Three-Dimensional Seismic Imaging of the Costa Rica Accretionary Prism: Structural Diversity in a Small Volume of the Lower Slope

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Conventional two-dimensional seismic reflection investigations have been generally relied upon to provide images of large to medium scale structural features in accretionary prisms. We undertook a three-dimensional seismic reflection survey of a small part of a prism arcward of the Middle America Trench off Costa Rica to more correctly image structure and to use the improved structural information to examine the processes of accretion. This survey reveals small features, with dimensions of hundreds of meters, while also defining features thousands of meters in lateral extent, both of which were underappreciated in conventional two-dimensional data from the same area. We have imaged active offscraping at the trench and both duplexing and out-of-sequence faulting a few kilometers arcward of the trench. Fault spacing and reflector geometry vary dramatically over a space of several hundred meters. Some of these variations are related to visible changes in morphology of the underlying oceanic basement, but others are not so easily documented. Fault surface reflections define an architecture which may control gross fluid motion through the prism. This architecture is apparently formed by duplexing and out-of-sequence faulting and has been maintained by periodic motion on some of the out-of-sequence faults. The slope sediment apron records multiple phases of deformation. Abundant small offset reverse faults break the seafloor and indicate recent shortening of a broad region of the underlying prism. A primary result of this survey is appreciation of the structural diversity across a small width of an accretionary prism.

INTRODUCTION

Investigations of the internal structure of modern accretionary margins rely on the combination of drilling and seismic reflection profiles. The relationship between the observed structures within cores and seismic images remains poorly understood but is thought to be a function of scale. Brown et al. [1990] have demonstrated this problem off Barbados, where the results of five drill sites and a seismic cross section over a 7-km-wide transect of the margin produces two different possible line-balanced cross sections. This difference is thought to result largely from lack of significant constraints by the seismic data. Another possibility is that the diversity of structures possible within this tectonic environment has not been fully appreciated. This uncertainty might reflect our inability to drill enough holes or to seismically image the structures properly. Structural studies of modern convergent margins present a challenging problem. Great water depths and hole instability make deep sampling a difficult technical problem, while the rapidly varying velocity fields and possible three dimensionality of structures degrade conventional seismic reflection imaging [Coltrin et al., 1989]. Even so, investigations of the structural framework and tectonic processes at modern convergent margins have improved steadily. We will present here results from the first three-dimensional (3-D) seismic survey of an active accretionary margin that overcomes some of the imaging problems. This data set covers a 8.5 km wide x 21.6 km long x 4 km thick volume of the accretionary prism just arcward of the Middle America Trench off Costa Rica.

Many models of convergent margin tectonic processes have been developed from studies of rocks now exposed in ancient deformed belts [Boyer and Elliott, 1982; Suppe, 1983]. These models have been applied to modern margin settings and used to guide interpretation of seismic cross sections. For example, Cowan [1985] related North American Cordillera melange types to specific positions within a model convergent margin, while Byrne [1986] and Sample and Moore [1987] used a model of convergent margin structure to explain deformation styles on Kodiak, Alaska. These comparisons are possible because of geochemical and structural features recorded in the rocks. However, the internal anatomy of a modern accretionary prism is poorly known. The general knowledge of the internal structure comes from a variety of seismic reflection studies across numerous active margins. Some exceptionally spectacular seismic reflection images include Nankai [Aoki et al., 1982; Moore et al., 1990], Aleutians [McCarthy and Scholl, 1985; Ryan and Scholl, 1989], Peru [von Huene et al., 1985a], and Barbados [Westbrook and Smith, 1983; Westbrook et al., 1988]. Even these, however, show few details more than 10 km arcward of the trench axis.
The purposes of our program were (1) to determine the degree to which 3-D acquisition and processing techniques improve imaging within the accretionary margins, and (2) to examine the internal anatomy of one such margin to investigate the basic tectonic processes associated with its growth. The first objective has been examined by Stoffa et al. [1991]. We chose to study this margin because of conflicting structural interpretations derived from conventional seismic data which poorly imaged the internal structure of the prism. For example this part of the Middle America Trench is about 500 km southwest of the area off Guatemala where Deep Sea Drilling Project (DSDP) drilling has shown the slope to be composed of Cretaceous ophiolite and little net accretion of sedimentary material since the Cretaceous [Aubouin et al., 1982]. This combined with evidence of a similar ophiolite complex onshore the Nicoya Peninsula has led to speculation that the offshore slope of Costa Rica is similar [Bourgois et al., 1984].

