JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. B11, 2511, doi:10.1029/2002JB002207, 2003

Fast rates of subduction erosion along the Costa Rica Pacific margin: Implications for nonsteady rates of crustal recycling at subduction zones

Paola Vannucchi,[1,2] César R. Ranero,[3,4] Simone Galeotti,[5] Susanne M. Straub,[3,6] David W. Scholl,[7,8] and Kristin McDougall-Ried[9]

Received 17 September 2002; revised 15 May 2003; accepted 13 June 2003; published 4 November 2003.

[1] At least since the middle Miocene (~16 Ma), subduction erosion has been the dominant process controlling the tectonic evolution of the Pacific margin of Costa Rica. Ocean Drilling Program Site 1042 recovered 16.5 Ma nearshore sediment at ~3.9 km depth, ~7 km landward of the trench axis. The overlying Miocene to Quaternary sediment contains benthic foraminifera documenting margin subsidence from upper bathyal (~200 m) to abyssal (~2000 m) depth. The rate of subsidence was low during the early to middle Miocene but increased sharply in the late Miocene-early Pliocene (5–6.5 Ma) and at the Pliocene-Pleistocene boundary (2.4 Ma). Foraminifera data, bedding dip, and the geometry of slope sediment indicate that tilting of the forearc occurred coincident with the onset of rapid late Miocene subsidence. Seismic images show that normal faulting is widespread across the continental slope; however, extension by faulting only accounts for a minor amount of the post-6.5 Ma subsidence. Basal tectonic erosion is invoked to explain the subsidence. The short-term rate of removal of rock from the forearc is about 107–123 $km^3\ Myr^{-1}\ km^{-1}$. Mass removal is a nonsteady state process affecting the chemical balance of the arc: the ocean sediment input, with the short-term erosion rate, is a factor of 10 smaller than the eroded mass input. The low ^{10}Be concentration in the volcanic arc of Costa Rica could be explained by dilution with eroded material. The late Miocene onset of rapid subsidence is coeval with the arrival of the Cocos Ridge at the subduction zone. The underthrusting of thick and thermally younger ocean crust decreased the subduction angle of the slab along a large segment of the margin and changed the dynamic equilibrium of the margin taper. This process may have induced the increase in the rate of subduction erosion and thus the recycling of crustal material to the mantle. *INDEX TERMS:* 1030 Geochemistry: Geochemical cycles (0330); 1040 Geochemistry: Isotopic composition/chemistry; 3030 Marine Geology and Geophysics: Micropaleontology; 8150 Tectonophysics: Plate boundary—general (3040); 9360 Information Related to Geographic Region: South America; *KEYWORDS:* convergent margins, tectonic erosion, Middle America Trench, Cocos Ridge

Citation: Vannucchi, P., C. R. Ranero, S. Galeotti, S. M. Straub, D. W. Scholl, and K. McDougall-Ried, Fast rates of subduction erosion along the Costa Rica Pacific margin: Implications for nonsteady rates of crustal recycling at subduction zones, *J. Geophys. Res.*, *108*(B11), 2511, doi:10.1029/2002JB002207, 2003.

1. Introduction

[2] Subduction erosion, the removal of rock mass from the overriding plate of convergent margins, is a major process affecting rock and fluid dynamics at subduction zones, the recycling of crustal material, and thus the long-term evolution of continents and island arcs [*von Huene and Scholl*, 1991, 1993]. Mass removal from the upper plate results in extension and subsidence of the forearc and, with subducted sediment, feeds the layer of particulate and fragmented continental material accompanying the movement of the lower plate toward the mantle. The rate of mass removal through time, which is affected by several factors and may vary along strike of the subduction zone, is a critically important factor for mass balance calculations and

[1]Dipartimento di Scienze della Terra, Università di Modena e Reggio Emilia, Modena, Italy.
[2]Now at Dipartimento di Scienze della Terra, Università di Firenze, Firenze, Italy.
[3]Forschungszentrum für marine Geowissenschaften, Kiel, Germany.
[4]Also at Sonderforschungsbereich 574, University of Kiel, Kiel, Germany.
[5]Istituto di Geologia, Università degli Studi di Urbino, Urbino, Italy.
[6]Now at Lamont Doherty Earth Observatory, Palisades, New York, USA.
[7]Department of Geophysics, Stanford University, Stanford, California, USA.
[8]Also at U.S. Geological Survey, Menlo Park, California, USA.
[9]U.S. Geological Survey, Flagstaff, Arizona, USA.

0148-0227/03/2002JB002207$09.00

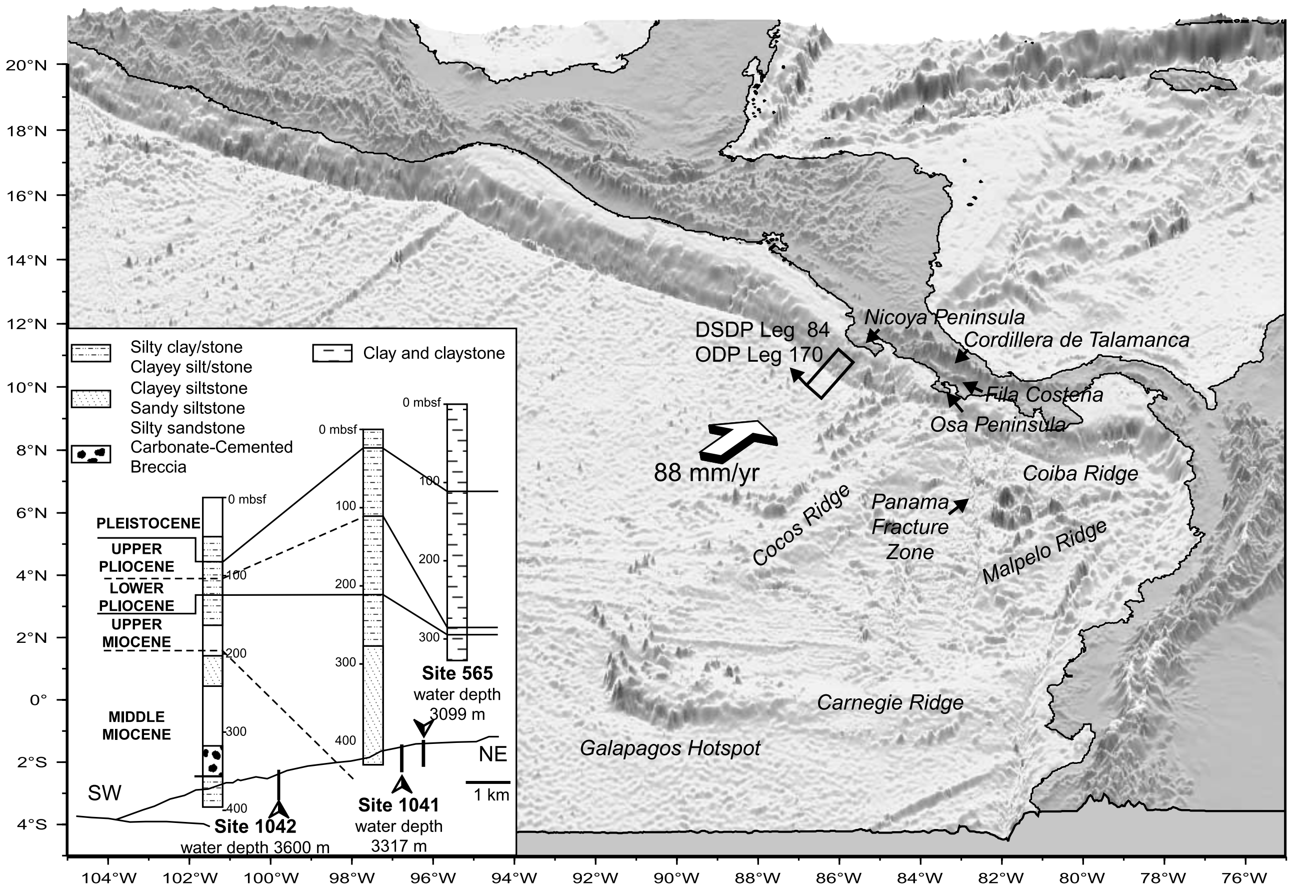

Figure 1. Perspective map of the Cocos Plate entering the Middle America Trench along the Nicaraguan and Costa Rican margins viewed from north to west. Elevation data from *Smith and Sandwell* [1997]. Inset shows location and bathymetric distribution of DSDP-ODP sites along the middle-lower slope offshore Nicoya Peninsula (DSDP Site 565 and ODP Sites 1041 and 1042); numbers along each column indicate meters below seafloor.

for determining the chemistry of the material recycled into the mantle.

[3] Evaluation of mass removal at convergent margins requires a multidisciplinary approach and the availability of high-resolution geological and geophysical data. The Pacific margin of Costa Rica (Figure 1) is one of the few subduction zones where this information is available, allowing good control on the margin evolution through time. Middle America Trench and Costa Rica, in particular, have been the focus of attention and discussion during the past decade, regarding the structure of the margin and the tectonic mechanisms shaping its form and evolution. On the basis of geophysical explorations, one model ascribes margin evolution to subduction accretion and compressional tectonics [*Silver et al.*, 1985; *Shipley et al.*, 1990, 1992], whereas widespread extension [*Aubouin et al.*, 1982] and subduction erosion [*Lallemand et al.*, 1992] were proposed as contrasting tectonic mechanisms. Collection of new seismic and bathymetric data in the area, as well as ocean drilling [*Kimura et al.*, 1997], finally resolved these differences in interpretation indicating subduction erosion as the controlling tectonic process. A subduction erosion hypothesis was presented by *Meschede et al.* [1999] supported by an ad hoc interpretation drawn on seismic data from *McIntosh et al.* [1993] and *Hinz et al.* [1996]. *Meschede et al.* [1999] ignored the structure imaged in the seismic data, where numerous landward dipping normal faults cut across the forearc [*McIntosh et al.*, 1993] and presented a cartoon interpretation of the forearc with pervasive seaward dipping faults as evidence for subsidence and tectonic erosion. Therefore no evidence of subsidence was presented by *Meschede et al.* [1999]. Databased interpretation of the forearc structure, as observed in other seismic lines and constrained by the drilled rocks, was presented by *Ranero and von Huene* [2000], *von Huene et al.* [2000], and *Vannucchi et al.* [2001]. The middle and upper continental slopes bordering the Nicoya Peninsula is constructed of an apron of low-velocity (2–3 km s^{-1}) sediment of mostly Neogene and younger age overlying a landward thickening, wedge-shaped unit of high-velocity rock (4.5–5.9 km s^{-1}), the margin wedge, forming the forearc basement. Wide-angle seismic data [*Ye et al.*, 1996], regional geology [*Bourgois et al.*, 1984; *von Huene et al.*, 2000], and Ocean Drilling Program (ODP) drilling [*Kimura et al.*, 1997; *Vannucchi et al.*, 2001] indicate that the margin wedge is composed of Nicoya complex, a fragment of the Caribbean oceanic plateau [*Hauff et al.*, 1997; *Sinton et al.*, 1997]. The Nicoya complex is widely exposed in the Nicoya Peninsula and consists of basic igneous rocks of mainly Cretaceous age [*Bourgois et al.*, 1984; *Hauff et al.*, 1997].

