Upper-plate deformation in response to flat slab subduction inboard of the aseismic Cocos Ridge, Osa Peninsula, Costa Rica

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ABSTRACT

Along the Middle America Trench in southern Costa Rica, flat slab subduction of the aseismic Cocos Ridge has uplifted and exposed the outer forearc, shortened the Terraba forearc basin sequence in the inner forearc (i.e., the Fila Costeña thrust belt), and uplifted the magmatic arc. The Osa Peninsula, an outer forearc high ~20 km inboard of the Middle America Trench and ~3 km to ~10 km above the plate interface at its trenchward edge, is deforming in response to variations in the bathymetry of the subducting aseismic Cocos Ridge where relief locally exceeds 1 km. Modern topography of the Osa Peninsula, elevation of the basement rocks (Early to Middle Tertiary Osa mélangé), elevations of Quaternary marine deposits (Marenco formation), and distribution of late Quaternary uplift rates directly mirror the bathymetry on the Cocos Ridge outboard of the Middle America Trench. Rates of late Quaternary uplift are calculated from eight new radiocarbon ages, five new optically stimulated luminescence ages, and 10 previously published radiocarbon ages. Rates of uplift range from 1.7 m/k.y. to 8.5 m/k.y. The Osa Peninsula is fragmented into small (~5 km), independently deforming blocks bounded by trench-parallel and trench-perpendicular, subvertical, normal and reverse faults that extend down to the plate interface, allowing for greatly different deformation histories over short distances. Quaternary deformation on the Osa Peninsula is modeled as a thin, outer-margin wedge that deforms in response to subduction of short-wavelength, high-relief asperities on the downgoing plate. Permanent deformation is largely accomplished by simple shear on a complex array of subvertical faults that allow the upper plate to adjust to variations in the slope of incoming ridges and seamounts. Currently, permanent deformation of the outer forearc does not appear to involve significant subhorizontal shortening of the margin wedge, although the global positioning system velocity field records elastic shortening related to locking of the plate interface. Permanent uplift and uplift rates in the outer forearc in southern Costa Rica are driven, to the first order, by the bathymetry associated with the subducting Cocos Ridge and not by the basal shear stress on the plate interface.

INTRODUCTION

Flat slab subduction of aseismic ridges has generated considerable scientific interest because of the profound impact it has on the tectonic, magmatic, and landscape evolution of the upper plate that can extend hundreds of kilometers inland from the trench. Subduction of aseismic ridges generally leads to rapid outer forearc uplift over a broad region immediately inboard of the trench (Corrigan et al., 1990; Gardner et al., 1992; Hsu, 1992; Macharé and Ortlieb, 1992; Sak et al., 2009); shortening in the inner forearc with development of a fold-and-thrust belt (Fisher et al., 2004; Sitchler et al., 2007); changes in the properties of the volcanic arc and cessation of arc magmatism (Carr et al., 1990, 2003; von Huene et al., 2000; Patino et al., 2000; Ramos et al., 2002; Phipps Morgan et al., 2008; Alvarado et al., 2009); or even broad uplift of the magmatic arc (Gräfe et al., 2002; Fisher et al., 2004; Morell et al., 2012) with uplift even extending into the backarc (Coates et al., 1992; Collins et al., 1995; McNeill et al., 2000; Ramos et al., 2002) and the foreland basin (Espurt et al., 2007). Taken together, these tectonic processes modify regional drainage patterns and broadly control landscape evolution (Espurt et al., 2007; Morell et al., 2008; Regard et al., 2009).

Along thinly sedimented convergent margins, subduction of rough crust and seamounts associated with aseismic ridges controls local margin erosion, subsidence, and deformation of the forearc (Ballance et al., 1989; Cloos, 1992; Gardner et al., 1992; Geist et al., 1993; Dominguez et al., 1998; von Huene et al., 1995, 2000; Gardner et al., 2001; Laursen et al., 2002; Bilek et al., 2003; Sak et al., 2004a, 2009; Pedley et al., 2010; Wang and Bilek, 2011). It has been demonstrated, under some conditions, that uplift and subsidence rates and topography of the outer forearc are directly related to seamount volume, relief, and the convergence rate between the upper and lower plates (Mann et al., 1998; Gardner et al., 2001; Meffre and Crawford, 2001; Sak et al., 2004a, 2009; Taylor et al., 2005). In some places, bathymetry of the subducting lower plate can affect the geometry of foreland fold-and-thrust belts up to a hundred kilometers from the trench (Fisher et al., 1994, 1998, 2004; Marshall et al., 2000, 2003; Espurt et al., 2007). Furthermore, subduction of bathymetric features such as seamounts, oceanic plateaus, and aseismic ridges can cause erosion of the upper plate ( Ranero and von Huene, 2000), leading to significant trench retreat (Clift et al., 2003; Vannucchi et al., 2003; Clift and Vannucci, 2004).

First-order control on the flat slab subduction of aseismic ridges is either buoyancy related to the thickness and age of the downgoing plate ( Protti et al., 1995; Gutscher et al., 1999, 2000; Gutscher, 2002; Alvarado et al., 2009) or trenchward motion of thick crustons over the incoming slab ( Manea et al., 2012). First-order
controls on the deformation of the upper plate that result from aseismic ridge subduction are plate convergence rate (Fisher et al., 2004; Sak et al., 2004a), relative plate material strengths, basement cover sediment thickness and porosity (von Huene and Ranero, 2003; Sak et al., 2004a; Taylor et al., 2005; Ryan, 2012), and volume and relief of the subducting asperity (Meffre and Crawford, 2001; Sak et al., 2004a; Taylor et al., 2005). In the outer forearc of southern Costa Rica (Figs. 1A and 1C), the relative plate motion rate is rapid (~85 m/k.y.), the subduction angle is shallow, 3° to ~10° (Fig. 1C), and the upper plate is tapered to less than 10 km (Protti et al., 1994, 1995; Kolarsky et al., 1995), and is composed of a deformed, accreted complex of seamounts (Denyer et al., 2006; Vannucchi et al., 2006; Buchs et al., 2009). Importantly, the downgoing plate has a thin sediment cover (Fig. 1B), but it also has considerable small-wavelength roughness, related to seamounts and plateaus, that is superimposed on the overall long-wavelength bathymetry associated with the aseismic ridge. Where aseismic ridges subduct, the strain rate in the thin, overriding margin wedge is determined by the curvature of the incoming bathymetry, while the uplift/subsidence rate is determined by the slope, and the duration and amount of uplift are determined by the relief of the underthrusting asperities (Sak et al., 2004a).

