Rapid pulses of uplift, subsidence, and subduction erosion offshore Central America: Implications for building the rock record of convergent margins

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ABSTRACT

Integrated Ocean Drilling Program (IODP) Expedition 334 to southern Costa Rica, Central America, documented unprecedented subduction erosion in an area of active seismic slip. Widespread subduction erosion of the upper plate initiated when the Cocos Ridge, an overthickened aseismic ridge, arrived at the Middle America Trench. Subduction erosion was coeval with the rapid formation of deposition centers on the forearc of the upper plate. The completely recovered shelf sequence constrains a short (<2 m.y.) interval of extreme subsidence (~1200 m) with a rapid pulse occurring during the first ~0.3 m.y. This event removed an estimated 1.2 × 10^6 km^3 of forearc material at a rate of ~1690 km^3/m.y./km of trench during a time of rapid (~1035 m/m.y.) shelf sediment accumulation. At this erosive margin, a sediment-starved trench persisted, in spite of abundant sediment supply, because subduction erosion led to the creation of forearc basins. Similar rapid pulses of subduction erosion may punctuate the evolution of many margins, contributing disproportionately to crustal recycling at subduction zones with implications for the evolution of continental crust and mountain belts, and recycling of continental material into the mantle.

INTRODUCTION

Subduction erosion is the frontal and basal removal of the upper plate at convergent margins. It currently occurs at roughly one-half of Earth's subduction zones (von Huene and Scholl, 1991; Clift and Vannucchi, 2004), accounting for one-third of the ~5.25 km^3 of continental crust consumed annually (Stern, 2011). It also plays an important role in supplying upper plate material to the megathrust zone (Vannucchi et al., 2012). Alteration of eroded material affects seismogenesis through the transition from stable to unstable slip. However, subduction erosion has proven difficult to study because it consumes the geologic rock record.

Subduction erosion is recorded by the bathymetry of modern convergent margins as kilometer-long indentations linked to subducting seamounts and other relief (e.g., von Huene et al., 2000). Its best proxy in the geological record is subsidence of the overriding plate as identified by increasing water depths recorded by benthic foraminifera (e.g., Vannucchi et al., 2003).

In 2011, Integrated Ocean Drilling Program (IODP) Expedition 334 drilled the Costa Rican margin offshore the Osa Peninsula (Central America), where the Cocos Ridge (CCR) now subducts almost parallel to the Cocos-Caribbean plate convergence vector (Fig. 1). This geometry focuses the effects of ridge subduction on a nearly stationary portion of the plate boundary.

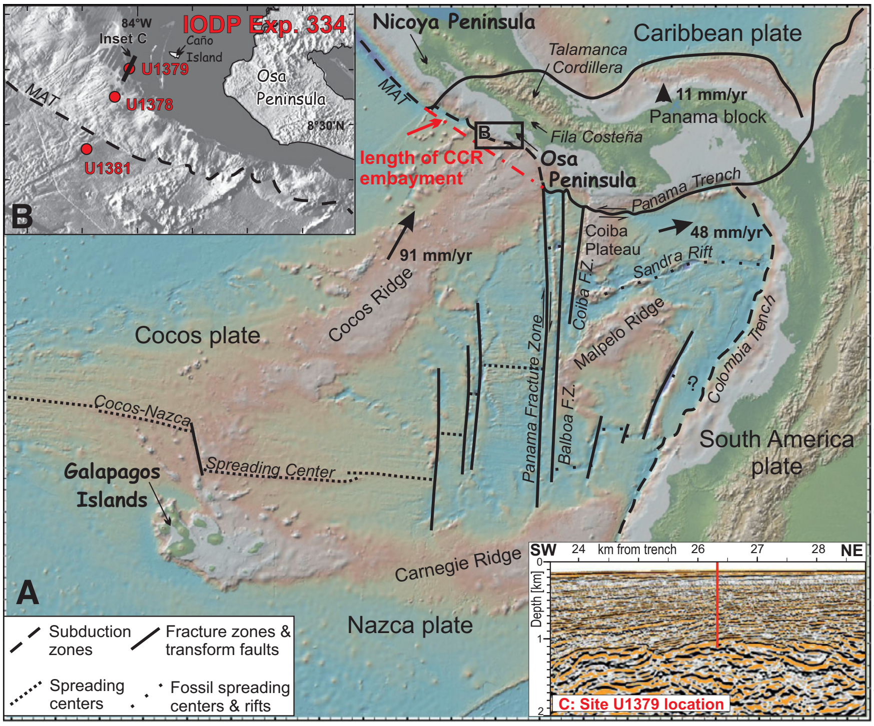

Figure 1. A: Digital elevation map of study area (http://www.geomapapp.org; Ryan et al., 2009) showing general plate tectonic setting. F.Z.—fracture zone. B: Detailed bathymetry near locations of Integrated Ocean Drilling Program Expedition (IODP Exp.) 334 drill sites discussed in text. Line crossing Site 334-U1379 shows location of seismic section in C. C: Post-stack depth migrated seismic section centered at Site 334-U1379 (detail of BGR99 Line 7, processed by Cesar R. Ranero). CCR—Cocos Ridge; MAT—Middle America Trench. Hole drawn to drilled depth.