[4] The lower boundary of the slope apron unit is marked by a high-amplitude reflection that is rough to smooth in lateral profile. The horizon can be traced from southern Costa Rica to Nicaragua and landward to near the coast [*von Huene et al.*, 2000; *Ranero et al.*, 2000]. The reflection marks the acoustic impedance contrast between the low-velocity sediments of the slope apron and the underlying high-velocity rock of the basement wedge. However, cores recovered at ODP Site 1042 disclosed that a 20–30 m thick sequence of high-velocity limestone of lower Miocene age forms the basal beds of the slope apron. Acoustically, on seismic records, the limestone beds are thus imaged as part of the high-velocity wedge of basement rock over which, at ODP Site 1042, they were unconformably deposited ~16.5 Ma [*Vannucchi et al.*, 2001].

[5] Drilling determined that in the study area the middle-slope stratigraphic unconformity was closely overlain by a 16.5 Ma shallow-water deposit of cemented limestone breccia, which reached at a depth of ~3592 m and beneath a 340-m-thick section of slope apron sediment [*Kimura et al.*, 1997]. The occurrence of nearshore limestone deposits implies that since the early Miocene the outer part of the continental slope had subsided at a mean rate of 0.25 km Myr^{-1}. Accounting for this amount of subsidence requires a corresponding volume removal rate of basement rock from the submerged forearc of 34–36 km^3 Myr^{-1} km^{-1} [*Vannucchi et al.*, 2001] (Figure 1).

[6] The slope apron sequence off the Nicoya Peninsula has been drilled at three sites: DSDP Site 565 [*von Huene et al.*, 1985], and ODP Sites 1041 and 1042 [*Kimura et al.*, 1997]. Two of these sites, 565 and 1041, had a continuous and good recovery of the apron sediment reaching a depth of 328 m below seafloor (mbsf) and 423 mbsf (Figure 1), respectively, compared with the depth to the unconformity of 900 and 550 mbsf. The slope apron sediment consists of clay and clay stone with variable amounts of silt and sand [*Baltuck et al.*, 1985; *Kimura et al.*, 1997]. Although the lower part of slope apron was not sampled, the new analysis of the benthic foraminifera fauna presented in this paper documents the evolution of the long-term forearc deepening at both sites. Furthermore, the benthic foraminifera reveal that subsidence did not occur at a steady rate but as a more complex history of vertical tectonism. The evidence for long-term subsidence obtained from the analysis of the faunal assemblages and geophysical and geological data are used to evaluate possible mechanisms leading to margin subsidence. Our preferred mechanism, subduction erosion, and the associated material removal have been quantified to provide a more accurate evaluation of the time-varying flux of solid-volume material into the subduction zone and probably recycled back into the mantle.

2. Paleobathymetry

[7] Using the depth classification of *Van Morkhoven et al.* [1986] and based on a comparison with Holocene fauna from similar environments [see *Murray*, 1991; *McDougall*, 1996; *Schmiedl et al.*, 1997 with references therein], the vertical distribution of benthic foraminiferal assemblages from DSDP Site 565 and ODP Site 1041 (S. Hasegawa, personal communication, 1998) can be used to infer the bathymetric evolution of the central area of the continental slope. At both sites a succession of variations in benthic foraminiferal assemblages record a stepwise deepening from the late Miocene (6.5–5 Ma) to the Pleistocene (~1.8 Ma).

[8] At DSDP Site 565, a dramatic decrease of benthic foraminiferal abundance occurs at the Miocene-Pliocene transition (Figure 2). In the same interval, the decrease in the abundance of outer neritic-upper bathyal (~200 m) species (e.g., *Bulimina alzaensis* and *Cibicidoides bradyi*) associated with the increase in the abundance of middle-lower bathyal (600–2000 m) taxa (e.g., *Cibicidoides wuellestorfi*, *Bulimina mexicana*, *Uvigerina hispida*) and the entrance of abyssal (>2000 m) taxa (*Laticarinina pauperata*, *Nuttallides umbonifera*, *Uvigerina senticosa*) is interpreted to reflect a deepening from an outer neritic-upper bathyal (~200 m) to an upper-middle bathyal (<800 m) setting.

[9] A further deepening is observed at the Pliocene-Pleistocene transition (~1.8 Ma), between 100 and 120 mbsf, where a sharp increase in the proportion of abyssal (>2000 m) taxa (*Epistominella exigua*, *U. senticosa*, *Melonis pompilioides*) occurs. In the same interval the appearance of uncoiled cassidulinids (e.g., *Cassidulinoides* spp.) is observed (Figure 2). According to *Bandy* [1960] a water-deepening trend can be recognized in the cassidulinids. Limbate, large, sharp-edged species of *Cassidulina*, typical of the inner shelf are replaced by either large globose (such as *Globocassidulina subglobosa*) or biumbilicate forms at greater depths. In the bathyal zone the test tends to uncoil giving rise to *Cassidulinoides* and *Ehrenbergina. B. alzaensis* and *C. wuellestorfi* show some reworking of the upper 80 m of the section at DSDP Site 565 and, in fact, the upper part of the section is characterized by widespread creeping [*Baltuck et al.*, 1985]. The carbonate preservation of planktonic foraminifera also implies subsidence at DSDP Site 565 with dissolution starting after about 7 Ma [*Bourgois and Glaçon*, 1985].

[10] A similar trend is observed at ODP Site 1041, where at about 250 mbsf a sharp change is observed at the Miocene-Pliocene transition (~5.5 Ma) from an older *Bolivina-Bulimina-Pseudoparrella*-dominated assemblage to a younger *Uvigerina-Stilostomella*-, and, less commonly, *Nuttallides*-dominated assemblage. This major change is clearly reflected in the record of paleobathymetric indices (Figure 2).

[11] In terms of paleoceanography, we interpret the up-section change observed in benthic foraminiferal assemblages at both sites to reflect the emplacement of a cooler/deeper water mass at the end of the Miocene-early Pliocene (5 Ma). *McDougall* [1996] reported a coeval change in benthic foraminiferal assemblages from the deeper-water DSDP Site 503 in the Guatemala Basin. McDougall interpreted the change observed at this site as reflecting a probable uplift of the sill between the Caribbean and the Pacific that terminated leakage of North Atlantic Deep Water into the Pacific, thus allowing the emplacement of cooler Pacific Deep Water north of the Galapagos Ridge.

[12] High abundance of uvigerinids in Pliocene assemblages at both Costa Rica sites may also imply enhanced organic flux and/or oxygen deficiency at the seafloor. However, *Brizalina argentea* together with *Bolivina spissa* form

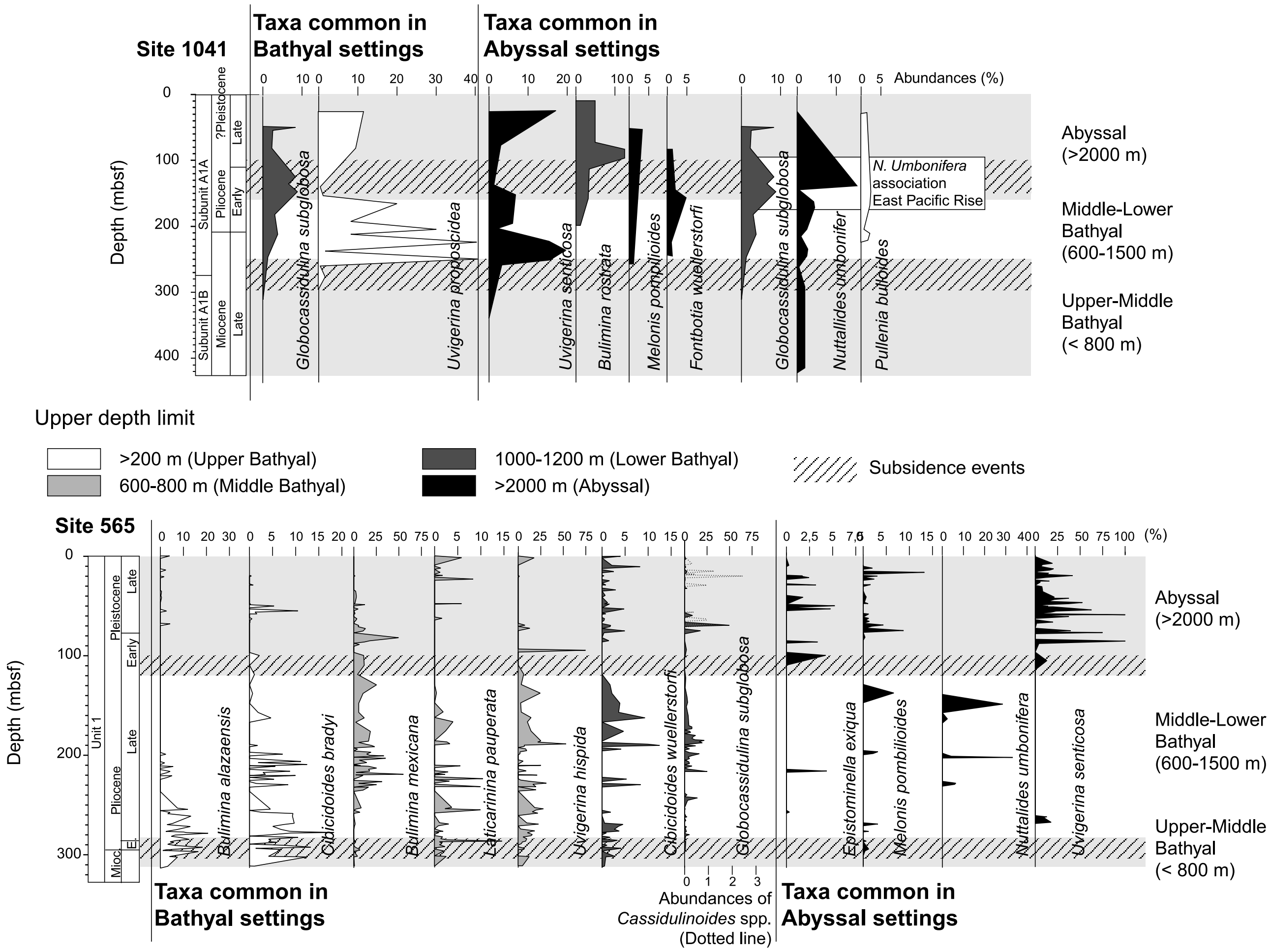

Figure 2. Vertical distribution of bathymetric indices in benthic foraminiferal assemblages from ODP Site 1041 and DSDP Site 565 based on a comparison with Holocene fauna from similar environments. Depth classification after *Van Morkhoven et al.* [1986].

