43. SUMMARY—LEG 67, MIDDLE AMERICA TRENCH TRANSECT OFF GUATEMALA[1]

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GENERAL SETTING AND STRUCTURE

The Middle America Trench transect off Guatemala is the second of two International Program of Ocean Drilling (IPOD) geophysical and drilling transects conducted by the Deep Sea Drilling Project (DSDP) across the convergent margins of southern Mexico and Central America. The first, a transect across the Middle America Trench north of the Tehuantepec Ridge off Oaxaca, was drilled on Leg 66 to investigate a convergent margin where the continent is truncated and the front of the margin is an inferred accretionary complex (Moore et al., 1979). Off Guatemala, our principal objective was to study a convergent margin where continuous accretion and imbrication were indicated by geophysical studies and a single deep drill hole (Seely et al., 1974). We hoped to strengthen the tie between onshore and offshore geology, to study modern sediment sequences in the Trench and on the slope, and to recover a continuous chronology of volcanic ash from explosive volcanism along the magmatic arc.

The Middle America Trench was recommended for study on the basis of past experience in drilling along other convergent margins. Previous drilling along the Oregon convergent margin, the Aleutian Trench, and the Nankai Trough showed that detailed age resolution is required to define stratigraphic repetitions expected in a sequence of imbricated and accreted modern trench sediment. Fine-scale age resolution is easier to achieve in low rather than high latitudes, because microfaunal diversity is greater in more temperate environments. In high latitudes, moreover, the great influx of terrigenous sediment during glaciation results in transport of terrigenous debris seaward of the trenches and makes it virtually impossible to differentiate much of the ocean-basin deposits from slope deposits by lithologic criteria. Thus it was reasoned that convergent tectonism would best be studied where terrigenous sources are moderate, where faunal diversity is great, and where subduction is relatively rapid. These conditions exist along much of Central and South America.

Another factor influencing the choice of the Leg 67 transect was the report by Seely et al. (1974) that included a processed multichannel seismic-reflection record and drill-hole information for the Guatemala segment of the Middle America Trench. These authors made a case for the convergent-margin, imbricate-thrust model that is now widely accepted and commonly referred to in the literature. Subsequently, as part of the IPOD site surveys, the University of Texas Marine Sciences Institute (UTMSI) made multichannel seismic-reflection site surveys (Ladd et al., 1978; Ibrahim et al., 1979). Their seismic record GUA-13 was selected as the main drilling transect because it included San José Canyon, where slope deposits are thin, allowing deeper drill penetration than elsewhere. It was also the only transect where the landward-dipping reflections so important in the imbricate-thrust hypothesis of Seely et al. (1974) were recorded. To study imbrication requires penetration of the slope deposits and sampling of the acoustic basement.

During Leg 67, drilling proceeded smoothly on the Cocos Plate (Site 495) and in the Trench itself (Sites 499 and 500) where the oceanic basement was reached. However, the presence of gas hydrate on the continental slope caused termination of drilling for reasons of safety at Sites 496, 497, and 498 prior to reaching the basement objective. The inability to sample basement on the landward slope of the Trench changed the emphasis of Leg 67. Because the strong landward-dipping reflector on the slope could not be sampled, the goal to extend on-land geology seaward was not achieved, except at the toe of the slope where a surprising sediment sequence from Quaternary to Upper Cretaceous was recovered. More successful was a detailed study of the Trench made by drilling to the oceanic crust at sites across the Trench floor and at the very base of the landward slope of the Trench.

The Middle America Trench, which marks the subduction of the Cocos Plate under Central America, is unique among circum-Pacific trenches because of its composite nature with respect to features both on the oceanic plate and on the continental plate (Fig. 1). On its seaward side, the aseismic Tehuantepec Ridge divides a northern from a southern part. The northern part is the Acapulco segment, bounded to the north by the Tamayo Transform Fault, and the southern part is the Guatemalan segment, bounded to the south by the aseismic Cocos Ridge. Along the Acapulco segment, the Middle America Trench borders the end of the North American continent, whereas along the Guatemalan segment it borders Central America, which is partly a volcanic massif associated with the present episode of subduction. The volcanic massif rests upon a Mesozoic to lower Tertiary tectonic edifice known, where it crops out in Costa Rica, as the Nicoya Complex. Because the Te-

[1] Aubouin, J., von Huene, R., et al., *Init. Repts. DSDP*, 67: Washington (U.S. Govt. Printing Office).

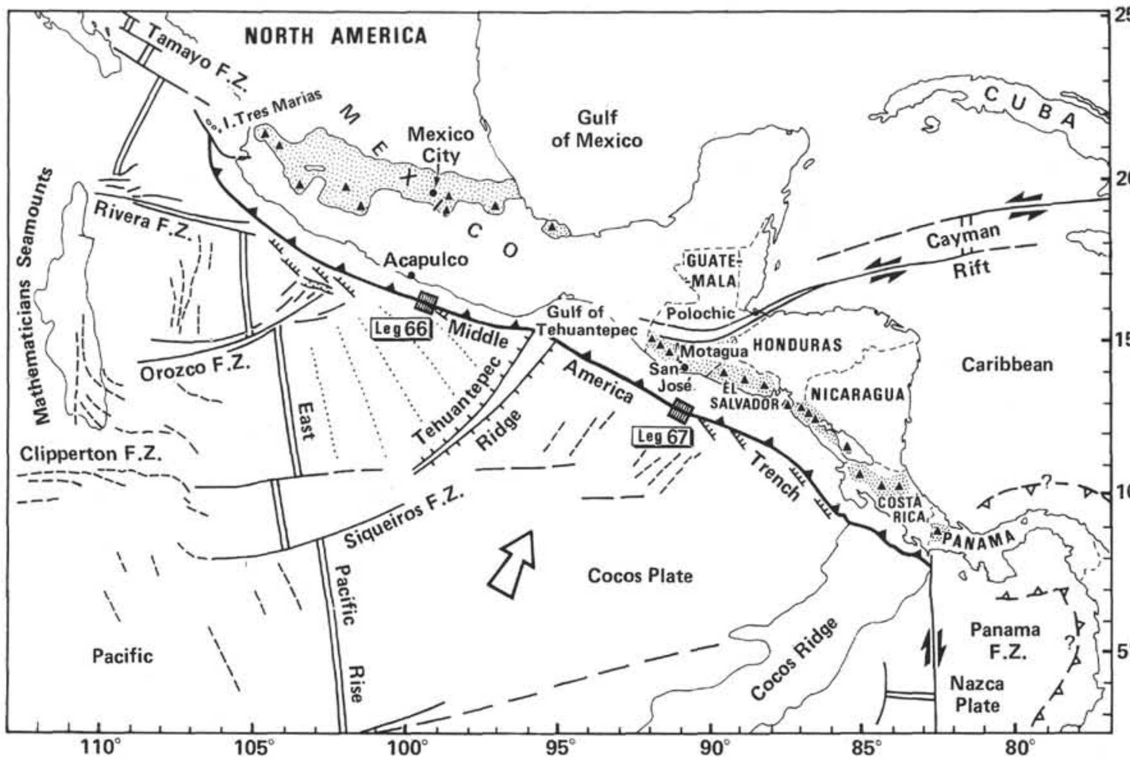

Figure 1. General setting of the Middle America Trench.

huantepec Ridge and the Polochic–Motagua faults are out of line by nearly 400 km, the Guatemalan part of the Middle American Trench actually borders both southern Mexico and Central America; in this sense the Guatemalan part of the Trench is composite, in contrast to the Acapulco part of the Trench.

The Guatemalan Trench segment parallels structures that probably formed during ancient tectonic episodes. The Mesozoic Nicoya Complex is very different from the pre-Cambrian, Paleozoic, and Mesozoic formations of southern Mexico. The Middle America Trench parallels its ancient trend off Central America, whereas off southern Mexico it transects the ancient trend.

The aseismic Tehuantepec and Cocos ridges are very pronounced features on the oceanic plate, but once subducted they seem to have little affect on the continental plate. Both ridges seem to constrict the Trench and they also correspond to the northwest and southeast ends of the wide Middle America continental shelf. But on the continental side, the Tehuantepec Ridge is associated with only a slight offset in structures, whereas the Cocos Ridge is associated with an uplift where the Nicoya Peninsula is elevated above sea level.

The margin of the Cocos Plate has a structural fabric trending N130° to N140° (Figs. 1 and 2), which shows as a series of alternating horst and graben (Renard et al., 1980; Aubouin et al., 1981) that form where the Plate is stressed as it is flexed downward into the Trench. This structural grain is parallel to the direction of the magnetic anomalies surveyed on the Cocos Plate in the Legs 66 and 67 study areas (Ladd et al., this volume). The orientation of magnetic anomalies suggests that the structural fabric was imparted by ocean spreading according to the model derived from the CYAMEX cruise on the East Pacific ridge (CYAMEX Scientific Team, 1981; Rangin and Francheteau, 1981). Thus the extensional faults on the seaward slope of the Trench, although related to the downward flexure of the oceanic plate into the Trench, are activated along a structural trend inherited from the genesis of the Cocos Plate at the East Pacific Ridge axis, as proposed for other areas (Coulbourn and Moberly, 1977).

The Trench floor is sectioned into a series of diamond-shaped basins separate by ridges (Figs. 2 and 3). The basins correspond to the graben in the Cocos Plate, and the ridges to the horst. This structure is a clear consequence of the progressive burial of the Cocos Plate beneath the sediment filling the Trench. The axis of flexure, the Trench axis, and the front of the subduction zone trend 20° to 30° from the topography of the oceanic plate, in agreement with the data of Heezen and Rawson (1977).