PALEODEPTH EVOLUTION OF THE SHELF OFFSHORE THE OSA PENINSULA

The CCR consists of rough seafloor rising ~2 km above surrounding seafloor, with overthickened oceanic crust as much as 19.5 km thick (Sallarès et al., 2003). It was produced by Galapagos hotspot volcanism over the past 20 m.y. (Hoernle et al., 2002).

IODP Site U1379 is located on the Caribbean plate shelf above the northwest flank of the CCR, ~34 km from the coast in 125-m-deep water (Fig. 1B). Drilling recovered ~100% of an 880-m-thick sequence of mildly deformed

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shelf sediment (Fig. 2), penetrated the unconformity responsible for the high-amplitude reflector at the base of this section (Fig. 1C), and drilled through 80 m of the material below the unconformity (designated unit V; Fig. 2) (Item DR1 in the GSA Data Repository[1]). The entire 960-m-thick drilled sequence is Pleistocene in age (ca. 2.5 Ma; Calcareous nannofossil zone NN17), indicating a rapid sediment accumulation rate that peaked at 1035 m/m.y. in the uppermost ~500 m (Fig. 2). Recovered sediment facies and associated benthic foraminifera distribution both document dramatic changes in water depth through time (Fig. 2) (Item DR1). Benthic foraminifera indicate seafloor paleodepths consistent with the middle bathyal zone (800–1200 m) at the bottom and center of the section, separated by an interval of nearshore depths (Fig. 2A).

Backstripping of the sediment column (Allen and Allen, 1990; Cardozo, 2011) (Item DR2) verifies that sediment-loading effects are minor (~100 m) in comparison to the tectonic subsidence in the early Pleistocene (Fig. 3). The paleodepth record reveals three main tectonic phases (Fig. 3): (1) rapid uplift of an older (older than 2.5 Ma) forearc basin from ~800 m (middle bathyal depths; Fig. 2A; Item DR1) to