The western edge of the Caribbean plate at the Middle America Trench is a classic, thinly

![Figure 1](https://pubs.geoscienceworld.org/lithosphere/lithosphere/article-pdf/5/3/247/3050422/247.pdf)
sedimented, erosive margin (von Huene and Scholl, 1991; Clift and Vannucci, 2004) extending from central Mexico (Clift and Vannucci, 2004) and Guatemala (Vannucci et al., 2004) through Nicaragua (Ranero et al., 2000) and Costa Rica (Vannucci et al., 2003) to the border with Panama (Gardner et al., 1992; von Huene et al., 2000; Sak et al., 2004a; Morell et al., 2011), the eastern boundary of the subducting Cocos plate. Along this margin, trench retreat rates from subduction erosion range from 0.9 m/k.y. in Guatemala (Vannucci et al., 2004; Clift and Vannucci 2004) to 3–3.6 m/k.y. in northern Costa Rica (Vannucci et al., 2001; Scholl and von Huene, 2007), the southernmost limit of currently available data. Net arcward migration of the Middle America Trench ranges from 20 to 30 km in Guatemala to 50–60 km in northern Costa Rica (Scholl and von Huene, 2007). Because subduction erosion leads to subsidence, the margin wedge, the outermost forearc, and the updip limit of the seismogenic zone are seldom exposed subaerially, critically limiting observations and direct measurements of tectonic processes, structural deformation, and stratigraphic relationships. However, in southern Costa Rica, flat slab subduction of the aseismic Cocos Ridge, a large bathymetric feature on the Cocos plate, results in the greatest uplift and unroofing of the upper plate anywhere along the margin. On the Osa Peninsula, the outermost forearc is subaerially exposed above the subducted portion of the Cocos Ridge, allowing for detailed structural and stratigraphic mapping of this critical upper-plate region.

In this paper, we integrate 10 previously published radiocarbon ages from coastal sections on the Osa Peninsula (Gardner et al., 1992) with eight new radiocarbon ages and five new optically stimulated luminescence (OSL) ages from the interior of the peninsula. New field mapping of Quaternary marine deposits along the central coast and within the interior of the peninsula allows for significant revision of the distribution and facies architecture of the Marenco formation, as originally described by Sak et al. (2004a), and a revised geologic map for the Osa Peninsula. These new data sets allow for construction of E-W and N-S structural cross sections along and across the peninsula. This was not possible from previous mapping and geochronology, which were confined to eastern (Gardner et al., 1992) and western (Sak et al., 2004a) coastal outcrops. From these new structural cross sections and revised stratigraphy, we constrain (1) rates of deformation across the peninsula, (2) the spatial and temporal distribution of those rates, and (3) the size of independently uplifting and subsiding blocks. We show that the basement rocks of the Osa Peninsula have experienced pervasive, brittle deformation related to subvertical faults that extend from the plate interface to the surface. Based on these constraints, we propose a more detailed model for deformation in the outer forearc along this part of the margin, where bathymetric relief on the subducting Cocos Ridge dominates over plate-boundary friction (i.e., basal shear stress) in causing permanent deformation of the upper plate.

**TECTONIC AND GEOLOGIC SETTING OF THE OSA PENINSULA**

**Regional Plate Tectonics—Cocos Plate, Caribbean Plate, and Panama Microplate**

In southern Costa Rica, the Cocos plate subducts under the Caribbean plate at a rate of ~91 m/k.y. nearly orthogonal to the Middle America Trench (DeMets et al., 1990; DeMets, 2001; Bird, 2003; Jin and Zhu, 2004) and under the Panama microplate at 85 m/k.y. (Morell et al., 2012; Fig. 1A). The Cocos plate is sharply segmented and changes significantly along strike of the Middle America Trench due to hotspot volcanism, which intrudes oceanic lithosphere that was created at the East Pacific Rise and the Cocos-Nazca spreading center (Barckhausen et al., 2001). Seismic imaging of the Wadati-Benioff zone along this margin indicates that the Cocos plate decreases from a steeply dipping (70°) slab at the Nicaragua–Costa Rican border to a very shallowly dipping slab (>10°) off southern Costa Rica (Protti et al., 1994, 1995; Fig. 1C). This shallowing of the subduction angle is caused by an increase in buoyancy resulting from a decrease in age of the plate (Barckhausen et al., 2001; Fig. 1A) and a significant increase in thickness of the plate (von Huene et al., 2000; Sallarès et al., 2003; Walther, 2003; Fig. 1B).

The most prominent morphological feature on the Cocos plate is the Cocos Ridge, which is formed by movement of the Cocos plate over the Galápagos hotspot. The Cocos Ridge, an aseismic ridge with a maximum crustal thickness approaching ~20 km along the ridge axis (Walther, 2003; Sallarès et al., 2003), rises over 2.5 km above the neighboring abyssal plain, with local bathymetric relief along the ridge crest in excess of 1 km. The Cocos Ridge is cut on its eastern edge by the north-south–striking Panama fracture zone, a right-lateral transform fault that forms the boundary between the Cocos and Nazca plates (Figs. 1A and 1B). Subduction of the Cocos Ridge dramatically increases uplift rates from the Nicoya Peninsula (Marshall and Anderson, 1995; Gardner et al., 2001) in the northwest to the Osa Peninsula (Gardner et al., 1992; Sak et al., 2004a, 2009) and Burica Peninsula (Corrigan et al., 1990; Morell et al., 2011) in the southeast (Fig. 1C). The global positioning system (GPS)–derived surface velocity field in the outer forearc overriding the ridge is consistent with strong coupling along the plate boundary (Norabuena et al., 2004; La Femina et al., 2009), with horizontal velocities up to 41 m/k.y. relative to the magmatic arc along an azimuth parallel to Cocos-Caribbean plate motion. An observed gradient in the magnitude of horizontal velocity arcward (La Femina et al., 2009) is consistent with buildup of elastic strain in the upper plate (Fisher et al., 2004). Geodynamic modeling of the distribution and rates of uplift within the outer forearc are predicted most accurately when the subducted part of the Cocos Ridge contains a steep, near-vertical eastern leading edge due to truncation against the Panama fracture zone (Gardner et al., 1992) and when the subducted part of the Cocos Ridge behaves as a shallowly subducting rigid indenter (Corrigan et al., 1990; La Femina et al., 2009).

Estimates for the time of arrival of the Cocos Ridge at the Middle America Trench offshore of the Osa Peninsula and the initiation of rapid, upper-plate deformation are wide ranging and have been controversial. Estimates range from ca. 1 Ma (Lonsdale and Klitgord, 1978; Gardner et al., 1992) from modern plate reconstructions; ca. 1 Ma (Corrigan et al., 1990) and 3.6 Ma (Collins et al., 1995) based on paleobathymetry from benthic foraminiferal stratigraphy; <3 Ma (Morell et al., 2012) to as much as ca. 5–7 Ma (Gráf et al., 2002) from unroofing of the Cordillera de Talamanca; to ca. 2–3 Ma (MacMillan et al., 2004), ca. 5 Ma (de Boer et al., 1995), and ca. 8 Ma (Abratis and Wörner, 2001) from the age and distribution of volcanic and igneous rocks in the magmatic arc inboard of the Cocos Ridge.

We favor a younger age, ca. 1.5–3 Ma, for the initiation of Cocos Ridge subduction offshore the Osa Peninsula for several reasons. First, the younger age is consistent with modern plate reconstructions, which predict that subduction of the Cocos Ridge is constricted to a time window ca. 1.5–3 Ma for the region offshore the Osa Peninsula (Lonsdale and Klitgord, 1978; Gardner et al., 1992; MacMillan et al., 2004; Morell et al., 2012). Second, river longitudinal profile analyses and the preservation of a low-relief landscape atop the magmatic arc restrict the onset of increased rock uplift induced by Cocos Ridge subduction to <3 Ma, given the tropical climate and high erosion rates (Morell et al., 2012). Third, the distribution of the youngest radiometric ages from plutons of the Costa Rica–Panama volcanic arc (e.g., de Boer et al., 2005; Wegner et al., 2011) suggests that the cessation of arc volcanism in Costa Rica may be unrelated to Cocos Ridge collision.
(Morell et al., 2012). This interpretation supports a younger Cocos Ridge arrival, given that many of the older estimates for the onset of Cocos Ridge subduction (e.g., 8 Ma; Abratis and Wörner, 2001) are derived from estimates related to the timing of arc inactivity. Therefore, the deformation we describe on the Osa Peninsula from subduction of the Cocos Ridge is most likely Quaternary in age.