Even so, most data suggest that the margin is a sedimentary body and that there is at least some modern offscraping [Crowe and Buffer, 1983; Shipley and Moore, 1986]. Cross sections of previously acquired data have been used to suggest that the deformed wedge of sediments may predate the unusually thick, relatively undeformed sedimentary apron suggesting the possibility of a nonaccreting margin [Crowe and Buffer, 1983]. On the other hand, Silver et al. [1985] interpreted the structure here as growing thrust duplexes with the slope section partially isolated by roof thrusts. Data collected previously off the Costa Rican margin included sparse multichannel seismic work of 1976-1978 vintage [Crowe and Buffer, 1983], high-resolution water gun reflection, and Sea Beam coverage in 1982 [Shipley and Moore, 1986], limited deep tow seismics in 1986 [Moore and Shipley, 1988], and a single DSDP site (565) that reached 328 m subbottom [von Huene et al., 1985b]. In addition, there has been continuing work on the geology of exposed upper Jurassic to lower Cretaceous marine sediments and oceanic crustal rocks onshore the Nicoya Peninsula and elsewhere along the margin [Bourgois et al., 1984; Lundberg, 1982; Baumgartner et al., 1984; Corrigan et al., 1990]. Another primary reason for choosing Costa Rica is that it is one of the few locations where the entire margin is within line-of-sight radio range of the shoreline, crucial for the high precision navigation required for the field experiment (Figure 1).

In this paper we briefly review the Costa Rica continental margin geology, including results from regional two-dimensional (2-D) seismic reflection data. Following the review, the results of the 3-D survey are described with sections devoted to the external prism structure, surface reflection amplitudes, and internal prism structure. In the discussion we present two variants of a model showing lower slope growth processes.

**COSTA RICA CONTINENTAL MARGIN GEOLOGY: TWO-DIMENSIONAL SEISMIC DATA**

The top of the downgoing slab was observed from the trench axis to the shelf edge on 24-fold multichannel seismic lines across the Costa Rica margin [Crowe and Buffer, 1983] and in recent higher-resolution 48-fold data (Figure 2). The age of oceanic crust being subducted is late Oligocene [Kligord and Mammerickx, 1982] and the convergence rate is about 8.7 cm/yr [DeMets et al., 1990]. The Cocos plate stratigraphy consists of about 250 m of oceanic pelagic carbonates overlain with about 175 m of more terrigenous hemipelagic material deposited as the plate deepened with age and approached the continental sediment sources [Shipley and Moore, 1986]. Normal faulting is evident seaward of the trench axis (at -2, -4, -6, -9 km in Figure 2). Because the trench axis deepens to the northwest and the absence of significant westward drainage systems in Nicoya Peninsula, the trench axis is nearly devoid of turbidites. Reflection profiles show that all of the oceanic pelagic sediments are subducted beneath the lower slope, while some of the hemipelagic section is scraped off above a well-defined decollement (between 0 and 5 km). Most of the hemipelagic section continues to dewater as it is subducted beneath the slope several kilometers to about where the 3-D survey starts [Shipley et al., 1990]. The shallow zone of offscraping appears to be responsible, in part, for the nearly reflection-free sediment wedge at the base of the slope (0 km to 4 km in Figure 2).

The small amount of offscraping and the frontal accretion suggest that much of the growth of the prism must be by underplating. An important zone of this underplating occurs between 10 and 25 km associated with a drop in the decollement and an increase in prism thickness (line 1, Figure 2). From 25 km to beneath the shelf edge at 55 km, a zone of reflections 500 to 1000 m thick with variable amplitude and continuity is well developed just above the downgoing slab. Some of these reflections lie subparallel to the basement, then ramp upward at 20 to 30 km from the trench. The upper extent of these ramps are often associated with small offsets at the top of the prism. The top of the prism produces a distinctive high-amplitude reflection surface which has been highly disrupted and offset by numerous faulting episodes (labeled rough surface).

The overlying slope sediment apron contains low-amplitude reflections that become less coherent and less continuous toward the trench. Several unconformities and a general trenchward downlapping reflection configuration are obvious. Normal faults are distinctly imaged near the arcward end of the profile between 30 and 45 km, with fault offset greatest and most prevalent in the middle and lower portions of the slope apron stratigraphy. The DSDP site 565 penetrated 328 m of terrigenous muds bottoming in lowest Pliocene sediments (planktonic foraminiferal zone N18 [Stone and Keller, 1985]) over 300 m above the top of the prism (Figure 2). Baltuck et al. [1985] demonstrated from the structural fabric of the cores that the slope is unstable and subject to significant creep and slope failure, particularly in the uppermost 40-50 m.

Thus the 2-D data define the downgoing slab, a thick wedge with few coherent internal reflections, a rough contact between an unusually thick seaward prograding sedimentary slope section and the underlying wedge, and small amounts of frontal accretion. One of the most unusual features revealed in the new 2-D data set is a well-defined series of reflections in the arcward third of the sections which define a ~1000 m-zone above the downgoing slab. We have no definitive explanation for these reflections, but the possibilities range from basement duplex to a subduction channel [i.e., Cloos and Shreve, 1988].

**RESULTS OF THE 3-D SEISMIC STUDY**

We chose the 3-D coverage to include the zone of initial underplating and extended it 22.6 km arcward. We located the grid so that we would image a pair of bathymetric reentrants between 3200 m and 3000 m which might indicate structure at depth. We also positioned the grid to take advantage of DSDP site 565 which sampled part of the slope sediment apron. Some conventions in line numbering will be useful for later reference to the figures. First, the basic 3-D portion of the survey...
Fig. 1. Map shows bathymetry offshore of the Nicoya Peninsula of Costa Rica. The bathymetry is a compilation of the University of Texas and Scripps Institution of Oceanography data. Inset shows plate tectonic setting. Ten long dip lines are 48-fold seismic profiles. Stippled area is 8.5 x 21.6 km 3-D grid consisting of 88 lines 100 m apart forming the 3-D volume. DSDP site 565 shown by dot.