nearly 80% of modern assemblages in dysaerobic setting (depositional environment with 0.1–1.0 ml of dissolved oxygen per liter of water) off southern California, shows peak abundances in a relatively narrow interval (219–204 mbsf) above the maximum abundances of uvigerinids, therefore excluding organic fluxes and/or seafloor ventilation as the main factors controlling the distribution of uvigerinids at Site 1041. Moreover, bolivinds, which are also regarded as indices of dysaerobic conditions and show peak abundances in eutrophic and oxygen-depleted environments [*Bernhard and Sen Gupta*, 1999], show maximum abundance below the maximal distribution of uvigerinids. For these reasons, the change observed in the benthic foraminiferal assemblages and particularly in the record of uvigerinids, is better explained as resulting from rapidly increasing water depth close to the Miocene-Pliocene boundary (from ~200 to ~2000 m of water depth).

[13] Above this level, a younger gradient of rapid deepening in the middle slope is possibly recognizable at both DSDP Site 565 and ODP Site 1041 between 150 and 100 mbsf, where the shallower-water hispid uvigerinids disappear and the abyssal morphotype *U. senticosa* becomes a common component of the assemblages. Accordingly, *Stilostomella* and other common components of lower bathyal-abyssal (≥2000 m) faunas in the eastern margin of the Pacific Ocean increase in abundance and become continuously present in the benthic foraminiferal assemblage. At ODP Site 1041, this phase culminates with the concomitant increase of *Pullenia bulloides*, *N. umbonifera*, and *G. subglobosa* that, at about 110 mbsf, reflects the emplacement of an assemblage comparable with that of the modern East Pacific Rise [water depth 2850–4649 m, see *Murray*, 1991]. In summary, the vertical distribution of benthic foraminiferal assemblages at DSDP Site 565 and ODP Site 1041 indicate a stepwise deepening of the middle-slope area from the late Miocene to early Pleistocene (6.5–1.8 Ma) (Figure 3). During this time interval, water-depth markers suggest two major pulses of forearc deepening. The first pulse took place at the late Miocene-Pliocene boundary (~6.5–5 Ma), and the second occurred at the late Pliocene-Pliocene-Pleistocene limit (~2.4 Ma).

3. Sedimentary Sequence Setting

[14] The dip of sedimentary bedding and structures related to deformation were measured at ODP Site 1041 (Figure 4).

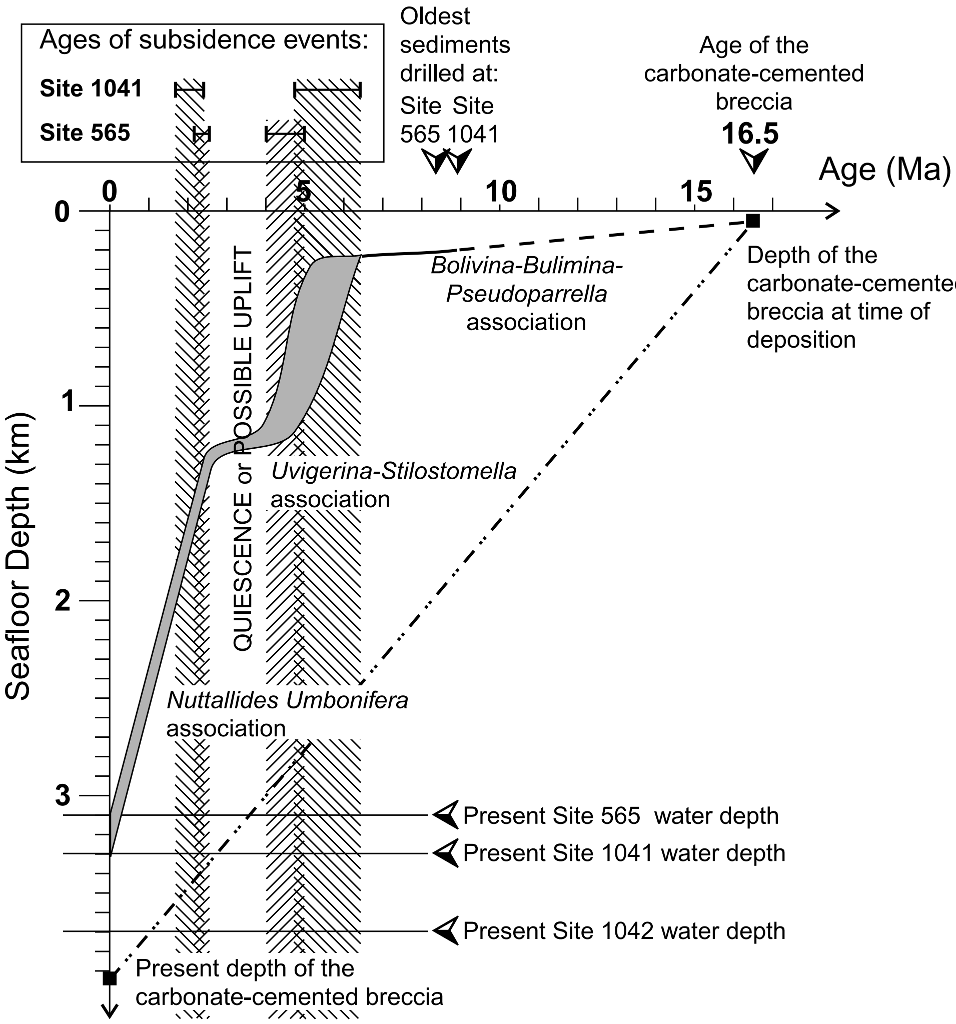

Figure 3. Water depth reconstruction combining ODP Sites 1042 and 1041 and DSDP Site 565 data and showing initial slow subsidence followed by more rapid subsidence, occurring in two steps, to modern depth. Vertical bars show uncertainties in age estimates.

Bedding dip ranges from 5° to 85° in the upper 280 m of the cored section, defining structural Domain 1. Nonsystematic bedding dips occur over short depth intervals that correlate with increases in the density of faults cutting the cores, suggesting that the changing dip reflects drag effects associated with small-offset faults cutting the slope apron. After cleaning the data of fault influence deformation, the down-section trend in dip variation shows two excursions, where dips increase with age and depth (Figure 4). The boundary between the two excursions is coincident with the quiescent period in the subsidence trends (Figure 3). Although accurate determination of in situ dip direction based on core samples is degraded by drilling disturbance, the seismic sections show a predominant southwestward downslope dip of the bedding fabric of the slope apron sequence (Figure 5). This observation suggests that the recorded change in bedding dip within the cores is linked to downslope tilting of the margin toward the trench. Whole margin deformation by tilting is in accordance with the igneous nature of the margin wedge, which provides a rigid base to slope deposits. Estimating the amount of margin tilting from the strata dip is difficult because it requires the assumption that sedimentary bedding was originally horizontal. The fine-grained nature of the muddy deposits of the slope apron implies that they accumulated at a depositional dip not much different than that of the existing slope angle, which is about 5°–7°. The higher dip limit of 85° at the base of Domain 1 is, on the other hand, very high and may reflect further tectonic disturbance or original deposition at a steeper angle. The data are too sparse to quantify the rates of forearc tilting, but a qualitative analysis suggests a linear trend for both excursions in measured dip angle (Figure 4). Beneath 280 mbsf, the dip of the apron sediment bedding abruptly decreases becoming consistently oriented between 20° and 45°, with a mean of 33° (Figure 4). This lower interval of late Miocene sediment defines structural Domain 2, which is also characterized by the absence of microfaults. The boundary between the two structural domains corresponds to a slight change in sediment grain size defining two lithological apron subunits [*Kimura et al.*, 1997] and indicates the presence of an angular unconformity. The attitude of bedding in Domain 2 implies that the pre-Pliocene sediment was tilted downward toward the trench as a unit. The boundary between the two domains is within

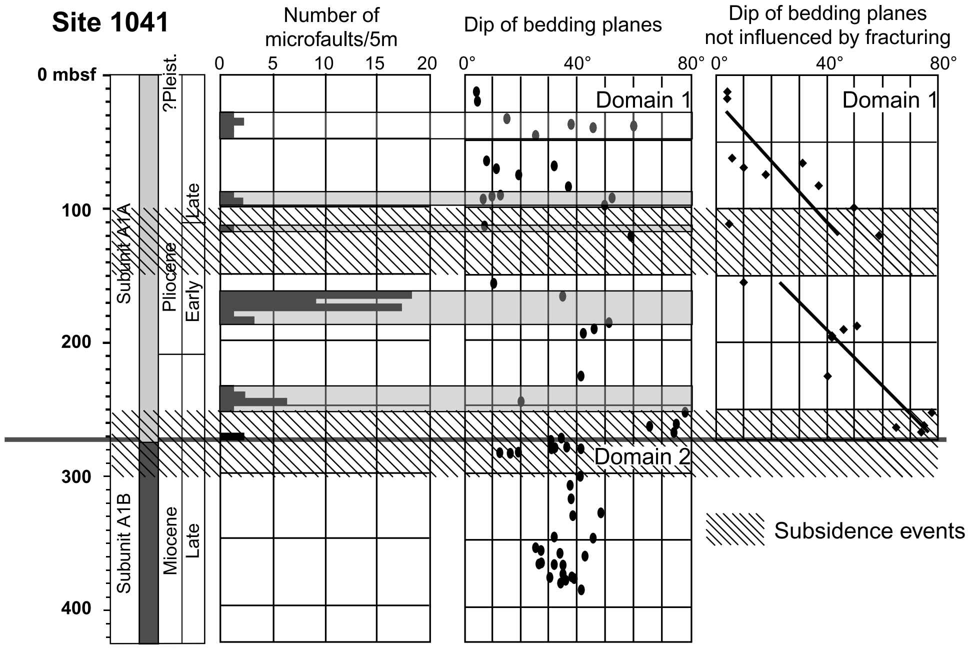

Figure 4. Diagram of major structural features along ODP Site 1041 section, including the number of microfaults every 5-m depth, variation in dip of sediment with depth. On the basis of dip, ODP Site 1041 section has been divided in two structural domains, whose boundary corresponds closely to the lithologic boundary between Subunits A1A and A1B. Domain 1 bedding dips, after cleaning the data recorded in deformed intervals (shown in the rightmost column), increase linearly with depth and age. This trend is repeated twice.

the period of time for which we infer the beginning of fast subsidence (Figure 4). Unfortunately, the lack of control on the dip direction orientation does not allow the calculation of the initial amount of tilting.

