Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos Plate, and Central American volcanism

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Abstract. Along Costa Rica, new geophysical data indicate considerable control of Quaternary convergent margin tectonics by the subducting lower plate. Three types of ocean crust enter the subduction zone: (1) Cocos Ridge with its underlying thick crust stands 2 km high, (2) on its north flank is normal crust covered 40% by seamounts, and (3) along the adjacent Nicoya margin the subthrust crust has a smooth sea floor. A 3- to 10-km-wide base of slope frontal prism varies little opposite different subducting crusts except where subducting seamounts eroded it. Once the breaching seamount has passed the prism it is quickly restored. The effect of oceanic crust on continental margin structure is most evident in the middle and upper slope. Where Cocos Ridge and its flanking seamounts subduct, erosion is pronounced relative to the stable slope where smooth lower plate subducts. Aligned upper plate features above lower slope segment boundaries extend more than 120 km landward of the trench axis and correspond in varying degrees with volcanic arc segmentation. The offset of volcanoes across the Costa Rica/Nicaragua border corresponds with a change in crustal structure and depth of the lava source. Subducted sediment shows little correlation with the slab signal in volcanic arc lavas but the magnitude of faulting associated with ocean plate flexure adjacent to the trench axis parallels it well. Thus fluids in ocean crust fractures and bound water in serpentinite may have a recognizable geochemical effect in arc lavas.

1. Introduction

In principle, upper plate tectonism appears to be driven by the character and relief of the subduction lower plate, but to what degree? This question is difficult to answer without isolating a variable convergence rate, slab dip, and sedimentation from variable ocean crustal character. The Middle America margin off Costa Rica and that off Nicaragua converge with the Cocos Plate at equivalent rates; both have sparse trench sediment, but they vary in crustal structure and the subducting oceanic crust. This situation is optimal for studying convergent plate interaction.

The variable morphology of the Cocos Plate and Pacific convergent margin off Costa Rica (Figure 1) has been known for more than 40 years [Fisher, 1961], and the variation in arc volcanism was noted even earlier [Sapper, 1897]. A relation between land and marine variability is indicated by current data. High-resolution geophysical data show an alignment of structures that continue from the deep ocean well into the continent. Mapping with multibeam echo sounders reveals the contrasting seamount-covered Cocos Plate abutting the rugged continental slope of central Costa Rica and a smooth seafloor abutting the linear continental slope off the Nicoya Peninsula [Shipley and Moore, 1986; von Huene et al., 1995]. When swath map soundings in each sweep were edited beam by beam [Heeren, 1996, and this study], the resolution of morphology in subsequent displays surpassed that of most other surface ship data and provided a high-resolution Quaternary tectonic map (Plate 1). These data were combined with seismic reflection data [Hinz et al., 1996], wide-angle seismic data [Ye et al., 1996; Stavenhagen et al., 1998; Christeson et al., 1999], and refined regional magnetic compilations [Barckhausen et al., 1998]. They provide a regional context in which to place new insights from drilling during Ocean Drilling Program (ODP) Leg 170 [Kimura et al., 1997].

Once recognized, segments can be compared to study the effects of subducting relief on forearc structure. At the scale of swath map resolution the subducted lower plate relief is sufficient to influence upper plate tectonism, and a linear relief associated with subducted plate segment boundaries can be traced far landward. The frontal prism and volume of trench sediment indicate little change in subducted sediment volumes. Quaternary lavas of the volcanic arc along Central America have a highly varying geochemistry thought to be derived from the subducting slab. The slab signal is very high in Nicaragua and decreases to almost nothing in central Costa Rica [i.e., Carr et al., 1990]. One previous explanation for that geochemistry was a variable volume of sediment bypassing an accretionary wedge and reaching the area of lava generation [Plank and Langmuir, 1993; Leeman et al., 1994]. However, observations that accretion off Costa Rica is far less than earlier studies indicated [von Huene et al., 1995; Hinz et al., 1996; Kimura et al., 1997] encouraged us to study the extent of accretion more thoroughly. We found differences in sediment input to the subduction zone insufficient to explain a geochemical variability, so we explored other possible physical causes.
We present a compilation of morphology and seismic data to show the Quaternary tectonic structure of the margin. On the basis of this compilation, we follow segmentation of the lower plate across the upper plate along structural features that transect the slope and shelf. These segment boundaries are consistent with coastal uplift and roughly the same as some geochemical variations along the arc. The physical correlation fits no single geochemical process but should be further investigated in the context of a multicomponent system.

2. General Setting and Previous Marine Studies

Off Costa Rica and Nicaragua the Cocos Plate was formed along the east trending Cocos-Nazca spreading center (CNS) and the north-south East Pacific Rise (EPR) spreading center [Hey, 1977]. The trace of the CNS-EPR crustal weld extending to Costa Rica (Figure 1) separates a rough CNS seafloor to the south from the smoother EPR seafloor on the north (rough-smooth boundary of Hey [1977]). With more complete magnetic coverage it was discovered that near the continent a previously unrecognized wedge of older CNS crust is inserted between EPR crust and the rough-smooth boundary [Barckhausen et al., 1998] (Plate 1). The older CNS crust appears less affected by Galapagos hot spot volcanism and has a "smooth" morphology like that of EPR crust. Therefore the rough-smooth morphological proxy for CNS and EPR crusts breaks down near the continent (Figure 1 and Plate 1).

Three morphotectonic segments correspond with the CNS magnetic anomalies: (1) Cocos Ridge, (2) a seamount-covered segment adjacent to the ridge, and (3) the smooth crust off the Nicoya Peninsula (Figures 1 and 2 and Plate 1). These crustal domains flex differently into the Middle America Trench, and therefore the trench axis is as little as 1 km deep at the crest of Cocos Ridge, increases to 3.5-km depth through the seamount province, is 4 km deep opposite the smooth ocean crust, and exceeds 5-km depth off
Figure 2. Tectonic map of the study area on the swath map base gridded at 500 m. SB denotes segment boundaries, and CNS denotes Cocos-Nazca spreading center crust [Barckhausen et al., 1998]. Triple junction denotes fossil triple junction which merges with rough-smooth boundary (Plate I inset). The extent of Figure 5a is indicated by the line along the Nicoya Peninsula. Small unmapped fractures are shown in perspective diagrams of Figure 5.