The bathymetry offshore of the Nicoya Peninsula of Costa Rica consisted of 88 parallel lines shot 100 m apart normal to the trench trend and 23 km long. Processing resulted in 170 lines, 50 m apart, for a width of 8.450 km. Each line consists of 650 traces, each 33.33 m apart, for a line length of 21.631 km. The line numbering convention (from 41 to 210) and trace numbers (150 to 799) are shown in Figure 3. Eleven additional dip lines extend out onto the Cocos plate and pass through the grid to the upper slope and shelf off Costa Rica and are referred to as swath lines. Finally, for convenience we will describe the position of some features relative to the distance from the trench axis (y axis) and parallel to the trench (x axis). The seismic sections will be labeled as such. The grid covers the area between 3 km (y) and 24.6 km (y) arcward of the trench. Stoffa et al. [1991] have presented a detailed description of the field program and processing procedures.

Derivation of reflection geometry from seismic traveltime data implies knowledge of a velocity field. All illustrations are shown with the vertical dimension of depth (or thickness) so that the geometry will be correctly represented. The velocity structure used in the direct depth migration of the 3-D grid is a simplified model based on both conventional velocity analyses within the slope apron and starting estimates for the prism and are consistent with the limited data available from DSDP site 565. Extensive 2- and 3-D migration trials were used to develop a reasonable estimate of the velocity structure within the prism. That velocity structure remains an estimate, however, because of the relative insensitivity of poststack migration velocities.

We developed a smooth velocity model for the margin which varies only with position normal to the margin. The seafloor, the top of prism and the top of basement were used to define two variable-travel time layers throughout the 3-D volume (Figure 4). A smooth velocity model is used so local variations in geometry will not be caused by localized velocity effects of the direct depth migration. Reasonable velocity gradients (estimated from Hamilton [1980]) decreased discontinuities in the vertical velocity field at the slope/prism boundary and the seafloor/slope apron boundary to help reduce migration artifacts. The basement velocity was kept unrealistically low to reduce migration artifacts within the overlying prism, the primary focus of this work. The resulting mean interval velocity of the slope apron varies from 1600 to 1700 m/s across
Fig. 2. Top is migrated, depth-converted, 48-fold multichannel seismic profile, swash line 1. Bottom is line drawing interpretation of swash line 1 but with the interpretation based on the 3-D survey where they overlap. DSDP site 565 is projected onto this line from about 300 m northeast where the slope apron is thinner than at the actual drill site. Vertical exaggeration is about 2X.
the grid. The mean interval velocity of the prism varies from 1650 to 3220 m/s. The seafloor dip is about 4° and the slab dip is about 3° with this velocity model within the 3-D survey area. The data volume was directly migrated to depth in a one-pass migration of the complete data set [Stoffa et al., 1991].

**EXTERNAL STRUCTURE**

**Oceanic Basement Surface**

The basement is difficult to define precisely arcward of 15 km (y) because of the lower signal levels and narrower bandwidth, but its general shape is identified to an uncertainty of one seismic wavelength (about 10 m at 3 km (y) to 150 m at 25 km (y)) (Figure 5). A well-defined graben structure with ~150 m of relief is parallel to both the plate fabric and the trench at 7 km (y). Just arcward of the graben is a horst block with similar trend and relief (at 8 km (y) between 6.5 and 8.5 km (x)). An unusual depression occurs between 7 and 12 km (y) at 0 and 2 km (x). This depression is about 250 m below the regional basement depth. The basement surface steepens abruptly arcward between 13 and 15 km (y) and again at about 45 km (y) (see also Figure 2), giving the downgoing slab an overall convex curvature. The dip increases from about 3° within the first 20 km of the trench, then to approximately 7°, and finally to more than 14° between 45 and 55 km (y). We are confident that the relatively abrupt dip changes portray the actual structure of the downgoing slab because the velocity field used for depth conversion (and migration) varies smoothly across these slope breaks.

**Base of Slope Apron/Top of Prism**

This top surface of the prism is the most complicated and roughest in the survey area (Figure 5). A high-amplitude reflection forms the boundary between the slope apron and underlying accretionary prism (Plate 1). We define the slope apron as a largely depositional sedimentary unit and the accretionary prism as a body formed primarily by tectonic addition of sediments. The greatly improved images of the surface, produced by the 3-D acquisition and processing techniques, show that it is composed of folded and multiply faulted thrust sheets that impart the observed rough texture (see Plate 2c and Figure 6). However, due to discontinuous and overlapping nature of the reflection, detailed correlation of the rough surface between lines only 50 m apart is still difficult and places limits our ability to map it precisely.