4. Marine Forearc Deformation

[15] In order to evaluate the subsidence history of the margin, we have attempted to identify the boundary between the shallow water sediment and the sediment recording the rapid subsidence of the margin. Using logging data from ODP Site 1041 we have located the boundary on line CR-20 shot ~1 km from the drill site [*McIntosh et al.*, 1993; *Kimura et al.*, 1997]. To improve seismic data resolution we have applied a poststack statistical predictive deconvolution followed by a spatial f-x filter and a time migration with velocities constrained by the logging data and a wide-angle profile collected in the vicinity [*Christeson et al.*, 1999]. In the middle-upper slope (common midpoint (cmp) 1 to ~1400 in Figure 5a) the sediment cover exhibits strata with a roughly slope-parallel attitude. The strata display moderate continuity and are cut by landward dipping normal faults, better imaged in the upper slope [*McIntosh et al.*, 1993]. However, the stratification becomes obscured downslope approaching ODP Site 1041 (Figure 5).

[16] The boundary between the early-middle Miocene shallow water sediment and the rapid-subsidence sequence is marked by a sudden increase in the *P* wave velocity gradient at ~250 mbsf [*Kimura et al.*, 1997] and occurs at ~0.295 s two-way time (TWT) below seafloor. At the projection of ODP Site 1041, the 0.295 s TWT is coincident with a change from a shallow, relatively transparent sediment sequence to a more reflective, deeper sediment package. This boundary can be followed upslope as it becomes progressively deeper (in TWT) below the seafloor (Figure 5b). We tested several predictive deconvolution filters and amplitude-balancing window lengths to check that this change in character is not an artifact of processing. The boundary can be traced along the slope to an angular unconformity clearer in the upper slope (at cmp 1–700, Figure 5a).

[17] The top of the margin wedge displays several large offsets that might have been created by landward dipping normal faults (Figure 5). Drilling and seismic data along the margin have been interpreted to indicate that the top of the margin wedge corresponds to a subaerial unconformity [e.g., *Vannucchi et al.*, 2001; *Ranero and von Huene*, 2000], and thus the faulting would imply significant extension across much of the marine forearc. However, faults with large offset are not imaged in the overlying sediment cover and do not cut the late Miocene unconformity implying that they have not been formed recently. Large-offset faulting predates the beginning of rapid subsidence of the margin and did not contribute to the deepening. Small-offset faulting imaged across the forearc sediment is probably a response to the progressive subsidence of the forearc rather than the origin of the subsidence. Based on regional geology and seismic data, *McIntosh et al.* [1993] suggest that faulting initiated at ~22 or ~5 Ma. The ~5 Ma timing is roughly coeval with the rapid subsidence recorded in the benthic fauna assemblages. Extension measured on all faults in the middle-upper slope in the ODP-DSDP area is 7–15% [*McIntosh et al.*, 1993], this number being an upper estimate

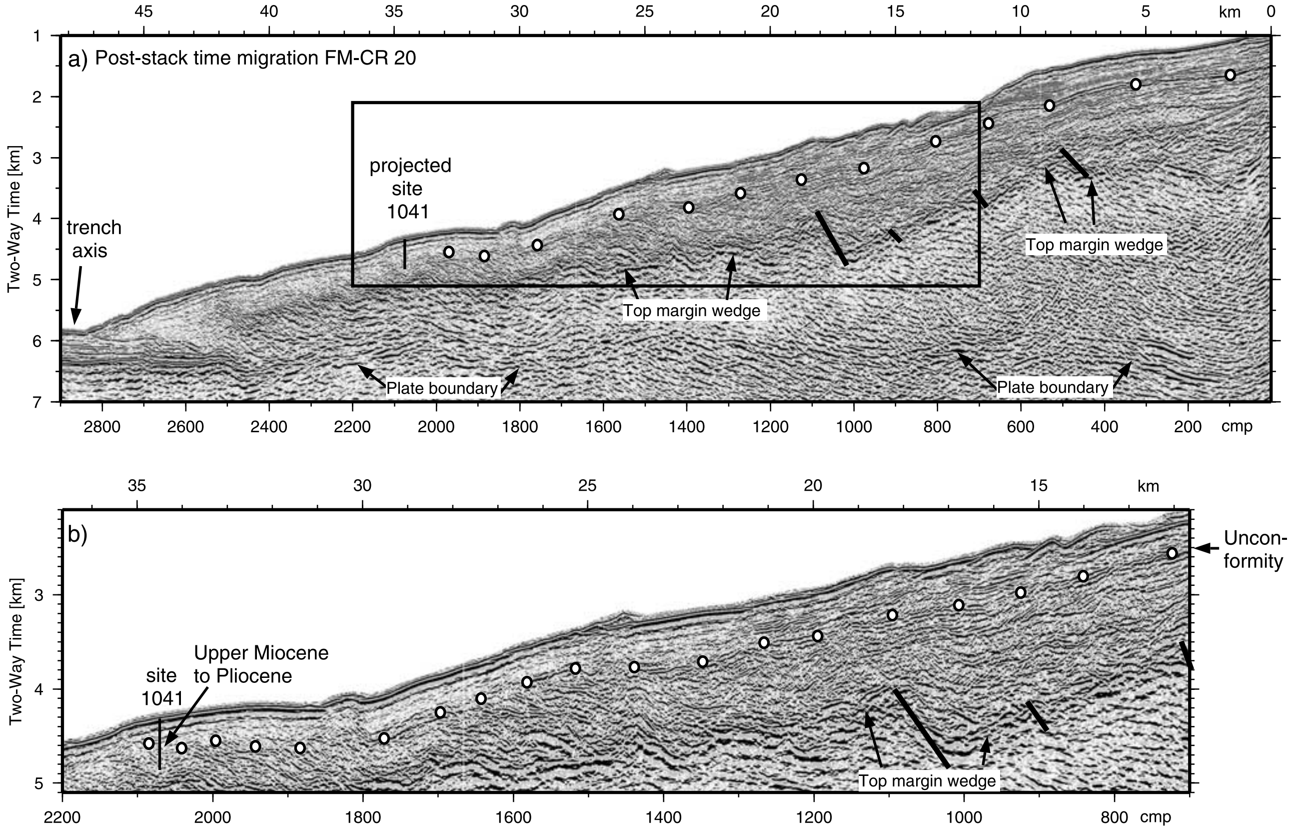

Figure 5. Seismic reflection profile FM-CR20 shot near ODP Site 1041. (a) Poststack time migration showing the slope sediment cover overlying the basement of the margin wedge. Sediment cover thins and stratification becomes obscured downslope. ODP Site 1041 is ~1 km from the seismic profile. The margin wedge shows some large offsets in the middle-upper slope that have been interpreted as large landward dipping faults (bold black lines). In the same area, the sediment cover is cut by small-offset faulting. Dots indicate the unconformity that separates upper-middle Miocene shallow water sediment from upper Miocene to Recent deeper water sediment. (b) Detail showing the location of the drill ODP Site 1041 and the interpreted unconformity.

for the late Neogene phase of rapid subsidence because some of the faults are older.

5. Discussion

5.1. Subduction Erosion: Rates and its Effects on Geochemical Fluxes

[18] Paleontological and structural information on slope apron sediment drilled during DSDP Leg 84 and ODP Leg 170 traces the history of vertical tectonism of the marine forearc of Costa Rica. For the midslope area, these data document the dominance of forearc subsidence from upper bathyal (200–600 m) in the early to middle Miocene (~16–17 Ma) to its modern abyssal depths (>2000 m) (Figure 3). From middle Miocene to late Miocene, sea level uplift of at least 100 m occurred along the Nicoya coast [*Gardner et al.*, 1992], but this marine transgression is of minor magnitude compared with the tens of hundreds of meters of subsidence recorded at DSDP Site 565 and ODP Site 1041. The subsidence rate was slow from middle Miocene to late Miocene and increased dramatically starting at about 6.5–5 Ma, taking place in two steps: the first occurred close to the Miocene-Pliocene boundary, the second close to the Pliocene-Pleistocene transition (Figure 3).

[19] These two pulses of rapid forearc subsidence correspond to regional unconformities recognized both offshore and along the Nicoya coast. Offshore, an angular unconformity separates the upper Miocene to Recent strata from an older sequence deposited in shallow water (Figure 5). An angular unconformity of similar age has been mapped in the continental shelf of Nicaragua [*Ranero et al.*, 2000]. The continental shelf sedimentation is represented by the Montezuma Formation, a shallow water deposit locally overlying the igneous basement of the Nicoya complex. The Montezuma Formation dates the marine transgression across the wave-base-eroded surface of basement rock to the late Miocene-early Pliocene [*Mora*, 1985] and several minor cycles of younger age, small-scale uplift, and subsidence of the coast (T. Gardner et al., unpublished data, 2002). These vertical events recorded along the coast have been related to margin response to subducting seamounts [*Gardner et al.*, 2001], but small coastal uplifts accompanying great margin subsidence are often observed simultaneously [*Lallemand*, 1995].