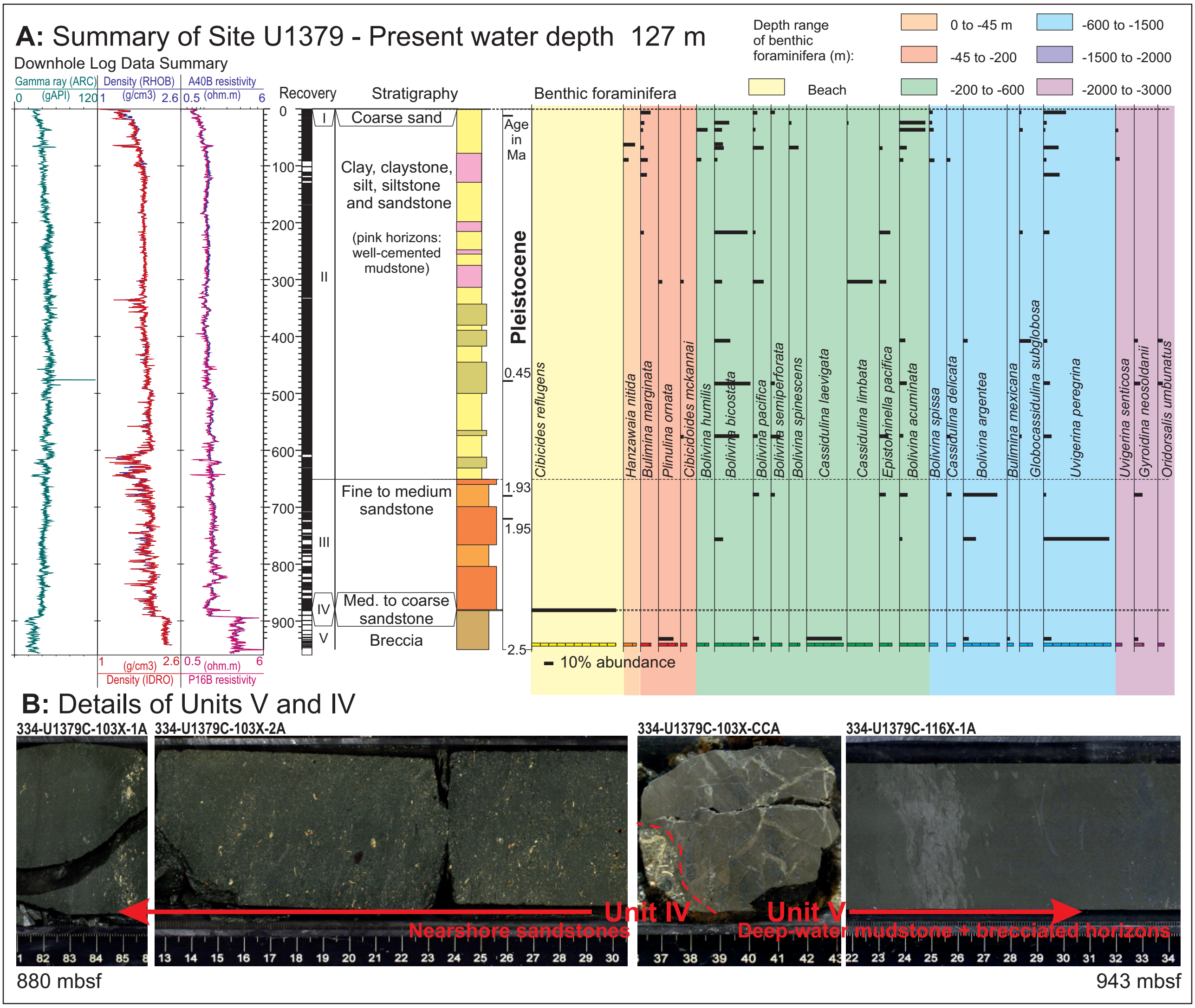

Figure 2. A: Summary of logging while drilling (LWD) measurements in Integrated Ocean Drilling Program (IODP) Hole U1379A (ARC—arcVISION tool; IDRO—image-derived density; RHOB—bulk density; P16B—phase-shift resistivity measured at 16 in source-receiver separation [arcVISION tool]; A40B—attenuation resistivity measured at 40 in source-receiver separation [arcVISION tool]). Lithostratigraphy and age are based on nannofossil analyses and benthic foraminifera distribution. LWD data show abrupt change in measured properties at 880 m below seafloor (mbsf), where high-amplitude reflector at top of acoustic basement in Figure 1C was crossed. Unit IV was found at depth of high-amplitude reflector imaged in Figure 1C, with unit V underneath. Benthic foraminifera distribution shows occurrence of abyssal species in unit V, whereas unit IV contains only beach species. Above unit IV, we observe rapid deepening of seafloor paleodepths to abyssal conditions throughout unit III and then rapid shallowing in uppermost part of unit II. B: Core images selected from units IV and V. From left to right: 334-U1379C-103X-1A—centimeter-thick shell layer and thin (millimeter thick) mud draping in horizontal layers; 334-U1379C-103X-2A—inclined laminated sands with preferentially oriented shell fragments within highly bioturbated sediment; 334-U1379C-103X-CCA—contact between unit V and unit IV. Mudstone of unit V is brecciated, with fractures filled by sediment. Fill consists of wall rock, bioclasts, and volcaniclastics in greenish matrix. Disconformity with scoured erosion surface marks passage to overlying unit IV, which has abundant heterogeneous shell debris.

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[1] GSA Data Repository item 2013278, Items DR1–DR4 (supplemental information on the drillcore, backstripping, IODP Site 1378, and plate tectonic setting surrounding the Cocos Ridge and Costa Rica), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

nearshore conditions in the early Pleistocene (ca. 2.3–2 Ma); (2) rapid subsidence of ~1200 m later in the early Pleistocene (ca. 2.3–2 Ma); and (3) relatively rapid uplift of ~1000 m from the middle-late Pleistocene to Holocene (ca. 1.9 Ma to now). IODP Site U1378, located on the middle slope in 526-m-deep water (Fig. 1B), shows similar patterns of uplift and subsidence (Item DR3). Site U1378 was drilled to 520 m below seafloor (mbsf), reaching ca. 1.5 Ma sediment. The benthic foraminifera association of Site U1378 indicates abyssal water depths (>2000 m) in the mid-Pleistocene (ca. 1.5–0.5 Ma) and rapid uplift in the past 0.5 m.y., mirroring the trend observed at Site U1379.