We have relied on a combination of continuity and amplitude to define this surface to produce the contoured structure map included in Figure 5. The rough surface is highly irregular, with relief of 150 m or more at wavelengths of a kilometer or less. The general structure is that of a trench parallel low, spanning the width of the survey between 4 km and 8 km (y), then a west plunging high in the middle third of the grid, and irregular trends in the arcward third. The depression in the surface at 5 km (y), 1 km (x) is offset from the low in the underlying basement, and there is no evidence for this depression in the seafloor.

**Seafloor Surface**

A seafloor surface contour map derived from the 3-D grid data is also shown in Figure 5. Stoffa et al. [1991] reported that these data define the seafloor with comparable detail to an existing 20-m contour map produced by Sea Beam which indicates that the navigation and basic processing of the seismic data set is correct (Figure 7). The general trend of contours is not parallel to the trench except at the trenchward end of the grid. The slope of the seafloor is significantly gentler between the 2900-m and 3200-m contour. This zone
seems to represent a modern depocenter and bench in the slope since many small channels in the upper slope terminate here and the slope cover is about 150 m thicker (Figure 5, slope isopach). Five seafloor mounds form mud volcanoes or linear mud fissures (Figure 7).

Isopach Maps

Isopachs for the two main units, the slope apron and prism, are also shown in Figure 5. The prism thickens arcward, varying from about 400 m to 2800 m. The thinnest section is at about 5 km (y), 1 km (x) in a persistent low, offset from the basement depression. The slope apron is thick above the thin section in the underlying prism. Conversely, a thin slope sediment apron, <600 m, corresponds to the west plunging high in the prism surface near 15 km (y). Thus the slope apron subdues much of the relief of the underlying prism structure, suggesting that apron distribution is mostly related to sedimentary processes.

Surface Reflection Amplitudes

Values of relative true amplitude (but without any corrections for spreading loss or earth propagation effects) are displayed in Plate 1 for the seafloor, prism, and basement reflection surfaces. The reflectivity of the surfaces, at the seismic frequencies, is not sensitive to small-scale surface roughness and backscatter but only to surface slope. Assuming a constant reflection coefficient, the more horizontal a reflecting interface, the more energy is reflected at normal incidence.

Basement surface amplitude. The basement amplitudes, in the southwest corner of the map in Plate 1, are anomalously high. Since the basement structure is fairly uniform in the trenchward portion of the area, the anomalous amplitudes are not likely an effect of basement geometry nor of variations in seismic propagation, because the overlying structures are simple. One explanation for the anomalous amplitudes is that the reflection is not simply the contact between sediment and volcanic rocks but is some approximation, including sediments which smooth basement irregularities. Thus the more continuous reflection identified as basement really may be produced in sedimentary rocks just above basement which smooths the interface. The high reflectivity in the southwest corner of the surveyed area, then, may be related to changes in the sediment depositional pattern just above basement and/or related to localized diagenesis in one broad, nearly flat-floored graben.

Prism surface amplitude. The top of the prism surface exhibits highly variable reflection amplitude. On seismic cross sections it often appears nearly as strong as the seafloor reflection (Plate 2b, line 60 true amplitude). Its polarity is usually positive, except in isolated bright spots associated with structural closure or in isolated sections near the trench. These bright spots may be related to areas where fluids may migrate along the boundary.

The generally high amplitude associated with the interpreted contact between the slope apron and the prism is predictable. A simple estimate of the reflectivity of the surface from the amplitude map indicates that the prism reflectivity is about 0.4 to 1.7 times that of the observed seafloor reflectivity. Estimates of near-seafloor velocity and density, from DSDP site 565, allow us to determine that the reflection coefficient
for the seafloor is about 0.16 [von Huene et al., 1985b]. Thus the reflection coefficient for the prism top is 0.06 to 0.27 (0.4 x 0.16 to 1.7 x 0.16), making no corrections for spherical divergence or other propagation effects which would tend to increase this ratio somewhat (possibly 20%). Using the migration velocity model (Figure 4) and density estimates from Hamilton [1980], the calculated reflection coefficients along this surface are from 0.07 to 0.28, essentially the same as the observed. Thus the velocity contrast is responsible for much of the observed reflection strength, and the velocity increase may result from the contrast in deformation history and age differences across the boundary, even though the boundary is faulted.

In map view, four bands of higher amplitudes trend WNW, and
Plate 1. Reflection amplitude maps of the seafloor, top of prism, and basement surfaces. These amplitudes are true values in the sense that all instrument gain has been removed and no corrections for spherical spreading loss have been applied. Blue colors represent low amplitudes, and red colors represent higher values. The explanation of the patterns is given in the text. The north-northwest trend in the seafloor map results from small offset reverse faults cutting the seafloor. These faults producing near-vertical scarp which do not reflect energy and thus are blue bands on this figure (see Figure 7) (mv, mud volcano; ha, high-amplitude band; fs, fault scarp).
Plate 2a. These color amplitude sections illustrate various features of the slope sediment apron and its diversity. Line 41 shows offset of the seafloor and its relationship to the top of the prism. Line 195 shows the transition between the slope sediments on the right and the offscraped section on the left. It is difficult to readily distinguish between the slope apron and the offscraped section. Note the structural fabric already developed in the otherwise nearly reflection-free offscraped section (see interpretation in Figure 6). The colors represent amplitude: red, high positive; white, zero; black, high negative. This same color scheme is used elsewhere in this paper.
Plate 2b. Line 60 illustrates one of the more continuous boundaries between the slope sediment apron and the prism and its well-defined offsets. At the same time, some shallow high-amplitude anomalies are present which may be related to the mud volcano.
Plate 2c. Line 165 shows arcward dipping structure in the slope apron, as opposed to the more normally observed seaward prograding relationship. We have not been able to decide if these represent primary bedding or deformation fabric. Line 120 illustrates an incipient mud diapir and well defined faults (see Figure 6).