Nicaragua. Trench sediment ponds where seamounts pass through the trench axis (Plate 1 and Figure 2). The frontal prism disrupted by a seamount is restored quickly to its former width even as the seamount is producing a debris trail farther up slope. We use the term frontal prism rather than accretionary prism because much of the material may consist of slope sediment that was kneaded into the prism without being transferred from the oceanic plate as described in section 5.1. In the ODP Leg 170 areas, only compacted slope sediment was reported from the prism although from seismic data in other areas, a transfer of some trench sediment (excluding slumps from the landward slope) is likely. We use the term margin wedge for consolidated rock (seismic velocity, 3.5 km/s and greater) that forms the backstop.

The morphology of the continental slope reflects the smooth or rough character on the adjacent ocean plate. Morphology is regular opposite the smooth ocean crust, rugged opposite the seamount domain, and consists of a short, steep incline to a raised shelf where the Osa Peninsula is uplifted over the subducting Cocos Ridge crest. The age of the current plate configuration could be 5-6 Myr [Collins et al., 1995; deBoer et al., 1995; Gram, 1998] as indicated by deformation and uplift across Costa Rica above the subducting Cocos Ridge.

Seismic reflection records [Hinz et al., 1996] indicate a basic structural configuration of the margin from the Osa Peninsula to the middle of the Nicoya Peninsula and Nicaragua as well [Ranero et al., this issue]. This configuration consists of a margin wedge covered by slope sediment, underthrust by trench sediment, and fronted by a small frontal prism. This basic structure probably existed prior to the current plate tectonic configuration and was modified by subduction of Cocos Ridge. This basic structure endured the onslaught of many subducting seamounts but not without short-term damage.

The upper surface of the margin wedge (the rough surface of Shipley et al. [1992] and the Base of Slope Sediment (BOSS) reflection of Kimura et al. [1997]) is buried by slope
sediment and has been interpreted differently. However, since Leg 170, it is generally agreed that the margin wedge is composed of older ocean igneous and associated sedimentary rock as was found off Guatemala.

3. Information Developed Since Earlier Cruises

During the R/V Sonne 81, 107, and 144 cruises the swath-mapped survey was extended beyond the Sonne 76 coverage [von Huene et al., 1995] to include the crestal region of Cocos Ridge, and the seaward margin of Nicaragua. Editing of the complete data set with the Mb system program [Caress and Chase, 1996] and in-house software [Heeren, 1996] allowed gridding at 100 m rather than at the previous 500-m intervals. The magnetic data from Sonne 107 were added to the compilation of Barckhausen et al. [1998] (Plate 1). Unprocessed seismic reflection data across the ocean crust were worked up and interpreted [Flores-Hernandez, 1996]. Several wide-angle seismic lines [Ye et al., 1996; Stavenhagen et al., 1998; Sallares et al., 1999; Christeson, 1999] constrained crustal depths. Study of samples from the area is still in progress [Mrazek et al., 1996] and geochemical analyses of rocks from oceanic areas have identified ocean crust of Galapagos hot spot affinities [Werner et al., 1999]. From bottom-simulating reflectors (BSRs) an inversion and analysis of heat flow over the accretionary prism were conducted [Pecker et al., 1998]. Swath mapping off Nicaragua [Mrazek et al., 1999] and reflection seismic data [Ranero et al., this issue] are the first modern data to compare with the extensive data off Costa Rica.

4. Rugosity of the Oceanic Crust

Morphology along the seaward slope of the Middle America trench is resolved from the 3-km relief of Cocos Ridge, through the 2-km relief of seamounts and ridges, to the less than 0.1-km relief of normal fault scarps. The seamounts are aligned roughly with Cocos Ridge and have a petrologic and geochemical affinity with the Galapagos hot spot [Mrazek et al., 1996; Werner et al., 1999]. Faunting on the seaward trench slope is influenced by crustal structure inherited from the Cocos-Nazca spreading ridge. As the ocean crust is depressed into the Middle America Trench, its axis of flexure is commonly at an angle to the strike of magnetic anomalies. Where that angle is not critically large, flexural stress is relieved by faulting along presumed zones of previous structural weakness as observed between Fisher Seamount and Quepos Plateau (Plate 1 and Figure 2). Where the angle between magnetic anomaly and the trench axis is nearly normal, faults cross the trend of magnetic anomalies as off the Nicoya Peninsula. However, thick crust of Cocos Ridge is faulted very little parallel to the axis of flexure at the subduction zone. Extensional structure in Cocos Ridge parallels the ridge axis as explained in section 4.1.

4.1. Cocos Ridge

The northwest flank of Cocos Ridge extends from its crestal area off Osa Peninsula to the Quepos Plateau (Figure 2). In our survey area, Cocos Ridge is a hot spot trace that trends 35° from the CNS magnetic anomalies [Barckhausen et al., 1998]. Ocean Bottom Hydrophone (OBH) refraction measurements midway between the crest and Quepos Plateau show a 12-km-thick crust [Stavenhagen et al., 1998] which thins away from the crest principally in the upper layered crustal section (Figure 3d). Reflection records display considerable layering in the upper ocean crust (Figure 3), suggesting many extensive lava flows.

Near the continental slope the ridge is a 1.5-km-high broad swell upon which a local seafloor relief (~0.5-1 km high) is superimposed. As the ridge enters the convergence zone, its seafloor flexes only half as much as the adjacent seamount segment, and essentially no trench parallel horst and graben structure is observed.

Adjacent to Osa Peninsula, the highest topography on Cocos Ridge is formed by tilted blocks which trend parallel to the ridge axis (Plate 1 and Figure 3a). The blocks tilt away from the crest and form a crestal graben which is filled with as much as 1 km of sediment some of which is accreted at the base of a 1.5-km-high slope.

4.2. Seamount Segment

The seamount segment extends from Quepos Plateau to Fisher Seamount and Ridge (Figures 2, 3b, and 3c). Oceanic crust in this segment is ~6–7 km thick [Ye et al., 1996] and has an age between 15 and 20 Ma [Barckhausen et al., 1998]. The seamounts have a Galapagos geochemistry and are 13–14.5 Myr old adjacent to the margin [Werner et al., 1999].

Quepos Plateau, an elongate volcanic feature that stands ~2 km above the surrounding seafloor, is the eastern exposed end of a 280-km-long seamount chain (Figure 1). Its internal structure in seismic records consists of subhorizontal layering (Figure 3b). The crest is flat, suggesting surf zone erosion, and this surface is punctuated by many small cones showing waning volcanism after subsidence below sea level. The steep flanks merge into a locally hummocky elastic apron (Figure 3b).

Fisher Seamount is ~14 Myr old and has a Galapagos geochemistry, but its southwest trending ridge is composed of enriched mid-ocean ridge basalt (EMORB) that formed at ~21 Ma [Werner et al., 1999]. About 50 km of the Fisher Ridge have been swath mapped (Figure 2). Satellite gravity indicates that aligned seamounts extend 200 km farther west (Figure 1). An eastward subdued continuation of this trend is indicated by a large underthrusting seamount landward of Fisher Seamount that disrupts the continental slope (Figure 2).