IMPLICATIONS

Response of the Forearc to the CCR Subduction

The shallowing recorded at Sites U1379 and U1378 is interpreted to reflect the onset of CCR subduction. The higher elevation of the subducting CCR could cause uplift of the overriding plate (2000 m of CCR relief on the seafloor and ~800 m of uplift ca. 2.3 Ma), while enhanced erosion at the base of the overriding plate triggers net subsidence. Plate reconstruction models (Barckhausen et al., 2001; MacMillan et al., 2004; Lonsdale, 2005) suggest that the leading edge of the CCR reached the trench ca. 2.8 Ma. The linear western edge of the Malpelo Ridge, the CCR conjugate along the Panama Fracture Zone (PFZ) (Hoernle et al., 2002), implies that the arrival of the CCR at the trench is associated with the eastward-migrating triple junction formed by the trench and the Cocos-Nazca plate boundary (Morell et al., 2012). Prior to CCR subduction, the rugged bathymetry and lithospheric heterogeneity of the obliquely subducting Coiba, Balboa, and Panama Fracture Zones already influenced the forearc. Subduction of these fracture zones correlates with the deep-water facies occurring in the older than 2.5 Ma forearc basin recovered at Site U1379. Arrival of the CCR at the trench was coeval with rapid, early Pleistocene uplift and created the unconformity responsible for the high-amplitude reflector at the base of the modern forearc sediment (Fig. 1C). It was also coincident with the emergence of the Central America land bridge at 2.8–2.6 Ma, and the last closure of the shallow-water connections in Panama at 2.5 Ma (Schmidt, 2007; Molnar, 2008).

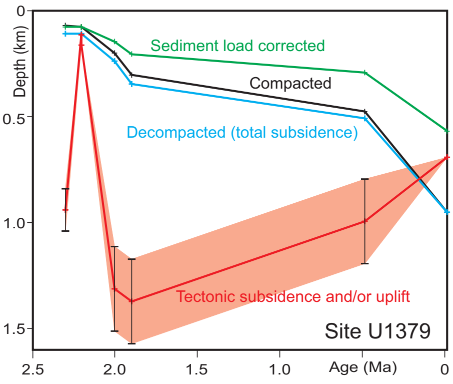

Figure 3. Subsidence or uplift pattern for Osa Peninsula shelf (Central America) after backstripping stratigraphic column recovered at Integrated Ocean Drilling Program (IODP) Site 334-U1379. We conservatively estimate subsidence by sediment loading assuming Airy isostatic model (Allen and Allen, 1990; Cardozo, 2011). Solid red line is our minimum tectonic subsidence or uplift component. Error in paleodepth is represented by vertical black lines; shadowed area shows uncertainty field.

In this interpretation, the abrupt rapid subsidence (ca. 2.2–2.3 Ma to ca. 1.9 Ma) began with the onset of CCR subduction. Coeval 2.5–1.8 Ma abrupt and rapid subsidence is also recorded to the northwest, offshore the Nicoya Peninsula (Fig. 1) (Vannucchi et al., 2003), suggesting a regional forearc subsidence event. Upper plate subsidence is therefore the most remarkable effect linked to CCR subduction.

Material Removal

Ongoing subduction of the CCR changed the geometry of the upper plate, leading to an ~350-km-long embayment extending from just southeast of the Nicoya Peninsula to the Panama Fracture Zone (Fig. 1). Upper plate thickness at the shelf edge decreases from ~15 km offshore the Nicoya Peninsula (Sallarès et al., 2001) to ~10 km toward the IODP Expedition 334 area (Stavenhagen et al., 1998). Where the embayment is most extensive the trench is aligned with the shelf edge and the upper plate thickness decreases to 0 km (Fig. DR4B in Item DR4). This change is consistent with the removal of upper plate material by subduction erosion. We consider that the forearc offshore the Nicoya Peninsula preserves the initial reference geometry: a 60 km distance between the trench and coastline, with a 15 km thickness of Caribbean plate at the shelf edge (Item DR4). If the embayment offshore central Costa Rica is the result of subduction erosion, then the pre-embayment initial volume of the forearc wedge was [350 km × 1/2 (60 km × 15 km)] = 157,500 km^3.

We parameterize the embayment as a triangle (Item DR4). The maximum width of the triangle is 60 km and the length of the embayment is divided in 2 portions, 270 km and 80 km. The current forearc volume remaining in the embayment is 1/3 [270 km × 1/2 (60 km × 15 km)] + 1/3 [80 km × 1/2 (60 km × 15 km)] = 52,500 km^3. This corresponds to a minimum net removal of 105,000 km^3 of forearc material. Additional forearc material has also been removed arcward of the embayment (Item DR4). To estimate this, we consider where the upper plate reaches 15 km thickness, ~15 km arcward of the trench (Dzierma et al., 2011) at the place of maximum removal. The triangular pyramidal geometry yields an additional 13,125 km^3 of forearc removal, for a total of 118,125 km^3.