A v-shaped zone occurs at 6 km (y), 5 to 9 km (x). These bands appear to be related to the intersection of intra-prism reflections and the top of the prism, with subcrop patterns shown in the bands or v-shaped patterns of high amplitude. This interpretation suggests some reflectivity enhancements associated with intra-prism reflections perhaps by fluid migration and mineralization. In addition to the bands, there are many isolated bright spots. Figure 8 is a relative true amplitude display,
showing a reversed polarity, high amplitude reflection (bright spot; note that seafloor reflection is a negative followed by a positive). The extent of these individual bright spots does not exceed 600 m$^2$. The wide negative lobe of the wavelet below the bright positive part of the wavelet must result from the negative impedance boundary very close to the positive impedance boundary, indicating a thin zone, probably containing gas.

**Seafloor surface amplitudes.** The seafloor amplitude map portrays a series of patterns related to both tectonic and sedimentation processes. The sedimentation patterns are represented by the low reflectivity from the sides of the channels in the arcward third of the survey. The blue bands in the amplitude map, like the channels in the seafloor bathymetry, trend toward (x) and define erosional channels. Three of the mud volcanoes are reverse faults). Their lesser prominence in the north-eastern third of the survey may be related to the rate of sediment accumulation on the slope which overwhelms many of the recent small offsets. The seafloor amplitude map provides a good method of correlation of major scarps into the subsurface.

**Internal Structure**

**Decollement and Underthrust Structure**

The underthrust section is visible beneath the decollement to about 8 km (y) where basement horst and graben structures and the overlying rough surface significantly reduce our correlation ability (see line 195, Plate 2a and Figure 6). Ramps in the decollement commonly occur at 3 to 5 km (y), resulting in partial underplating of the underthrust hemipelagic section. Beyond about 6 km (y) the decollement is not well imaged and loses its relatively high reflectivity. This loss may be related to the origin of the reflectivity of the decollement. Synthetic seismogram modeling of the decollement reflection in the first 6 km indicates that the initially reversed polarity may be caused by the contrast between the underthrust, water-rich sediment and the overlying more deformed, offscraped material [Shipley et al., 1990], and not necessarily to fluid flow along the contact as has been demonstrated off Barbados [Bangs and Westbrook, 1991]. By 6 km (y), the underthrust section has undergone additional dewatering, and the underthrust oceanic carbonate section is likely to obtain much higher velocities from cementation. The impedance contrast would therefore be reduced, resulting in low reflection amplitude and no polarity reversal [Shipley et al., 1990].

The details of the decollement structure and fate of the underthrust section are surprisingly diverse across the 8.5 km width of the 3-D grid. To illustrate this diversity, portions of five lines across the lower slope are included in Plate 3 with line drawing interpretations in Figure 9. Line 210 shows an abnormally thick zone of material between the rough surface and the decollement as well as a thin section between the rough surface and the seafloor. The pelagic section and much of the hemipelagic section are thrust beneath the thick zone (on the downthrown side of the normal fault), suggesting that the thickening of the prism is accomplished not only by local underplating in the lower half of the thickened zone but also by deforming previously accreted material with out-of-sequence thrusting. Line 185 shows underplating in progress and the development of a steeply dipping fabric. Lines 185 and 210 also show that the basement structure significantly influences the trajectory and stratigraphic position of the decollement, thus affecting the mode of deformation and the resulting prism structures. Note the widespread incipient thrusting on the upthrown fault block at 3-6 km (y).

Line 121 is interpreted to have a throughgoing decollement in the upper hemipelagic section. However, dipping and discontinuous reflections below the decollement reveal internal deformation probably as a precursor to underplating. On line 102 the decollement appears to stay at a consistent stratigraphic level, at least until it approaches the basement horst block at 6 km (y), with little evidence for deformation below the decollement. The structureless decollement may contribute to the consistent seafloor dip along this section, with wedge taper maintained by numerous out-of-sequence thrusts. Line 56 exhibits active underplating with steps in the decollement at 4.5 km (y) and 8 km (y) and incipient thrusting below the decollement. The relatively high-amplitude reflection at the

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Fig. 6. These are line drawing interpretations of portions of lines 120 and 195 illustrated in Plate 2c. In line 195, note the broken nature of the sedimentary horizon just above the basal decollement (dotted horizon). It is broken by a series of fault splays off of the decollement.
SEAFLOOR FEATURES

3D REFLECTION

Fig. 7. On the right is 20-m contoured bathymetry derived from digitizing the seafloor reflection throughout the final 3-D depth-migrated grid; it compares well with the more poorly navigated Sea Beam data collected in 1982. On the left is an interpretation of the features of the seafloor amplitude map shown in Plate 1. The amplitude map defines the steep slopes of the seafloor related to channels, flanks of mud volcanoes, and faults. The lateral extent of these small offset reverse faults was not appreciated until the color amplitude map was displayed.