[20] The rapid margin subsidence of about 0.55–0.6 km Myr^{-1} during the last 6.5–5 Myr cannot be accounted for by sea level changes. ODP Site 1042, near the base of the slope, drilled Late-early Miocene (16.5 Ma) shallow water

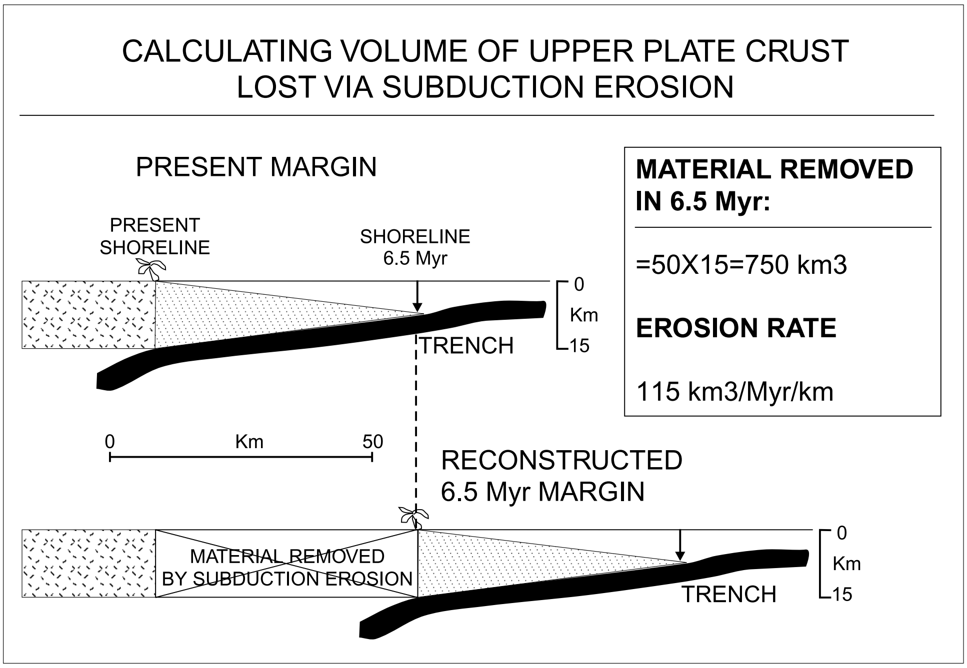

Figure 6. Cartoon showing the mass removal as calculated in the present paper.

limestone overlying the Nicoya complex basement was drilled at ODP Site 1042 near the base of the slope. Assuming that the structure of the Neogene margin was similar to the present configuration, the limestone was deposited over a 14–16 km thick basement of 16.5 Ma. However, the limestone now lies at a depth of ~4 km above a basement that is only about 2 km thick. To explain the current depth of the top of the margin wedge at ODP Site 1042, it is necessary to invoke a mechanism that has thinned the original upper plate by 12–14 km. Elsewhere, thinning of the overriding plate at convergent margins has been related to extension driven by slab rollback, eventually leading to back-arc seafloor spreading [*Uyeda and Kanamori*, 1979]. Normal faulting has been seismically imaged across the slope along much of the Costa Rican margin [*McIntosh et al.*, 1993; *Ranero and von Huene*, 2000]. However, measuring fault offsets along a profile in the vicinity of the drill hole transect can only account for a small amount of the thinning inferred for the upper plate (Figure 5). Plate kinematics consideration for the area [e.g., *Barckhausen et al.*, 2001] also indicate that the subducting ocean plate offshore the Nicoya Peninsula has probably become younger in the last few million years, increasing buoyancy, which, together with the modest amount of extension by normal faulting, makes slab rollback a less likely mechanism to explain the subsidence during Neogene time. Thus subduction erosion is the inferred major process causing the thinning of the upper plate in this area of the Middle America Trench [*Ranero and von Huene*, 2000; *Vannucchi et al.*, 2001] and along other areas of Costa Rica and Nicaragua [*Ranero et al.*, 2000; *Ranero and von Huene*, 2000; *von Huene et al.*, 2000]. This mechanism involves the removal of material from the underside of the upper plate and its transport deep into the subduction zone. The volume of missing material can be calculated by assuming that the cross-sectional geometry and surface profile of the present margin is similar to the configuration of the Miocene and Pliocene margins (Figure 6). For our calculations, we assume that the erosion rate has been constant during the last ~6.5 Myr and that the load of the upper plate on the subducting plate has remained essentially the same through time because of the rapid deformation. This assumption allows simplification of the modeling and automatically accounts for isostatic effects. However, our reconstruction, as outlined below, provides evidence for slab dip shallowing during the last ~5–6.5 Myr because of the Cocos Ridge entering the subduction zone (Figure 7). This model is thus conservative, and the volume removal rates presented in this paper are minimum values.

[21] Considering the thickness of the overriding plate at the coastline as calculated by *Sallares et al.* [2001] at 14 km and by *Christeson et al.* [1999] at 16 km, the volume loss since the late Miocene (6.5 Ma) is 700–800 km^3 km^{-1} (Figure 6) along the trench, equivalent to a rate of 107–123 km^3 Myr^{-1} km^{-1}. The new estimates of overriding plate thickness increases the calculated volume loss with respect to the estimates of *Vannucchi et al.* [2001], because they considered a long-term rate based on the age of the limestone breccia overlying the margin wedge. This late Neogene-Quaternary rate of subduction erosion offshore of the Nicoya Peninsula is well above the long-term (>10 Myr) global average rate of subduction erosion estimated by *Scholl and von Huene* [2001] to be ~40 km^3 Myr^{-1} km^{-1} of trench. Long-term rates estimated for other eroding margins are 55–95 km^3 Myr^{-1} km^{-1} of trench for Japan [*von Huene and Lallemand*, 1990; *Lallemand et al.*, 1992], 45–50 km^3 Myr^{-1} km^{-1} for north Chile [*von Huene and Ranero*, 2003], 31–60 km^3 Myr^{-1} km^{-1} for Peru [*von Huene and Lallemand*, 1990; *Lallemand et al.*, 1992; *Clift et al.*, 2003], 31–47 km^3 Myr^{-1} km^{-1} for South Sandwich Trench [*Vanneste and Larter*, 2002], and 34 km^3 Myr^{-1} km^{-1} for Tonga Trench [*Clift and MacLeod*, 1999]. Short-term rates of 320 km^3 Myr^{-1} km^{-1} have been estimated for Peru since the arrival of Nazca Ridge 11 Myr [*Clift et al.*, 2003] and of 74 km^3 Myr^{-1} km^{-1} for the Tonga Trench in the sector where

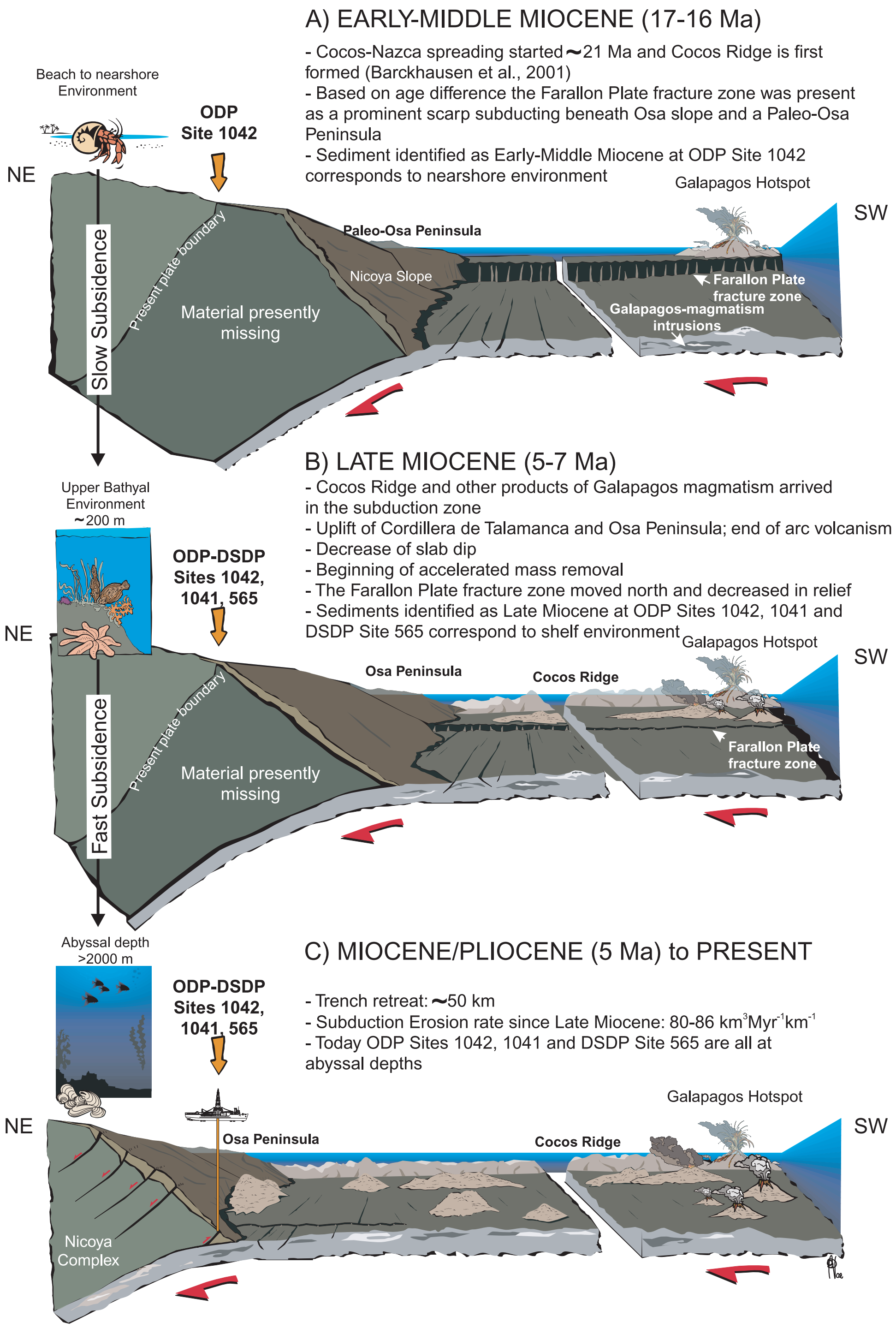

Figure 7. Perspective diagrams of the Miocene to present tectonic evolution along the Costa Rica convergent margin. Present plate boundary position at Miocene time has been calculated based on a forearc basement tilting of 30° since that time.

the Louisville Ridge has been subducting [*Ballance et al.*, 1989].

