Accretion, underplating, subduction and tectonic evolution, Middle America Trench, Southern Mexico : results from DSDP Leg 66

Arc-trench systems
Middle America Trench
Accretion
Offscraping, underplating
Gas hydrate

Système arc-fosse
Fosse d'Amérique Centrale
Accrétion, arrachement
Coincement sous plaque
Gaz hydraté

J. S. Watkins [a], J. C. Moore [b], T. H. Shipley [c], S. B. Bachman [d], F. W. Beghtel [e], A. Butt [f], B. M. Didyk [g], J. K. Leggett [h], N. Lundberg [b], K. J. McMillen [a], N. Niitsuma [i], L. E. Shepherd [j], J. F. Stephan [k], H. Stradner [l].

[a] Exploration and Production Division, Gulf Science and Technology Company, P.O. Box 2038, Pittsburgh, Pennsylvania 15230, USA.
[b] Department of Earth Sciences, University of California, Santa Cruz, California 95060, USA.
c University of California, San Diego, La Jolla, California 92093, USA.
[d] Cornell University, Ithaca, New York 14853, USA.
[e] Phillips Research Center, Bartlesville, Oklahoma 74004, USA.
[f] Geology and Palaeontology Institute, Tübingen University, Sigwartstrasse 10, 74 Tübingen, FRG.
[g] Research Development Laboratory, Empresa Nacional del Petroleo, Concon, Chile.
[h] Department of Geology, Imperial College of Science and Technology, South Kensington, London SW7 2AZ, UK.
[i] Institute of Geosciences, Shizuoka University, 836 Ohya, Shizuoka City, Japan.
[j] Department of Oceanography, Texas A & M University, College Station, Texas 77843, USA.
[k] Department de Géotectonique, Université Pierre et Marie Curie, 4, place Jussieu, 75005 Paris, France.
[l] Geologie Bundesanstalt, Vienna, Austria.

ABSTRACT

During Leg 66 eight sites were drilled to form a transect across the Middle America Trench off southwestern Mexico. Cores from these sites show that accretion began approximately 10 MY ago and has continued to the present. Accretion began with offscraping followed by a 2- to 4- MY episode of folding and faulting with uplift rates of 400-500 m/MY ; uplift then slowed to 100-200 m/MY, and seismically resolved deformation ceased as the wedge appeared to rise evenly. Approximately 33 % of the sediment flux input into the subduction zone, mainly trench sand and slump deposits, is scraped off and incorporated into the toe of the lower slope ; an additional 33 % is initially subducted but then peeled off to underplate the accretionary wedge ; the remaining 33 % is subducted landward beneath the overhanging lip of continental crust. Although we find no direct evidence of tectonic erosion, the large amount of sediment subducted makes tectonic erosion feasible.

Plate reorganization and the onset of sinistral strike-slip faulting roughly 23 MY ago are thought to be responsible for the truncated appearance of geologic basement features onshore. After strike-slip faulting, the ocean transgressed the margin 22 MY ago, and the edge of the continental crust subsided rapidly, reaching a depth at or slightly greater than the carbonate compensation depth 19 MY ago. Thereafter, the crust has risen slowly at a rate of about

90 m/MY. The onset of accretion 10 MY ago probably marked the end of strike-slip faulting and the beginning of the oblique convergence observed today.

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RÉSUMÉ

Accrétion, plongement de plaques, subduction et évolution tectonique de la fosse d'Amérique Centrale, Mexique méridional : résultats du Leg 66 DSDP.

Les huit puits forés lors du Leg 66 sont situés sur une transversale de la fosse d'Amérique Centrale au large du sud-ouest du Mexique méridional. Les carottes récupérées montrent que l'accrétion a débuté il y a 10 mA environ et a continué jusqu'à l'Actuel. L'accrétion a débuté par un ripage en avant, suivi pendant 2 à 4 mA d'une phase de plissement et de faillage avec des taux de soulèvement de 400-500 m/mA ; la vitesse de soulèvement s'est ensuite ralentie jusqu'à 100-200 mA, et la déformation responsable des séismes a cessé lorsque le prisme s'est aussi soulevé. 33 % environ de l'apport sédimentaire dans la zone de subduction, sous forme de grès et de dépôts glissés, sont arrachés et incorporés à l'extrémité de la pente inférieure ; 33 % ont subi un début de subduction, mais ont été décollés et coincés sur le prisme d'accrétion ; les 33 % restant étant subductés sous le rebord de la croûte continentale. Bien qu'il n'y ait pas d'évidence d'érosion tectonique, la grande quantité de sédiment subducté rend ce phénomène envisageable.

La réorganisation des plaques et l'instauration d'un système décrochant senestre il y a 23 mA sont probablement responsables de la troncature apparente des traits géologiques du socle émergé. Après le décrochement, l'océan a transgressé la marge, il y a 22 mA, et la bordure de la croûte continentale a subsidé rapidement, atteignant une profondeur au moins égale à la CCD il y a 19 mA. Par la suite, la croûte s'est soulevée lentement à un taux de 90 m/mA. Le début de l'accrétion il y a 10 mA a probablement marqué la fin du décrochement et le début de la convergence oblique observable actuellement.

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INTRODUCTION

Objectives of the Leg 66 drilling off southwestern Mexico were investigations of :

1) the accretionary mechanism including a test of the imbricate thrust model of Seely *et al.* (1974) ;

2) sediment subduction and tectonic erosion of the overriding plate during the subduction process ; and

3) the geologic history of the margin with particular emphasis on the periods immediately before, during, and immediately after the onset of subduction.

This paper focuses on the processes of mass addition. We use "accretionary prism" or wedge to refer to all material that is tectonically transferred from the lower to the upper plate during crustal convergence. "Offscraping" describes accretion (principally of trench sediments) at the base of the trench slope. "Underplating" designates a process of mass addition at depth beneath the rind of offscraped deposits. In our usage, the term accretion refers to mass addition in general, whereas offscraping and underplating indicate a particular tectonic setting for the accretionary process.

Accretion

The concept of accretion evolved during the late 1960's and early 1970's. Seyfert (1969) first pointed out that accretion related deformation of trench sediments could explain the abrupt disappearance of seismic reflectors observed at the foot of the slope in seismic traverses across turbidite filled trenches and inner trench walls. Dickinson (1971) suggested that although oceanic basement is carried down with the descending lithosphere, lighter sediments probably are scraped off against the overriding plate. These sediments combine with ophiolitic scraps to form melanges. Dickinson further observed that the tectonic thickness of a melange zone depends on the amount of turbidite sediment fed into the subduction zone.