Prism Structure

The most mappable structures within the prism are a series of reflections which extend over 50 to 90% of the 3-D area. However, correlation of the surfaces is possible only by using a combination of the vertical (strike and dip) and horizontal
sections. In detail, the reflections may be discontinuous on any one vertical section but often have great continuity (up to 8.5 km) in horizontal and strike-parallel sections (arrows in Plates 4 and 5). These reflections have low dips and extend from the vicinity of the downgoing slab (near 20 km) upward to 5 km) in horizontal and strike-parallel sections (arrows in Plates 4 and 5). These reflections have low dips and extend from the vicinity of the downgoing slab (near 20 km) upward to the base of the slope apron (5 to 15 km, Figure 2). Individual reflections define generally arcward dipping surfaces but with considerable undulations. The surfaces have much greater extent than any known unfaulted stratigraphic horizons, leading to the very important conclusion that they represent fault zone reflections. That is stratigraphic units on the oceanic plate and trench are broken by normal faults every 1 to 5 km. The reflection amplitudes along these zones vary considerably because this surface is broken from multiple deformation events. This section is located near the mud volcano at 14 km (y) and 7 km (x).

Fig. 8. Example of a nearly flat spot at the contact between the prism and slope sediment apron. This bright spot is on a very small closure at the prism top. These type of features suggest that fluids are trapped at the boundary given the appropriate structural trap. These amplitude anomalies are fairly rare, because this surface is broken from multiple deformation events. This section is located near the mud volcano at 14 km (y) and 7 km (x).

Slope Apron Structure

The slope apron is a remarkably thick sequence of terrigenous muds, the upper 328 m of which were sampled at DSDP site 565. Plate 2 and Figure 6 show the slope apron and the relatively low amplitude and discontinuous nature of the reflections. Although revealing considerable slope deformation, the reflections tend to be oriented subparallel to the seafloor, with at least two prominent unconformities in the arcward half of the grid. The slope apron pinches out downslope as expected for a sedimentary cover younging toward the trench but more abruptly than expected for a continuous process of frontal accretion (Figure 2). Correlation to site 565 is difficult because of the discontinuous nature of the reflections. One implication of the correlation shown in Figure 2 is that much of the slope apron (one third to two thirds) is early Pliocene (the age at total depth of site 565) or younger. It is also apparent that, using the mean sedimentation rate of 60 m/m.y. calculated for site 565, the extrapolated age at the top of the rough surface could be as old as 10 m.y. We observe slope parallelism and downslope pinch-out of apron reflectors, but there are exceptions. In the trenchward half of the survey, the slope apron is generally slope parallel and does not strongly prograde over the rough surface. Also, arcward dipping apron reflections that intersect the rough surface are found in a several areas (e.g., line 165, Plate 2c).

There is ample evidence for fluid migration and small fluid traps within this margin. Most prominent are a series of mud volcanoes observed at the seafloor. These appear to be associated with local structural closure on the top of the prism and the through-going thrust surfaces identified within the prism (line 120, Plate 2c and Figure 6). The two largest volcanoes at about 3100 m depth are elongated in a westerly direction (Figure 7), perhaps indicative of their relationship to structure at depth. The top of the prism in some places exhibits amplitude anomalies, reflection polarity reversals and flat spots all indicative of a fluid contact (Plates 1 and 2). Clearly, the slope apron acts as a partial barrier to fluid flow from the underlying formations. These observations do not, of course, allow any direct estimate of the state of pore pressures.

All these observations are made in a slope apron of very low reflectivity which also contains perhaps three other structural overprints. One common overprinting consists of arcward dipping structures associated with faults that pass from the prism into the overlying apron, either thickening the apron and/or offsetting the seafloor (e.g., line 120, Plate 2c and Figure 6). Some of these appear to be related to the larger intraprism reflections, others to smaller-scale adjustments of the rough surface. Another overprint are numerous high-angle, arcward dipping reverse faults which further disrupt the slope apron stratigraphy. Where these faults offset the seafloor, they create near-vertical surfaces which, as expected, do not produce reflections. The result is that the traces of the faults are evident in amplitude maps of the seafloor (Plate 2 and Figure 7). Their presence indicates pervasive, recent offset of the seafloor along a series of subparallel reverse faults. In contrast, as illustrated in Figure 2, the slope apron upslope from the 3-D grid exhibits a third overprint, a series of high-angle normal faults. With this complex structural evolution disrupting much of the original slope apron stratigraphy, it is challenging to separate structural and sedimentation reflection geometries. Analysis of the slope apron structures is a topic of a separate paper (K.D. McIntosh et al., manuscript in preparation, 1992).
Plate 3. These five sections illustrate the structural diversity in the lower slope. The lines names and their x positions are annotated. The y position is from the edge of the survey at 3 km (y) to 9.5 km (y). See interpretation for these lines in Figure 9. RS, rough surface; BS, basement; and the arrows on line 56 point to high-amplitude reflections at the top of the underplated section, similar to the rough surface. Vertical exaggeration is 2X.
DISCUSSION