4.3. Smooth Segment

The smooth segment morphological domain extends from Fisher Seamount and Ridge to the northwestern part of the Nicoya Peninsula (Figure 2). The ocean crust is from 20 to 25 Myr old on the basis of magnetic anomalies and is 5-7 km thick. In contrast to the sharp rough-smooth boundary to the west that shows up well in satellite gravity anomalies (Figure 1), the boundary to the northwest between CNS and EPR crusts has little morphological contrast but occurs along a small escarpment (Figures 1 and 2 and Plate 1) that extends discontinuously across the oceanic plate and across the continental slope.

The crust breaks into normal faults trending subparallel to the axis of flexure and essentially perpendicular to the CNS.
Figure 3. Seismic records across the oceanic plate: line location shown in Plate 1: (a) Line 1 showing crest of Cocos Ridge and its southeast flank, (b) northwest flank of Cocos Ridge and Quepos Plateau, (c) section across Fisher Ridge, and (d) diagram showing crustal thickness of the oceanic plate derived from seismic refraction (arrows) and reflection data (numbers keyed to Plate 1). CMP, common midpoint; UT, University of Texas; TJ, fossil triple junction.
magnetic anomalies but vertical displacement is less than the thickness of sediment on the Cocos Plate. A subtle change in fault pattern occurs across the low escarpment that corresponds to the change from CNS-I to EPR crusts (Figure 5a).

5. Character of the Continental Slope

The relief along boundaries segmenting the ocean crust continues up the continental slope as aligned transverse-trending subdues features. Continuations of the Fisher Seamount and Quepos Plateau segment boundaries divide the slope into three segments. The large subducted seamount landward of Fisher Seamount is aligned with Cabo Blanco and the southern margin of the Nicoya Peninsula (Figures 2, 5a and b, and 7c). The subducted extension of Quepos Plateau is aligned with a ridge across the continental slope, a low dome on the shelf, and the northwest end of the Terraba deformed belt onshore (Figure 2 and Plate 1). Between these boundaries the middle and upper slope structures differ in character. The lower slope frontal prism seems little affected by various morphologies except where destroyed by a subducting ridge or seamount.

5.1. Lower Slope-Frontal Prism

As mentioned in section 2, we use the term frontal prism to include tectonically incorporated slope sediment as was discovered during ODP Leg 170 drilling. Like much of the Middle America Trench, the sparse trench fill off Costa Rica is commonly subducted [Shipley and Moore, 1986; Shipley et al., 1990, 1992; Hinz et al., 1996; Ranero et al., this issue]. The term frontal prism helps distinguish between two processes: (1) elevating pore pressure and reducing basal friction (facilitating sediment underthrusting) and (2) storing material transferred from the lower plate (accretion).

The frontal prism displayed in seismic reflection images is a mappable unit in our morphology (Figure 2). In seismic images we consider the prism the reflective sequence seaward of the margin wedge or seaward of a recognizable BOSS reflection and a semicoherent slope sediment section (Figure 4). The prism corresponds to the "outer wedge" of Langseth and Silver [1996] and the sedimentary wedge of Sites 1040 and 1043, Leg 170 [Kimura et al., 1997]. The contact between the prism and the margin wedge is associated with a rapid landward increase in seismic velocity in both wide-angle and normal incidence reflection seismic data [Ye et al., 1996]. The backstop is not a sharp interface but a transition between presumed moderately consolidated (velocity 2 km/s) and well-consolidated (velocity 4 km/s) rocks. In reflection images the base of the prism is commonly defined by a detachment reflection. Thick underthrust sediment sequences cut by normal faults are commonly imaged beneath the prism and the detachment (Figure 4 bottom).

The frontal prism morphology resembles the large slide adjacent to Fisher Seamount but with lineaments parallel to the strike (Plate 1 and Figures 2 and 5a). The landward boundary of the frontal prism is commonly a low escarpment. The prism is 5-8 km wide narrowing to 3 km wide over some parts of Cocos Ridge and is temporarily removed across 10 to 20-km gaps by subducting relief (Figure 5b). Balancing the cross-sectional area of the prism with sediment input, and assuming all of it is sediment transferred from the subducting plate, indicates that more than 95% of the sediment remains on the subducting plate passing the backstop [Hinz et al., 1996]. For at least 350 km along the trench the frontal prism has a common morphology and structure across all three tectonic segments. Along Cocos Ridge, where thick sediment in the crestal graben enters the subduction zone, the frontal prism is clearly accretionary (Plate 1 and Figures 2 and 5c). The 1-km-thick sediment in this graben and sediment ponds along the trench axis (Figure 2) indicate a substantial continental sediment source and efficient sediment subduction.

Gaps in the prism, formed as seamounts transit through it, appear to heal rapidly by local tectonic thickening and accretion (Figure 6). The rate of this accretion was estimated from the length of adjacent tracks left by two seamounts that entered the subduction zone at different times. The seamount subducting near Quepos Plateau (Plate 1, Line 3) has migrated 23 km from the deformation front through the frontal prism and margin wedge. Here the prism is still completely breached. The next subducted seamount to the northwest (Plate 1, Line 13) has migrated 35 km, and here a 6-km-wide prism fills the breach. At a plate convergence of 88 mm/yr the time difference of migration past the deformation between the two seamounts is 140 kyr. During this time, underthrusting of the complete oceanic section, accretion of trench fill, and incorporation of slope sediment have restored the prism, indicating that frontal prism construction can be very rapid when conditions are favorable. There also appears to be a maximum limit beyond which growth stops. The prism is probably stable at the present taper (-10i) and 3-10 km width.

The uniform width and rapid restoration of the frontal prism despite contrasting subducting plate morphologies show a strong disposition toward a stable configuration. Prism growth seems to be a self-limiting process. A slope or trench source of its material and variable abundance of trench fill is apparently less important than achieving a critical size and elevating pore fluid pressure to allow sediment subduction. The frontal prism off Costa Rica stores an insignificant volume of trench sediment compared to the Cocos Plate sediment input, and an elevation of pore fluid pressure appears to be its primary function. However, this prism is not tectonically static as indicated by the termination of canyons at its landward limit (Figure 2). Canyons have developed across seamount trails some Kiloyears after the seamounts passed. Considering this development time, the absence of canyons indicates tectonic activity in the prism of similar age.