The landward slope of the Trench is locally formed of rectilinear topographic steps. The normal or reverse nature of the bounding faults is not clearly revealed in seismic records, because diffractions obscure structure on either side of the faults. The local distribution and irregular topography of the steps argues more for normal than reverse or thrust faulting, as discussed in the next section. Thus in the Leg 67 area the Middle America Trench morphology seems to indicate collapse, but this morphology must be a secondary manifestation of the primary process of convergence. The apparent collapse of both the landward and seaward slopes of the Trench

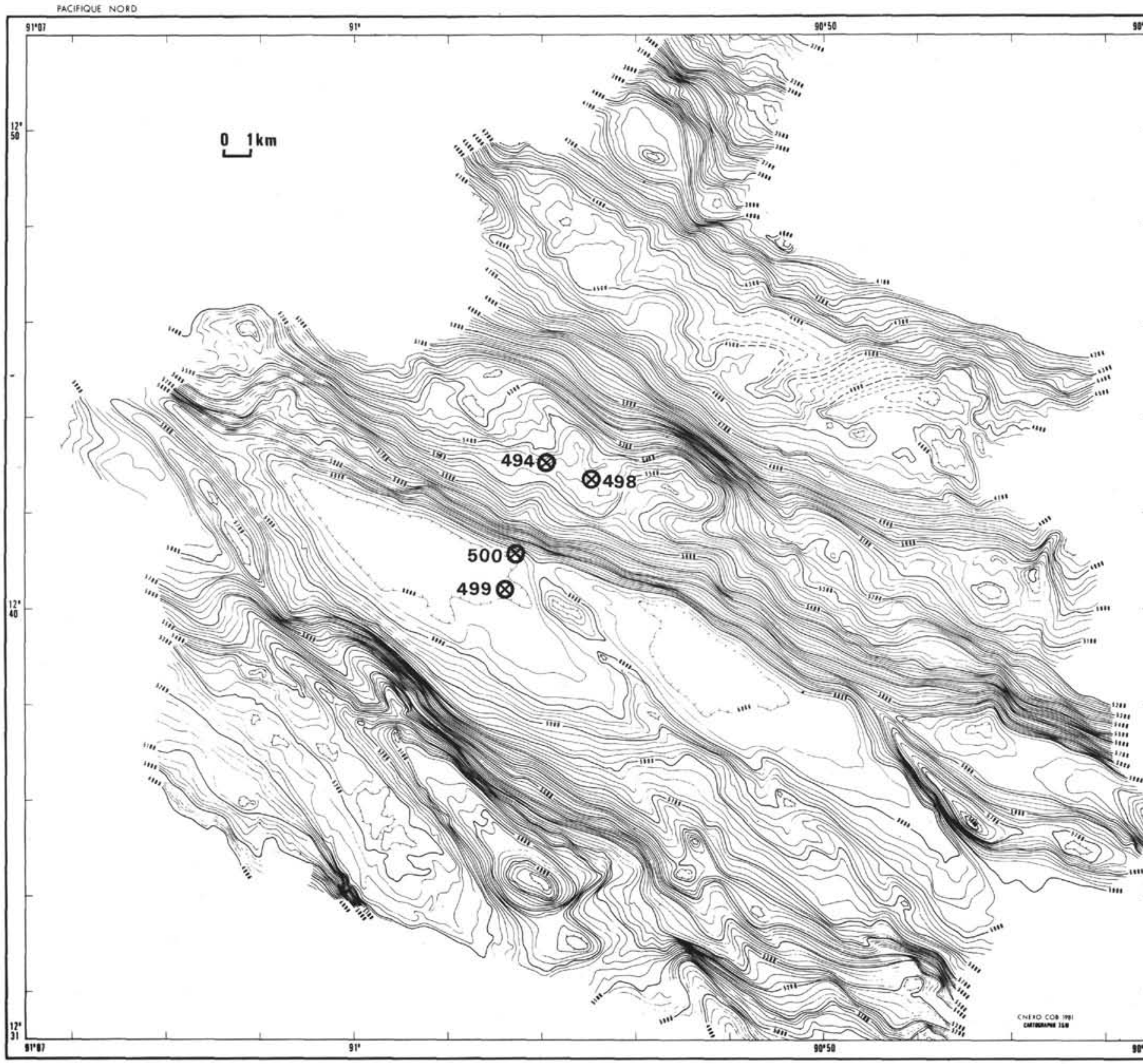

Figure 2. Seabeam bathymetric map showing trends of fault scarps of the Cocos Plate that deviate 20° to 35° from the trend of the Trench axis. (Positions of four Leg 67 sites are indicated. From Renard et al., 1980).

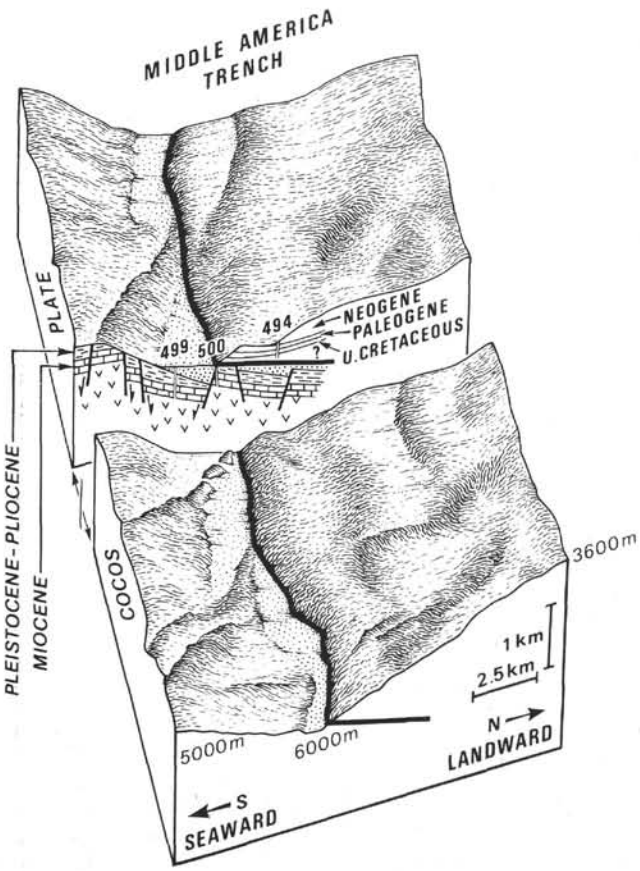

Figure 3. A scaled block diagram of the Seabeam map area. (Shown at a large vertical exaggeration is a geologic section across three DSDP sites along seismic reflection record GUA-13 [from Aubouin, von Huene, et al., 1981].)

adjacent to the Trench floor somehow accompanies the subduction process.

In the detailed topography provided by the Seabeam and deep-tow surveys, one can see the positions of Site 494 on a small terrace, Site 500 at the base of the landward slope just at the front of the subduction zone, and Site 499 at the base of the seaward slope. The location of Site 500 is critical: it is situated at the very front of the subduction zone and on the southwestern edge of a horst coming into the Trench from the Cocos Plate (Coulbourn, this volume, Moore et al., this volume).

On the landward slope, the detailed topography shows, on each terrace, ponded basins that have trapped slope sediment. The lithologic similarity of ponded sediment in slope basins and in trenches seems to invalidate any simple lithologic criterion (e.g., grain size) as an indicator of trench-axis or slope-basin facies. For example, the grain size and mineralogy of Aleutian Trench sediment and the adjacent slope sediment show no marked differences (Kulm, von Huene, et al., 1973). A similar lack of distinguishing properties has also been noted for Japan Trench and slope sediment (Arthur et al., 1980). The deep-tow data clearly show the absence of an axial channel interrupting the sediment ponds of the Trench axis. The Seabeam map shows that the Middle America Trench axis is a series of isolated, diamond-shaped ponds (Aubouin et al., Seabeam survey, this volume). Axial transport has been noted in other modern trenches, for example, the Chile Trench, Aleutian Trench, and Sunda Trench (Schweller, 1976; Piper et al., 1973; Moore, 1980); and the facies distribution presumed from channeled transport has been used to infer trench axis environments in ancient sedimentary sequences. Off Guatemala, however, the basins of the Trench axis and the slope basins have a similar depositional environment.

GEOPHYSICS

The Guatemalan area contains most of the tectonic features associated with subduction zones: flexure of ocean crust as it descends into the trench axis, subduction of ocean crust beneath the front of the continent, emplacement of slabs that are tilted landward in the landward slope of the trench, a pronounced structural arch at the edge of the continental shelf, and subsidence of a broad fore-arc basin adjacent to the coast. These major features are commonly depicted in simple diagrams of a subduction zone. But as with many simple models that illustrate an end-member concept, closer examination reveals a great variety of features even at the hundreds-of-meters resolution afforded by the seismic-reflection technique in 1 to 5 km of water. At the finer tens-of-meters resolution of the Seabeam map and deep-tow data, the variety of features resolved increases considerably. Unfortunately only a small area was mapped with the Seabeam and deep-tow systems.

Seaward of the Trench and unaffected by the tectonism of the subduction zone, the igneous crust of the deep ocean basin has a surface with minor irregularities upon which rests a conformable sediment blanket of uniform thickness (Fig. 4). The sediment blanket, usually referred to in geophysical studies as "pelagic," is known at Site 495 to be pelagic chalks covered by equally thick terrigenous, hemipelagic sediment. In seismic-reflection records, the seaward slope of the Trench is step-faulted as the ocean crust breaks under the stress of downward flexure. As mentioned previously, the longest faults parallel the structural grain originally inherited by the crust at the spreading ridge, but sparse and short fault segments also parallel the Trench axis. The 20° to 35° divergence from the axis of flexure is perhaps near the critical angle where the crust would break more easily parallel to the axis of flexure and across the original Cocos Plate structural fabric. The Trench axis morphology contains a succession of horst that form ridges. In Figure 4 one such ridge can be seen near its point of collision against the sharp straight foot of the landward slope.