The upper plate in southern Costa Rica is the Panama microplate (PM, Fig. 1A) and was first identified by Vergara Muñoz (1988a, 1988b) on the basis of seismicity, earthquake focal mechanisms, and bounding structural zones. The Panama microplate is separated from the Caribbean plate by a series of east-west–striking offshore thrust faults located north of the isthmus (North Panama deformed belt of Silver et al., 1990), and a diffuse zone of deformation that runs through central Costa Rica (Central Costa Rican deformed belt of Marshall et al., 2000). Offshore of the Osa Peninsula, the Cocos plate subducts under the Panama microplate along the relative plate motion vector at ~85 m/k.y. (Fig. 1A). Here, we focus on the thin outer forearc of the Osa Peninsula along the southern edge of the Panama microplate where Cocos Ridge subduction has exhumed the Late Cretaceous to middle Miocene Osa igneous complex and Osa mélange and exposed the overlying late Neogene and Quaternary marine sediments.

**Basement Rocks**

Stratigraphy on the Osa Peninsula directly inboard of the Cocos Ridge ranges from Late Cretaceous oceanic basement rocks to late Neogene slope cover turbidites and finally Quaternary shallow marine, estuarine, and alluvial sediments (Fig. 2). A prominent, high-relief unconformity (Ivosevic, 1977; Lew, 1983; Barritt and Berrangé, 1987; Sak et al., 2004a) separates the basement rocks from the overlying late Neogene and Quaternary sedimentary units (Fig. 2, bold unconformity).

The outer forearc basement of the Osa Peninsula is composed of two major rock bodies, the Osa igneous complex, an exotic sliver(s) accreted to the margin of the Caribbean plate in the Paleocene and Eocene (Buchs, 2003; Denyer et al., 2006; Buchs et al., 2010) on the landward side, and the Osa mélange on the seaward side. Basement rocks on the seaward side of the Osa Peninsula are composed of the Osa-Caño accretionary complex (Di Marco et al., 1995), which is now called the Osa mélange (Buchs, 2003; Sak et al., 2004a; Vannucchi et al., 2006; Buchs and Baumgartner, 2007; Buchs et al., 2009). The mélange, characterized by a block-and-matrix fabric, is exposed along coastal wave-cut platforms, sea cliffs, and in river gorges that are incised below the basement-cover unconformity. The Osa mélange sequence consists of sheared sandstone-mudstone, marble, pelagic sediments (radiolarian chert), basalt, and gabbro. Locally, the mélange consists of intensely sheared greenstones with web-like arrays of scaly fabrics that reveal polished, striated surfaces. In many places, the boundary between clasts and matrix is a shear zone or fault. Foraminifera in the mélange matrix indicate a latest Cretaceous to middle Miocene age (Lew, 1983; Di Marco et al., 2006; Buchs et al., 2010) on the landward side, and the Osa mélange on the seaward side. Basement rocks on the seaward side of the Osa Peninsula are composed of the Osa-Caño accretionary complex (Di Marco et al., 1995), which is now called the Osa mélange (Buchs, 2003; Sak et al., 2004a; Vannucchi et al., 2006; Buchs and Baumgartner, 2007; Buchs et al., 2009). The mélange, characterized by a block-and-matrix fabric, is exposed along coastal wave-cut platforms, sea cliffs, and in river gorges that are incised below the basement-cover unconformity. The Osa mélange sequence consists of sheared sandstone-mudstone, marble, pelagic sediments (radiolarian chert), basalt, and gabbro. Locally, the mélange consists of intensely sheared greenstones with web-like arrays of scaly fabrics that reveal polished, striated surfaces. In many places, the boundary between clasts and matrix is a shear zone or fault. Foraminifera in the mélange matrix indicate a latest Cretaceous to middle Miocene age (Lew, 1983; Di Marco et al., 2006; Buchs et al., 2010). The Osa mélange sequence consists of sheared sandstone-mudstone, marble, pelagic sediments (radiolarian chert), basalt, and gabbro. Locally, the mélange consists of intensely sheared greenstones with web-like arrays of scaly fabrics that reveal polished, striated surfaces. In many places, the boundary between clasts and matrix is a shear zone or fault. Foraminifera in the mélange matrix indicate a latest Cretaceous to middle Miocene age (Lew, 1983; Di Marco et al., 2006; Buchs et al., 2010).

**Tertiary and Quaternary Stratigraphy of the Osa Peninsula**

![Figure 2. Compilation of Tertiary and Quaternary stratigraphic investigations for the Osa Peninsula. Bold jagged line is a regional unconformity. MIS—marine isotope stage.](https://pubs.geoscienceworld.org/lithosphere/lithosphere/article-pdf/5/3/247/3050422/247.pdf)
Upper-plate deformation in response to flat slab subduction, Costa Rica

Neogene and Quaternary Stratigraphy

Basement rocks on the Osa Peninsula are unconformably overlain by Neogene and Quaternary, locally derived, semilithified, greenish gray to orange, graywacke-type marine and continental conglomerates, sandstones, siltstones, and claystones (Ivosevic, 1977; Barritt and Barrangé, 1987). The unconformity occurs on either unweathered Osa mélange with a sharp contact into the overlying sediment or a deeply weathered paleosol locally incorporating angular, colluvial clasts of Osa mélange (Barrangé, 1989). Relief on the unconformity can exceed 10 m at the outcrop scale, but locally relief can exceed 100 m. Abrupt variations in facies architecture and thickness of the overlying sediments on the Osa Peninsula indicate that block faulting was coeval with sedimentation (Ivosevic, 1977; Barritt and Barrangé, 1987; Barrangé, 1989). Facies immediately above the unconformity can vary from subaerial colluvial and alluvial sediments to high-energy beach deposits consisting locally of mullowan-bored Tertiary limestone cobbles or shallow-water estuarine or open-marine siltstone and mudstones. Thickness of the sedimentary cover above the unconformity varies from nearly zero to almost 500 m across buried, steep paleotopography that bounds active tectonic basins and paleovalleys (Barrangé, 1989; this study).

The late Neogene and Quaternary stratigraphy of the outer forearc was initially described on the Burica Peninsula, ~30 km southeast of the Osa Peninsula (Fig. 1C), from molluscan fauna, planktonic foraminifera, and calcareous nanofossil distributions, and it was assigned to the Pliocene Charco Azul Formation or the Pleistocene Armuelles Formation (Coryell and Mossman, 1942; Olsson, 1942; Terry, 1941, 1956). On the Burica Peninsula, a transitional, time-transgressive unconformity separates the deep-water turbidites of the Charco Azul Formation from the overlying and rapidly shallowing-upward early Pleistocene to Holocene Armuelles Formation (Corrigan et al., 1990). These units are truncated by an extensive flight of late Quaternary marine terraces of the Monteverde formation (Morell et al., 2011). The Charco Azul and Armuelles Formation were formally applied to the Osa Peninsula by Sprechmann (1984) and subsequently used by many later researchers (Fig. 2). However, some researchers, have preferred to use the informal designation Punta La Chanca formation (Lew, 1983) or Osa group (Barritt and Barrangé, 1987; Barrangé, 1989; Buchs and Baumgartner, 2007) instead of the Charco Azul Formation (Fig. 2) and the Puerto Jimenez Group (Barritt and Barrangé, 1987; Barrangé, 1989) or the Marenco formation (informal designation; Sak et al., 2004a; this study) instead of the Armuelles Formation because of significantly different tectonic histories and facies architecture between the two peninsulas. Osa group sediments have been assigned to the middle–late Pliocene based on planktonic and benthic foraminiferal assemblages and were deposited as turbidite fans in water depths ranging from 200 m to as much as 1200 m (Lew, 1983; Barrangé, 1989).