5.2. Middle and Upper Slope, Smooth and Seamount Segments

The smooth segment morphology is characterized by an upper slope with many canyons and a gentler middle slope with shallower canyons and tracts smoothed by recent sedimentation (Figures 5a and 7 and Plate 1). Only a representative part of the smooth segment morphology is illustrated as a perspective diagram here (Figure 5a). Near the ODP Leg 170 drill area, major canyons are absent across the middle slope, but large canyons occur just upslope of the drill
Figure 4. Time-migrated sections with and without a subducted seamount. Line 13 shows a seamount that was also imaged in refraction data [Ye et al., 1996]. The headland at the edge of the shelf displays eroded strata. Line 17 shows a frontal prism against the margin wedge backstop marked by the rough surface. In both lines the normal faulting in subducted sediment of the Cocos Plate is preserved for at least 10 km after subduction (see Figure 6b).
Figure 5. Perspective diagrams of the study area morphology illustrating detail: (a) diagram extending from the Leg 170 area to Fisher Seamount (smt) showing the adjacent slide and the trailing flank of a large subducting seamount, (b) diagram extending from Fisher Seamount to the flank of Cocos Ridge, and (c) diagram looking down the trench axis and extending over the crest of Cocos Ridge. In Figure 5a and b, a fracture pattern over the crest of the seamounts indicates extension of the sediment section. Many short normal faults extend across the middle slope and resemble the crevasses in a flowing glacier. In Figure 5b, note termination of canyons at the frontal prism. In Figure 5c, note the lower slope retreat over the ridge crest and the sharp juncture where tilted block ridges are subducted.
Seafloor material flux from erosion by the removal of material from the underside of the upper plate by underthrust seamounts is resolved with difficulty in two-dimensional seismic dip lines (Figure 6c). Along the strike line (Figure 7, Line 6, km 55-75), ~500-700 m of thinning is observed just forward of the peak of an underthrust seamount (see depth section of Ranero and von Huene [1993]). Extensional fractures are resolved in perspective diagrams across most of the middle slope seafloor (Figure 5) just downslope of the canyons.

The smooth segment is not complicated by recent subduction of lower plate seafloor relief and Cocos Ridge. Its upper slope has been sufficiently stable for development of deep canyons. The middle slope is at critical dip, consistent with creep in the upper 40-80 m of the section [Baltuck et al., 1985]. The underlying margin wedge (basement) transfers little interplate compression that affects Quaternary tectonics in the sediment section.

Subducted seamounts are indicated by rounded uplifts or domes most clearly observed on the middle slope (Plate 1 and Figures 2 and 5). The seamounts are 1.5-2.5 km high on the oceanic plate and 1.5 km high where seismically imaged beneath the margin wedge (Figure 7) [Ye et al., 1996]. In the mid-slope area where the crust is ~5 km thick, the domes above 1.5-km-high underthrust seamounts are clearly resolved in swath map data (Plate 1 and Figures 2 and 5b). Above subducted seamounts the upper sediment section fails on the oversteepened seaward or trailing slope with as little as 3°-4° of added tilt. Despite substantial albeit temporary uplift, the margin wedge along a seamount track remains coherent (Figures 6 and 7), and mainly the frontal prism is breached. The features associated with seamount subduction off Costa Rica were studied with analog modeling [Domínguez et al., 1998] and convincingly replicated including the surface fractures and slope failures apparent in Figure 5.

Three seismic images along seamount tracks (Figure 6) show how rapidly margin structure can be restored after a seamount has tunneled beneath the upper plate. After the first 10-15 km of underthrusting the upper plate is uplifted but not severely dismembered (Figure 6b). Only the upper half of the slope sediment section fails as shown in both the dip and strike lines across a seamount 25 km from the trench axis (Figure 7a, km 90-95). Once the seamount trail has aged ~0.5 Myr, the seismic image and morphology become nearly indistinguishable from an undisturbed seismic section across the frontal prism. Seafloor material flux from erosion by single seamounts is small and difficult to quantify without three-dimensional images.

Slope strata rest on the BOSS reflection, which has a relief that is commonly greatest (500 m high) from the middle slope to the frontal prism. Although the upper surface has a rough two-dimensional morphology, faulting of Quaternary sediment involves only small (~100 m) vertical displacements mostly on extensional faults [Mcintosh et al., 1993]. Extensional fractures are resolved in perspective diagrams across most of the middle slope seafloor (Figure 5) just downslope of the canyons.

In the middle slope a 40- to 80-m-thick creeping sediment blanket was documented with microfauna transported from shallower water, paleomagnetics, and sediment reworking in cores from Deep Sea Drilling Project (DSDP) Leg 84, Site 565 [Baltuck et al., 1985]. The difficulty in clearly imaging strata in slope sediment in many seismic reflection sections [i.e., Shipley et al., 1992] is consistent with stratal disruption during downslope creep. Drilling at Sites 565 and 1041 documents a change in tectonism at ~280-m depth from a lower more deformed to an upper less disturbed and less consolidated sediment. This boundary within the late Miocene may correspond to an unconformity locally observed in seismic records. Precluding more precise dating, we note the possible coeval arrival of Cocos Ridge and the unconformity.

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Figure 6. Seismic reflection images showing stages in subduction of seamounts: (a) Line 11, where seamount has breached the frontal prism and its trailing flank slide debris are reaching the trench, (b) Line 13, where seamount has migrated ~25 km from the trench axis and the structure of frontal prism is restored (see Figure 4), and (c) Line 12a, where lower slope has been restored ~0.5 Ma after seamount was underthrust and its track can no longer be distinguished in a seismic record across the margin front. See Plate I for locations.
Figure 7. Migrated time sections comprising a strike line across the study area, 25-30 km from the deformation front (Plate 1): (a) Line 6, (b) Line 7a, and (c) Line 7. Embayments are indicated, and the resolution of slope sediment thickness between the rough surface and plate boundary is shown. A depth-migrated section across the subducted seamount at km 65, Line 6, is presented in Ranero and von Huene [2000].
Plate 1. Multibeam bathymetry and topography with earthquake epicenters [Proots et al., 1995] and seismic reflection data tracks superimposed. Swathmapping is from R/V Sonne cruises 76, 81, 107, 144, and a track from the R/V Revelle, and were processed with Mysiswrit [Corum and Chaffee, 1990] and GMT software [Wessel and Smith, 1991]. A map of seafloor spreading magnetic anomaly boundaries is inset. Magnetic data recorded during swathmapping were merged with regional data [Bhattacharyya, unpubl.] Site 565 of Deep Sea Drilling Program Leg 84 (black dot) and sites of Ocean Drilling Program Leg 170 (white circles filled with black) are shown. Bold tracks are profiles and segments of profiles in Figures 3, 4, 6, 7, and 8.
segment. The latter embayment was probably opposite lower plate relief as indicated not only by failed slope sediment and transverse faults (Figures 2 and 5a) but also by seamounts seaward of our study area (Figure 1) and in the direction of plate convergence.