[22] The subsidence curves for the Costa Rica margin document a high degree of time variability in the rates of erosion and subsidence, becoming similar only over tens of millions of years to the global average of that in the work of *von Huene and Scholl* [1993].

[23] The subduction erosion rate for Costa Rica must impact the physical and geochemical character of the subduction zone and its overlying mantle lithosphere and asthenosphere. The effect of crustal material subducted at trenches is generally thought to reflect the influx of oceanic sediment to the mantle less the volume of sediment accreted to the bedrock framework of the margin [*Morris et al.*, 2002]. At a sediment thickness of 400 m at the trench [*Kimura et al.*, 1997], the volume of oceanic sediment subducted into the Central America subduction zone off the Nicoya Peninsula is 36.0 km^3 Myr^{-1} km^{-1}, calculated

Table 1. Middle America Trench Influx Calculations Based on Leg 170 Parameters

Parameter	Value
Convergence rate	9 cm yr^{-1}
Thickness of incoming section	400 m total (180 m without carbonates)
Density of oceanic sediments	1.41 g cm^{-3}
Water, wt%	48.7%
Density of forearc basement rocks	1.8 g cm^{-3}
Oceanic sediment influx	36 km^3 Myr^{-1} km^{-1}, 2.6 × 10^{10} t Myr^{-1} km^{-1}
Eroded mass influx, calculated using *Vannucchi et al.*'s [2001] erosion rate of 35 km^3 Myr^{-1} km^{-1}	6.3 × 10^{10} t Myr^{-1} km^{-1}
Eroded mass influx, calculated using the present paper erosion rate of 115 km^3 Myr^{-1} km^{-1}	20.7 × 10^{10} t Myr^{-1} km^{-1}

with the parameters given by *Kimura et al.* [1997] and reported in Table 1. This is equivalent to a material flux of 2.6 × 10^{10} t Myr^{-1} km^{-1}, after correction for the water content (48.7% H_2O, [*Kimura et al.*, 1997]). The total volume of the eroded material is 107–123 km^3 Myr^{-1} km^{-1} (average 115 km^3 Myr^{-1} km^{-1}) since ~6.5 Myr, yielding to an eroded material flux of 20.7 × 10^{10} t Myr^{-1} km^{-1}, one order of magnitude larger than the oceanic sediment flux (Table 1). Consequently, the eroded material contaminates and dilutes the flux of the oceanic sediment to an extent that it must dominate the return flux of the crustal material to the mantle and affects the mass balance of chemical species across convergent margins. For example, the high flux of crustal material eroded from the forearc could provide an explanation for why ^{10}Be concentration in the Costa Rican arc volcanics is exceptionally low [*Morris et al.*, 2002]. Measurable ^{10}Be occurs in the upper 180 m of the incoming oceanic sediment (Pliocene to present noncarbonate sediment) with an average concentration of ~320 atoms g^{-1} [*Morris et al.*, 2002]. Thus the influx of ^{10}Be from the trench can be as high as 38 × 10^{17} at Myr^{-1} km^{-1}. Without the eroded material contamination, the ^{10}Be influx would only be diluted by half, i.e., 17 × 10^{17} at Myr^{-1} km^{-1}, by the underlying ~220-m-thick section of non-^{10}Be bearing carbonate forming the lower part of the sediment section entering the subduction zone [*Kimura et al.*, 1997]. The large volume of eroded material decreases the ^{10}Be influx by one order of magnitude, i.e., 2.5 × 10^{17} at Myr^{-1} km^{-1}. Thus the very low ^{10}Be concentration in the volcanic arc of Costa Rica does not require accretion of sediments and may be explained by dilution with eroded material. These results require that subduction erosion must be considered when a mass balance of convergent margins is performed.

5.2. The Response of the Continental Margin to the Subduction of the Cocos Ridge

[24] The sudden increase in subsidence rate of about ~5–6.5 Ma indicates a change in subduction zone parameters. A prominent feature that seems to greatly influence subduction processes in the area is the Cocos Ridge, which is the trace of the Galapagos hot spot on the Cocos Plate (Figure 1). The crest of Cocos Ridge subducts beneath southeastern Costa Rica, but as discussed below, its influence probably extends further northwest along the subduction zone. Crust at the crest of Cocos Ridge is ~20 km thick [*Walther*, 2002], but the magmatic products of the hot spot activity have reached a much broader area. West of the ridge, from 84°W to about 85°30′W, a flanking zone of seamounts overlying thinner oceanic crust collides with the margin, while farther westward the plate underthrusting the Nicoya Peninsula lacks large bathymetric highs [*von Huene et al.*, 2000] (Figure 1). The DSDP-ODP drilling area offshore Nicoya Peninsula (~86°W) is northwest of the seamount region and the nearest major edifice, Fisher Seamount which formed ~14 Ma on 19 Ma Cocos crust by Galapagos hot spot volcanism [*Werner et al.*, 1999], is the closest to the study area. ODP Site 1039, located on 24 Ma Cocos Plate crust [*Barckhausen et al.*, 2001], did not reach basement because a thick intrusive sill of pyroxene gabbro closely overlying basement was not fully penetrated. The intrusive gabbro has a Galapagos geochemical affinity [*Kimura et al.*, 1997] and is 15 Ma (K/Ar date) (J. Griffin, personal communication, 1998). This age, comparable to that of Fisher Seamount, is much younger than the magnetic-anomaly-based age of the ocean crust at ODP Site 1039. The presence of Galapagos magmatism in the study area implies a wide zone of hot spot perturbed crust so that the Nicoya margin, 250 km to the northwest of the main hot spot trace of the Cocos Ridge, has been influenced by subduction of more buoyant crust, and possibly in the past, by crust topped by now-subducted seamounts.

[25] The Cocos Ridge is a 2-km-high and >200-km-wide edifice formed by the northeastward motion of the Cocos Plate over the Galapagos hot spot (Figure 1). The subduction of this young and buoyant crust causes slab shallowing beneath Middle America, most prominent at Osa Peninsula, where the Wadati-Benioff Zone is not observed deeper than 50 km suggesting a subhorizontal slab for the forearc [*Protti et al.*, 1995]. Two hundred and fifty kilometers to the northwest, offshore of the Nicoya Peninsula, the inclination of the slab is 23° for the offshore area of the forearc, increasing to 80° beneath the arc [*Protti et al.*, 1995]. Considering the major impact that the subduction of the Cocos Ridge must have had on the tectonic configuration of the margin, all reconstructions of the tectonic evolution of the margin depend crucially on determining the time when the Cocos Ridge entered the subduction zone of the Middle America Trench. A Pleistocene (1–0.5 Ma) arrival of the ridge at the trench has been inferred based on geometric considerations of the relative offset position across the Panama Fracture Zone between the Malpelo and the Cocos Ridges [*Lonsdale and Klitgord*, 1978] and on the faster Quaternary uplift of the Osa Peninsula [*Gardner et al.*, 1992]. However, the geology of the continental forearc indicates older ages of collision: the age of the inversion of the forearc Terraba Basin [*Kolarsky et al.*, 1995], the extinction of calc-alkaline magmatic activity along the Cordillera de Talamanca 3.5 Ma [*Drummond et al.*, 1995; *Gans et al.*, 2002], the emplacement of adakitic rocks derived from partial melting of the underthrusting

ridge [*Abratis and Wörner*, 2001] and, perhaps most definitively, the implications of thermochronological information, fission track, $^{40}Ar/^{39}Ar$ and Rb/Sr data, on the uplift of the Cordillera de Talamanca [*Graefe et al.*, 2002] constrain the arrival of the Cocos Ridge to the trench between 5 and 7 Ma. The extinct magmatic arc in the Cordillera de Talamanca also documents the influence of the subduction of the Cocos Ridge on the evolution of the forearc. This is one of the major outcomes of new field and $^{40}Ar/^{39}Ar$ studies, which also provide innovative insights into how the Central American volcanic arc evolved since the early Miocene [*Gans et al.*, 2002]. Arc magmatism dates back to at least 24 Ma, but volcanism has been strongly episodic. There has been a 30° counterclockwise rotation of the arc from its middle Miocene position to the present volcanic front, with a pole of rotation centered on southern Costa Rica. The early-middle Miocene arc (24–15 Ma) extends from southeast Nicaragua to the Cordillera de Talamanca in southern Costa Rica. At ~3.5 Ma volcanism shut off in southern Costa Rica due to subduction of the Cocos Ridge. The beginning of the uplift of the Cordillera de Talamanca during the late Miocene indicates, in agreement with the plate motion models of *DeMets* [2001] and the present convergence direction [*DeMets et al.*, 1990] (Figure 1), that the subducting Cocos Ridge has been stationary during the last ~5–7 Myr in southeast Costa Rica without any significant drifting along the margin. The age of impact of the Cocos Ridge also correlates to the beginning of rapid subsidence of the Nicoya forearc at 5–6.5 Ma, indicating that the swell related to the hot spot activity probably extends farther than the area of thick crust of the Cocos Ridge. This hypothesis is supported by the bathymetry of the Middle America Trench (Figure 1). The trench axis steadily shallows from offshore Nicaragua toward southern Costa Rica suggesting that the long wavelength relief of the hot spot track affects the entire Costa Rica subduction zone.

[26] Based on these considerations, in the early-middle Miocene (~17 Ma), during nearshore deposition of the rock drilled at ODP Site 1042, the Cocos Ridge and the Cocos oceanic crust modified by Galapagos magmatic intrusions were far from the trench (Figure 7a). At that time the Farallon Plate fracture zone [*Barckhausen et al.*, 2001] could have been a morphologically prominent feature (Figure 7a) but any evidence has been subducted (Figure 7).