Mapping and radiocarbon dating of the late Quaternary Marenco formation have been restricted to the southeastern (Gardner et al., 1992) and coastal sections along the northwestern part (Sak et al., 2004a) of the Osa Peninsula. Facies analyses and radiocarbon dating defined two chronostratigraphic units (Fig. 2). Chronostratigraphic sequence I is composed of unconcorded beach ridge, beach, shallow marine, and estuarine facies of mid- to late Holocene age (marine isotope stage [MIS] 1, 0–10 ka). Chronostratigraphic sequence II (Gardner et al., 1992) or the Marenco formation (Sak et al., 2004a) is composed of poorly lithified, shallow marine to estuarine facies of late Pleistocene (MIS 3, ca. 27–60 ka) age. Those initial investigations (Gardner et al., 1992; Sak et al., 2004a) provided the first radiocarbon ages for the late Quaternary stratigraphy. Gardner et al. (1992) proposed a simple tectonic model requiring regional down-to-the-northeast tilting with minor block faulting. More detailed mapping and radiocarbon dating allowed Sak et al. (2004a) to extend the late Quaternary Marenco formation to the northwest corner of the Osa Peninsula and to identify small, independently moving blocks that experienced uplift and subsidence in response to bathymetry on the subducting Coco Ridge.

Late Quaternary Stratigraphy, Structure, and Deformation of the Osa Peninsula

Marenco Formation Facies and Ages

The Marenco formation consists of poorly lithified, poorly consolidated, predominantly marine sediments. Facies are assigned to depositional environments and water depths by comparison to modern environments around the Osa Peninsula (Gardner et al., 1992; Sak et al., 2004a). The most conspicuous deposits are high-energy beach and cobble beach and tidal facies (Fig. 3A). This facies is assigned a water depth of 0.0 m ± 1.2 m. Pebble composition is predominantly basalt, with mixtures of chert, limestone, and lithic fragments derived from the Osa mélangé or Osa igneous complex. Limestone cobble clasts are frequently bored and locally comprise most of the cobbles. Pebbles vary from well rounded to angular (Fig. 3B), with basalt clasts being the most angular. The coarsest and most angular clasts tend to occur...
Figure 3. Photographs showing: (A) high-energy, sand to pebble and cobble beach and tidal facies of the Tigre member of the Marenco formation; (B) high-energy, angular to rounded, basalt cobble beach facies from the Rincón member of the Marenco formation; (C) wavy, ripple-bedded fine sands and silts from the Tigre member of the Marenco formation; (D) plane parallel-bedded mudstones and siltstones from the Tigre member of the Marenco formation dipping ~10° to the northwest; (E) northwest-striking normal fault in the Tigre member of the Marenco formation along Río Tigre (view is to southeast; arrows mark location of fault; person to left of fault provides scale; downthrown side is to northeast, toward Gulfo Dulce); and (F) oblique aerial photo looking southwest from the Gulfo Dulce in the foreground onto the Osa Peninsula. Central graben (Fig. 4, E-W cross section) is visible on the skyline in the center of the photo. X marks location of sample for radiocarbon dating; O marks location of sample for optically stimulated luminescence dating. See Figure 5 for sample ID and photograph locations.
in high-energy deposits closest to the unconformity where paleorelief is highest. These facies can locally contain a diverse assemblage of thick-walled mollusks and gastropods.

High-energy beach and tidal facies interfinger laterally and vertically into fossiliferous, shallow shelfal, wavy to ripple-bedded, interbedded, brown, often bioturbated, fine sands and silts (Fig. 3C). These sediments were deposited above wave base and are assigned a facies depth of ~4.5 m ± 4.5 m. In many locations away from paleotopography, sediments in the Marenco formation are plane parallel-bedded, jointed, gray to olive green mudstones and siltstones (Fig. 3D) that may contain a more limited assemblage of thin-walled gastropods and articulated mollusks. These facies are assigned to a water depth below wave base of >9 m. Locally, mangrove-lagoon-swamp facies with woody debris and leaf impressions on bedding planes are well preserved, but are volumetrically insignificant. This facies is light- to dark-gray clay with in situ mangrove stumps and rooted horizons.

Here, we report eight new and 10 previously published radiocarbon ages (Table 1) and five new OSL ages (Table 2) for the Marenco formation in the central part of the Osa Peninsula. These new ages revise and elaborate on published radiocarbon ages (Table 1) and five mangrove stumps and rooted horizons.

These new ages for the Marenco formation and new mapping within the interior of the peninsula allow us to produce a revised geologic map for the Osa Peninsula (Fig. 4) that significantly reduces the areal extent of the Osa mélange as mapped by Sak et al. (2004a) and the Osa group as mapped by Buchs and Baumgartner (2007) while expanding and refining the areal extent of the Marenco formation, mapped by Coates et al. (1992) and Vannucchi et al. (2006) as their Armuelles Formation (Fig. 2).

Radiocarbon ages compare favorably within outcrops. Radiocarbon samples from the same outcrop give similar ages, and stratigraphically overlying beds yielded younger radiocarbon ages within statistical error. For example, radiocarbon samples 5 and 6, adjacent to each other, (Table 1; Fig. 5, N-S cross section) yield ages of 35.2 ka ± 1.8 ka and 35.5 ± 0.5 ka for upper beds in the Tigre member, which are statistically indistinguishable. Samples 8 and 10 (Table 1) from stratigraphically lower beds in the Tigre member yield ages of 39.9 ± 1.2 ka and 40.6 ± 0.6 ka, also statistically indistinguishable, but older than ages for the overlying beds.