Removal of material from the embayed area might be inferred from a comparison of seismic records across embayments and the headlands between them (Figure 4) [Hinz et al., 1996, Plate 1]. Across each headland, structure of sediment strata indicate the edge of the shelf basin near or just beyond the current shelf edge (Figure 4). If prior to subduction of Cocos Ridge, the margin configuration along all of the Costa Rica margin was like that off northwest Nicoya Peninsula [cf. Shipley et al., 1992], the volume of material missing from the three embayments is 783, 1085, and 1543 km$^3$ from northwest to southeast, respectively. The latter volume may include some nonerosional features. Although mass wasting and downslope material transport are indicated, the volume of missing material is larger than can be explained with surface erosion of only slope sediment. Removal of material along the plate boundary in the embayed area is likely, but its volume is not well constrained.

5.3. Cocos Ridge

Above the crest of Cocos Ridge the continental slope rising to the Osa platform is short, steep, and without canyons (Plate 1 and Figures 2 and 5c). The slope and the shelf edge are indented landward over the ridge crest, indicating erosion accompanying subduction of Cocos Ridge. The continental slope accommodates subducting ridges and seamounts on the ridge crest with only minor upper plate disruption.

Osa Peninsula is the emergent part of an equally extensive uplifted area comprising Osa platform (Figure 2). Seafloor erosion of the platform section displayed in seismic record P1600 has removed $\sim$1 km of strata (Figure 8, km 50-65). Erosion is greatest near the current shelf edge and decreases landward. Arching over the crest of the ridge, presumed from studies on land [cf. Fisher et al., 1998; Kolarsky et al., 1995; Gardner et al., 1992; Corrigan et al., 1990], was confirmed over the northwest flank in strike line 6 (Figure 7a). The seafloor rises 1.5 km, the plate boundary shoals $\sim$1 km, and the slope sediment section is folded. The wedge has a 10; taper in the 25 km beneath the continental slope [Stavenhagen et al., 1998], which is 2-3; less than the taper where normal oceanic crust subducts. Above the ridge crest the slope is indented $\sim$15 km. Beneath the slope, landward dipping reflections are truncated at the plate boundary (Figure 8, km 35-45). Thus, over Cocos Ridge, wave base erosion at the sea floor, retreat of the slope, and narrow taper accompany erosion.

The highest ridge parallel normal fault scarps in the crestal graben measures 1 km at the seafloor and extends 0.8 km beneath the sediment pond (Figure 3a). Its trend continues into a transverse offset of the slope, a partly surveyed elevation at the shelf edge, and an indentation in the coast which is aligned with a ridge across the Osa Peninsula (Plate 1). That ridge is located near an area of rapidly uplifted marine shoreline features on the Peninsula [Gardner et al., 1992]. A $\sim$7-km-thick upper plate beneath the Osa Peninsula [Stavenhagen et al., 1998] has apparently not completely attenuated surface uplift over local relief on the lower plate that is $\sim$1.8 km high on the exposed crest of the ridge.

A temporal relation is documented between subduction of Cocos Ridge and development of the Terraba Basin and Cordillera Talamanca uplifts (Figure 2) [Grafe, 1998; deBoer et al., 1995], a gap in the Quaternary volcanic arc, and tectonism in the back arc [Collins et al., 1995; Kolarsky et al., 1995]. The uplifted Quaternary Terraba Basin sediment was compressional thickening during the past 5 Myr, exhumation of the Talamanca began between 4 and 3 Ma. A cause and effect relation between deformation in the upper plate and subduction of Cocos Ridge is generally accepted, but the tectonic mechanism is unexplained. Subduction of Cocos Ridge resulted in considerably greater permanent deformation than observed where the Nazca Ridge [Hsu, 1988] subducts. Lack of pronounced deformation along the Peruvian coast may be attributed to migration of the subducting Nazca Ridge along the margin whereas Cocos Ridge and its flanking seamounts have subducted in the same general area during perhaps 5 Myr.

6. Basal Friction

The evidence that some lower plate morphology remains intact as far as the coast and into the seismogenic zone is a general sign of relatively weak coupling along the plate boundary. Off Osa Peninsula the seemingly passive subduction of the high tilted block ridges on Cocos Ridge shows unhindered accommodation. ODP Leg 170 drilling and seismic data along the margin show subduction of essentially the entire sediment section, which indicates a basal friction along the detachment near the shear strength of trench sediment. In the first 5-10 km landward of the trench axis in Line 13 (Figure 6) the underthrust sediment section remains essentially intact indicating interplate friction close to or lower than the sediment section shear strength. Farther down the subduction zone where subducting seamounts $\sim$2 km high are buried beneath a 5-km-thick upper plate, their peaks appear essentially intact, and no unusual seismicity is observed (Figures 4 and 7) despite erosion of the upper plate. The upper plate domes up over subducting seamounts and ridges without the dismemberment expected from high-friction shear zones, but material flux is locally observed [Ranero and von Huene, 2000]. Sufficient plate boundary friction to produce teleseismic earthquakes begins 35-45 km landward of the trench off Costa Rica, where the upper plate is 7-12 km thick. The clustering of earthquakes beneath the shelf and the alignment of these clusters with the trend of seamount chains (Plate 1) allude to seamounts as physical asperities in the seismogenic zone. Uplift patterns along the coast are attributed to subducted lower plate relief [Marshall and Anderson, 1995; Fisher et al., 1998]. It is inferred that seamounts may be detached there to explain thickening of the crust. Alternatively, the uplifts might last only during the passing of the seamounts beneath the coast.

The physical evidence of friction at the level of sediment shear strength to 5-km depth and friction at or below the shear strength of a seamount to depths of 25 km beneath the coast is reminiscent of the San Andreas weak fault paradox [i.e., Zoback and Beroza, 1993]. The physical evidence is consistent with inferences of weak coupling along the
7. Segmentation

We have followed the morphological proxy for boundaries that separate different oceanic crustal segments for 70-110 km from the trench axis across the Costa Rica margin. The two with a pronounced seafloor relief seaward of the trench axis are also coincident with concentrations of earthquakes beneath the shelf. Each type of ocean crust modulates material input to the subduction zone and has different intensities of normal faulting imparted by crustal flexure into the trench. We now relate marine tectonic observations to the character of the volcanic arc noting that if initial subduction of Cocos Ridge began at 5 Ma the geochemistry of recent lavas developed in a tectonic system similar to the current one.