Von Huene (1972), with improved seismic-reflection data, observed oceanic crust and overlying undeformed pelagic sediments extending as much as 12 km landward of the Aleutian Trench beneath deformed slope sediments. Although thrust faults were not clearly evident in the slope seismic data, von Huene's interpretation included a master thrust fault deep in the second oceanic layer. Beck's (1972) multifold seismic section across the Java Trench near Bali showed undeformed oceanic crust gently dipping beneath the inner wall for a distance of about 40 km landward of the trench. Seismic features in the region above oceanic crust, though strongly hyperbolated with diffractions, suggested landward dipping reflections.

Dickinson (1973) strengthened the argument for accretion with the observation that, with few exceptions, widths of arc-trench gaps are proportional to ages of the respective island arc-trench systems. This correspondence resulted, he

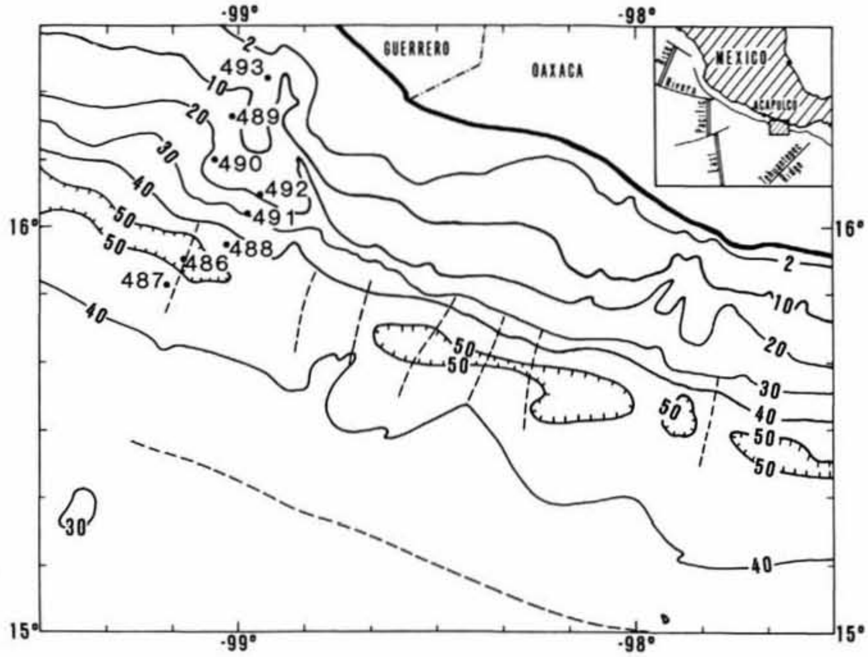


Figure 1
Index map of DSDP Leg 66 transect showing sites, bathymetry, and location of seismic data (dashed lines) used to estimate flux of trench turbidites and oceanic pelagites and hemipelagites being accreted and/or subducted. Contour interval is 100 m ; 5000-m contours roughly outline turbidite ponds in the trench.

thought, from steady accretion of crustal materials by the inner wall.

DSDP Leg 31 drilled the toe of the slope landward of the Japan Trench off the island of Shikoku in mid-1973. Cores recovered showed that Pleistocene trench sediments had been compressed to about half their original volume and given a distinct cleavage within 6 km of the trench. Elevation of these sediments to 300 m above the trench floor (Karig *et al.*, 1975), provided further evidence of accretion.

Seely *et al.* (1974) integrated the foregoing observations in their interpretation of multifold, common-depth-point seismic-reflection data collected off Guatemala and Oregon, inferring that the inner wall comprised :

1) a surficial apron of undeformed sediments overlying ;

2) a zone of deformation containing landward dipping reflectors (LDRs) all overlying ;

3) relatively undeformed, gently landward-dipping oceanic crust.

Seely *et al.* suggested rotation of LDRs during accretion with the result that dip increased with increasing elevation within the section. They interpreted this mechanism to mean that older upper melange slices rotated upward as younger slices were progressively emplaced by underthrusting (Fig. 2).

Sediment subduction

The previously mentioned investigations, although providing abundant evidence of accretion, did not preclude subduction of a significant fraction of the pelagic-hemipelagic-turbidite flux. Von Huene *et al.* (1980 *b*) noted that calculations suggest subduction of 80 % of the sedimentary input into the Japan Trench, and Karig and Sharman (1975), in their review of the accretionary mechanism, suggested that some of the sedimentary cover may reach considerable depths before shearing off. Results of Leg 67 in the Middle America Trench off Guatemala strongly suggest sediment subduction (von Huene *et al.*, 1980 *a*).

Subduction erosion

Not all old trench systems have wide arc-trench gaps, and some appear to have anomalously small accretionary wedges for their inferred ages. Did these systems ever have larger wedges ? If so, where are they now ? And if they did not have wedges, why not ? Tectonic erosion has been suggested as the answer.

Hussong *et al.* (1976) examined perhaps the best example in the Peru-Chile trench between 8°-12°S latitude. Here, volcanic studies on land show evidence of subduction as old as mid-Mesozoic. Multifold seismic-reflection and detailed seismic-refraction studies, however, suggest a narrow (10-km) accretionary wedge comprising low-velocity material (2.0-3.5 km/sec.) that is currently being uplifted. Immediately landward, the lower slope consists of a low-velocity apron of undeformed sediments underlain by rocks with velocities of 5 km/sec., velocities more consistent with those of continental meta-igneous rocks than with deformed trench turbidites. Hussong *et al.* also found evidence of normal faulting within the 5 km/sec. zone. They interpret these data as indicating not only that are sediments being

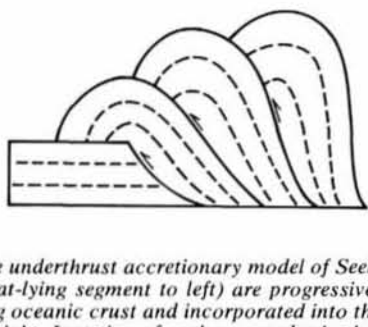


Figure 2
The imbricate underthrust accretionary model of Seely et al. *(1974). Sediments (flat-lying segment to left) are progressively scraped off the underlying oceanic crust and incorporated into the accretionary wedge to the right. Insertion of each new wedge in the bottom of the stack elevates and rotates overlying wedges with the result that major boundaries and internal stratigraphy (possibly LDRs) progressively steepen in dip upslope.*

subducted but also that the subduction process is eroding the leading edge and underside of the continental crust and subducting continental crust, a process called subduction erosion by Scholl *et al.* (1980).