Where radiocarbon samples yield infinite ages, optical results give finite ages slightly older than the minimum radiocarbon age. For example, radiocarbon samples 13 (older than 34.62 ka), 15 (older than 42.2 ka), and 16 (older than 40.04 ka), from the lowest part of the Tigre member just above the unconformity with the Rincón member (Table 1; Fig. 5, N-S cross section), yield different infinite ages (depending on sample size), but the optical age for that outcrop, sample 21, is 53 ka ± 11 ka (Table 2). Similarly, radiocarbon sample 14 yields an infinite radiocarbon age (older than 38 ka; Table 1), but the optical age for that outcrop, sample 22, is 53 ka ± 12 ka (Table 2). There was one inconsistent age between dating techniques. Radiocarbon samples 11 and 12 from lower beds in the Tigre member (Table 1; Fig. 5, N-S cross section) give ages of 42.6 ± 0.5 ka and 47.8 ± 0.7 ka, but the optical age for that outcrop, sample 19, is statistically younger, 33 ka ± 7 ka (Table 2). However, another optical analysis, sample 20, from an outcrop immediately overlying samples

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Sample ID*</th>
<th>14C age† (k.y. B.P.)</th>
<th>Age† (ka)</th>
<th>Modern elevation** (m)</th>
<th>Facies depth†† (m)</th>
<th>Sea level†† (m)</th>
<th>Uplift rate‡‡ (m/k.y.)</th>
<th>Marenco formation member</th>
</tr>
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<tr>
<td>1</td>
<td>(24917)**</td>
<td>6.35 ± 0.07</td>
<td>7.389–7.299</td>
<td>5.0 ± 1</td>
<td>0.0 ± 1.2</td>
<td>–8 ± 1</td>
<td>1.9 ± 0.4</td>
<td>Jiménez</td>
</tr>
<tr>
<td>2</td>
<td>(20841)**</td>
<td>7.15 ± 0.08</td>
<td>8.098–7.979</td>
<td>4.5 ± 1</td>
<td>0.0 ± 1.2</td>
<td>–9 ± 1</td>
<td>1.7 ± 0.4</td>
<td>Jiménez</td>
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<td>3</td>
<td>(240569)**</td>
<td>25.75 ± 0.28</td>
<td>30.9 ± 0.3</td>
<td>330 ± 20</td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>(229278)**</td>
<td>26.79 ± 0.16</td>
<td>32.1 ± 0.2</td>
<td>330 ± 20</td>
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<tr>
<td>5</td>
<td>(20941)**</td>
<td>29.78 ± 1.80</td>
<td>35.2 ± 0.5</td>
<td>40 ± 10</td>
<td>–4.5 ± 4.5</td>
<td>–86 ± 10</td>
<td>3.7 ± 0.9</td>
<td>Tigre</td>
</tr>
<tr>
<td>6</td>
<td>(24918)**</td>
<td>30.07 ± 0.52</td>
<td>35.5 ± 0.5</td>
<td>50 ± 10</td>
<td>–4.5 ± 4.5</td>
<td>–83 ± 10</td>
<td>3.9 ± 0.8</td>
<td>Tigre</td>
</tr>
<tr>
<td>7</td>
<td>(20840)**</td>
<td>33.07 ± 0.52</td>
<td>38.5 ± 0.5</td>
<td>7 ± 2</td>
<td>0.0 ± 1.2</td>
<td>–87 ± 10</td>
<td>2.4 ± 0.4</td>
<td>Tigre</td>
</tr>
<tr>
<td>8</td>
<td>(DIC-3153)**</td>
<td>34.53 (+1.21, –1.42)</td>
<td>39.9 ± 1.2</td>
<td>40 ± 5</td>
<td>–4.5 ± 4.5</td>
<td>–89 ± 10</td>
<td>3.4 ± 0.5</td>
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</tr>
<tr>
<td>9</td>
<td>(24914)**</td>
<td>34.88 ± 0.51</td>
<td>40.1 ± 0.5</td>
<td>25 ± 5</td>
<td>–4.5 ± 4.5</td>
<td>–87 ± 10</td>
<td>2.7 ± 0.5</td>
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</tr>
<tr>
<td>10</td>
<td>(25780)**</td>
<td>35.29 ± 0.62</td>
<td>40.8 ± 0.6</td>
<td>40 ± 10</td>
<td>–4.5 ± 4.5</td>
<td>–83 ± 10</td>
<td>3.2 ± 0.7</td>
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</tr>
<tr>
<td>11</td>
<td>(229075)**</td>
<td>37.52 ± 0.66</td>
<td>42.6 ± 0.5</td>
<td>170 ± 10</td>
<td>–4.5 ± 4.5</td>
<td>–77 ± 10</td>
<td>5.4 ± 0.6</td>
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<tr>
<td>12</td>
<td>(226447)**</td>
<td>43.57 ± 0.77</td>
<td>47.8 ± 0.7</td>
<td>170 ± 10</td>
<td>–4.5 ± 4.5</td>
<td>–77 ± 10</td>
<td>5.4 ± 0.6</td>
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<tr>
<td>13</td>
<td>(25344)**</td>
<td>&gt;34.62</td>
<td>&gt;34.62</td>
<td>&gt;34.62</td>
<td>95 ± 1</td>
<td>–4.5 ± 4.5</td>
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<tr>
<td>14</td>
<td>(240568)**</td>
<td>&gt;38.0</td>
<td>&gt;38.0</td>
<td>30 ± 10</td>
<td>–4.5 ± 4.5</td>
<td>Tigre</td>
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<td></td>
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<td>15</td>
<td>(216480)**</td>
<td>&gt;42.2</td>
<td>&gt;42.2</td>
<td>90 ± 10</td>
<td>–4.5 ± 4.5</td>
<td>Tigre</td>
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<tr>
<td>16</td>
<td>(20839)**</td>
<td>&gt;40.04</td>
<td>&gt;40.04</td>
<td>110 ± 10</td>
<td>–4.5 ± 4.5</td>
<td>Tigre</td>
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<td>17</td>
<td>(229276)**</td>
<td>&gt;45.93</td>
<td>&gt;45.93</td>
<td>110 ± 10</td>
<td>0.0 ± 1.2</td>
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<td>&gt;37.80</td>
<td>&gt;37.80</td>
<td>90 ± 10</td>
<td>&gt;9</td>
<td>Rincón</td>
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Radionuclide concentrations§

<table>
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<tr>
<th>Sample ID</th>
<th>Water†</th>
<th>Modern elevation (m, a.s.l.)</th>
<th>Facies depth (m)</th>
<th>K (ppm)</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
<th>Optical age (ka)</th>
<th>Uplift rate (mm/ka)</th>
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<tr>
<td>CR05-01</td>
<td>4</td>
<td>10 ± 3</td>
<td>1.2</td>
<td>0.29 ± 0.05</td>
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<td>0.04 ± 0.02</td>
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<td>CR05-04</td>
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<td>20 ± 5</td>
<td>2.5</td>
<td>0.54 ± 0.04</td>
<td>0.61 ± 0.12</td>
<td>0.45 ± 0.10</td>
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<td>0.37 ± 0.04</td>
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<td>1.2</td>
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<td>0.45 ± 0.10</td>
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<tr>
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<td>1.2</td>
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<td>0.38 ± 0.09</td>
<td>0.02 ± 0.01</td>
<td>0.01 ± 0.01</td>
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</table>

Note: Modern elevation is from: 1—uncorrected global positioning system (GPS) (Garmin); 2—Sokkia AIR-HB-1L handheld digital barometer. Facies depths of deposits, measured positive upward from mean sea level, are assigned probable water depths based upon comparisons to the modern shoreface environment. Given a tidal range of 2.4 m, facies of Holocene samples are assigned to mean sea level. extinct and longest lived of the MIS 5 eustatic sea-level highstands. This age assignment is also consistent with (1) the development of moderately thick, red (Munsell 10R-2.5 YR) soil B-horizon and (2) weathering rind thicknesses of ~2 cm in basaltic clasts, similar to other MIS 5.5 deposits in southern Costa Rica (Bullard, 1995; Murphy, 2002; Sac et al., 2004; Fisher et al., 2004), and on the Burica Peninsula (Morell et al., 2011), further supporting the radiocarbon and OSL ages.