The stated purpose of this project is to test the effectiveness of using 3-D seismic reflection techniques to improve imaging of an accretionary prism and to use those improved images to examine the internal anatomy of the prism and to discover the basic processes that shape the prism. While the 3-D acquisition and processing techniques have produced a superior representation of the prism structure off Costa Rica, as shown in Plate 3, the improved images and dense control reveal a diversity of structures that resists a simple, regionally applicable explanation of the active prism processes. Due to this structural complexity, external constraints are necessary to complement the observational evidence provided by the seismic data. Two constraints we have are a good estimate of the incoming sediment supply (87 km/m.y. and 425 m thick = \(37 \text{ km}^3/\text{m.y. per km of trench}\)) and a minimum age of the prism of about 5.3 Ma at 14.5 km (y) [Stone and Keller, 1985]. A simple volume balance shows that the material seaward of site 565 could be accumulated in less than 1 m.y. if the entire incoming sedimentary section is accreted. This raises the possibility of non-steady state growth processes along the Costa Rica margin. However, if an average of 20 to 40% of the section is accreted in the toe and lower slope area (constrained by site 565), then we can attempt to construct a steady state model to build the prism with currently active, observed processes. This rate of accretion is possible through time given that observed offscraping varies from 0 to 90 m [Shipley and Moore, 1986] and frontal underplating from 0 to about 200 m.

Two primary variants of one model have been devised to link the observed lower slope accretion and deformation processes with the current prism structure (Figure 11). The main difference in the two variants is related to the evolution of the offscraped section. These two variants are discussed because of a critical uncertainty in whether or not the identified slope apron contains a lower sequence of offscraped material that overlies the rough surface and underlies the true slope sediments. Common to both variants are offscraping (with refaulting and thickening variant 1 or uplifted without more thickening variant 2), underplating by duplexing and out-of-sequence
faulting, and some sediment subduction. The preferred variant 1 shows that material is offscraped at the trench and subsequently refaulted to maintain critical wedge taper. These two early phases of deformation may allow efficient dewatering and consolidation of the offscraped sediments. Subsequently, the top of this section forms the high-amplitude, rough surface as it is overlain by low-velocity slope sediments. Much of the initially underthrust part of the hemipelagic section is accreted through duplexing and out-of-sequence thrusting, processes that thicken the prism and produce long, continuous intraprism reflectors. The pelagic section, however, bypasses the lower slope as required by the age/volume constraint imposed by site 565. Our alternative, variant 2, shows that the offscraped material is uplifted during underplating and the top of underplated sediments marks the rough surface. Thus the overlying section, referred to as the slope apron, is composed of both offscraped material and slope sediments. As in variant 1, the internal structure of the prism is developed by additional underplating and out-of-sequence thrusting.

Variant 1 is preferred for several reasons. The relatively high-reflection amplitude of the rough surface can be explained by the expected velocity contrast between relatively undeformed slope sediments and the multiply deformed, offscraped sediments below. Such a juxtaposition can be expected to occur through time unless offscraping and sedimentation rates change significantly. This is important because the rough surface appears to be present from nearly the prism toe to the shelf edge and, although not well constrained, likely formed during a span of tens of millions of years. Out-of-sequence thrusting also appears to persist through time and probably can explain the deformation and unexpected thickness of the lower slope apron.

Variant 2 was conceived primarily on the basis of a series of lines such as line 56 (Plate 3 and Figure 9) that show a high-amplitude reflection at the top of a set of underplated thrust sheets, similar in amplitude, continuity, and shape to the rough surface reflection. Variant 2 explains both the unexpected thickness and amount of deformation above the rough surface because the section is composed of slope sediments and offscraped material. One disadvantage of model 2 is a difficulty in explaining the impedance contrast between offscraped and underplated material sufficient to produce the rough surface reflection; both units are derived from the hemipelagic section and experience deformation during accretion. This pattern of accretion is only likely to produce the required impedance contrast if the lower hemipelagic section is significantly more
dewatered than the upper section, at the time of accretion. We also question whether this process has been maintained through time to produce the rough surface that extends nearly to the shelf edge. Given possible changes in sediment supply and associated accretionary processes, model 1 is more likely to produce a consistent prism structure. A problem with proving the validity of either model is that the rough surface generally dies out at about 6 km (y) (Plate 3), so that the link with offscraping or underplating is not obvious.