Although it is clear that ocean crust or the slab contributes material to volcanic arc magmas, a lesser consensus relates to the terrigeneous clastic material that travels with the subducting plate. On a global scale, subducted sediment volumes and elemental fluxes appear important [Plank and Langmuir, 1993]. However, along only Middle America, the case for this relation has not been made strongly. The case for along-strike variability in the volcanic arc was clearly argued a decade ago by Carr et al. [1990]. They explained this variability on the basis of slab dip and its effects on focusing the distribution of fluids released from oceanic crust. Leeman et al. [1994] argued that slab temperature was important. The fluids would be released earlier from a hot slab relative to a cool one. However, the elevated temperature associated with Cocos Ridge and abnormally cold temperature off Nicoya [Langseth and Silver, 1996] create a large northwest cooling temperature gradient, which is inconsistent with currently known southeast decreasing slab signal gradient. These gradients were well displayed by Herrstrom et al. [1995], showing a subduction component decreasing steeply in southern Nicaragua but gently in Costa Rica. Herrstrom et al. favored a combination of increased slab flux and changes in the composition of the mantle to explain along-strike magma variations. Although no author argues forcefully for differences in subducted terrigeneous sediment volumes as a major control for variability, the point is often discussed informally and in oral presentations.

Indicators of subducted terrigeneous or upper oceanic crustal components are Ba/La ratios [Carr et al., 1990], Be isotopes [Morris, 1991], and U/Th ratios [i.e., Patino et al., 2000]. High 10Be/9Be, U/Th, and B/La ratios in Nicaraguan lavas and the very low ones in central Costa Rica have led to some investigators to speculate that much of the trench sediment was subducted in the former compared with the latter. However, our observation of little variation in size of the frontal prism along Costa Rica and a similar frontal prism off Nicaragua [Ranero et al., this issue] indicate little modulation of subducted sediment flux from accretion. The search for another relation between input at the trench and arc lava geochemistry recalls the opinion of Leeman and Carr [1995]: the lateral heterogeneous geochemistry probably reflects a combination of different ages and evolution of subducting oceanic crust, its thermal state, configuration of the subduction zone, as well as subducted terrigeneous material. Patino et al. [2000] present evidence that hydrous fluids dominate the transfer of components from the slab to lavas and speculate that more fluids might be released where the subducting crust was highly fractured during flexure.

7.1. Physical Segmentation

Three segment boundaries divide the Cocos Plate and the continental slope (Figure 9). A transverse trend recognized by early investigators consists of the successive features aligned with Fisher Seamount and the associated ridge jump between older CNS-1 and younger CNS-2 crusts [Barckhausen et al., 1998]. Landward of Fisher Seamount, this trend includes a large subducted seamount (Plate 1 and
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Figure 9. Top. A diagram showing ocean crust segment boundaries off Costa Rica and Nicaragua. Solid triangles show the location of Quaternary volcanoes. Open triangle (labeled EX) is a 2 Myr old dome site. TU, Turrialba; IR, Irazú; BA, Barba; PO, Poás; AR, Arenal; CH, Chopo; RV, Rincón; CO, Concepción. Bottom. (a) Regional variations in the Ba/La trace element ratio along the arc, which indicates variation in the slab signal [from Patino et al., 2000]. (b) Width of the flexed and fractured ocean crust (dashed line) and the vertical displacement of the seafloor across the flexed zone (solid line), which display a trend similar to the slab signal. The width of the frontal prism (dashed line) varies little along Nicaragua and Costa Rica. Approximate location of segment boundaries shown by the following lines: VO, volcanic offset; CNS-EPR, crustal junction along fossil triple junction; FS, Fisher Seamount.

Figures 2, 5, and 9), coastal uplift at Cabo Blanco [Marshall and Anderson, 1995], the linear southeast coast of the Nicoya Peninsula including the Cobano earthquake cluster (Plate 1) and the left lateral offset and gap between Platanar and Arenal volcanoes, which occurs over the Quesada Sharp Contortion of Protti et al. [1995]. The volcanoes on either side of this boundary are very different in morphology and large-ion lithophile (LIL) elements [Patino et al., 2000]. This transverse trend is more obvious than those on either side.

Quepos Plateau is a morphological proxy marking the transition to normal crust from the thick Cocos Ridge crust (Figure 3). Once subducted, the transverse boundary
Figure 10. Nicaragua and Costa Rica normal faulting adjacent to trench in comparative perspective views: (a) off central Costa Rica; (b) clustered bathymetric profiles (vertical exaggeration, VE=15:1) for the seamount, the smooth, and the Nicaraguan segments; and (c) off Nicaragua (a 100-km-wide section). Note difference in fault spacing, displacement, and width of flexure.

continues into a headland marking the northwest end of the Osa platform, an earthquake cluster and associated low dome on the shelf (Plate 1), the end of the Valle General and Terraba belt [Kolarsky et al., 1995], and perhaps the end of significant Quaternary volcanism. In the Cordillera Talamanca at Rio Lori near Cerro Durika, 2 Myr old andesitic to dacitic domes occur on a projection of the Quepos segment boundary [Abrais, 1998]. Seismicity aligned with the Quepos Plateau segment boundary extends across the continental slope to the 2 Myr old volcanic arc (Plate 1) and is sharply
defined in the local earthquakes recorded since 1995 by the Boruca network [Arroyo, 1999]. Together with the Fisher Seamont segment boundary, the Quepos lineament bounds the central Costa Rica earthquake rupture zone of Protti et al. [1995].

A third transverse boundary on ocean crust is found between the CNS and EPR lithospheres off the Nicoya Peninsula (Plate 1 and Figures 2, 5a, 9, and 10). The boundary is a fossil triple junction except adjacent to the trench where it separates crust of different ages (Plate 1 inset). It has a morphological proxy in a discontinuous low transverse escarpment on the ocean crust and its subducted extension is marked by uplift and sediment failure up the slope. At the shore the convex coast of the northern Nicoya Peninsula becomes concave seaward to form a broad embayment that parallels the embayment in the continental slope (Figure 9).