The oldest optical age, sample 21 from the Rincón member, is 109 ka ± 28 ka (Table 2; Fig. 5, N-S cross section). Given the large analytical error, we assign this sample to MIS 5.5 at ca. 125 ka, which would be the highest and longest lived of the MIS 5 eustatic sea-level highstands. This age assignment is also consistent with (1) the development of moderately thick, red (Munsell 10R-2.5 YR) soil B-horizon and (2) weathering rind thicknesses of ~2 cm in basaltic clasts, similar to other MIS 5.5 deposits in southern Costa Rica (Bullard, 1995; Murphy, 2002; Sac et al., 2004; Fisher et al., 2004). It is not possible to resolve the Rincón member into separate, older marine isotope stages with the available OSL dating.

Samples 3 and 4 from a freshwater lacustrine deposit within the Tigre member yielded radiocarbon ages of 30.9 and 32.1 ka (Table 1; Fig. 5, N-S cross section at km 4.5). These samples are well-preserved, delicate leaves on bedding planes in thin, horizontally bedded muds. Because these samples are from lacustrine deposits that formed behind a landslide dam, they are not useful for uplift rate calculation because the elevation at the time of deposition is unknown.

We interpret the distribution (Fig. 4), facies architecture, thickness, and structure (Fig. 5) of the late Quaternary Marenco formation on the Osa Peninsula to be controlled by interaction among eustatic sea-level fluctuations, paleotopography on the major unconformity with basement rocks and the Osa group, and the nature of block faulting (see next section). For deposits of the Marenco formation within the range of Quaternary eustatic sea-level fluctuations, between ~66 m and ~125 m, eustatic sealevel highstands (MIS 1, 3, 5, etc.) allow for transgressions and deposition in topographically low, subsiding, fault-bounded basins around emergent paleotopographic highs.
Late Quaternary Structure

Geologic mapping and new radiometric ages throughout the central part of the peninsula allow us to construct two structural cross sections across the peninsula (Fig. 5). This has not been possible in previous studies (Gardner et al., 1992; Sak et al., 2004a) because of the geographic limits of those studies to mostly coastal sections.

Bedding in the sedimentary cover above the unconformity dips generally to the north-northwest, although dip can be locally quite variable in direction and steepness (Fig. 4B). Dips tend to be steeper in the older Osa group sediments than in the younger Marenco formation. Bedding strikes generally west to northwest, but it also can be highly variable. The general northeast dip and northwest strike probably reflect shortening from out-of-sequence, landward-dipping thrust faults offshore (Barritt and Berrangé, 1987; Vannucchi et al., 2006) that formed during initial subduction of the Cocos Ridge.

Mapped faults form an intersecting network that controls the topography and the orientation of streams and valleys (Fig. 4). However, most faults cannot be traced along strike very far in the dense jungle vegetation. The dominant set of faults strike northwest parallel to the trench and northeast perpendicular to the trench (Lew, 1983; Meschede et al., 1999; Sak et al., 2004a; Vannucchi et al., 2006; Buchs et al., 2009; this study). Faults extend through all members of the Marenco formation to the surface (Fig. 3E). These subvertical, through-going faults (Barritt and Berrangé, 1987) record an active period of pervasive brittle deformation (Sak et al., 2004a; Vannucchi et al., 2006; this study) and, as we will suggest later, extend through the Osa mélangé to the plate boundary (Vannucchi et al., 2006). These faults are the first-order control on the structural relief of the basement Osa mélangé (Fig. 5). Fault motion is predominantly dip slip with both normal and reverse sense of motion, similar to that observed on the northwest coast (Sak et al., 2004a) and central coast (Lew, 1983; Vannucchi et al., 2006). Fault slip indicators show that some faults are reactivated with the opposite sense of motion (Vannucchi et al., 2006), consistent with inferred up-down motion that controls deposition of the Marenco formation (Sak et al., 2004a).

These active faults cut the peninsula into a set of independent, actively deforming blocks. Most blocks are less than 5 km on a side. One such block locally ponds drainage in the northeastern interior of the peninsula (Fig. 4A, Laguna Chocuaco). The north-south cross section (Fig. 5) contains numerous faults that cut the section into at least six distinct, independently moving blocks. One of the larger, less-elevated blocks defines the Laguna Corcovado swamp and central graben, one of the more prominent topographic features on the peninsula (Fig. 3F; Fig. 5, E-W cross section). Higher topography on the most elevated blocks is underlain by the older (MIS ≥5) Rincón member of the Marenco formation. Distribution of the younger (MIS 3) Tigre member of the Marenco formation is confined to lower elevations on less-elevated blocks. As we will show later, this topography and vertical deformation on the Osa Peninsula correlates directly to bathymetry on the subducting Cocos Ridge, immediately offshore at the Middle America Trench only 20 km to the south.
Late Quaternary Uplift Rates

We quantified Quaternary vertical uplift on the Osa Peninsula from radiocarbon and optical ages at 15 locations (Tables 1 and 2) using

\[ U \left( \frac{m}{ky} \right) = \frac{E(m) - F(m) - S(m)}{T(ka)} \]  

where \( U \) is uplift rate, \( E \) is modern sample elevation above mean sea level, \( F \) is facies elevation relative to mean sea level, \( S \) is elevation of mean paleo–sea level, and \( T \) is sample age (Gardner et al., 1992, 2001; Pinter, 1996; Sak et al., 2004a; Morell et al., 2011). Elevation is positive upward from modern mean sea level. Calculated uplift rates range from 1.7 ± 0.4 m/k.y. to 8.5 ± 2.8 m/k.y. (Tables 1 and 2). Time-averaged uplift rates can be shown graphically (Fig. 6A), where samples are plotted on the eustatic sea-level curve according to facies elevation and age, and a line is drawn from each sample to the modern elevation of that sample. The slope of each line is the time-averaged uplift rate and is the average elevation path followed by each sample through time. Time-averaged uplift paths do not capture potential short-term coseismic deformation, which would be expressed as small steps along any line.

We define the block structure on the Osa Peninsula by outcrop distribution of the Marenco members, fault boundaries, and differences in uplift rates between adjacent blocks (Figs. 4, 5, and 6B). The N-S cross section (Fig. 5) can be divided into six independently moving blocks.

Figure 5. Geologic cross sections across the Osa Peninsula. A contains three radiometric ages for the Jiménez member ranging from 0.9 ka to 2.02 ka from Gardner et al. (1992); B contains 14 radiometric ages for the Tigre member ranging in age from 32.22 ka to >51.54 ka from Sak et al. (2004a). Cross sections are located on Figure 4A. Faults in cross sections are shown as thick red lines in Figure 4A. Black dots in Osa Peninsula insets are optically stimulated luminescence (OSL) sample locations; blue dots are \(^{14}C\) sample locations. Small boxes show locations of photographs in Figure 3. Note location of central graben on E-W cross section and on photograph in Figure 3E. Sample numbers refer to Tables 1 and 2. FB on N-S cross section refers to fault block numbers in Figure 6. VE — vertical exaggeration.
with distinctly different rates of uplift. Rate of uplift is greatest, 5.5–8.5 m/k.y., on fault block 3 (Fig. 6B) in the central part of peninsula. Here, the Tigre member is inset into the Rincón member. Although this fault block has the highest time-averaged uplift rate, it is not the topographically highest block on the peninsula. The topographically highest block in the N-S cross section is fault block 2, which is capped by the Rincón member. On fault block 5, the thickness of the Tigre member, ~100 m, is in excess of the sea-level rise from MIS 4 to MIS 3, i.e., ~80 m, requiring subsidence of at least 20 m during MIS 3. Subsidence of individual blocks has also been reported along the northwest coast (Sak et al., 2004a).