The Mexican margin in the Leg 66 area resembles the Peru-Chile margin in some respects. Land studies suggest that lower Tertiary and Cretaceous volcanic arcs lay much closer to the trench than does the present volcanic axis. As in the Peru-Chile Trench, seismic-reflection data suggest an anomalously small accretionary wedge considering the probable age of the subduction. Seismic evidence of subduction erosion, however, is less extensive in the Leg 66 region than in the Peru-Chile Trench.

Geologic history

Investigations of trenches and subduction zones generally provide very little information about the onset of subduction because material involved in sedimentary and tectonic events occurring at this time is rapidly buried to depths inaccessible to shallow coring investigations, while simultaneous deformation renders structures seismically indecipherable. By the time a melange is uplifted and exposed by erosion, multiple tectonic overprinting makes identification of early history difficult, if not impossible.

A knowledge of the early history would be useful in the understanding of the subduction mechanism. For example, if subduction is a convective process, why is relatively young, lower density oceanic crust subducted in the eastern Pacific while much older, denser crust appears stable along North Atlantic margins ? Knowledge of the early history may shed light on the upper slope break as well. Karig and Sharman (1975) observed that the upper slope topographic break usually separates a zone of uplift, including the active part of the accretionary wedge, from a zone of subsidence encompassing a forearc basin. Seely (1979) suggested that the upper slope break represents the topographic expression of the initial rupture in the oceanic crust at the time subduction begins.

Pre-drilling studies in the Leg 66 area (Shipley *et al.*, 1980) suggested that the present episode of subduction and accretion in the Leg 66 area is relatively young and that drilling might be able to reach rocks of facies and structures inaccessible in other areas. Thus a major objective of the Leg 66 drilling program was the sampling of sediments closest to the continental crust boundary, sediments thought to have been deposited during the earliest stages of subduction in the area.

GEOLOGIC SETTING

The Leg 66 area of the Middle America Trench lies within a segment bounded by the Tehuantepec Ridge to the southeast and the Rivera Fracture Zone to the northwest. This trench segment has characteristics atypical of most other active trench systems. The trench is relatively shallow, the distance from all trench axis to the shoreline is narrow, continental structures of Precambrian to Mesozoic age appear truncated (Karig, 1974 ; Karig *et al.*, 1978), and there is no forearc basin. Earthquake hypocentral depths do not exceed 200 km and define a diffuse, shallowly dipping Benioff zone (Molnar, Sykes, 1969). The present-day volcanic arc occurs 200-300 km inland along an axis markedly divergent from the trench-axis trend. Present-day convergence is about 7 cm/yr at the drilling locality (Minster, Jordan, 1978).

Onshore, the Guerrero-Oaxaca massif underlies post-Paleozoic rocks (Alvarez, 1949 ; Guzman, 1950 ; de Cserna, 1965). This massif, comprising rocks of Precambrian to Paleozoic age, appears to have undergone several periods of metamorphism. A few narrow, northwesterly trending belts contain calcareous miogeosynclinal and eugeosynclinal rocks of Triassic age. Jurassic seaways transgressed across the massif after uplift and fracturing in the Triassic.

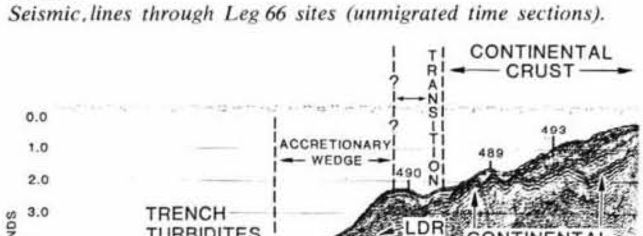
Southern Mexico experienced major orogeny in Late Cretaceous and Eocene times including emplacement of volcanic sequences and intrusion of batholiths. The orogeny culminated in folding of the massif and the overlying sedimentary-volcanic sequence. Volcanic activity along the margin continued through the lower Tertiary but appears to have been concentrated along the trans-Mexican volcanic belt in post-Oligocene time.

Offshore the upper slope dips gently (3°) for an average distance of roughly 35 km. Here, at a depth of about 2,000 m, the dip increases and the lower slope falls away at a relatively steep dip of slightly more than 8°. Maximum depths of 5.0-5.3 km occur in the trench axis at a distance of 50-60 km from the shoreline.

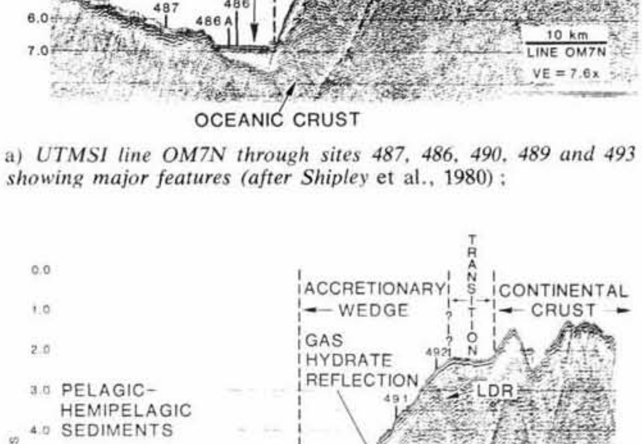
Seismic-reflection data, seismic-refraction data, and dredge hauls obtained during site surveying for Leg 66 (Shipley *et al.*, 1980) suggest that continental crust extends seaward from the shore for a distance of 25-30 km (Fig. 3), or almost

Figure 3

Seismic, lines through Leg 66 sites (unmigrated time sections).



a) *UTMSI line OM7N through sites 487, 486, 490, 489 and 493 showing major features (after Shipley* et al., 1980) ;



b) *UTMSI line MX16 through sites 488, 491, and 492 showing mahor seismic structures (after Shipley* et al., *1980).*

out to the mid-slope break. Seismic velocities calculated from sonobuoy refraction studies show that the inferred continental basement rocks generally have velocities of 4.0 km/sec. or greater. Local near-surface velocities of 3.3 km/sec. probably indicate weathering or fracturing. Landward dipping reflectors (LDRs) similar to those reported by Seely *et al.* (1974) occur within the upper part of the lower slope.

Seismic velocities in the wedge are as great as 3.5 km/sec. Velocities of sediments in the trench axis and oceanic pelagic-hemipelagic sediments on the oceanic crust seaward of the trench slope are 2.0 km/sec. or less. Seismic-reflection data near the toe of the slope and in the trench suggest thrust faulting. A hemipelagic apron, with typical velocities of 1.7-1.9 km/sec., extends from shore downslope. In parts of the area, the apron extends almost to the base of the slope ; in other areas, it is seismically resolved only on the upper slope and uppermost lower slope.