[27] The arrival of the Cocos Ridge at the trench may have suddenly changed the configuration of the subduction system, with an abrupt shallowing of the subducting slab (Figure 7b). This slab dip change may have caused initial forearc uplift, but subsequent basal erosion has dominated the subduction zone. In fact, at the Osa Peninsula, where the thickest crust of the hot spot track is currently subducting the upper plate beneath the Osa shelf is reduced to <7 km thick, the thinnest along the margin [*Ranero and von Huene*, 2000]. Moreover, the subduction of the morphological highs of the hot spot perturbed crust might have contributed to the massive breakage of the margin enhancing overpressure and hydraulic fracturing [*Dominguez et al.*, 2000], decreasing the reaction time of the margin to material removal.

[28] Geological and geophysical data collected offshore of the Nicoya Peninsula imply that along the Costa Rica Pacific margin, the effect of Cocos Ridge subduction and related hot spot perturbed buoyant crust altered the dynamic equilibrium of the margin taper, defined here as a composite stack of basement rock and slope apron sediment (Figures 7b and 7c). Beginning at 6.5 Ma, off the Nicoya Peninsula, the underthrusting of oceanic crust modified by Galapagos hot spot volcanism initiated rapid late Miocene subsidence recorded by the benthic foraminifera recovered at DSDP Site 565 and ODP Site 1041 (Figures 7b and 7c). The warmer underthrusting slab reduced the descent angle enough to change the dynamics controlling slope taper sufficiently to increase the rate of basal subduction erosion and thus subsidence. The end product, similar to the situation in the Osa area, is an enhanced rate of forearc thinning. However, in contrast to the Osa region, Nicoya Peninsula subsidence occurred in the absence of both forearc basin inversion, as represented by Fila Costeña, and strong and long-term coastal uplift, as represented by the Cordillera de Talamanca. This reflects the absence of subducting a continuous morphological high. Inboard of subducting seamounts, Holocene uplift rates in Nicoya Peninsula range from 3.0 to 6.5 m kyr^{-1} [*Marshall and Anderson*, 1995; *Gardner et al.*, 2001]. These rates are an order of magnitude greater than those observed inboard of the smooth subducting crust to the north. Subduction of the Cocos Ridge involves uplift of the Osa Peninsula/Platform and oversteepening of the continental slope [*von Huene et al.*, 2000]. Onshore, uplift has been accompanied by shortening and formation of a coastal fold-and-thrust belt, the Fila Costeña. The thrust belt of the Fila Costeña is only shallowly rooted and does not involve, for example, the largely mafic rock of Cretaceous age that forms the basement of Osa Peninsula.

[29] After an abrupt beginning, rapid subsidence was interrupted by a period of low-to-no subsidence or possible slight uplift (Figure 3). We speculate that quiescent period related either to a dramatic decrease in tectonic erosion rate or even perhaps to a limited period of accretion during which tectonic erosion may not have occurred at all. The slowing down of the erosional process might have been triggered by slight changes in the parameters governing the dynamic equilibrium of the taper angle, such as the sedimentation rate of trench deposits, or the thickness of the magmatic material contributed by the Galapagos hot spot.

6. Conclusions

[30] Offshore drilling data from the Costa Rica margin document rapid subsidence of the forearc. Subsidence did not occur as a steady process but occurred with a variable rate since the early Miocene. Benthic foraminifera indicate that 16.5 Ma beds of nearshore limestone breccia recovered at a depth of ~4000 m (ODP Site 1042 [*Vannucchi et al.*, 2001]) near the base of the lower continental slope, subsided from ~200 m depth to its present abyssal depth during the last 5–6.5 Myr. Prior to this time, subsidence proceeded only slowly at about 200–500 m in 10 Myr. After 5–6.5 Ma subsidence increased by a factor of about 10. The beginning of rapid subsidence is coincident with the arrival of the Cocos Ridge crest at the Costa Rican trench about 250 km southwest of Nicoya Peninsula. This event changed the configuration and dynamics of the Costa Rica sector of the Middle America Trench. The thick and/or warm (thermally rejuvenated) ocean crust accompanying the Cocos Ridge

crest extends as a broad swell across the entire plate subducting underneath Costa Rica. The subduction of the anomalous lithosphere is thought to have modified the slab angle and modified the seaward taper of margin bedrock and slope apron deposits and induced rapid subduction erosion from the ridge northwestward and beneath the length of the Nicoya Peninsula. Subsidence occurred in two major steps with a relative quiescent interval separating them at the Pliocene-Pleistocene boundary. This quiescence may either be an interval characterized by minor erosion, by accretion or by a spatial reorganization of the two processes along the subducting slab, in the hypothesis that they are not mutually exclusive.

[31] Calculated mass removal rate (i.e., crustal thinning) changes remarkably from a long-term rate inferred over 16.5 Myr of $\sim$45 km^3 Myr^{-1} km^{-1}, to a post-6.5 Ma rate of 107–123 km^3 Myr^{-1} km^{-1}. This value is high compared with the long-term rates of other margins, as Japan, Chile, Peru, Tonga, and South Sandwich. Short-term rates of mass removal have been calculated for Peru (46 km^3 Myr^{-1} km^{-1} [*von Huene and Lallemand*, 1990]) and the Louisville Ridge sector of the Tonga Trench (74 km^3 Myr^{-1} km^{-1} [*Ballance et al.*, 1989]) and they are commonly a factor from 1.5 to 3 higher than long-term rates. Costa Rica short-term/long-term rate comparison is within the above general proportion, but they are surprisingly high if related to the tectonic setting with no major ridges having affected the margin offshore Nicoya Peninsula. The Peru short-term rate value of mass removal of 320 km^3 Myr^{-1} km^{-1} has been calculated for the time interval and in the trench sector where the Nazca Ridge subducted. Also, the Tonga rate has been estimated during the accelerated tectonic erosion caused by the Louisville Ridge in the area where the ridge subducted and the value is comparable to Costa Rica, where the rate has been calculated 250 km from the Cocos Ridge sector.

[32] Our study of the subsidence history of the Costa Rica margin shows that material transport of oceanic sediment and material tectonically eroded from the upper plate is not constant over time intervals of 5–10 Myr and that the geodynamic setting of the margin can change dramatically in just a few million years.

[33] **Acknowledgments.** The stack of the seismic reflection profile FM-CR20 was downloaded from the UTIG web site (www.ig.utexas.edu). Peter D. Clift, Serge Lallemand, and the associate editor Bruce Nelson are gratefully acknowledged for their revisions. This paper was supported by Consiglio Nazionale delle Ricerche (grant CNRG0037AE to P. Vannucchi). This work is contribution 31 of the Sonderforschungsbereich 574 "Volatiles and fluids in subduction zones" from Kiel University.

References

Abratis, M., and G. Wörner, Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm, *Geology*, *29*, 127–130, 2001.

Aubouin, J., R. von Huene, M. Baltuk, R. Arnott, and J. Bourgois, Leg 84 of the Deep Sea Drilling Project, subduction without accretion: Middle America Trench off Guatemala, *Nature*, *247*, 458–460, 1982.

Ballance, P. F., D. W. Scholl, T. L. Vallier, A. J. Stevenson, H. Ryan, and R. H. Herzer, Subduction of a Late Cretaceous seamount of the Louisville chain at the Tonga Trench: A model of normal and accelerated tectonic erosion, *Tectonics*, *8*, 953–962, 1989.

Baltuck, M., E. Taylor, and K. McDougall, Mass movement along the inner wall of the Middle America Trench, Costa Rica, *Initial Report DSDP Leg 84*, edited by R. von Huene and J. Aubouin, pp. 551–570, U.S. Govt. Print. Off., Washington, D. C., 1985.

Bandy, O. L., General correlation of foraminiferal structure with environment, paper presented at International Geological Congress, Copenhagen, 1960.

Barckhausen, U., C. R. Ranero, R. von Huene, S. C. Cande, and H. A. Roeser, Revised tectonic boundaries in the Cocos Plate off Costa Rica: Implications for the segmentation of the convergent margin and for plate tectonic models, *J. Geophys. Res.*, *106*, 19,207–19,220, 2001.

Bernhard, J. M., and B. K. Sen Gupta, Foraminifera of oxygen-depleted environments, in *Modern Foraminifera*, edited by B. K. Sen Gupta, pp. 201–216, Kluwer Acad., Norwell, Mass., 1999.

Bourgois, J., and G. Glaçon, Foraminifères planctoniques et paléoenvironnement post-Oligocène du mur interne de la fosse d'Amérique Centrale (Leg 84 du *Glomar Challenger*, Guatemala et Costa Rica), *Bull. Soc. Geol. Fr.*, *3*, 329–342, 1985.

Bourgois, J., J. Azéma, P. O. Baumgartner, J. Tournon, A. Desmet, and J. Aubouin, The geologic history of the Caribbean-Cocos Plate boundary with special reference to the Nicoya ophiolite complex (Costa Rica) and D.S.D.P. results (legs 67 and 84 off Guatemala): A synthesis, *Tectonophysics*, *108*, 1–32, 1984.

Christeson, G. L., K. D. McIntosh, T. H. Shipley, E. R. Flueh, and H. Goedde, Structure of the Costa Rica convergent margin, offshore Nicoya Peninsula, *J. Geophys. Res.*, *104*, 25,443–25,468, 1999.

Clift, P. D., and C. J. MacLeod, Slow rates of subduction erosion estimated from subsidence and tilting of the Tonga forearc, *Geology*, *27*, 411–414, 1999.

Clift, P. D., I. Pecher, N. Kukowski, and A. Hampel, Tectonic erosion of the Peruvian forearc, Lima Basin, by subduction and Nazca Ridge collision, *Tectonics*, *22*(3), 1023, doi:10.1029/2002TC001386, 2003.

DeMets, C., A new estimate for present-day Cocos-Caribbean Plate motion: Implications for slip along the Central American volcanic arc, *Geophys. Res. Lett.*, *28*, 4043–4046, 2001.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein, Current plate motions, *Geophys. J. Int.*, *101*, 425–478, 1990.

Dominguez, S., J. Malavieille, and S. E. Lallemand, Deformation of accretionary wedges in response to seamount subduction: Insights from sandbox experiments, *Tectonics*, *19*, 182–196, 2000.