Rates of uplift decrease systematically away from the central part of the peninsula toward both coasts in both cross sections. However, in the E-W cross section, the Rincón member is dropped down several hundred meters in the central graben (Fig. 5, E-W cross section) relative to adjacent blocks, which have the highest topography on the Osa Peninsula, in excess of 500 m to 700 m. On the E-W cross section, uplift rates decrease toward the coast, where the Tigre member (Gardner et al., 1992; Sak et al., 2004a) and locally where the Jiménez member (Gardner et al., 1992) are exposed. We will show in the next section that this topography, structural relief, and distribution of uplift rates are closely correlated to the bathymetric relief on the subducting Cocos Ridge.

A first-order model for uplift of the Osa Peninsula through time can be constructed from the uplift rates and eustatic sea levels that are appropriate for the age of a sample. In this model (Fig. 7), we assume a time-averaged, spatially uniform, maximum uplift rate of ~4 m/k.y. These model assumptions do not reproduce the subleties of individual block movements nor reproduce exact facies depths for individual samples, but the model does predict the general uplift and timing for exposure of the Osa Peninsula above sea level and does reproduce the distribution of facies in Marencio formation rather well. Samples and facies from field observations (Fig. 3) are located on each model time step. The model begins (Fig. 7A) when the Osa Peninsula becomes subaerially exposed at the Rincón member. On fault block 5, the thickness of the Tigre member, ~100 m, is in excess of the sea-level rise from MIS 4 to MIS 3, i.e., ~80 m, requiring subsidence of at least 20 m during MIS 3. Subsidence of individual blocks has also been reported along the northwest coast (Sak et al., 2004a).

**DISCUSSION: EVOLUTION OF THE PLATE MARGIN**

**Osa Topography and Cocos Ridge Bathymetry**

The spatial distribution of deformation rates, topography, and structural fabric are, to the first order, controlled by bathymetry on the subducting Cocos Ridge. In fact, a stunning relationship exists between bathymetry on the subducting Cocos Ridge and topography and deformation on the Osa Peninsula (Fig. 8). This is true, in part, because the upper plate is relatively thin under the Osa Peninsula and can consequently deform in response to small (>0.5 km relief) bathymetric features on a stronger subducting plate. Estimates of the dip of the Wadati-Benioff zone under the Osa Peninsula, and thus the thickness along the seaward edge of the Osa mélangé, are poorly constrained because of the diffuse seismicity (Protti et al., 1995). Estimates range from as low as 3° (3 km thickness; Kolarsky et al., 1995) to ~10° (~10 km thickness; Protti et al., 1994, 1995) to possibly as much as 20° (15 km thickness; Corrigan et al., 1990; DeShon et al., 2003; Norabuena et al., 2004). However, estimates of plate dip derived from historical seismicity by DeShon et al. (2003) and Norabuena et al. (2004) are northwest of the Osa Peninsula along the central Pacific coast, where the plate boundary is better imaged and more steeply inclined. Therefore, the thinner estimates, ~3 km to 10 ~km, are more reasonable.

The thin basement that makes up the bulk of the margin wedge on the Osa Peninsula must deform around subducting bathymetric features. This leads to a strong correlation between topography and bathymetry. Topographically low areas on Osa (the central graben, the eastern lowlands, and the opening into the Gulfo Dulce) line up along the relative plate motion vector with the axial and lateral grabens on the Cocos Ridge. The western uplands and the central ridge on Osa line up with the flanking ridges.
Figure 7. Sequence of illustrations showing the uplift of the Osa Peninsula: (A) at approximately marine isotope stage (MIS) 5.5, last interglacial highstand (ca. 125 ka); (B) approximately early MIS 3 (40–60 ka); (C) approximately late MIS 3 (30–40 ka); (D) approximately MIS 2 (15–20 ka); (E) modern Osa Peninsula. See Figure 4A for geologic map. Land surface digital elevation model was derived from SRTM 90 m elevation data. Images assume age-appropriate eustatic sea levels and time-averaged, spatially uniform uplift rate of 4 m/k.y., the time-averaged uplift rate from Figure 6.
Upper-plate deformation in response to flat slab subduction, Costa Rica

The highest peak on Osa, the unnamed peak at 780 m elevation, lines up with the shallowest bathymetry immediately offshore on the Cocos Ridge (Fig. 8, cross-sections A-A' and B-B'). However, linear features on the Cocos Ridge are not parallel to the relative plate motion vector between the Cocos plate and Panama microplate. Based on the obliquity and orientation of the Middle America Trench, these features move northwestward through time (Fig. 8, white arrows). This is clearly seen as a scarp along the margin wedge immediately inboard of the trench where the eastern flanking ridge of the western lateral graben is subducting (Fig. 8). On Osa, this northwestward drift of the flanking ridge is also manifested in the curvature of the coast between the central ridge and eastern lowlands (Fig. 8).

Bathymetry on the Cocos Ridge also correlates closely to structure and uplift rates on the Osa Peninsula. The structurally highest areas are along the central ridge where the Osa mélangé reaches elevations approaching 400 m (Fig. 5, E-W cross section). The central graben, which is inboard of the lateral western graben, is structurally lower that the bounding central ridge and western uplands (Fig. 5, E-W cross section). The highest uplift rates are recorded along the central ridge (Figs. 5 and 6, fault block 3) and decrease toward the coast, both along strike of the ridge (N-S cross section in Figs. 5 and 6B) and perpendicular to the ridge (Fig. 5, E-W cross section, locations A and B).

Fault block 3 has the highest time-averaged uplift rate, 5.5–8.5 m/ky. (Fig. 6A), but it is not the topographically highest block on the peninsula (Fig. 5). The topographically highest block in the N-S cross section is fault block 2, which is capped by the Rincón member. Two possible explanations are possible for this distribution of uplift rates on these two blocks. In the first possibility, block 2 has been uplifting at a slower rate for a longer time, producing a higher elevation than fault block 3. However, it is also possible that fault block 2 did, in the past, experience a rate of uplift that is similar to the current rate of uplift on fault block 3, but then began to subside with passage of a subducting seamount, in essence reversing the sense of motion. In this case, the long-term, average uplift rate would be lower for block 2. We prefer the second scenario because previous stratigraphic (Sak et al., 2004a) and structural (Vannucci et al., 2006) studies have shown that fault motions can reverse, and blocks with a history of uplift can subsequently subside—similar to upper-plate deformation from seamount subduction in the New Hebrides and Solomon Arcs (Taylor et al., 2005). We interpret these vertical motions as a wave of rapid uplift followed by subsidence that propagates.