Actual subduction begins at the base of the landward slope where the ocean crust continues beneath the continental framework (Fig. 5). The fate of the sediment on the subducted ocean crust is problematical because there is no evidence of a Neogene accretionary complex along the drilled transect; presumably, very little sediment is presently being scraped off. Once subducted, however, reflections from the oceanic sediment sequence are not

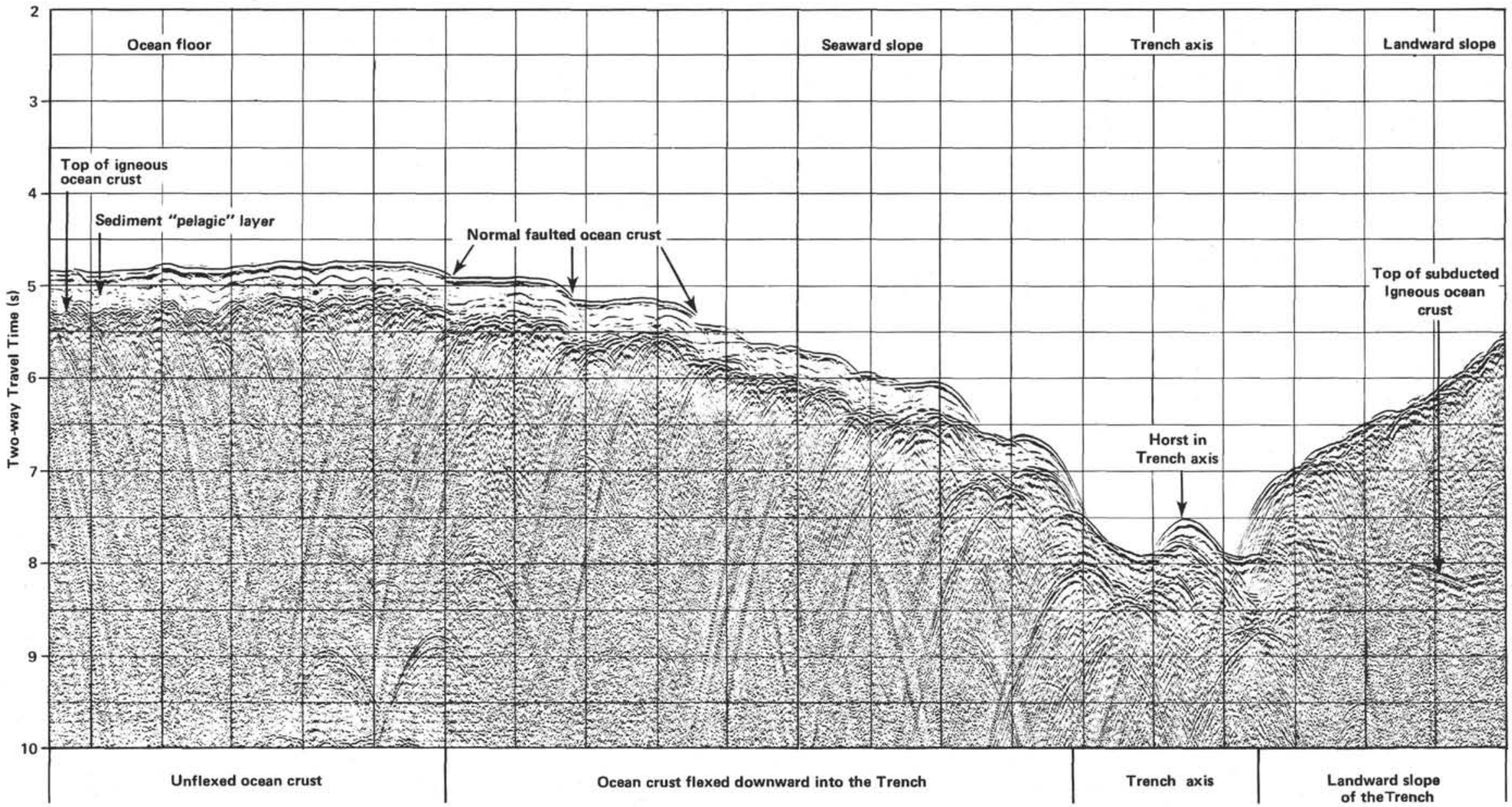

Figure 4. Seaward part of seismic reflection record GUA-2 (from Ladd et al., 1978) showing development of horst and graben as the ocean crust is flexed into the Middle America Trench. (Vertical exaggeration is ×13.5.)

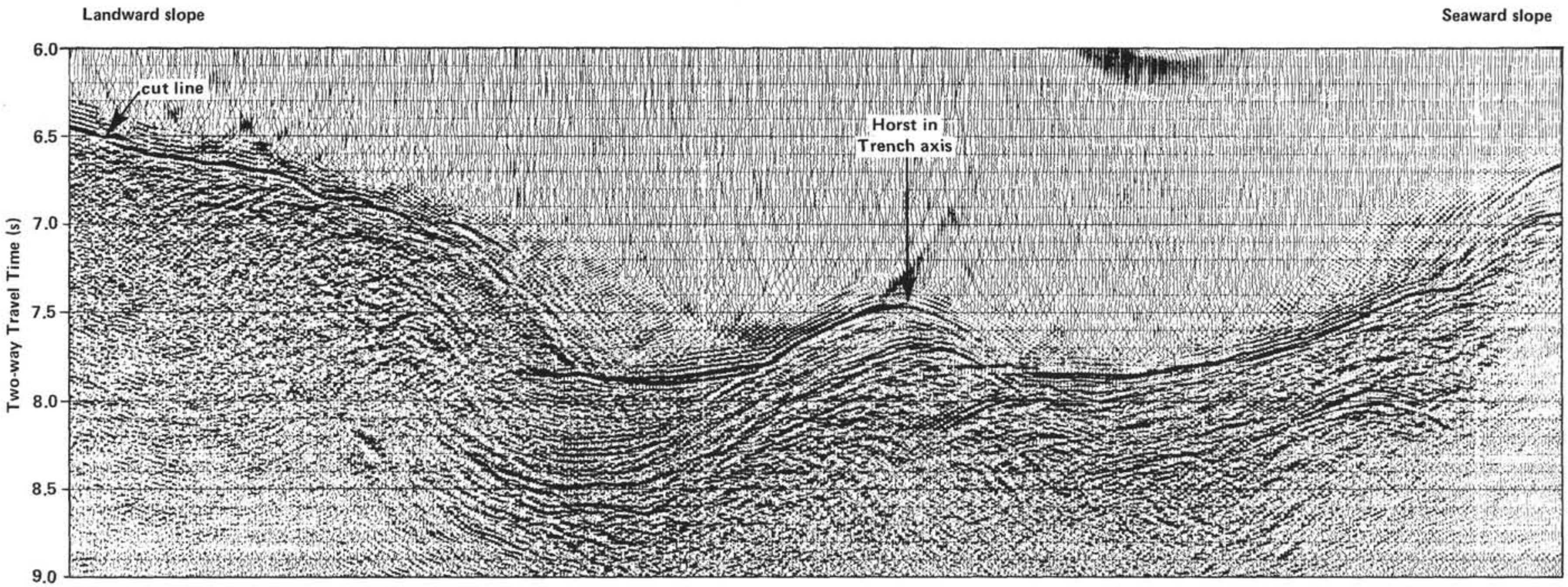

Figure 5. Part of seismic record GUA-2 across the axis of the Middle America Trench, migrated to eliminate some diffractions (compare with Fig. 4) and showing the undeformed nature of Trench-fill strata and the underlying oceanic sediment section as it is subducted beneath the Trench landward slope. (Vertical exaggeration is about ×3.) Seismic noise from migration and wavelet filtering has not been muted above the seafloor.

readily observed, except in the simplest structural situation. We assume that because no scraped-off sediment was recovered, the Trench sediment must be subducted. Subducted sediment has been defined convincingly in seismic records along the Nankai Trough (Aoki and Tamano, in press). As shown in one seismic record adjacent to the GUA-13 transect, undisrupted Trench sediment is clearly beneath the front of the subduction zone (Fig. 5). Two other records show, only a few kilometers down the subduction zone, clear reflections from undisrupted sediment layers resting on igneous ocean crust (von Huene et al., Some Geophysical Observations, this volume).

The fate of the ridges and troughs being subducted and their influence on the overlying continental framework is also obscure. Two of those ridges stand more than 400 meters above the floor of the Trench (Fig. 2), and their collision with the foot of the slope should leave a morphological signature, at least near the point of collision. Although some reflection records along the foot of the slope show a great deal of relief of the subducted igneous ocean crust, and although some of the highs are aligned with the ridges seen in the Trench, others are not. At present, the seismic evidence that the ridges shown in the Seabeam map continue beneath the slope is unconvincing. Nonetheless, at the present rate of convergence, many ridges and troughs have collided with the foot of the landward slope and have disappeared without leaving a topographic trace even at the front of the subduction zone.

Benches are characteristic of the morphology along the Leg 67 transect (Figs. 2 and 6). In the Seabeam map the bench on which Site 494 is located is 28 km long and has a small-scale irregular topography (Figs. 2 and 7). In other areas the lower slope lacks benches and is surprisingly smooth (Fig. 7). The step topography resembles a normal faulted bench because it has limited extent, is irregular, and does not appear to result from long folds behind which sediment is deposited. The gradual rotation of the sediment in the slope basin depicted by Seely (1979) and Moore and Karig (1976) in thrust-faulted benches is not very apparent off Guatemala, and on the lowest bench the slope sediment dips slightly seaward rather than landward (Fig. 6). Compressional structure is absent in cores of the slope deposits. Therefore, although the slope is basically a site of compressional tectonism, we favor an extensional or composite tectonic origin of the benches.

A combined interpretation of deep reflection and refraction data provide a case for landward-dipping slabs beneath the upper slope (Ladd et al., this volume). The high seismic velocity and associated magnetic anomalies indicate involvement of igneous rock, an inference consistent with an interpretation of gravity data (Couch and Woodcock, 1981). The dipping slabs were emplaced prior to deposition of the overlying early Miocene slope sediment. The greatest disappointment of Leg 67 was the inability to meet the primary tectonic objective—sampling the inferred slabs of igneous rock.

The slope deposits drilled during Leg 67 have a much lower velocity and probably a lower density than the underlying acoustic basement. This contrast suggests a contact between rocks of different consolidation rather than continuous sedimentary sequence. Slope sediment rests on three types of topography (Fig. 7). The shelf edge is broadly arched but has a steep (15°) seaward flank that forms the upper slope of the Trench. The midslope area has a rough topography. The lower slope is relatively smooth except along seismic record GUA-13 in the Leg 67 area, where it is broken by the benches. The contrasting basement topographies probably reflect differing types and perhaps periods of tectonism.

Prior to Leg 67, only one possible base of gas-hydrate reflection was noted (T. Shipley, personal communication, 1978), but new displays of the seismic records made after Leg 67 drilling showed more clearly the bottom simulating reflections (BSRs) (Fig. 8). Lines on which BSRs were recognized are all on the middle slope in zones of thick slope sediment. A group of points on these BSRs has the same relation of water depth to depth below the seafloor as that established for other Central American and Atlantic base of gas-hydrate reflections (Shipley et al., 1979). With enhancement of shallow reflections, about 110 km of base of gas-hydrate reflections were observed. The BSR positions are also consistent with thermal gradients measured in the Leg 67 drill holes and the Petrel well.