Structural Diversity

Clearly, we are impressed by the diversity of structures along our 8.5 km wide study area and our ability to image them with the 3-D seismic method. However, consideration of prism response to basement structure suggests that the diversity may be strongly tied to irregular basement morphology. For example, if the incoming section were uniform in thickness and composition and the underlying oceanic basement were a smooth, structureless surface, then we could reasonably expect consistent prism structure and taper along the accreting margin. Allowing basement structure (i.e., normal faults) parallel to the margin, we can expect changes in prism taper and internal structure, but these should remain nearly uniform along strike. However, if basement structures are not parallel to the accreting margin and the relief is of sufficient magnitude, then significant structural variation along strike is required; prism taper and internal structure are strongly affected by large fault offsets but are unaffected in areas of smooth basement. Cocos plate normal faults have variable offset with up to 300 m of basement relief along trends that range from nearly parallel to highly oblique to the trench. Consequently, the prism structures most likely reflect adjustments to prism taper, especially by underplating and out-of-sequence thrusts, in response to irregular basement structure. In many cases this relationship can be directly observed with deformation in progress (Plate 3 and Figure 9), while in other cases the structures are probably remnants of previous basement interaction.
Plate 5. Another pair of vertical and horizontal sections. Illustration of some particularly well developed intraprim reflections (arrows) and their continuity in the horizontal dimension across the entire width of the survey.

Fig. 10. Line drawing interpretation of the center line of the grid. Illustration of the complexity of structure and the multiple stages of deformation. In this section the decollement remains higher than in some other places. Only a subset of the fault surfaces are highlighted in this interpretation. Some of the out-of-sequence faults splay upward to the base of slope sediment apron; others pass through the slope apron and even offset the seafloor.
Regional Applicability of 3-D Data and Interpretation

The structural interpretation of the 3-D data and the volume balance indicate the general processes and rate at which the lower slope portion of the accretionary prism may have been constructed. Because this accounts for only the last 6 to 10 m.y., it is important to consider what implications these data have for the growth and structure of the rest of the prism. As shown in Figure 2 and mentioned above, the rough surface extends from near the toe of the prism to the shelf edge. Its occurrence near the toe appears to be related to the accretionary process, either offscraping or underplating, so its landward extent argues for similar accretion processes for much of the prism's growth history. Although the system of relatively continuous, high-amplitude intraprism reflections identified in the 3-D grid are largely absent in the landward portion of the prism (Figure 2), this effect may be explained by several causes that do not require different growth processes. In particular, these reflections appear to be truncated and disrupted by steeper out-of-sequence faults starting near the landward edge of the 3-D grid. In addition, the 2-D data generally only resolved reflection fragments, only in the 3-D data did it become apparent that they represented laterally extensive surfaces. Consequently, we find little evidence to indicate that the rest of the prism formed in a fundamentally different manner that that presently observed.

Conclusions

Sediments are actively accreted to the prism at the trench by offscraping the upper portion of the hemipelagic section. Just a few kilometers arcward of the trench, prism growth and thickening are accomplished by a combination of both duplex and out-of-sequence thrusting. The observed rates of accretion are consistent with steady state growth of the lower slope portion of the prism for the last 5 to 10 m.y. as constrained by DSDP site 565. Duplex and out-of-sequence thrusting are occurring at only a few kilometers beneath the seafloor, very early in the deformation history. Thus adjustments to maintain critical taper begin very early in the accretion processes, must be fairly continuous, and may help explain the complexity of structure in the very young accreted section and overlying slope apron. Clear relationships frequently exist between basement with respect to fault spacing, length and shape. In other cases the overlying structure has no apparent relationship to basement morphology. However the high convergence rate and frequent basement structures suggests a similar, if not directly identifiable, cause for the overlying structures.

At the largest scale, intraprism fault zone reflections have greater extent than any known, unfauluted, stratigraphic horizons. These structural features were not previously recognized to be spatially significant surfaces on individual lines in this area. We believe that these are evidence for a fairly well-defined structural architecture that potentially controls prism-wide fluid flow pathways and influences continuing prism deformation. The amplitude of the fault reflections are fairly high and become highest where they intersect the top of the prism, suggesting that they have at times influenced fluid motion and mineralization. Where these surfaces splay upwards near the base of slope the reflections become particularly bright and reversed in polarity. In addition, bright spots in local closures at the top of the prism indicate that upward fluid movement is impeded given the right structural trap. The fault surfaces mainly result from the nature of the thickening at or near the bottom of the prism, accompanied with later continued (episodic?) motion on out-of-sequence faults, which help maintain the fault reflection continuity over time.

The boundary between the mainly slope sediments and underlying prism is the most prominent feature in the seismic data, for both its consistently high amplitude and broken and discontinuous nature. The amplitudes are largely the result of the low-velocity slope sediments (about 1700 m/s) overlying higher-velocity accreted and more deformed sediments (1800-2400 m/s) but enhanced in places by fluid accumulations at the boundary. Numerous faults break the surface into small segments, most much less than 1 km² in map view. The faulting which disrupted this surface extends into the overlying slope sediment apron which records these multiple deformation phases and complexly juxtaposes the primarily accreted rocks and slope apron rocks. In addition, the numerous faults with scarp delineated on the amplitude map of the seafloor further disrupt the slope structures. These high-angle, small offset faults are important because they define recent active shortening of a broad region of the underlying prism. This implies a fairly weak rheology but broad coupling of the stress into the overriding plate.

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