Trench turbidite ponds occur discontinuously along the trench (Fig. 1 and 3). Turbidite thickness ranges form seismically unresolved (< 50 m) to 625 m and averages 270 m. The pelagic-hemipelagic section immediately above the oceanic crust and beneath the trench turbidites ranges in thickness from seismically unresolved to 225 m when measured along the trench axis ; its thickness averages 110 m along a seismic line 50 km seaward of, and parallel to, the trench.

A seaward dipping reflector, subparallel to the seafloor and increasing in depth beneath the seafloor as the seafloor deepens, occurs beneath much of the lower slope. This reflector appears to cross-cut LDRs. Drilling results indicate that this reflector represents the base of a gas hydrate zone (Moore *et al.*, 1979 *a* ; Shipley *et al.*, 1979).

DRILLING RESULTS

We drilled eight sites along a transect perpendicular to the Mexican margin in the vicinity of 15°N, 99°W. Figure 1 shows locations of drill sites and location of essential seismic control superimposed on generalized bathymetry, Figure 4 shows generalize stratigraphic columns, and Figure 5 shows a composite cross section inferred from seismic-reflection data and drilling data.

The drill sites fall into three groups according to drilling objectives :

1) oceanic and trench reference sites drilled to sample oceanic pelagite-hemipelagite and trench turbidite sections, respectively ;

2) lower and mid-slope sites drilled to sample the accretionary prism ; and

3) upper slope sites drilled to determine the nature and extent of the continental crust and to document the sedimentary and vertical tectonic history of the region.

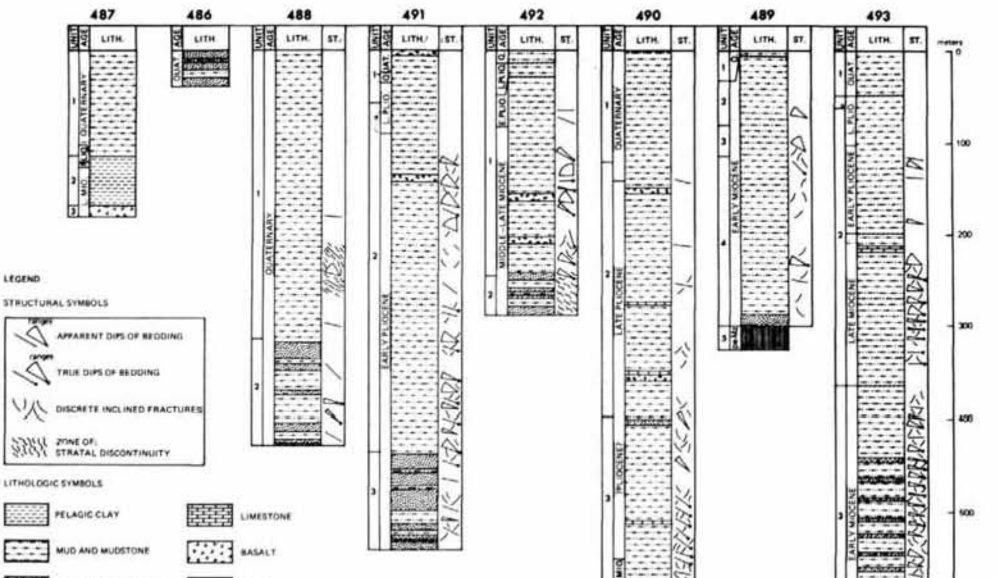


Figure 4
Stratigraphic colums showing results of Leg 66 drilling (after Moore et al., *1979* a).

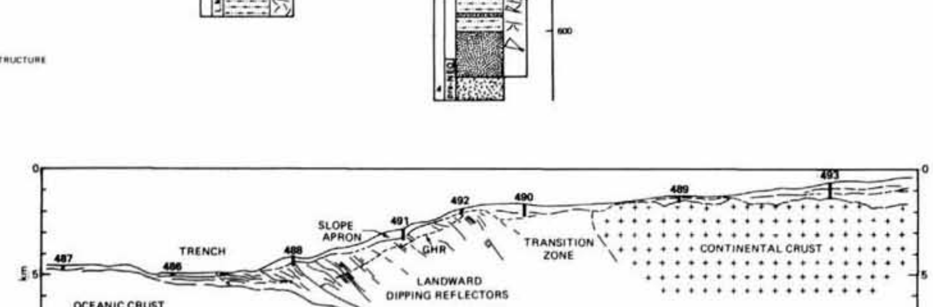


Figure 5
Composite structure cross section based on drilling results and migrated depth sections of UTMSI seismic lines OM7N and MX16 (Moore et al., *1979* a).

Sites 487 and 486 comprise the oceanic-trench reference group. Site 487 penetrated 115 m of Pleistocene to late Pliocene hemipelagic mud overlying 55 m of Pliocene to late Miocene brown clay before bottoming in basalt. The hemipelagic mud evidently derives from the Mexican mainland from whence it is transported down into the trench and thence seaward probably by density currents. The transport mechanism is surprisingly long ranging. Plate reconstruction suggest that the oldest hemipelagic mud may have been deposited as far as 100 km from the trench axis and at an elevation 1 km above the trench floor.

Site 486 provided a 38-m section of predominantly fine to very coarse sand. The unconsolidated sand flowing into the drill hole threatened to seize the bit, thereby precluding deeper drilling. Density underflows probably carried the sand from the Mexican margin into the trench via a prominent submarine canyon immediately east of the transect. Piston coring during the site survey recovered coarse sand from the mouth of this canyon and gravel from the axis in the middle slope.

The trench sediment can be contrasted with hemipelagic slope sediments and hemipelagic mud and rare fine sand and silt from the lower slope basin. No site survey piston cores taken from the slope recovered coarse sand. Trench sand also differs from shelf sand in that shelf sand contains a substantial carbonate component (McMillen, Haines, 1981). The unique character of the trench sand indicates that the sand was derived directly from sources onshore and bypassed the shelf and slope en route to deposition in the trench.

Holes at sites 488, 491, and 492 penetrated in the mud slope apron and sampled the upper part of the accretionary wedge. Each site bottomed in sand which Moore *et al.* (1979 *b*) interpreted as trench sand on the basis of seismic and lithologic similarity to contemporary trench sand. Trace fossil assemblages and carbonate dissolution data suggest that the sand has deposited in lower slope or trench water depths, thereby strengthening the evidence that the sand is an uplifted trench deposit.

The coincidence of sand and LDRs at sites 488, 491, and 492 suggests that the impedance contrast between sand and surrounding silt and mud is responsible for the seismic reflections. The reflections dip landward, but the dips do not increase upslope as suggested by Seely *et al.* (1974).