Geochemical samples from the Leg 67 cores showed that the gas hydrate consisted mainly of methane. If all BSRs are from methane hydrate, this distribution indicates a thermal structure similar to that measured across the Japan Trench and margin (Langseth and Burch, 1980).

GENERAL STRATIGRAPHY AND SEDIMENTOLOGY

A major result of Leg 67 is the strong contrast between the lithologies recovered from opposite sides of the subduction zone. On one side are the oceanic and Trench sites where a Miocene to Quaternary sequence was recovered above oceanic crust; on the other side, an Upper Cretaceous to Quaternary sequence was recovered at the front of the continental slope. The recovery of such contrasting lithologies confirms subduction at the base of the slope but does not fit the hypothesized constant addition to an accretionary prism.

Cocos Plate: Site 495

Site 495, the oceanic reference site, is on oceanic crust on an isolated ridge 22 km seaward of the Trench axis and about 1925 meters above it (Fig. 9). The sediment cover, as seen in seismic records, is generally of uniform thickness (0.4 s) and mimics basement topography in a manner typical of pelagic sedimentation. Magnetic anomalies at the site are known only from reconnaissance data and were indicated to be Eocene (Pitman et al., 1974).

The sediment sequence has a lower part typical of low-latitude oceanic areas and an upper part of hemipelagic character. Forty cores were obtained with 75% recovery, and their lithology is summarized in Figure 10. The sequence consists of:

1) 0–171 meters: hemipelagic, diatomaceous green and olive gray mud (upper Miocene to Present);

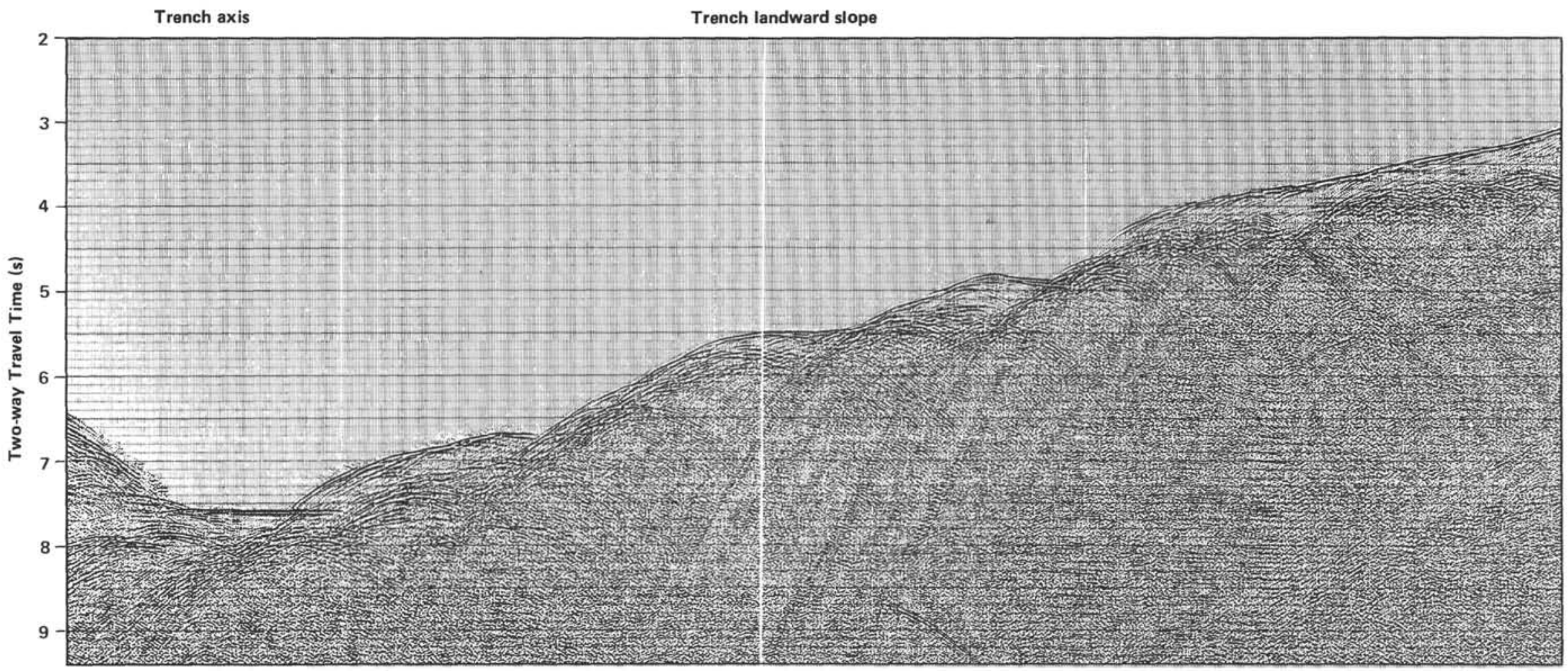

Figure 6. A portion of seismic reflection record GUA-13 showing development of benches on the Trench landward slope (see Fig. 2).

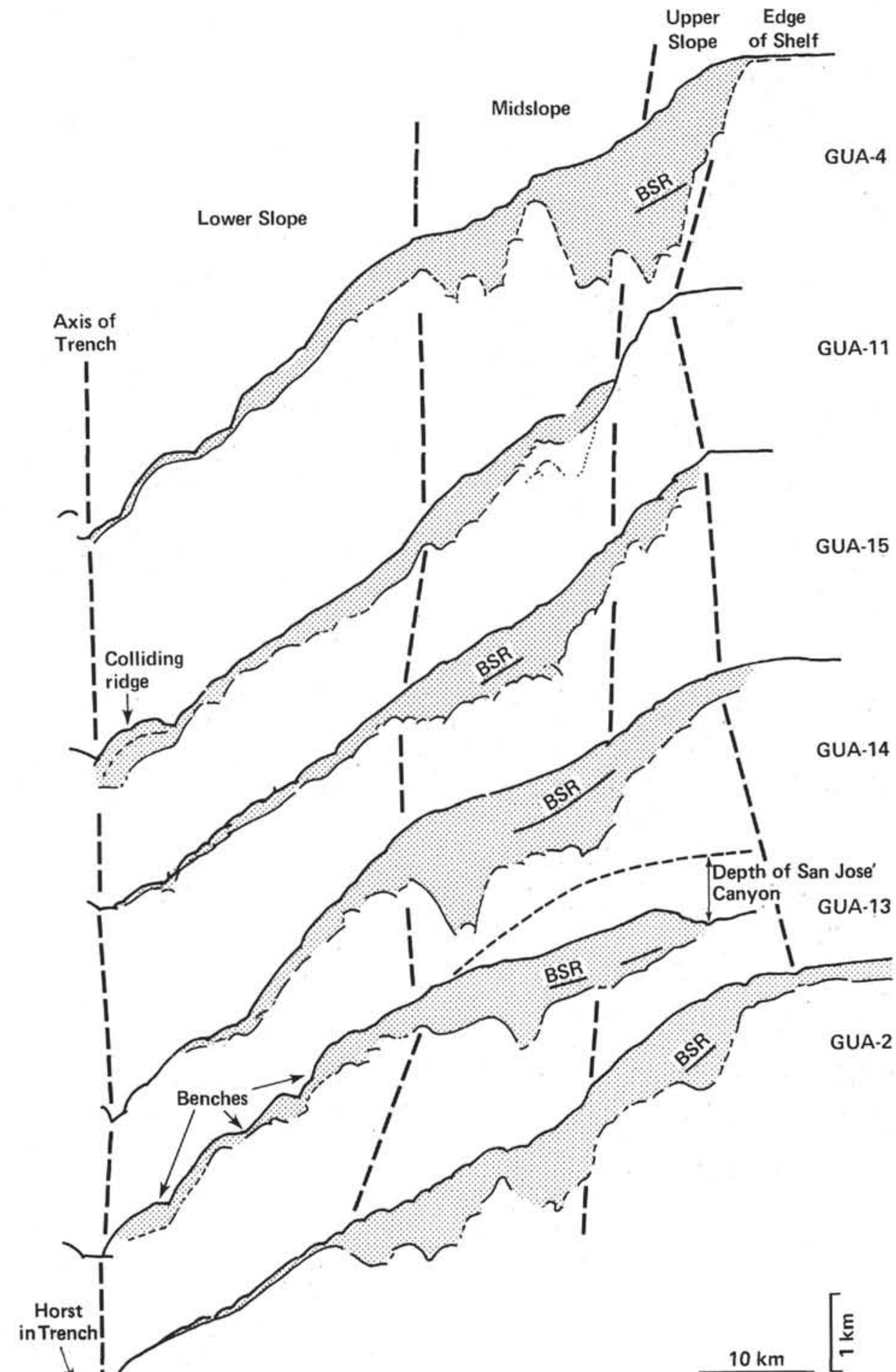

Figure 7. Sections across the landward slope along seismic records showing the base of the slope deposits. (The vertical exaggeration [VE] is × 13.5. Lines GUA-2 and -13 include parts of San José Canyon; thus their upper slopes have been modified.)