Considering this volume of missing material, the average subduction erosion rate over 2.2 m.y. is ~153 km^3/m.y./km of trench. Most removal occurred during the 0.3 m.y. event, at an average rate of ~1125 km^3/m.y./km of trench. Because of the geometry of the embayment the enhanced erosion rate varied along the strike of the trench, from 0 at the northwest and southeast limits of the embayment to ~1690 km^3/m.y./km offshore the Osa Peninsula. For net rates of subduction erosion, the background rate of ~100 km^3/m.y./km calculated offshore the Nicoya Peninsula (Vannucchi et al., 2003) needs to be added.

Sitchler et al. (2007) proposed ≥36 km of underthrusting of the outer forearc (Osa Peninsula) under the inner forearc to create the thin-skinned fold-and-thrust belt of the Fila Costeña (Fig. 1A), driven by flat subduction of the CCR. If half the embayment formed by such underthrusting, estimates of subduction erosion would be halved. However, recent seismic studies do not indicate flat subduction (Dinc et al., 2010; Dzierma et al., 2011). Moreover, the Osa Peninsula Quaternary deformation does not involve significant subhorizontal shortening (Sak et al., 2009), while Fila Costeña is actively deforming (Sitchler et al., 2007). Marine data constrain subduction erosion to have been a short-lived pulse, while slip in the Fila Costeña was active since the Pliocene (Sitchler et al., 2007). Alternative mechanisms driving the thin-skinned Fila Costeña thrusting could, instead, be linked to uplift of the Cordillera de Talamanca.

Effects on Plate Boundary Location and Seismogenesis

At 1.9 Ma, subsidence was interrupted by a second pulse of shallowing (Fig. 3). The current 125 m water depth was reached through ~1000 m of tectonic uplift and rapid sediment accumulation in the uppermost ~500 m at Site U1379. We interpret this upper plate uplift as the direct effect of subducting thickened CCR crust. As thick CCR crust subducts, active tectonic erosion occurs during an interval of net uplift, with CCR buoyancy (temporarily?) prevailing over subduction erosion–driven subsidence.

Calculated subduction erosion rates imply upward migration of the plate boundary interface in the forearc from ~2.5 km/m.y. (average rate 153 km^3/m.y./km) to ~28 km/m.y. (for rapid rates of 1690 km^3/m.y./km). The persistent upward diversion of the megathrust is likely to affect its geometry, frictional nature, and hydrogeology. Therefore, the stresses along the fault and individual earthquake rupture characteristics are also expected to be anomalous. Here plate interface seismicity is abundant (DeShon et al., 2003). GPS measurements above the subducted CCR indicate that most of the plate interface in the seismogenic region is accumulating a slip deficit (LaFemina et al., 2009). The extensional fault systems deforming the forearc (Ranero et al., 2008) suggest low plate-boundary friction (Davis et al., 1983).

It remains an open question whether this evolution of the megathrust can reconcile the apparent contradiction between the CCR eroding a margin at an inferred low friction plate boundary, and yet still favor large shallow slip near the trench linked to the tsunamigenic earthquakes inferred for erosive margins (Bilek, 2010).

Feedbacks on Sedimentation

Along the Osa Peninsula, extreme subduction erosion was linked to the rapid formation of a deep (~1 km) sediment-filled forearc basin where sediment accumulation reached a peak rate of 1035 m/m.y. In contrast, the adjacent trench remained unfilled, as indicated by IODP Site U1381 (Fig. 1B), 5 km outboard of the trench, where a thin (96 m) veneer of recent to Middle Miocene (Serravallian) sediment mantling the CCR was recovered. Thus the highly erosive margin off the Osa Peninsula had a large volume of sediment delivered offshore, but this sediment never reached the trench and was instead captured within a rapidly subsiding forearc basin. At erosive margins, it is clear that sediment-starved trenches do not necessarily imply low rates of sediment supply.

Subduction erosion and subducting bathymetric relief may account for large volumes of material missing from the preserved rock record of ancient subduction complexes (e.g., Amato and Pavlis, 2010). A clear understanding of the destructive and depositional consequences of such processes at modern subduction zones must be obtained before the more subtle evolution of ancient subduction complex can be determined.

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