The ages of sand-bearing units increase upslope from Pleistocene at site 488, the lowermost slope site, to Pliocene at site 491, and then to late Miocene at site 492, the lowermost slope site. The observed age sequence is as predicted by Seely *et al.* (1974) and constitutes strong evidence of offscraping during Pliestocene to Late Miocene time interval. If LDRs are bedding planes, as inferred in the preceding paragraph, then the age relations represent an apparent stratigraphic inversion, probably due to underthrusting parallel or subparallel to bedding.

Lower sections of cores recovered at these sites exhibit substantial deformation characterized by steep dips, local folding and scaly clay (Fig. 4). At each site, deformation increases in intensity downhole, beginning at shallow depths but in sediments of greater age at successive upslope holes. The age threshold of significant deformation is 0.6, 3.0, and 5.8 MY (Moore *et al.*, 1979 *b*), respectively, at sites 488, 491, and 492. Deformation is generally restricted to sediments deposited in the trench and on the lowermost slope and thus occurs early in the accretionary process.

Uplift history parallels deformational history in that maximum uplift rates occur early, then give way to a period of slower uplift. Site 491 appears to have been uplifted at a rate of about 400 MY for roughly 2 MY, and uplift thereafter slowed to about 100 m/MY. Site 492 appears to have been initialy uplifted at a rate of 500 m/MY and thereafter at a rate of 200 m/MY.

Sites 490, 489, and 493 were drilled on the upper slope to investigate the vertical tectonic history of the Mexican margin and the transition from continental crust to accretionary prism. Sites 489 and 493 bottomed in igneous and metamorphic continental crust after penetrating sediments ranging in age from Pleistocene to early Miocene. Both holes contain shallow-water sand overlying subaerially eroded basement. The sand and overlying hemipelagic sediments document a marine transgression, beginning approximately 22 MY ago, followed by rapid subsidence to depths of 3,000 m or more before the onset of slow uplift beginning roughly 19 MY ago.

Site 490 sediments are anomalous with respect to lower and middle slope sediments of sites 488, 491, and 492, on one hand, and with sediments of upper slope sites 489 and 493, on the other. Although drilling at site 490 penetrated deeper than any lower or middle slope holes the cores showed no deformation typical of lower parts of holes 488, 491, and 492 (Fig. 5). At site 490, tilting and fracturing appear to have resulted from faulting normal to the trench axis. Pre-upper Pliocene sediments deposited below the carbonate compensation depth at site 490 have been subsequently uplifted at a rate of about 90 m/MY, which is somewhat slower than uplift of sites 488, 491 and 492. We infer that site 490 sediments were probably deposited in a relatively stable transition zone about 10 km wide between the edge of continental basement to the north-northeast and the accretionary wedge to the south-southwest.

Overall, the tectonic picture is one of rapid subsidence of the continental crust during the period 19-22 MY ago, followed by slow uplift thereafter. Accretion began at least 10 MY ago and has continued to the present (Fig. 6). The tectonic picture between 10 and 19 MY is enigmatic.

DISCUSSION

Accretion

Uplifted trench sands in the Leg 66 area support the imbricate underthrust mechanism of Seely *et al.* (1974) at least in the lower slope. The sands appear to have been

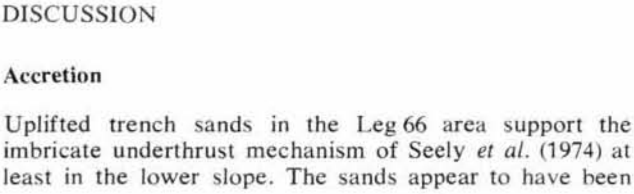


Figure 6

Line drawing of toe of slope from UTMSI migrated seismic line MX16 showing LDRs and inferred thrust faults. Chaotic zone probably consists of slump deposits (from Shipley et al., *1980).*

uplifted at relatively rapid rates during offscraping at the toe of the slope, then uplifted at slower rates once they were incorporated within the slope. The increase in age of sands upslope is one of the strongest arguments for the offscraping model.

We did not penetrate thrust faults that we could biostratigraphically document although seismic data suggest penetration of a Pleistocene thrust fault in lower slope sediments at site 488. Thrust faults are evident elsewhere in the seismic data (Fig. 6). Failure to penetrate a demonstrable thrust fault is not surprising in light of our discovery that LDRs are sand bodies and the fact that we did not penetrate far below the slope sediment apron. The high sedimentation rates in the area require large fault offsets in order to biostratigraphically to verify existence of a fault.

Although our data indicate offscraping in the Leg 66 area, some doubt remains regarding the universal applicability of the model. Shipley *et al.* (1980), in their analysis of approximately 2000 km of multifold seismic-reflection data in the Leg 66 area, observed that internal reflections are more common in the west half of the Leg 66 area. They further infer that reflectors occurring in discrete zones are uplifted turbidites, and that their occurrence in the west half of the area is associated with the presence of submarine canyons and turbidite ponds there. Shipley *et al.* (in press) examined data from the Middle America Trench off Mexico, Guatemala and Costa Rica, areas of intensive investigation and extensive data collection by the University of Texas Marine Science Institute. Data from these areas support the idea that sandy turbidites greatly enhance offscraping. Much, if not all, ocean-floor pelagic and hemipelagic sediments seem to be subducted.

Von Huene *et al.* (1980 *a*) drilled into the lower slope off Guatemala during Leg 67 and produced results strikingly different from those off southwest Mexico. In a hole 3 km landward of the trench, Leg 67 penetrated a Cretaceous to Pleistocene claystone and hemipelagic sequence before bottoming in mafic and intermediate igneous rock atypical of oceanic basalts. Seismic data suggest several hundreds of meters of sedimentary rock between the botton of the hole and oceanic crust. Ladd *et al.* (1978) and Ibrahim *et al.* (1979) showed that seismic refraction and reflection interval velocities within the main body of the Guatemala accretionary wedge range from 4.1 to 6.5 km/sec. Coring in the Leg 67 area produced relatively fresh mafic rock fragments. These data suggested to J. W. Ladd (pers. comm., 1978) the possibility of ophiolite slivers within the Guatemala slope.

Dickinson's (1973) observation that the widths of arc-trench gaps (and, by inference, the volumes of accretionary wedges) are for the most part proportional to the ages of the respective subduction zones suggests that accretion may also proceed by a mechanism other than offscraping of sandy turbidites such as observed at the Leg 66 site. One other such mechanism is the accretion of slices of oceanic crust, sea mounts, or other crustal topographic irregularities. These two models may be end members of a sequence with mature accretionary prisms and melanges including examples of both.