Drummond, M. S., M. Bordelon, J. Z. de Boer, M. J. Defant, H. Bellon, and M. D. Feigenson, Igneous petrogenesis and tectonic setting of plutonic and volcanic rocks of the Cordillera de Talamanca, Costa Rica-Panama, Central American Arc, *Am. J. Sci.*, *295*, 875–919, 1995.

Gans, P. B., I. Macmillan, G. Alvarado-Induni, W. Perez, and C. Sigaran, Neogene evolution of the Costa Rican arc, paper presented at 2002 Annual Meeting, Geol. Soc. of Am., Denver, Colo., 27–30 Oct. 2002.

Gardner, T. W., D. Verdonk, N. M. Pinter, R. Slingerland, K. P. Furlong, T. F. Bullard, and S. G. Wells, Quaternary uplift astride the Cocos Ridge, Pacific coast, Costa Rica, *Geol. Soc. Am. Bull.*, *104*, 219–232, 1992.

Gardner, T., et al., Holocene forearc block rotation in response to seamount subduction, southeastern Peninsula de Nicoya, Costa Rica, *Geology*, *29*, 151–154, 2001.

Graefe, K., W. Frisch, I. M. Villa, and M. Meschede, Geodynamic evolution of southern Costa Rica related to low-angle subduction of the Cocos Ridge: Constraints from thermochronology, *Tectonophysics*, *348*, 187–204, 2002.

Hauff, F., K. Hoernle, H. U. Schmincke, and R. Werner, A mid Cretaceous origin for the Galapagos hotspot: Volcanological, petrological and geochemical evidence from Costa Rican oceanic crustal segments, *Geol. Rundsch.*, *86*, 141–155, 1997.

Hinz, K., R. von Huene, C. R. Ranero, and PACOMAR Working Group, Tectonic structure of the convergent Pacific margin offshore Costa Rica from multichannel seismic reflection data, *Tectonics*, *15*, 54–66, 1996.

Kimura, G., et al., *Proceedings of the Ocean Drilling Program, Initial Reports, Leg 170*, 458 pp., Ocean Drill. Program, College Station, Tex., 1997.

Kolarsky, R. A., P. Mann, and W. Montero, Island arc response to shallow subduction of the Cocos Ridge, Costa Rica, in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, edited by P. Mann, *Spec. Pap. Geol. Soc. Am.*, *295*, 235–262, 1995.

Lallemand, S. E., High-rates of arc consumption by subduction processes—Some consequences, *Geology*, *23*, 551–554, 1995.

Lallemand, S. E., P. Schnurle, and S. Manoussis, Reconstruction of subduction zone paleogeometries and quantification of upper plate material losses caused by tectonic erosion, *J. Geophys. Res.*, *97*, 217–239, 1992.

Lonsdale, P., and K. D. Klitgord, Structure and tectonic history of the eastern Panama Basin, *Geol. Soc. Am. Bull.*, *89*, 981–999, 1978.

Marshall, J. S., and R. S. Anderson, Quaternary uplift and seismic cycle deformation, Península de Nicoya, Costa Rica, *Geol. Soc. Am. Bull.*, *107*, 463–473, 1995.

McDougall, K., Benthic foraminiferal response to the emergence of the Isthmus of Panama and coincident paleoceanographic changes, *Mar. Micropaleontol.*, *28*, 133–169, 1996.

McIntosh, K., E. Silver, and T. Shipley, Evidence and mechanisms for forearc extension at the accretionary Costa Rica convergent margin, *Tectonics*, *12*, 1380–1392, 1993.
Meschede, M., P. Zweigel, and E. Kiefer, Subsidence and extension at a convergent plate margin: Evidence for subduction erosion off Costa Rica, *Terra Nova*, *11*, 112–117, 1999.
Mora, C. R., Sedimentología y geomorfología del sur de la Península de Nicoya (Provincia de Puntarenas, Costa Rica), Tesis de licentiatura, 148 pp., Esc. Centroam. de Geol., Univ. de Costa Rica, San José, Costa Rica, 1985.
Morris, J., R. Valentine, and T. Harrison, ^{10}Be imaging of sediment accretion and subduction along the northeast Japan and Costa Rica convergent margins, *Geology*, *30*, 59–62, 2002.
Murray, J. W., *Ecology and Paleoecology of Benthic Foraminifera*, 397 pp., Addison-Wesley-Longman, Reading, Mass., 1991.
Protti, M., F. Güendel, and K. McNally, Correlation between the age of the subducting Cocos Plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica, in *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, edited by P. Mann, *Spec. Pap. Geol. Soc. Am.*, *295*, 309–343, 1995.
Ranero, C. R., and R. von Huene, Subduction erosion along the Middle America convergent margin, *Nature*, *404*, 748–752, 2000.
Ranero, C. R., R. von Huene, E. Flueh, M. Duarte, and D. Baca, A cross section of the forearc Sandino Basin, Pacific Margin of Nicaragua, *Tectonics*, *19*, 335–357, 2000.
Sallares, V., J. J. Danobeitia, and E. R. Flueh, Lithospheric structure of the Costa Rican Isthmus: Effects of subduction zone magmatism on an oceanic plateau, *J. Geophys. Res.*, *106*, 621–643, 2001.
Schmiedl, G., et al., Recent benthic foraminifera from the eastern South Atlantic Ocean: Dependence on food supply and water masses, *Mar. Micropaleontol.*, *32*, 249–287, 1997.
Scholl, D. W., and R. von Huene, Mass flux of continental material at Cenozoic subduction zones—New global and trench-sector calculations using new geological and geophysical observations, *Eos Trans. AGU*, *82*(47), Fall Meet. Suppl., Abstract V11B-01, 2001.
Shipley, T. H., P. L. Stoffa, and D. F. Dean, Underthrust sediments, fluid migration paths, and mud volcanoes associated with the accretionary wedge off Costa Rica: Middle America Trench, *J. Geophys. Res.*, *95*, 8743–8752, 1990.
Shipley, T. H., K. D. McIntosh, E. A. Silver, and P. L. Stoffa, Three-dimensional seismic imaging of the Costa Rica accretionary prism: Structural diversity in a small volume of the lower slope, *J. Geophys. Res.*, *97*, 4439–4459, 1992.
Silver, E. A., M. J. Ellis, N. A. Breen, and T. H. Shipley, Comments on the growth of accretionary wedges, *Geology*, *13*, 6–9, 1985.
Sinton, C. W., R. A. Duncan, and P. Denyer, Nicoya Peninsula, Costa Rica: A single suite of Caribbean oceanic plateau magmas, *J. Geophys. Res.*, *102*, 15,507–15,520, 1997.
Smith, W. H. F., and D. T. Sandwell, Global seafloor topography from satellite altimetry and ship depth soundings, *Science*, *277*, 1956–1962, 1997.
Uyeda, S., and H. Kanamori, Back-arc opening and the mode of subduction, *J. Geophys. Res.*, *84*, 1049–1061, 1979.
Van Morkhoven, F. P. C. M., W. A. Berggren, and A. S. Edwards, Cenozoic cosmopolitan deep-water benthic foraminifera, *Bull. Cent. Rech. Explor. Prod. Elf Aquitaine*, *11*, 421, 1986.
Vanneste, L. E., and R. D. Larter, Sediment subduction, subduction erosion, and strain regime in the northern South Sandwich forearc, *J. Geophys. Res.*, *107*(B7), 2149, doi:10.1029/2001JB000396, 2002.
Vannucchi, P., D. W. Scholl, M. Meschede, and K. McDougall-Reid, Tectonic erosion and consequent collapse of the Pacific margin of Costa Rica: Combined implications from ODP Leg 170, seismic offshore data and regional geology of the Nicoya Peninsula, *Tectonics*, *20*, 649–668, 2001.
von Huene, R., and S. Lallemand, Tectonic erosion along the Japan and Peru convergent margins, *Geol. Soc. Am. Bull.*, *102*, 704–720, 1990.
von Huene, R., and C. R. Ranero, Subduction erosion and basal friction along the sediment starved convergent margin off Antofagasta, Chile, *J. Geophys. Res.*, *108*(B2), 2079, doi:10.1029/2001JB001569, 2003.
von Huene, R., and D. W. Scholl, Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental-crust, *Rev. Geophys.*, *29*, 279–316, 1991.
von Huene, R., and D. W. Scholl, The return of sialic material to the mantle indicated by terrigeneous material subducted at convergent margins, *Tectonophysics*, *219*, 163–175, 1993.
von Huene, R., et al., Site 565, in *Initial Report DSDP Leg 84*, edited by R. von Huene and J. Aubouin, pp. 21–78, U.S. Govt. Print. Off., Washington, D. C., 1985.
von Huene, R., C. R. Ranero, W. Weinrebe, and K. Hinz, Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos Plate, and Central American Volcanism, *Tectonics*, *19*, 314–334, 2000.
Walther, C., Crustal structure of the Cocos Ridge northeast of Cocos Island, Panama Basin, *Geophys. Res. Lett.*, *29*(20), 1986, doi:10.1029/2001GL014267, 2002.
Werner, R., K. Hoerle, P. van den Bogaard, C. R. Ranero, R. von Huene, and D. Korich, A drowned 14-m.y.-old Galapagos archipelago off the coast of Costa Rica: Implications for tectonic and evolutionary models, *Geology*, *27*, 499–502, 1999.
Ye, S., J. Bialas, E. R. Flueh, A. Stavenhagen, R. von Huene, G. Leandro, and K. Hinz, Crustal structure of the Middle American Trench off Costa Rica from wide-angle seismic data, *Tectonics*, *15*, 1006–1021, 1996.

S. Galeotti, Istituto di Geologia, Università degli Studi di Urbino, Campus Scientifico Località Crocicchia, I-61029 Urbino, Italy. (s.galeotti@uniurb.it)

K. McDougall-Ried, U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001, USA. (kris@usgs.gov)

C. R. Ranero, GEOMAR, Wischhofstr. 1-3, D-24148 Kiel, Germany. (cranero@geomar.de)

D. W. Scholl, Department of Geophysics, Stanford University, Stanford, CA 94305, USA. (dscholl@usgs.gov)

S. M. Straub, Lamont Doherty Earth Observatory, 61 Route 9W, Palisades, NY 10964, USA. (smstraub@ldeo.columbia.edu)

P. Vannucchi, Dipartimento di Scienze della Terra, Università di Firenze, Via La Pira, 4, I-50121 Firenze, Italy. (paolav@geo.unifi.it)