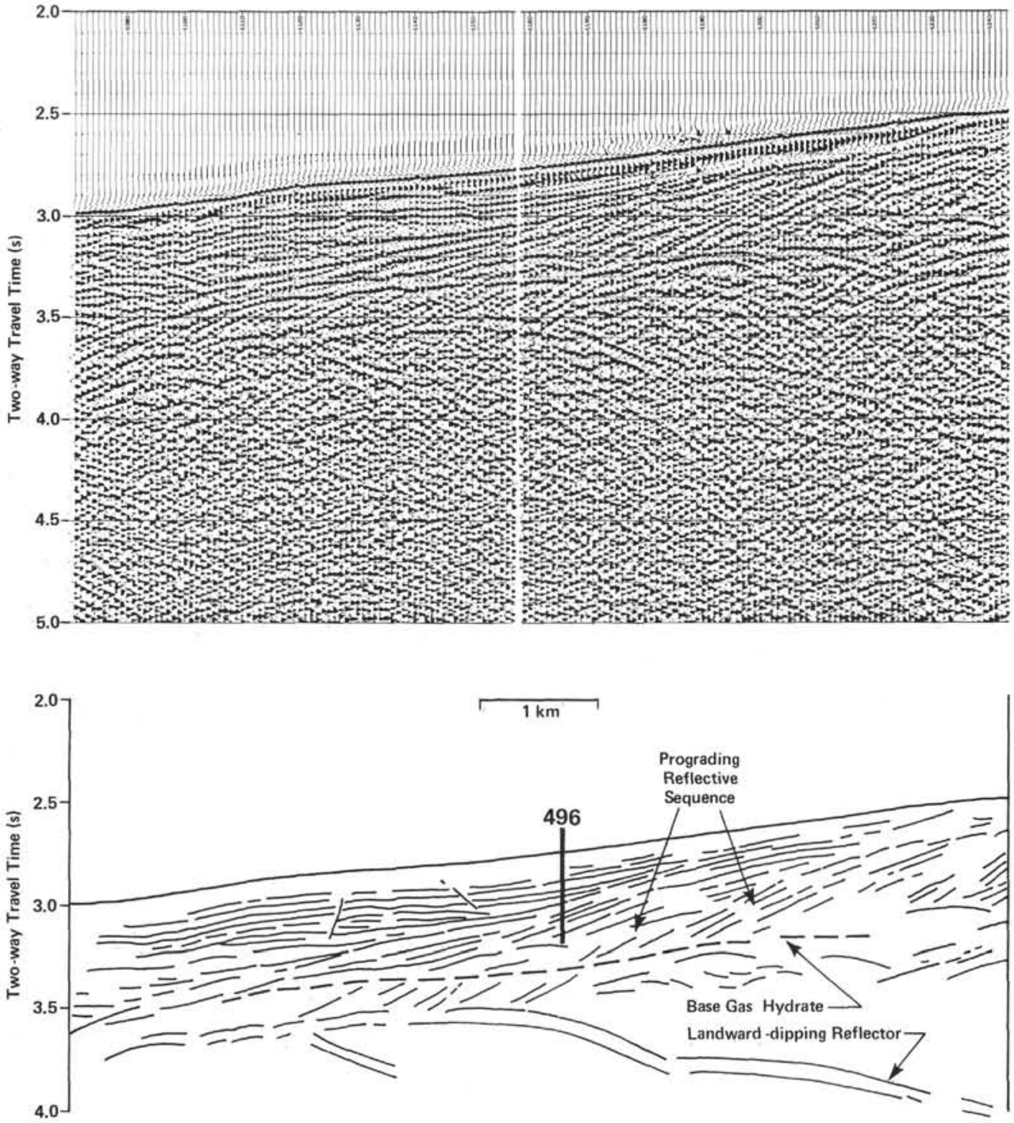

Figure 8. Part of seismic record GUA-13 across the midslope area where Holes 496 and 497 were drilled, and an interpretive tracing of the record pointing out the structure of the slope deposits, the BSR, and the landward-dipping reflector. (The main feature above acoustic basement is a sediment lobe that has subsequently been buried by slope deposits.)

2) 171–178 meters: abyssal brown clay (top of middle Miocene);

3) 178–406 meters: chalky carbonate ooze with chert in the lower part (lower to middle Miocene);

4) 406–428.5 meters: manganiferous chalk and chert (base of lower Miocene); and

5) 428.5–446.5 meters: basalt.

The microfossil assemblages recovered indicate an unbroken sediment sequence from Quaternary to lower Miocene. Foraminiferal and nannoplankton assemblages are well preserved except in the middle and upper Miocene section where poorly preserved foraminifers are an indication that the site was at depths near the calcite compensation depth (CCD). Assemblages of benthic foraminifers indicate a gradual increase in depth with decreasing age and perhaps a slight uplift at the end of the Quaternary. Tertiary movement of the Cocos Plate into the equatorial belt of high productivity is recorded by an early and middle Miocene increase in the rate of biogenic sedimentation. Today this belt is near the Galapagos Archipelago. A contrasting section of upper Miocene abyssal clay and slow rates of sedimentation indicate deposition in environments presently found at 10°N to 15°N just north of the carbonate belt. These abyssal clays are thin and are immediately overlain by hemipelagic sediment. The sediment section at Site 495 therefore records northward passage of the Cocos Plate through the equatorial carbonate belt to an environment of slower pelagic deposition, and finally to an environment within reach of a terrigenous source. Superimposed on this trajectory are the effects of subsidence as the newly formed ocean crust moved away from the ocean ridge and cooled.

The origin of the 170-meter-thick hemipelagic cover is difficult to explain, because the site is 20 km seaward and almost 2000 meters above the Trench. Given that

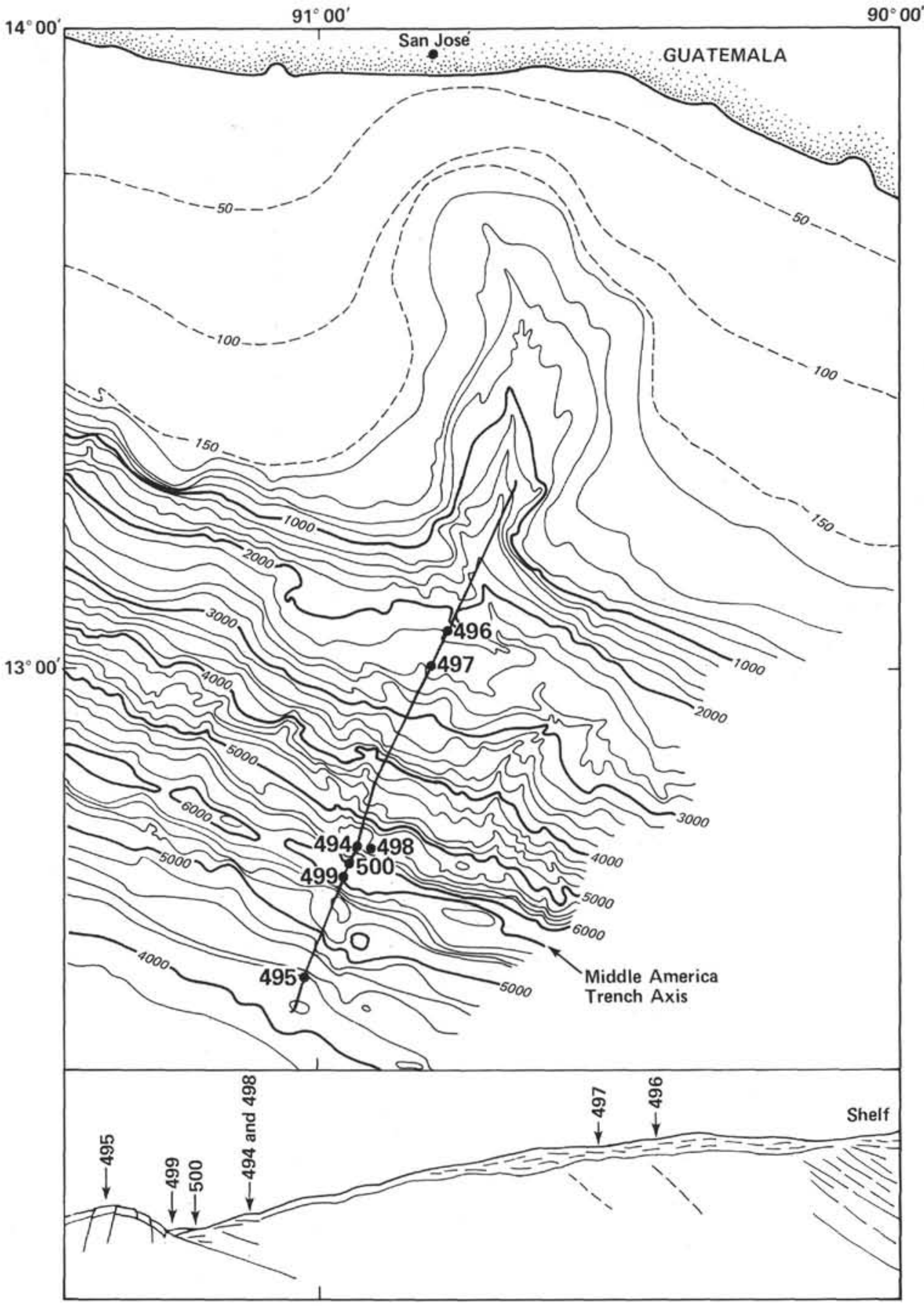

Figure 9. Map and cross section showing the location of Leg 67 sites.

the Middle America Trench is about 3000 km long, silt- and even sand-sized grains must have been transported across the Trench and not around it. If the present rate of convergence, 9 cm/yr., were constant during the entire interval of hemipelagic sedimentation (10 m.y.), the site would have been 900 km away when hemipelagic sediment first reached it. Such a great distance is not consistent with the occurrence of hemipelagic sediment noted at other DSDP drilling sites in the region. For instance, only volcanic ash and no hemipelagic mud was recovered from Sites 156 and 157, about 500 km off South America, and from Sites 84 and 158, which are 240 km and 300 km from land, respectively. Projecting plate-convergence rates and directions 10 m.y. back in time may therefore be too simplistic an interpretation.

The crust now entering the Trench is earliest Miocene or possibly late Oligocene; this age assignment is firmly established by the drilling results from Site 495 and other Leg 67 sites.