Consumption

The question of consumption of sediments was recognized early by von Huene (1972) who estimated a deficiency of the volume of sediment accreted in the Aleutian subduction zone. Dickinson's (1973) observation of increasing arc-trench gaps and, by implication, of increasing size of accretionary wedges with age pointed at the problem. Karig and Sharman (1975) indicated the possibility of consumption. Moore *et al.* (1979 *a* ; *b*) and Shipley *et al.* (1980) suggested sediment consumption in the Leg 66 region, and von Huene *et al.* (1980 *a*) indicate the necessity of consumption in the Leg 67 area.

The Leg 66 data offers a good opportunity for calculation of the amount of sediment being consumed. The current accretionary event began about 10 MY ago. The relative youth of this system in comparison with may other subduction systems minimizes errors arising from changes in convergence rate and direction. Data from the East Pacific show that the latest ridge jump and possible plate reorganization occurred about 10-15 MY ago, before the onset of the current accretionary event (Handschumacher, 1976 ; Van Andel *et al.* (1976). The plate system appears to have been stable thereafter.

Seismic velocities indicate that virtually the entire accretionary wedge in the Leg 66 area consists of sediments. The velocities are sufficiently well defined to permit good estimates of the porosity and hence estimates of degree of partitioning of subducted fluids and rock.

Density of seismic data, both reflection (Shipley *et al.*, 1980 ; Helsley *et al.*, 1975 ; and Mooney *et al.*, 1975), are sufficient to define mainly the geometry of the accretionary wedge and of the trench turbidite wedge and the thickness of the pelagic-hemipelagic ocean crust component.

Our procedure for calculating sediment consumption was as follows :

1) Estimate thickness of sedimentary units
a) pelagic-hemipelagic component,
b) turbidite wedge component ;

2) calculate porosity from drill core (L. Shepherd, pers. comm.) and seismic velocities (see Eaton, Watkins, 1970) ;

3) calculate equivalent amount of non-porous rock ;

4) assume present-day convergence rate of 7 cm/yr (Minster, Jordan, 1978) applicable to last 10 MY ;

5) calculate sediment input for 10 MY.

Accretionary wedge volume

1) Construct structure cross section from data of Shipley *et al.* (1980), Moore *et al.* (1979 *a* ; *b*), Helsley *et al.* (1975), Mooney *et al.* (1975) and Keller *et al.* (1979) (Fig. 7) ;

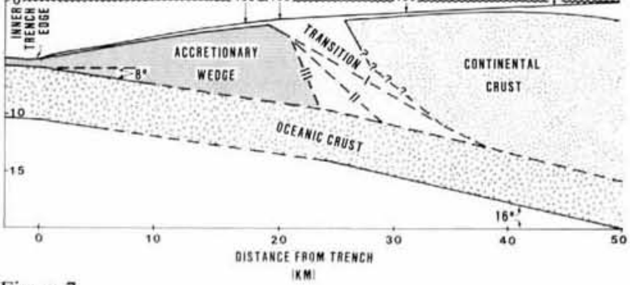


Figure 7

Hypothetical model used to estimate volume of the accretionary wedge. Base of crust near site 493 and the trench is constrained by seismic refraction data (Helsley et al., *1975 ; Mooney* et al., *1975) ; top of the oceanic crust beneath the trench and seaward part of the wedge is constrained by seismic reflection data (Shipley* et al., *1980). Remaining features are inferred from a combination of Leg 66 drilling data and seismic reflection data (Shipley* et al., *1980). I, II and III represent minimal, probable, and maximum landward extents of the accretionary wedge.*

Table 1
Calculated thickness

Unit	Thickness Min. (m)	Max. (m)	Avg. (m)	Vel. (km/sec)	Est. Por.• (%)	Equiv. Rock (m)
Pelagic-hemipelagic	0[1]	200 +	110	1.6	75[2]	30
Trench Turbidites	0[1]	625	2 %	1.8	40[3]	160
Accretionary Wedge	—	—	—	3.5	20[4]	

[1] Below limit of seismic resolution of about 25-50 m.
[2] From core measurements, site 487.
[3] Estimated from core recovered, site 486.
[4] Estimated from seismic velocities.

2) measure area of accretionary wedge ;

3) calculate equivalent volume of non-porous rock per/kilometer of trench as in input flux steps 2 and 3.

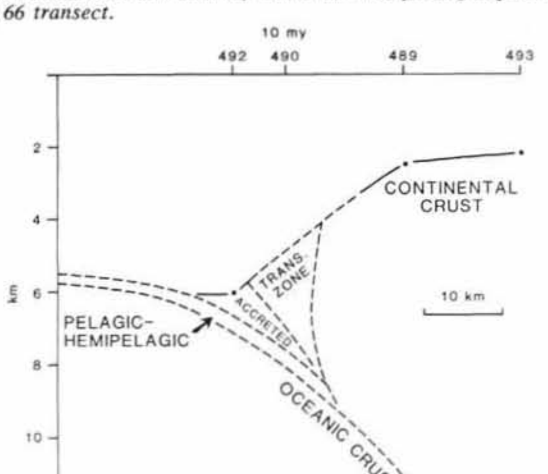
Compare results

Thicknesses of pelagic-hemipelagic and turbidite sand units vary locally. Thicknesses were averaged from data from seven seismic dip lines for trench turbidites and along a 100 km seismic line 50 km seaward of, and parallel to, the trench for the pelagic-hemipelagic component (see Fig. 2). Results are summarized in Table 1.

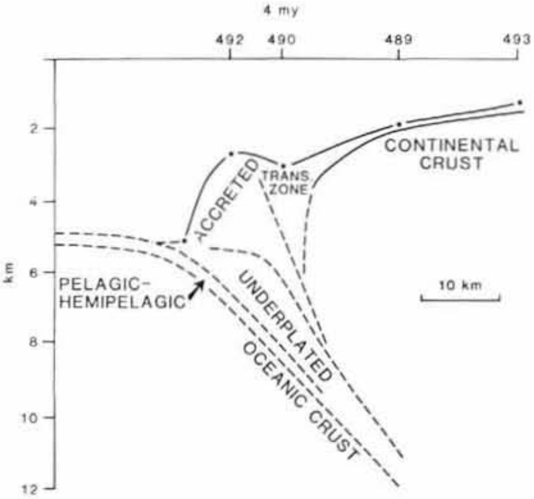
Clearly, trench turbidites (and associated downslope transported deposits) account for most of the sediment flux. It appears that a column equivalent to approximately 190 m of non-porous rock has been fed into the subduction zone at a rate of 7 cm/yr or 70 km/MY for the past 10 MY. This volume aggregates 135 km^3/MY.