A major offset and long-standing division in the arc occurs between Costa Rica and Nicaragua [Carr and Stoiber, 1990]. Unusual is the position of the arc with relation to the dip of the Benioff Zone. Off Nicaragua, where the Benioff Zone is very steep, the arc is landward and over a deeper part of the zone than in Costa Rica where the Benioff Zone is shallow. This condition predates the beginning of upper plate deformation associated with the subducting Cocos Ridge. The Miocene arc in Costa Rica was nearer to the coast and has migrated landward. Conversely, the middle Miocene arc in Nicaragua and northwestern was farther landward and has migrated seaward [Weinberg, 1992; Balzer, 1999], so the arc offset was formerly greater. A fundamental difference in crustal structure is observed between Costa Rica and Nicaragua [Ranero et al., this issue; Walther et al., 2000; Christeson et al., 1999; Sallares et al., 1999], a change that corresponds with a terrane suture of pre-Miocene age. This suture appears inactive as indicated by lack of active transverse structure across the continental slope and absence of a corresponding boundary across the ocean crust in swath mapping opposite the international border [Ranero et al., 1999]. However, the morphological character of the continental slope, changes noticeably on either side of this upper plate segment boundary. Therefore the volcano offset is perhaps more closely associated with the difference in upper plate crustal structure rather than a current boundary in the subducting oceanic plate.

7.2. Geochemical Segmentation

The subducting ocean crustal segmentation corresponds in varying degrees to geochemical changes along the arc. Landward of the Quepos lineament, 2 Myr old andesitic to dacitic domes have a trace element signature (heavy rare earth element (HREE) depletion) characterizing them as partial melting products of the subducted basaltic oceanic crust with garnet in the residue (adakites) [Aabraiz, 1998]. Both alkaline back arc magmatic rocks and adakites in southern Costa Rica show a plume-related isotope signature by their \(^{206}\)Pb/\(^{207}\)Pb ratios which are higher than the calc-alkaline magmatic rocks of the older arc. Large-ion lithophile element (LILE) enrichment is variable in the adakites, but they contain among the highest concentrations of LILE, for example, Ba (1500-2000 ppm), and the highest Ba/Th ratios (900-1500) sampled in the area.

The offset in volcanoes along the Fisher lineament is accompanied by step-like change in slab components: Ba/La and Sr-Nd isotopic systematics are discontinuous here. In Sr-Nd plots the slab signal from Rincon to Arenal disappears in central Costa Rica [Patino et al., 2000].

The CNS-EPR boundary is aligned with the change in Pb isotopes noted between Chopo and Tenorio volcanoes [Feigenson et al., 1996]. A Galapagos Pb signature in lavas opposite the CNS crust is missing opposite the EPR crust, consistent with a subducted ocean crustal boundary here.

The Tertiary volcanic history of Costa Rica is completely different from that of Nicaragua and the rest of northern Central America [Carr and Stoiber, 1990]. Volumes of lava in northern Costa Rica are about twice that in Nicaragua per equivalent length of arc [Alvarado et al., 1992]. The geochemical slab signal increase in central Nicaragua is summarized elsewhere [Carr and Stoiber, 1990; Patino et al., 2000].

7.3. Relation of Marine Geology to Geochemical Trends

The current physical trends from Cocos Ridge toward Nicaragua developed with subduction of the ridge beneath Costa Rica. These trends include a northwest decrease of ocean crustal thickness, subduction erosion, and thickness of ocean basin sediment. Conversely, slab dip, lower plate flexure, and normal faulting adjacent to the trench increase northwestward. Geochemical variation thus parallels the intensity of faulting in the ocean crust (Figures 9 and 10) and a steepening of dip of the seismogenic zone [Protti et al., 1995].

Sediment input to the subduction zone is fairly well constrained along Costa Rica but the Nicaraguan swath bathymetry is supported by a single seismic section (Ranero et al., this issue). Off Nicaragua the sediment cover on ocean crust is 250-300 m thick whereas in the Leg 170 area it is 400 m thick. Transport northwest along the trench axis from Cocos Ridge toward Nicaragua distributes trench sediment input but each seamount entering the trench off central Costa Rica blocks axial sediment flow for ~0.5 Myr. Frequent slides from the middle slope of Nicaragua (Figure 10) [Ranero et al., this issue; Mrazek et al., 1999] could also redeposit the upper layers of slope sediment across the trench axis. So there is no indication of a pronounced difference in sediment input to the subduction zone that parallels the variation in elements of the arc lavas.

The possible connection between intensity of fracture and variation in element ratios may be related to hydration of the subducting lower plate. In the past attention has been directed mainly toward the fluid flow in accreted sediment. During accretion, fluid first drains from the upper sediment layers above the decollement and vents at the seafloor, but drainage from lower layers is impeded as shown quantitatively along an Alaska seismic transect [von Huene et al., 1998]. Below the decollement at ODP Site 1043, 1 km from the Costa Rica deformation front, the upper 75 m had compacted 37%, the next 55 m had compacted only 9%, and the remaining 185 m had not compacted at all [Moritz et al., 2000]. Fluid in subducted sediment below the decollement has a drainage path that lengthens with increasing subduction. This drainage pattern slows fluid discharge which may thus continue tens of kilometers down the subduction zone. The mud volcanoes
near the upper slope off the Nicoya Peninsula [Shipley et al., 1990; McAdoo et al., 1996] indicate focused drainage of fluid nearly 40 km from the deformation front. Pore fluid in the subducting oceanic crust will be released even farther from the trench, because it must first penetrate a sediment layer that has a low permeability until it is sufficiently fractured. Just where a fracture permeability develops is unknown as is fluid flow to a detachment which probably forms a principal drainage path updip. Normal ocean crust contains 10-15% fluid [Fisher, 1998], and the additional fluid taken into the faulted zone of flexure adjacent to a trench is unknown but must vary with intensity of fracturing. Off Nicaragua, ocean crustal layer 2a has a notably low seismic velocity (3.3-3.4 km/s) whereas the global average for 20 Ma crust is 4.5 km/s [Walther et al., 2000]. The low velocity is attributed to fracturing and increased fluid in the fracture porosity. In the zone of flexure and faulting the entire crust and upper mantle are brittle because the ocean lithosphere is more than 13 Myr old [Werner et al., 1999; Morgan et al., 1994]. Normal faults displacing the ocean plate seafloor off Nicaragua are associated with dipping intrabasement reflections [Ranero et al., 2000] interpreted as deep penetrating faults. A few dipping reflections are also visible beneath normal faults in the ocean plate off Costa Rica (Figure 4). Thus, when the lithosphere is flexed, brittle faulting may allow the entire crust to become hydrated. The 5.5-km-thick ocean crust also has a low-velocity zone at the base of layer 3. This could indicate alteration of the lower crust but the thickness of the low-velocity zone is poorly constrained. Alternatively, alteration may have occurred at the spreading ridge prior to ocean crust flexure [Walther et al., 2000].