Trench Floor: Sites 499 and 500

Sites 499 and 500 are located in the Middle America Trench. With the exception of a cover of turbidites, the stratigraphic sequences recovered above oceanic crust at

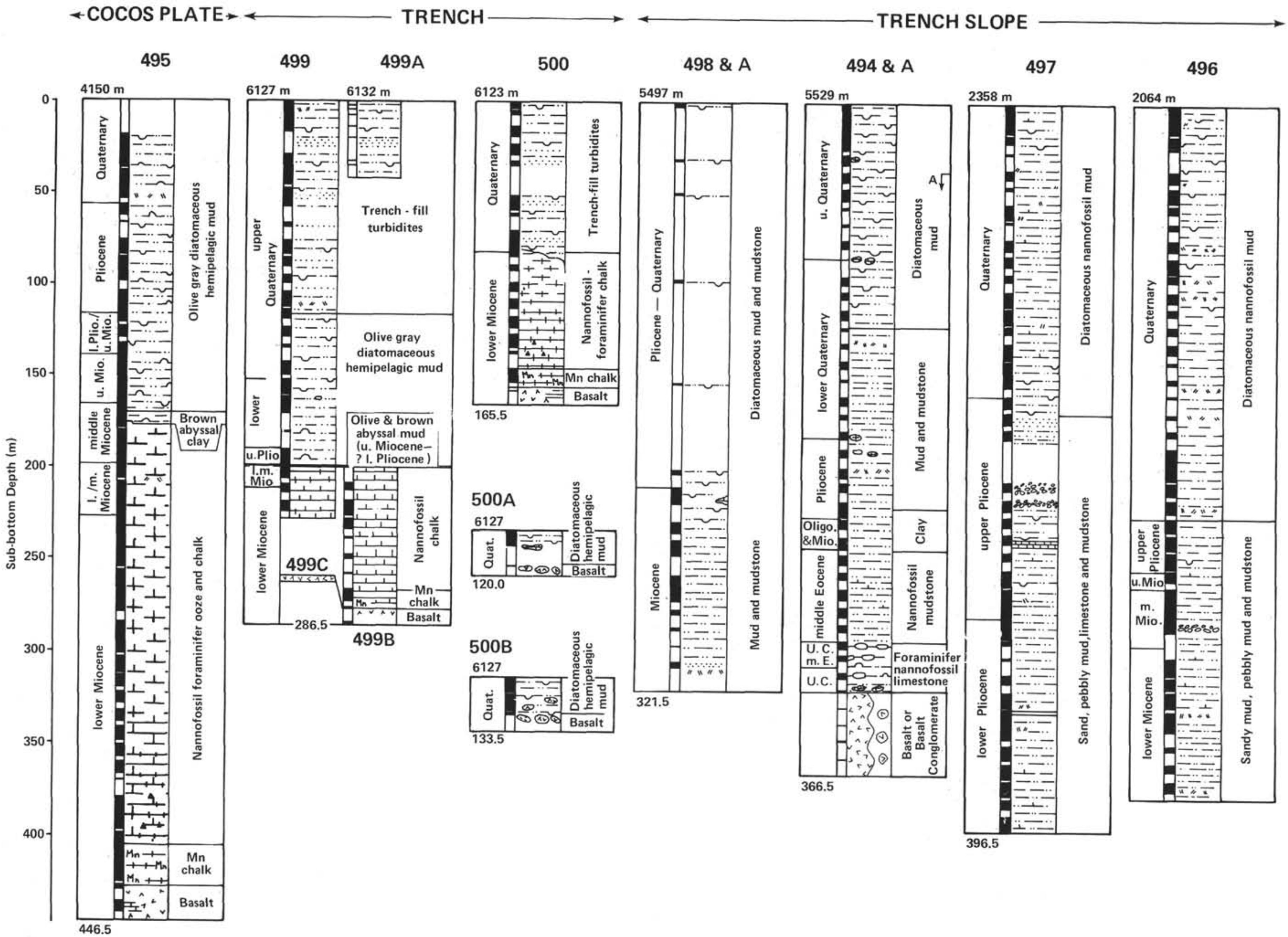

Figure 10. Summary of lithostratigraphy and biostratigraphy of Leg 67 sites.

both sites are the same in age and facies as at the oceanic reference Site 495; and basement is formed by the Cocos Plate, as confirmed by the eight holes drilled at these sites (Figs. 9 and 10).

High-frequency seismic-reflection records show a sequence of horizontal strata, presumed to be Trench fill, underlain by a sequence of strata with a gentle landward dip, presumed to represent the deep oceanic section. Hole 499 was drilled just seaward of a small depression within the Trench axis and consisted largely of mud. Subsequently, that small depression was drilled at Hole 499A to define lateral facies changes in the Trench fill. Then Hole 499 was paralleled at 499B, which was drilled to a rubbly basalt that impeded drilling to the point where there was danger of getting the drill string stuck. Those basalt cobbles were altered and rounded—not a convincing indication of basement; therefore Hole 499C, offset 300 meters along strike, was washed to basement. Again, the rubbly nature of "basement" caused the drill to stick and necessitated abandoning the hole. Hole 499D was washed to 216 meters, where basalt pebbles and cobbles were encountered about 50 meters shallower than the original seismic basement depth estimated.

The axial turbidites that cover the Trench floor are as much as 117 meters thick and predominantly muddy (85%), although some sandy layers may not have been recovered. Turbidites are similar at Hole 499 and in the shallow depression at Hole 499A, about 1 km away. Apparently there is no lateral facies change across the Trench floor. The drill results are consistent with the deep-tow records that show extensive lateral continuity of individual reflectors across the Trench floor (Moore et al., this volume). At Site 499, the turbidites are in sharp contact with the underlying burrow-mottled hemipelagic mud, which in turn overlies calcareous ooze and chalk. The calcareous section is, however, about one-third as thick as it is at Site 495. Chalk overlies rubbly basalt at Site 499.

Microfossils occur in the same succession as at Site 495, with the addition of the Quaternary turbidites. That Trench fill has abundant reworked and transported calcareous microfossils, and the 400,000-yr. radiolarian zonal marker clearly exists below the Trench fill.

Thus the Trench is filled with a uniform sequence representing the last 400,000 yr. of alternating muddy, and to a lesser extent, sandy turbidites, transported from shallower areas including nearshore areas, and deposited rapidly at more than 6000-meters depth. The youth of these deposits, specifically their short time of residence, implies rapid subduction. The sediment age is not known with enough precision to refine the gross rates of plate convergence estimated from global magnetic anomaly patterns. Within the calcareous section, there is more dissolution of foraminifers than at Site 495, indicating deposition nearer the CCD. The oldest sediment is earliest Miocene, as at Site 495. Not only biogenic constituents and lithology but also physical properties and gaseous hydrocarbons change between the Trench fill and the underlying deep-ocean section.

Site 500 is at the base of the Middle America Trench landward slope just seaward of the juncture of the slope and the Trench floor. Lithologies and ages are basically the same as at Sites 499 and 495, but hard undrillable zones of basalt cobble conglomerate or igneous basement were encountered at unexpectedly shallow depths due to either redeposition or faulting. In Hole 500, the sequence of Quaternary Trench-filling turbidites is either normally faulted or deposited against a fault scarp in lower Miocene chalk; basalt basement is at 161 meters. At Hole 500A and 500B, near the center of the Trench, turbidites are thicker. Coarse, rubbly basalt and sandstone cobbles were encountered at 115 and 125 meters depth, respectively, and proved impenetrable in both holes. The Trench fill contains biogenic debris, including wood fragments that are more characteristic of the slope deposits at Site 494 than the turbidites at Site 499. Pyrite and H_2S odor suggest that anoxic conditions exist in the Trench.

Site 500, at the front of the subduction zone, shows no deformational features, and physical properties are essentially the same as at Sites 499 and 495. The largest structure appears to be a normal fault developed during flexure of the Cocos Plate as it is bowed downward into the Trench. When the sites are located on the Seabeam map, the depths to basalt are consistent with the horst and graben structure in the map; thus the basement relief inferred from topography is confirmed by drilling.

Landward Slope: Sites 494, 496, 497, and 498

The recovery of slope sequences was limited by the occurrence of gas hydrates. For reasons of safety, three of the four holes were terminated prior to reaching the major objective, which was the rock of the seismic basement.

Lower Slope: Sites 494 and 498

Site 494, on the lower slope, is about 3 km landward of the Trench axis and 580 meters above it. It is situated on a 2-km-wide terrace formed by steps in the slope (Figs. 9 and 10).

Below the Pleistocene sediment, the average core recovery was less than 30%. A relatively complete sequence of microfossil assemblages was recovered, indicating strata in an orderly stratigraphic sequence of young over old except at the bottom of the hole. Benthic foraminiferal assemblages are displaced downslope, especially in the post-Miocene. The microfossils indicate three long hiatuses in sedimentation separating sections of different age and provenance. The recovered lithologies are:

1) 0–213 meters: Holocene to Pliocene dark gray diatomaceous mud containing abundant fauna displaced from 1000 to 2000 meters water depth; sedimentation rate is 55 m/m.y.;

2) 213 meters: unconformity, contact observed;

3) 213–231 meters: blue gray hemipelagic clay containing lower Miocene to upper Oligocene foraminiferal and radiolarian fauna and middle Miocene nannofossil assemblages typical of open-ocean environments (rather than areas of coastal upwelling); deposited near the CCD;[2]

[2] In view of the similarities with altered serpentinite recovered on Leg 84, this unit should be restudied.

4) 231 meters: unconformity, contact observed;

5) 231–295 meters: dark, sandy, lower Eocene mudstone in which one undisturbed and very complete section has many closely spaced faults with small displacement; fauna were deposited below the foraminiferal CCD but above the nannofossil CCD; sedimentation rate is 10 m/m.y.;

6) 295 meters: unconformity or fault, contact not observed;

7) 295–304 meters: dark gray mudstone mixed *in situ* or by drilling disturbance with blue gray micritic limestone; middle Eocene and Upper Cretaceous, respectively;

8) 304–323 meters: medium gray Upper Cretaceous mudstone with an open-water marine fauna containing abundant *Globotruncana;* deposited above the CCD; and

9) 323–358 meters: five cores with a total recovery of 1 meter of altered mafic and intermediate igneous rock atypical of ocean floor basalts.

Underlying this sequence, seismic records indicate a continuation of material with a reflection velocity of 3.1 and 4.1 km/s.

Site 498 was drilled about 1.8 km east-southeast, along strike, from Site 494 to fill the gaps in the stratigraphic section at Site 494 and to penetrate into the presumed underlying oceanic section. Recovery of gas hydrate, however, necessitated that the Site be abandoned prior to reaching a depth greater than that penetrated at Site 494 (Fig. 11).

The mud and mudstone from the uppermost 213 meters at Site 498 resemble those at Site 494. Pleistocene sediment is underlain by Miocene sediment, and both were transported from upslope. The Miocene lithology is different from the lithology of equivalent-age rock at Site 494. The unbrecciated part of the section is dark olive gray mudstone, although chips of the familiar blue gray Oligocene or Miocene mudstone of Site 494 are abundant in the drilling breccia, which constitutes most of the cores. Poor recovery and drilling conditions below 213 meters at Site 498 indicate that the section is fragmented.

The similarity of Pliocene and Pleistocene lithologies at Sites 494 and 498 is indicative of comparable origins, but the differences between Miocene lithologies at equivalent depths is unexplained. The distinctive blue gray mudstone from below the Pliocene unconformity at Site 494 occurs as abundant clasts in the olive gray Miocene slope sediments of Site 498.