It is now necessary to estimate the volume of the accretionary wedge. The principal uncertainty in the calculation is the size and shape of the landward part of the accretionary wedge triangle. overhanging continental crust both obscures reflections from depth and introduces serious errors in refraction calculations. Thus, we project the Moho both landward and seaward using refraction data from Helsley *et al.* (1975) and project oceanic crust landward using reflection data from Shipley *et al.* (1980) (Fig. 8). The undetermined upper landward surface of the accretionary wedge we divide into three cases, I, II, III, (Fig. 7), representing our estimate of minimum, probable, and maximum volumes of the accretionary wedge. Our « probable » case, II, results

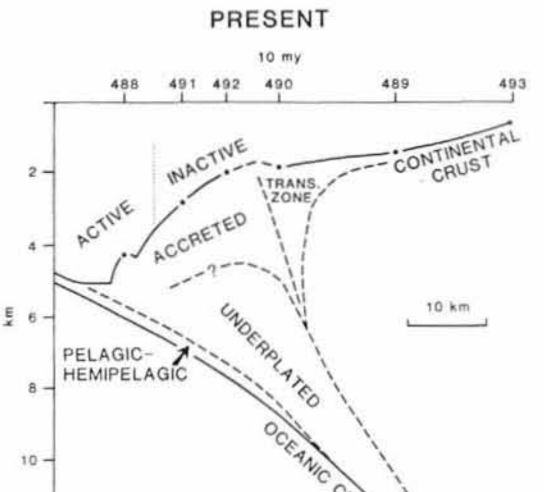
Figure 8
Hypothetical reconstruction of accretion-underplating sequence for Leg 66 transect.



a) *Onset of accretion, 10 mY. " Transition zone " may consist of sediments deposited before onset of accretion or earliest accreted sediments. Data from site 490 favor the pre-accretion model ;*



b) *Early Pliocene, 4 MY. Accretionary wedge is building seaward, underplating causes uplift of crust, transition zone, and innermost accretionary wedge ;*



c) *Present. Underplating continues to elevate margin from sites 491 tp 493. Active accretion limited to vicinity of Trench-488.*

from projection landward of the landwardmost strong LDR, which we interpret as at or near the top of the accretionary wedge. Case IV includes the transition zone within the accretionary wedge. We consider this case improbable. Table 2 summarizes the case estimates.

Table 2

Estimated volume of accretionary wedge

Case	Volume oj accretionary wedge (km^3/km)	Equivalent volume of non-porous rock (km^3)	Amount subducted (km^3)	(%)
I	97	77	58	43
II	111	89	46	34
III	135	108	27	20
IV	161	129	6	4

Table 2 gives a range of values derived from varying assumptions regarding the shape of the accretionary wedge. The value we consider most likely, on the basis of our interpretation of the available data, is 34 %. Percentages of subducted sediments in cases I, II, III, which range from 20 to 43 %, exceed thè pelagic-hemipelagic input and require subduction of a significant fraction of trench deposits. This result supports Shipley *et al.*'s (1980) interpretation that most pelagic and hemipelagic sediments entering the Middle America Trench are being subducted. our result is also consistent with Leg 67 data requiring subduction of a major part of the pelagic-hemipelagic flux there (von Huene *et al.*, 1980 *a*).

From a mechanical point of view, it is probably significant that the input sediment flux contains water volumes roughly equal to the volume of non-porous rock. Some water, especially in trench turbidites, is probably squeezed out during initial deformation, but seismic evidence of undeformed pelagic-hemipelagic layers extending to depths of several kilometers suggests that a considerable volume of water remains trapped within the sediments. The combined high clay content and high water content of these sediments probably result in overpressuring and a low coefficient of friction. These factors provide a good decollement surface.

Pelagic-hemipelagic input thus appears to be preferentially subducted while overlying sediment may or may not be scraped off and accreted. Scholl and Marlow (1974) observed that pelagic sediments are rare within melanges, and the absence of these sediments in any of the three holes on the lower slope and the one on the transition zone of Leg 66 supports their preferential subduction.

Underplating

We have previously mentioned that folding, dewatering, fracturing, and thrusting in the Leg 66 area occur early in the accretionary process. After this initial period of deformation the accretionary wedge rises slowly at roughly the same rate as the upper slope. The vertical distance between the accreted turbidites and the downgoing oceanic crust widens with time. The mechanism of Seely *et al.* (1974) proposed uplift by rotation of imbricate wedges. Because this mechanism appears inoperative in the Leg 66 area except near the foot of the slope, some other must be responsible for uplift of the middle and upper slope. We believe underplating to be that mechanism (Fig. 8).

If the underplating model is correct, then the upper crust of the accretionary wedge consists of trench turbidites and associated slope sediments. Judging from the thickness of the zone of active offscraping in the toe of the accretionary wedge (e.g., Fig. 6), we estimate that the thickness of this crust is about 2 km and that its volume is about 60-65 km^3/trench-km. Velocities of 3 km/sec., appropriate to this upper zone, suggest an average porosity of 30 % and an equivalent volume of non-porous rock of 45 km^3/km, or 33 % of the 10-MY input flux. this value, together with previous calculations, suggest that about one-third of the input sediment flux is subducted beyond the zone defined by the accretionary prism in Figure 7. Thus, about 33 % of the total is being scraped off to form a rigid " crust " of the accretionary prism ; another 33 % is initially subducted, then progressively "skimmed off" and underplated on the accretionary prism ; and the remaining 33 % is carried to greater depths. Because there is no reason to differentiate between underplating of the accretionary prism and underplating of the continental crust, it is simpler to divide our margin into 1) an accreted rigid crust ; 2) an underlying zone of underplating ; and 3) a lowermost subducting zone of pelagites and hemipelagites (Fig. 8 *c*). The boundary between 2) and 3) will progressively deepen in the section as pelagites and hemipelagites are skimmed off at depth.

Tectonic erosion

Leg 66 drilling provided no direct evidence of tectonic erosion. Abundant evidence of consumption of sediments, however,suggets that tectonic erosion of the margin is mechanically plausible. Margin subsidence recorded at sites 489 and 493 suggests thinning of the crust, and a period of tectonic erosion might have preceded the onset of accretion.

Forearc basins

The Leg 66 area is anomalous in several respects, including the absence of a forearc basin. Some evidence suggests, however, that an incipient forearc basin may be forming in the vicinity of site 490. Paleobathymetric reconstruction (Fig. 9) indicates that the region of sites 490-492 is rising faster than that of sites 489-490. Furthermore, seismic reflections in the slope apron near site 490 are tilted

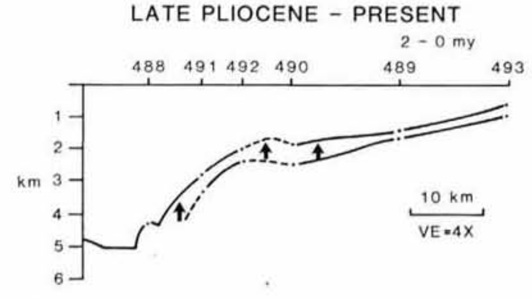


Figure 9

Paleobathymetric reconstruction for the period late Pliocene to present (0-2 MY) showing inferred uplift rates. Higher uplift rates in the region of sites relative to the region of sites 490-489 will, if continued, lead to the formation of a forearc basin.

landward similar to those of the Iquique Basin (Seely, 1979). If the different rates of uplift observed in the region of sites 489-490-492 persist, a forearc basin will develop.