Since the zone of flexure is 3 times as wide off central Nicaragua as off Costa Rica and its vertical displacement is 3 times as great (Figure 9), fracture zones off Nicaragua will be exposed to the ocean 3 times longer (0.6 Myr) than off Costa Rica. The sealing of basement aquifers by hemipelagic sediment, as documented at the Juan de Fuca Ridge [Giambalvo et al., 2000], will increase that contrast. Greater vertical displacement along the faults off Nicaragua fully ruptures the sediment but it does not off Costa Rica. Therefore pore fluid and the fluids bound in altered ocean crust entering the subduction zone are probably much greater off Nicaragua than off Costa Rica. However, we are not in a position to discuss the up-take of trace elements in hydrated and serpentinized ocean crust and these geochemical aspects are more fully covered by Patino et al., [2000], who also relate ocean crust fracture to the variation in arc geochemistry.

As seawater is admitted and migrates downward into the ocean crust, it reaches elevated temperatures and mafic rock that serpentinizes easily. Subducted water bound in serpentine will be released by dehydration at stages later than the initial drainage of pore waters from fractures and subducted clastic materials. Serpentinized lower ocean crust and upper mantle are proposed to generate much of the volatile flux along or above subduction zones [cf. Ernst, 1999]. Therefore the intensity of fracturing as the ocean crust is flexed into the trench, by its mode of fluid storage and later release, could provide a controlling factor in frictional behavior and formation of arc magmas.

8. Summary

The resemblance between the continental slope and the adjacent subducting lower plate morphologies along Costa Rica is clearly resolved with high-resolution reprocessed swath bathymetry. Its integration with seismic data provides a regional structural picture. Differences in ocean crust thickness, seafloor relief, and in flexure of the Cocos Plate produce structural differences on the adjacent middle to upper continental slope where the relatively thin upper plate beneath the continental slope acts as a cover through which the muted lower plate relief is visible. Subducted seamounts elevate the upper plate into broad seafloor domes that migrate to the shelf. Uplift from a ~2-km-high seamount was resolved well where the upper plate is 7-10 km thick. On the trailing flanks of these migrating seamount domes, oversteepened sediment failure leaves a trail-like slump scar to the shelf edge. Current coastal uplift along projections of seamount chains has been attributed to migrating seamounts [Marshall and Anderson, 1995; Fisher et al., 1998]. The assembled evidence indicates that seamounts can remain attached to the subducting plate at least 30-60 km into the seismogenic zone and to depths of ~25 km.

The frontal prism grows rapidly after being destroyed by a subducting seamount, but growth ceases when it reaches 5-10-km width. We speculate that the prism grows until it elevates pore pressure to a level where the reduced friction allows most incoming sediment to be subducted. The narrow prism along the Middle America Trench stores only a minor amount of sediment. Two broad embayments in the middle and upper slope are anomalous to Middle America margin morphology. Their position opposite a rugged subducting lower plate suggests an erosional origin. In addition to frontal erosion, erosion along the underside of the upper plate is required.

The near linear continuation of the transverse trend of aligned but perhaps en echelon segments from Fisher Seamount to the Quepos contortion of Potti et al. [1995] corresponds to an offset in the volcanic arc. The lower plate transit time from the trench to the arc is 2 Myr. The more than 150-km-long subducted extension from Fisher Seamount to the arc together with the 90-km-long exposed volcanotectonic lineament is indeed long but of a length similar to that of the exposed Quepos transverse lineament (Plate 1). Despite its length, the Quepos lineament has a less apparent effect on continental structures. The 15° angle between the convergence vector and the Quepos lineament causes migration of its point of impact at the trench. With no boundary subducted in one place over time, upper plate deformation from lower plate asperities may be dispersed.

The CNS-EPR junction also has a smaller apparent effect despite its near alignment with the direction of convergence. Although this juncture corresponds with a major ocean crustal boundary, an ocean floor relief is not obvious at the scale of satellite gravity anomalies. Little is known regarding the petrology on either side of the boundary. Clearly there is a plate tectonic break in the oceanic crust along the CNS-EPR junction, but not a pronounced break in volcano geochemistry.

The change in volcanism across the Costa Rica-Nicaragua border corresponds with an older inactive crustal boundary.
The Nicaragua seismogenic zone steepens, and volcanoes are located above a deeper part of the subduction zone relative to Costa Rica. Here crustal configuration rather than ocean crust compositional differences may dominate segmentation processes.

Cocos Plate physical segmentation offers some explanations for geochemical differences in arc lavas and has been considered in various comprehensive geochemical studies. The low Ba/La ratio in central Costa Rican lavas and the very high ratios of Nicaragua [Carr et al., 1990] are not explained by accretion versus nonaccretion or by a subduction erosion input (i.e., dilution of subducted sediment with a fluid-rich slurry eroded from the base of the upper plate). The intensity of normal faulting that allows charging of the upper oceanic crust with water offers another constraint in explaining the difference between the high slab signal in Nicaragua and the low one of central Costa Rica. Circulation of water along faults, serpentinitization, and later release of bound water deep in the subduction zone during serpentine dehydration are intriguing subjects for further study.

Basal friction in the aseismic part of the subduction zone can be derived from the persistence of structures in subducted sediment on the lower plate. Below the frontal prism, basal friction is locally equal to or less than the shear strength of the sediment section on the Cocos Plate. Beneath the middle and upper slope the basal friction equals or does not exceed that of a seamount's peak or outer layers. Where stick-slip behavior begins, friction does not yet appear to exceed the shear strength of the seamount main body.

The degree to which subducting ocean crust affects the upper plate is perhaps unusual off Costa Rica. Unique to the Costa Rica margin is the extent of a segment boundary along a trend that subducts essentially normal to the margin and therefore in one area for a significant period. Cocos Plate segmentation is emphasized morphologically at the seafloor by hot spot volcanic construction, and this morphology facilitates geophysical detection through the upper plate despite deep subduction.

Acknowledgments. The Research Vessel Sonne, supported by the Bundesministerium für Forschung und Technologie (German Federal Research and Technology Agency), is the platform from which most of the data in this study were acquired. Discussions with M. Carr and K. Hoernle were particularly helpful. We thank M. Protti, who provided us with an electronic file of his earthquake epicenters, and Harry Doust of Shell Internationale Petroleum Mij.B.V., who provided the field tapes of Line P1600. We also thank Stewart Smith of the Scripps Institute of Oceanography, Geological Data Center, who provided data from the Roger Revelle acceptance cruise. Reviews by Terry Plunk, an anonymous reviewer, and Gaku Kimura helped greatly in improving an earlier version, especially the geochemical aspects.

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(Received June 25, 1999, revised December 8, 1999; accepted December 13, 1999.)