Upper Slope: Sites 496 and 497

Drilling at Site 496 ended about 300 meters short of the target—a landward-dipping reflector at the top of a high-velocity interval thought to be ocean crust (Ladd et

Figure 11. Gas hydrate (Sample 498A-15-2, 110–125 cm) during decomposition. (This photograph was taken less than 5 min. after the sample was brought aboard the *Challenger*. The hydrate is contained in a volcanic ash; the central part is solid, whereas the outer parts are a bubbling fluid.)

al., 1978, and this volume; Ibrahim et al., 1979). The sediment above the dipping reflector appears to unconformably drape the seismic basement (Fig. 8). Drill samples from Site 496 show that the cover includes an upper sequence of mud and mudstone (0–266 m) and a lower sequence of Pliocene to lower Miocene semilithified sandy mudstone (226–387 m). Both units are rich in terrigenous detritus and contain some volcanic ash and rare lignite.

All microfossil groups were recovered from this section. Above 283 meters, the calcareous nannoplankton assemblages are oceanic; below 283 meters, they are typical of shallow water. Benthic foraminifers also indicate subsidence of this area in the Miocene, from shelf to lower bathyal depths. A well-defined reduction in rate of sedimentation or perhaps a hiatus occurs in the upper Miocene and Pliocene.

The lithostratigraphy and biostratigraphy at Site 496 are interpreted as showing a lower Miocene sediment lobe and an overlying apron of hemipelagic slope sediment. The subsidence of this site in the early and middle Miocene is coincident with the submergence of the edge of the adjacent shelf, as reported by Seely (1979).

Site 497 was also abandoned about 500 meters short of the primary objective, because of gas hydrate. As at Site 496, the primary objective was to sample a landward-dipping reflective horizon in the seismic basement. The dominant lithology is olive gray mud, with varying minor biogenic and vitric tuffaceous constituents. A short interval of rapidly deposited sandy mud and pebbly mudstone occurs at about 280 to 296 meters. Near vertical, dark colored veinlets, probably associated with the escape of water, occur in the lower, more lithified part of the section.

Several lines of evidence document the presence of gas hydrate at this site. Probably the most convincing were pieces of frozen vitric sand that were allowed to come to ambient temperature in a pressure vessel. The amount of gas released during decomposition was much greater than the amount of methane soluble in water.

TECTONICS

The Guatemalan margin was one of the areas Seely et al. (1974) used to demonstrate a simple underthrusting model for trench inner slopes. The Guatemalan margin contains local landward-dipping reflections that suggest accretion (Ladd et al., this volume; Seely et al., 1974). However, the temporal control from Leg 67 drilling has indicated that although some periods may have been accretionary, nonaccretion marks other periods throughout the Tertiary.

Tectonic Features in Cores

In the convergent-margin tectonic environment sampled during Leg 67, several investigators studied tectonic problems on the scale of the core, but with different approaches. These approaches included: observations of physical properties, laboratory experiments, and visual observations of structural features and fabrics (Faas, Gravitational Compaction Patterns, this volume; Cowan, this volume; and Dengo, this volume). Most investigators tried to extend conclusions from microstructures to macrostructure, and the results agree in many areas but not in others.

Regular patterns of gravitational compaction occur in the Leg 67 sediment cores, and compaction is related to rates of lithostatic loading, sediment type, and perhaps the generation of methane gas (Faas, Gravitational Compaction Patterns, this volume). In the Middle America Trench axis, sediments below and interbedded with the turbidites exhibit undercompaction, probably due to rapid lithostatic loading of sediment in an environment of rapid sediment accumulation. Slow drainage of interstitial pore waters results in a sedimentary section possessing low unit weight, high water content, and low shear strength.

The compaction behavior of the sediments on the Cocos Oceanic Plate is controlled by sedimentation rate and sediment type. The slowly accumulating hemipelagic sediments are normally compacted. The water-rich siliceous ooze below impermeable hemipelagic clay shows relative undercompaction as a result of impeded drainage. Lithified chalk is overcompacted because void spaces are filled with recrystallized calcite.

Structure seen in the core is dominantly fracturing and, to a much lesser degree, faulting (Dengo, this volume). On the seaward slope of the Trench, two faults in a core from Site 495 suggest horizontal compression, but most of the sedimentary structure at that site indicates extension. Because of their high porosity, the lower layer of chalks may have deformed substantially more than the overlying terrigenous sediment. The slope sediment on the landward slope of the Trench lacks structural evidence of compressive horizontal tectonism, and most structure indicates extension. Slumping or other downslope gravitational processes explain the small-scale structure of the landward slope. Lateral compressive forces associated with a convergent margin do not seem to have been important except possibly in acoustic basement as an explanation of the fracturing in Eocene rock at Site 494, located near the front of the subduction zone.

Hemipelagic muds recovered at Sites 496 and 497 contain abundant, vertical to subvertical, dark, sigmoidal veins that are generally less than 2 mm thick and are spaced from one to several millimeters apart. Vein fillings are mineralogically and texturally similar to surrounding matrix, but the very fine-grained platy minerals within are preferentially oriented parallel to vein boundaries (Cowan, this volume). Veins are interpreted as water-escape conduits that are geometrically analogous to extension fractures. They formed as horizontal confining pressure was relaxed preferentially in one direction, allowing water from interbedded, unconsolidated, more porous layers to escape upward. Deformation, which imparted a penetrative foliation to muds, may have occurred in response to modest gravity-driven downslope extension of part of the blanket of sediments on the upper slope.

Tectonic History

The tectonic history of the Guatemalan margin begins with deposition of a deep-water oceanic Late Cretaceous section (Seely, 1979). The Late Cretaceous section at Site 494 (Campanian-Maestrichtian) may have been more distal than the section at the Petrel well, perhaps located on an ocean ridge and above the CCD. The continental slope may have been to the north or northeast of the present edge of the shelf and sufficiently proximal to the Petrel well to supply abundant terrigenous sediment. This upper Campanian-Maestrichtian deposition may have followed a strong tectonic episode seen on the Santa Elena Peninsula involving slabs of oceanic crust and the Nicoya Complex (Azéma et al., this volume; Ladd et al., this volume).

In the Paleocene the present area of the outer fore-arc basin and certainly the upper slope were uplifted to about sea level; the present fore-arc basin has existed since the Eocene (Seely, 1979). During erosion in the Oligocene the outer shelf and much of the present upper slope were emergent to form a sharp unconformity at the shelf edge. During the early Miocene the slope received sediment that was rapidly deposited in a lobate body at Site 496 (and perhaps in other lobate sediment bodies seen in the seismic records).

The Neogene was a time of local subsidence on the midslope as well as in the fore-arc basin areas, but not along the arch at the edge of the shelf (Seely, 1979). The arch remained a structural high but was breached by San José Canyon. There are no products of Neogene accretion at the front of the margin, although some may have accumulated and have then been subducted.

CONCLUSIONS

The results of Leg 67 indicate a Late Cretaceous to Quaternary history with tectonic periods of varying character. The most pronounced differences in rock types on the oceanic and continental plates are apparent in the pre-Pliocene rock. Lower Miocene chalk and basalt of the incoming ocean-basin lithosphere are immediately adjacent to Upper Cretaceous through Miocene mudstone of the landward slope of the Trench. The implications of this discovery are the most important of the Leg 67 results. During the Neogene, thousands of kilometers of oceanic plate were subducted, and no sediment was accreted to the continent.

The pre-Pliocene rock can be separated into an oceanic and a continental group. The oceanic group has Miocene sediment that records the northward passage of the Cocos Plate beneath the equatorial carbonate belt and into proximity with a terrigenous source. This oceanic sequence is broken by normal faults as it enters the Trench, and before subduction it is capped, except on the highest parts of the ridges, by ponded Trench turbidites (Sites 499, 500). The section cored at the foot of the Trench landward slope records neither an increase in deformation nor consolidation to mark its passage across the Trench to the vicinity of the thrust zone between the oceanic and continental plates.

Just how the rough horst and graben topography slips beneath the upper plate without affecting the front of the continental slope is puzzling. Relief of the ocean basement is not smoothed off by subduction, but the tectonic mechanisms involved are barely alluded to in the seismic records of this study. The subduction of considerable sediment is probably facilitated by the subduction of graben hundreds of meters deep. The subduction of hundreds of kilometers of horst and graben topography should produce a great deal more deformation. An accommodation of large topographic features is also seen in the subduction of the Cocos and Tehuantepec ridges without much effect on the continent. The seemingly passive tectonic character of the subduction zone requires extensive mechanical decoupling.

The contrast in lithology across the Trench-slope juncture diminishes in the Pliocene and Pleistocene sediment to become almost imperceptible. The Trench landward slope is covered with mud and some sand. The same sediment is transported downslope and beyond the Trench into the deep-ocean basin. Transport to the Trench is rapid enough to bury shallow-water benthic foraminifers before their dissolution in corrosive waters beneath the CCD. Sediment blanketing most of the landward slope has a lithologic as well as a biostratigraphic character that indicates extensive downslope movement by multiple transport mechanisms. This lithologic character would be very difficult to distinguish given an overprint from alteration and metamorphism.

The lower Miocene volcanic ash recovered at Sites 496 and 498 indicates an early Miocene magmatic arc, consistent with the arc volcanic rock on land (Kennett et al., 1977). Early Miocene to present volcanism indicates convergence off Guatemala during the Neogene, and the change in the tempo of volcanic activity studied on land is also revealed in the marine ash chronology.

The Cocos Plate is oldest at the Middle America Trench where drilling at three sites recovered lowest Miocene sediment on top of ocean basalt. From magnetic anomaly studies, however, the age of this crust was thought to be Eocene (Pitman et al., 1974). The same disparity between magnetic anomaly determinations for the Cocos Plate and sediment ages was also noted on Leg 16.

Leg 67 samples verified the existence of marine gas hydrates. Melting of the ice liberated greater quantities of gas than are soluble in water at *in situ* pressure and temperature. Gas hydrates were recovered at two sites and were probably recovered at a third. Temperature gradients from logging and a downhole instrument show that the pressure-temperature conditions on much of the margin are well within the gas-hydrate stability field. Suitable pressure-temperature conditions, however, are only a partial requirement for gas hydrate; gas in proper quantity and composition is also necessary. The regular association of gas hydrate with vitric sands suggests that in order for massive gas hydrate to form in this environment porosity must be greater than that of the hemipelagic mudstone. The gas hydrates are probably massive only in vitric sands and if they have much lateral extent they exist as thin sheets and not as a thick, solid layer. Hydrates are seen only where slope sediment is thick; they have not been detected seismically in the Paleogene rock of the continental framework.