The mechanism responsible for this pattern of uplift may be the higher rate of underplating closer to the trench. This mechanism would cause the zone of maximum uplift to move seaward with time. Tectonic, thermal, and isostatic subsidence dominate in the landward part (Karig, Sharman, 1975). Seaward migration of the trench-slope break as observed in Iquique Basin (Seely, 1979) would be an expected consequence of underplating, and forearc basins would widen with time, as proposed by Karig (1974).

Margin history

The history of the margin in the Leg 66 area is interwoven with the history of the Pacific plate, the Cocos plate, and perhaps the Rivera and Caribbean plates as well. Evidence of the motions of these plats is confusing and sometimes contradictory. Consequently, the history of the Leg 66 site is not clear, especially during the period from 25-10 MY.

Data from Leg 66 sites 493 and 489 suggest the following history for the continental crust part of the transect.

22 MY Subsidence and marine transgression.
19 MY Subsidence below CCD.
< Gradual, uniform uplift to present position.

Data from sites 488, 491 and 492 on the lower slope indicate the following history for the accretionary wedge part of the transect.

10 MY Earliest observed accretion.
< 10 MY progressive accretion and seaward expansion of accretionary wedge.

Inclusion of sediment from the transition zone in the accretionary wedge would push the onset of accretion back to 12-13 MY. However, the absence of LDRs in the transition zone and the atypical evolution evidenced by transition-zone sediments suggest that this zone was never part of the accretionary wedge.

The data suggest that truncation and rifting, probably strike slip (Karig *et al.*, 1978 ; Malfait, Dinkleman, 1972), away of the former continental margin (including a preexisting accretionary wedge and perhaps a forearc basin) occurred during a major plate reorganization placed by Handschumacher (1976) between 26 and 29 MY ago. Subsidence and marine transgression in the Leg 66 area suggest that this event occurred no later than 22 MY. Cessation of subduction 23 MY ago, indicated by the end of volcanic activity in the Sierra Madre Occidental (Clabaugh, McDowell, 1976), coincides well with the marine transition.

It is not clear whether the ancient slope and shelf slipped dextrally northwest as part of the San Andreas development (Atwater, 1970), as suggested by several other investigators (e.g. Malfait, Dinkleman, 1972). The best evidence regarding this dichotomy may be that reconstruction of slippage on the Cayman Fracture Zone of 2 to 4 cm/yr (MacDonald, Holcomb, 1978) places the Guatemala-Honduras corner of the Caribbean plate near the Leg 66 area 12.5-25 MY ago, or during the time of plate reorganization suggested by Pacific magnetic anomalies and in the gap between the end of subsidence and onset of accretion. Also, Central American rocks south of the Motagua-Polochi fault, which separates the Caribbean and North American plates, contain granodiorite intrusive bodies of Cretaceous and Tertiary age (Seely, 1979, Fig. 8). We have, however, no information indicating close lithologic affinities of these and Leg 66 intrusive rocks. The evidence, although not compelling, favors sinistral strike-slip motion.

The absence of evidence for accretion during the interval from 22 to 10 MY ago may indicate that motion was largely strike-slip during that time. Handschumacher (1976) places the breakup of the EPR south of the Baja California at 10 mY. Magnetic anomalies, however, are indistinct and interpretation ambigous.

The transition zone at site 490 may contain at depth sediments shed during the 22- tp 10-MY interval. A deep penetration hole here should be rewarding in revealing the history of the Mexican margin and the reconstruction of Pacific plate motion.

SUMMARY AND CONCLUSIONS

We drilled eight sites along a transect of the Middle America Trench off southwestern Mexico to investigate accretion and consumption of sediments and rock during the subduction process and to investigate the history of a young subduction zone. The eight sites included two reference sites on oceanic crust and in the trench, respectively, to document lithologies being subducted and/or accreted, three sites on the lower slope to sample accreted sediments, and three sites on the upper slope to document the history of the continental crust.

Samples collected indicate that accretion has been occurring in the area for 10 MY or perhaps slightly longer. We recovered trench sand ranging in age from Pleistocene to Miocene and uplifted as much as 2-3 km above the present-day trench floor, and we observed that the age of trench sand decreases downslope, as the accretionary model predicts. Landward dipping reflectors thought in other areas to represent thrust faults were found here to result from bedding in uplifted trench turbidite sequences.

Uplifted sediments record an early period of deformation and uplift. In this period, which lasted 2-4 MY for our samples, rates of uplift were 600-800 m/MY. After this initial episode, most deformation ceased and uplift rates fell to 100-200 MY.

Of sediment entering the subduction zone, 33 % (mainly trench turbidites) is offscraped at the toe of the slope, 33 % is initially subducted but then underplates the previously offscraped sediments, causing them to continue to rise with time, and 33 % (probably including all the pelagite-hemipelagite oceanic component) is subducted landward beneath the continental crust. Trench turbidites and slumps account for 85 % of the equivalent flux of non-porous rock and the oceanic component accounts for 15 %. Porosites of 75 % ensure that large quantities of water are being subducted along with the pelagite-hemipelagite component. The water probably causes overpressuring and plays a major role in the lubrication of the suture. The average rate of accretion is 8 km^3/km-MY of equivalent dewatered, non-porous rock.

We find no direct evidence of tectonic erosion but conclude that tectonic erosion is mechanically feasible in view of the large quantities of sediment being subducted.

The absence of a forearc basin in the area of investigation is probably due to the youth of the subduction regime. Site 492 is currently rising faster than site 490 ; if this pattern of relative uplift continues a forearc basin could form.

The history of the region documented by sediment cores and interpreted in light of the history of the neighboring plates is as follows.

23 MY Reorganization of the Pacific plate ; cessation of volcanism in the Sierra Madre Occidental ; subsequent eastward shift of volcanic axis ; sinistral strike-slip rifting away of existing continental margin. Marine transgression in Leg 66 area 22 MY ago followed by rapid subsidence.

19 MY Margins sinks to, or just below, CCD and begins slow rise.

10 MY Baja California rift forms ; change from strike-slip motion to oblique convergence in Leg 66 area. Accretion begins in Leg 66 area and continues to present.

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