies association is unique to a particular environment, but some types may be more frequent in one than in another. Thus, for instance, slumping or soft-sediment deformation might be more frequent on trench slopes or in slope basins as compared to a basin on the shelf, and if the sediment is sufficiently sandy there is probably a relative abundance of certain facies associations that could aid in distinguishing one environment from another. The key to identifying tectonically displaced sedimentary environments in ancient rock may be a relative comparison of the facies across the whole margin. In convergent margin environments, the sediment distributed across the margin in over a short period of time should be studied because sediment pathways and basins change as the trench slope morphology is re-sculptured by the rapid tectonic movement associated with subduction.

CONCLUSIONS

Perhaps we have biased this summary by discussing the unanticipated results at greater length than the results consistent with previous concepts. Without much doubt, the accretionary tectonic model for convergent margins has been prominent in the evolution of plate-tectonic concepts. During the past decade, this model was applied in a majority of interpretations for both ancient fold belts and modern margins, seemingly to the exclusion of other mechanisms that had been suggested in the past. For instance, so convincingly has the accretionary tectonic model of continued thrust wedges seemed to explain parts of the Franciscan complex of California or the modern southeast Asian arc-trench systems that other tectonic concepts seemed overshadowed. Thus, through the discovery of features that cannot be explained by accretion, the IPOD results may have renewed curiosity about other tectonic mechanisms. Nearly 20 years ago, Coats (1962) struggled with the concept of sediment subduction in his analysis of Aleutian island arc magmatism. His concept was furthered by Gilluly (1969 ; 1973) and extended by Scholl and Marlow (1974 *a*, *b*) and by Karig (1974) and Moore (1975) relative to subduction of pelagic deposits. Perhaps what is needed to further knowledge of the sediment subduction concept are samples from an active Benioff zone to help constrain some physical parameters such as geopressuring, sediment consolidation, and stress so that the process can be modeled. A more convincing argument for sediment subduction requires a physical explanation for the underthrusting of soft sediment. Subduction erosion is also not a new idea ; it was suggested more than a decade ago by Van Bemmelen (1966) and has been treated infrequently and in a speculative way for some time in studies of ancient margins. To make persuasive arguments for subduction erosion is difficult because the process is recognized by the absence of rock and is difficult to observe in the geologic record. Nonetheless, the retreat of the leading edge of a convergent margin and the massive subsidence of continental crust above an active subduction zone are probably sufficient evidence for some form of subduction erosion.

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