Leg 67 Results and the Regional Geology of Central America and the Caribbean

In southern Costa Rica, in Panama along the Pacific, and at the southwest base of the volcanic cordillera, Central America is fringed by tectonized volcano-sedimentary terranes forming, from north to south, the Santa Elena, Nicoya, Osa, Sona, and Azuero peninsulas (Fig. 12). Basement rock of the Santa Elena Peninsula, which is exposed beneath an upper Campanian-Maestrichtian to Tertiary transgressive sedimentary cover, is a massif of peridotites, including an ophiolitic complex of tectonized harzburgites, cumulate gabbros, and dolerites. These have been overthrust onto a volcano-sedimentary complex of diabase and radiolarites (Azéma and Tournon, 1980). The Nicoya Peninsula is formed by a volcano-sedimentary series that contains radiolarians deposited in the Late Jurassic(?) through Late Cretaceous (Azéma et al., 1979; Galli, 1979; Schmidt-Effing, 1979; Azéma and Tournon, this volume). The relation between the Santa Elena peridotites and the Nicoya Complex is unknown; most probably the Santa Elena peridotites represent a tectonically higher unit, tectonized prior to the upper Campanian-Maestrichtian, and then thrust over the Nicoya Complex.

The Sona and Azuero peninsulas are covered by an upper Campanian-Maestrichtian transgressive sedimentary sequence (Fig. 12). Also exposed are rocks of a

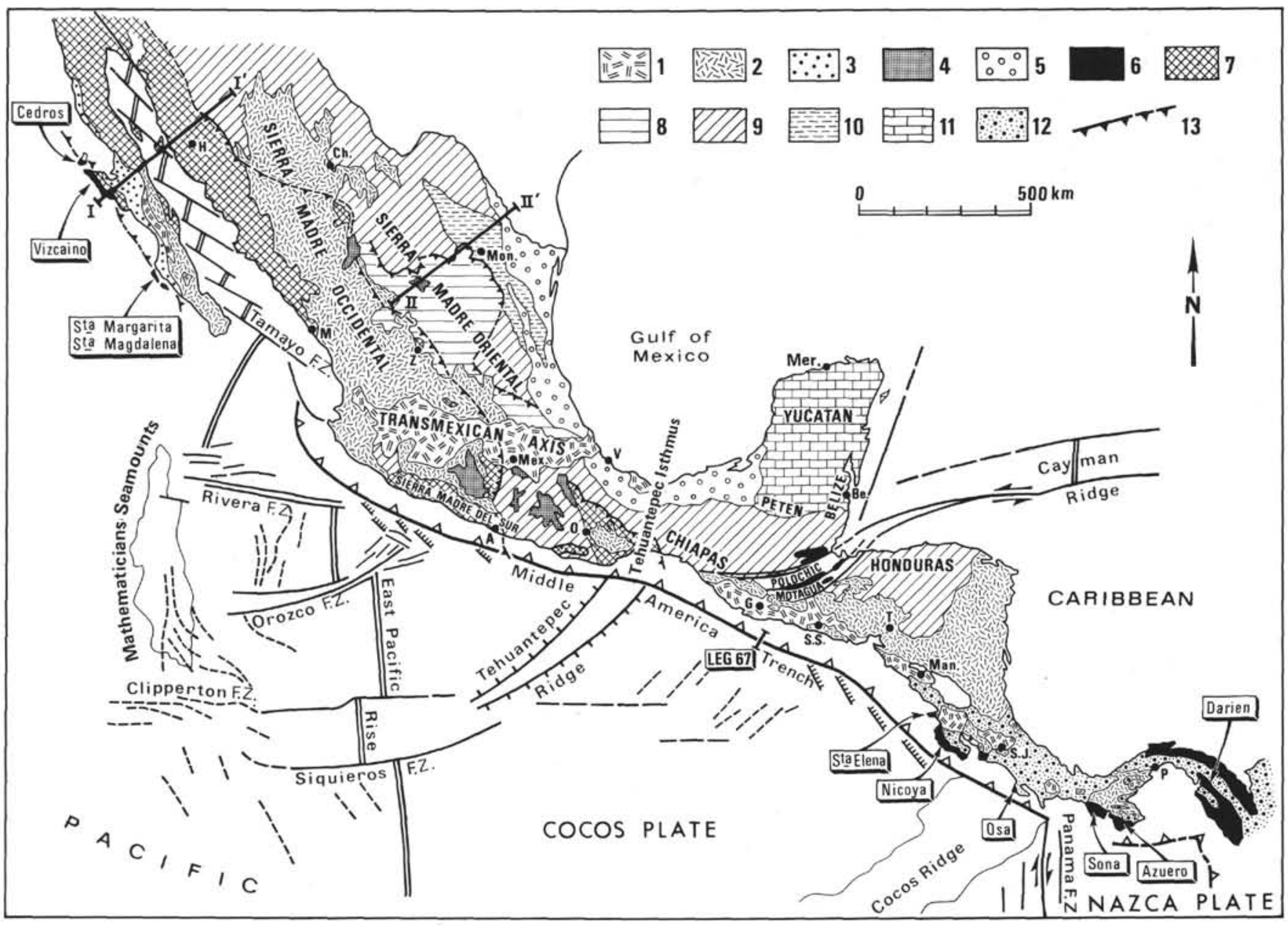

Figure 12. Geologic sketch map showing the main Mesozoic and Cenozoic structural areas of Mexico and Central America. 1–2. Recent volcanism: 1. Pliocene and Quaternary; 2. Oligocene and Miocene. 3–5. Late tectonic formations: 3. unconformable terrigenous marine terranes deposited in the Cretaceous–Cenozoic [Baja California]; 4. unconformable terrigenous continental terranes [molasse] deposited in the Eocene to Miocene [Mexican antiplano]; 5. terrigenous marine Eocene to Miocene terranes [Gulf of Mexico coastal plain]. 6. Oceanic Mesozoic complexes: A. ophiolitic with blueschists [Baja California: Cedros, Vizcaino, Santa Margarita, Santa Magdalena; Guatemala: Polochic–Montagua Zone] or without [Costa Rica: Santa Elena]; B. tholeiitic and volcaniclastic deposited in the Late Jurassic(?)–Early Cretaceous-Late Cretaceous [Costa Rica: Nicoya, Osa; Panama: Sona, Azuero]; C. tholeiitic and volcaniclastic deposited in the Late Cretaceous [Panama: Darien]. 7. Western Sierra Madre terranes [Mexico]: volcaniclastic belt deposited in the Triassic–Jurassic–Early Cretaceous. 8–10. Eastern Sierra Madre terranes [Mexico]: nonvolcanic belt of [Triassic] Jurassic–Cretaceous: 8. allochthonous terranes including flysch nappes; 9. autochthonous platform of Texas, Coahuila, San Luis Potosi, Oaxaca, Chiapas, Honduras, with Paleozoic basement [Oaxaca, Honduras]; 10. Sabinas Basin. 11. Cenozoic platform of Yucatan, Peten, Belîze. 12. Cenozoic formations of southern Central America. 13. Main overthrusts [front of the nappes]. A. = Acapulco; Be. = Belîze; Ch. = Chihuahua; G. = Guatemala City; H. = Hermosillo; M. = Mazatlán; Man. = Managua; Mer. = Mérida; Mex. = Mexico; Mon. = Monterrey; O. = Oaxaca; P. = Panama; S. J. = San José de Costa Rica; S. S. = San Salvador; T. = Tegucigalpa; V. = Vera Cruz; Z. = Zacatecas. I–I′ = cross section of Fig. 3 (in Aubouin et al., this volume), II–II′ = cross section of Fig. 4 (in Aubouin, Azéma et al., this volume).

metamorphic greenschist facies for which there are no equivalents elsewhere in Central America (del Giudice and Recchi, 1969); their age is still unknown. These rocks are probably part of a volcano-sedimentary complex, because ancient basalts and graywackes have been identified in the metamorphic terranes. The Central American isthmus south of Guatemala was therefore, constructed of Pacific oceanic terranes and then tectonized at the end of the Cretaceous. There is no indication of a continental basement, there is to the north beneath Mexico. The Central American isthmus probably originated as an intra-oceanic edifice.

The results of Leg 67, especially those from Site 494, are important for regional geology, especially with regard to the origin of the Caribbean Plate. The Caribbean Plate is presently bounded by the sinistral Polochic–Motagua–Cayman–Bartlett–Puerto Rico fault complex to the north, the dextral Oca–El Pilar fault complex to the south, the Antilles subduction zone to the east, and Central America to the west (Fig. 12). Because of its present relatively eastward motion, the Caribbean Plate is generally considered to be a part of the East Pacific Plate (see Malfait and Dinkelman, 1972). But the upper Campanian–Maestrichtian carbonates recovered at Site 494 are of the same age as the transgressive sedimentary cover in the peninsulas of Santa Elena, Osa, Sona (Cosa Rica), and Azuero (Panama), whereas a complete section for the Uppermost Jurassic to the present has been described in the Nicoya Complex and above it in Costa Rica (see Azéma and Tournon, this volume). Thus a continuous belt of Upper Cretaceous terrigenous sediment runs along Central America from Guatemala to the north (Site 494), to Panama in the south (Azuero Peninsula), and perhaps to the west coast of Columbia (Goosens et al., 1977).

This continuity of Cretaceous terranes rules out the possibility of the Caribbean Plate having a Pacific origin since the end of the Cretaceous. Besides, in the absence of data regarding the initiation of tectonism at the paleolatitude of the Nicoya Complex in which Upper Jurassic, and Lower-Middle and Upper Cretaceous rocks occur, the uncertainty of a Pacific origin of the Caribbean Plate since the Late Jurassic or Early Cretaceous offers some interesting alternatives (Aubouin and Azéma, 1980). The Caribbean region could have been part of the westernmost Tethys Ocean during the Mesozoic (Aubouin et al., 1977) and subsequently isolated from it by the opening of the Central Atlantic around the Mid-Cretaceous.

The Guatemalan margin could be a part of the long Mesozoic belt fringing the Pacific side of the Americas and cropping out in Alaska, in the Californias (including western Baja, Cedros Island, Vizcaino massif, Islas Santa Margarita, and Santa Magdalena), in Central America, and in northwestern South America.

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