Figure 8. Shaded relief image showing bathymetry and topography for a section of the Cocos Ridge and Osa Peninsula, respectively. Vectors (white arrows resolved into trench-parallel and trench-perpendicular components) show amount of motion of the Cocos plate relative to the Panama microplate in 100,000 yr, i.e., approximate length of glacial-eustatic sea-level cycle. Dark-gray lines show projection of grabens on the Cocos Ridge (elg—eastern lateral graben; wlg—western lateral graben) into corresponding grabens on the Osa Peninsula and projection of flanking ridges on the Cocos Ridge into uplifted areas on the Osa Peninsula. Black star shows location of highest peak on Osa at 780 m. Bathymetric data were provided by C. Ranero and published in Ranero et al. (2003). Image was processed in GeoMapApp using data provided by W. Weinrebe. Land surface topography is from GTOPO 30 data set. Sun angle declination is −45°; inclination is 35°. E-W topographic profile A-A' across the Osa Peninsula generally follows the E-W cross section in Figure 5 passing through the highest (782 m) unnamed peak on Osa (star on cross section line in Fig. 8), but it does not pass through Cerro Brujo on the E-W cross section in Figure 5. Maximum relief on the Osa Peninsula is ~0.8 km. Bathymetric profile B-B' runs across the Cocos Ridge immediately outboard of the Middle America Trench (MAT). Maximum relief on the Cocos Ridge is ~0.8 km. Bold lines connecting A and B show projection of the Cocos Ridge bathymetry into the Osa Peninsula topography. Bathymetric profiles C-C' and D-D' are along the Cocos Ridge parallel to the relative plate motion vector. See Figure 1C for general location. VE—vertical exaggeration.
across the peninsula, parallel to the relative plate motion vector along the plate boundary, and tracks variations in the highest bathymetry on the subducting Cocos plate. Structures such as faults record permanent deformation as the upper plate deforms to override the curvature in the subducting plate, but the topography is ephemeral, rising and collapsing in response to subducting bathymetry on the Cocos Ridge. Given a Quaternary uplift rate distribution that is largely due to variations in the bathymetry of the underthrusting plate, the permanent deformation and uplift on the Osa Peninsula should occur coseismically when the roughness of the downgoing plate is episodically forced under the margin wedge as described next.

**Deformation as a Player Piano Model**

In the outer forearc, where the upper plate is only several kilometers thick, the margin wedge must deform to allow for subduction of rigid asperities on the incoming plate (Fig. 8; Fisher et al., 2004; Sak et al., 2004a). Flanking ridges and seamounts on the Cocos Ridge are composed of basaltic crust that is stronger than the much thinner and extensively faulted Osa mélangé in the upper plate (Figs. 9A–9D). In such a system, the strain rate in the upper plate is a function of the relative plate motion rate and straining distance (Kniepe, 1985), a distance that is a function of the curvature of subducting bathymetric features (Sak et al., 2004a). Straining regions (Fig. 9E, in red) experience up-shearing and down-shearing expressed as subvertical faults. We believe these active faults, which are extensive on the Osa Peninsula (Figs. 4 and 5), extend from the surface to the plate interface because the upper plate is thin, 3–10 km thick, and because of the close correspondence of bathymetry on the Cocos Ridge to topography, uplift rates, and structural relief on the Osa Peninsula.

The rate of uplift or subsidence is determined by the slope of the asperity parallel to the relative plate motion vector and the rate of relative plate motion (Fig. 9F). Assuming an average slope of ~7° for a flanking ridge that is at the trench (Figs. 8 and 9F) and a relative plate motion rate of ~50 m/k.y. (the difference between the Cocos–Panama microplate relative plate motion rate and the rate of out-of-sequence thrusting in the Fila Costeña; Sitchler et al., 2007), we calculate a time-averaged uplift rate of ~4 m/k.y. This value, used in Figure 7 to produce the time-averaged emergence of the Osa Peninsula above sea level, reproduces the regional uplift of the Osa Peninsula over the last glacial cycle and agrees well with the distribution of facies and ages of sediments. It is generally consistent with values for rates of uplift ranging from ~2 m/k.y. to 6 m/k.y. and subsidence up to ~6 m/k.y. along the northwest coast (Sak et al., 2004a) and uplift rates ranging from ~2 m/k.y. to 6 m/k.y. along the eastern coast (Gardner et al., 1992). Therefore, we interpret the rates of vertical motion across the overriding outer forearc to be a function of the rate of relative plate motion and the complex surface geometry of the underthrusting plate. Under these circumstances, a margin may experience rapid uplift during subduction of the leading edge of a bathymetric high followed by subsidence along the trailing edge (Ballance et al., 1989; Dominguez et al., 1998; Mann et al., 1998; Sak et al., 2004a), with the amount of uplift or subsidence related to the volume of the bathymetric feature (Meffre and Crawford, 2001). Uplift is due not to shortening, but rather to the positive slope of the underthrusting ridge or seamount. Given the thin upper plate, even small asperities (~0.5 km height) will deform the upper plate.

We do allow for some transfer of mass from the upper plate (subduction erosion) along hanging-wall shortcuts that can develop at sharp curvatures around subducting bathymetric features (Fisher et al., 2004; Sak et al., 2004a). Similarly, we allow for some transfer of mass to the upper plate by underplating at the point arcward of where the thickness and strength of the upper plate are sufficient to shear off asperities (Fig. 9D). However, very little current uplift in the outermost forearc is attributable to permanent shortening, as occurs inboard of the d'Entrecasteaux Ridge in the New Hebrides Arc (Taylor et al., 2005). In the inner forearc, where the upper plate is thicker than in the outer forearc, small-wavelength bathymetric features have no effect on the uplift and shortening patterns, and the lateral distribution of shortening related to inversion of the Terraba basin is largely determined by the width and thickness of the Cocos Ridge and the regional plate-boundary stress related to flat slab subduction (Sitchler et al., 2007; Figs. 9C and 9D). Underplating and subduction erosion ultimately result in downdip smoothing of the plate boundary, but these are currently secondary processes with regard to the uplift pattern in the outer forearc.

The keys on a player piano serve as a good mechanical analogy for the independently moving blocks on the Osa Peninsula. The keys (blocks on Osa) move up and down in response to teeth on the metal spool (bathymetry on the Cocos Ridge) that rotates and activates the keys on the player piano. The key is depressed or elevated by the length of the tooth and rate of rotation of the muscle spool with very little transfer of mass from one plate to the other. The thin, outer wedge represented by Osa mélangé deforms in response to strain that accumulates along northe- and northwest-trending, high-angle faults that extend from the surface to the plate boundary (Fig. 5). Small blocks, several kilometers on a side (Fig. 5; Sak et al., 2004a; Vannucci et al., 2006), uplift and subside (riﬄ ing; von Huene et al., 2004) in response to asperities on the subducting Cocos Ridge. Uplift and subsidence occur as a passive response to variations in relief on the Cocos Ridge (Adamek et al., 1987). Along this region of the margin, there was an initial period of protracted uplift, possibly as much as 2–3 km (Corrigan et al., 1990; Gardner et al., 1992), as the blunt front end of the Cocos Ridge collided with the outer part of the margin wedge. Superimposed on this uplift are shorter time scale variations related to the along-axis roughness of the ridge itself. These uplift “events” are ephemeral in the sense that topographic collapse follows uplift as three-dimensional bathymetric features along the crest of the ridge subduct underneath the Osa Peninsula.

**CONCLUSIONS**

New radiocarbon and OSL ages allow for refinement of the Quaternary stratigraphy and provide constraints on outer forearc deformation along the Middle America Trench in southern Costa Rica. On the Osa Peninsula, the Marenco formation is subdivided into three members: the Jiménez member (MIS 1), the Tigre member (MIS 3), and the Rincón member (MIS 5). Sediments in all members of the Marenco formation are predominantly marine. The mapped distribution, facies architecture, and structure of the late Quaternary Marenco formation on the Osa Peninsula are controlled by interaction among eustatic sea-level ﬂuctuations, paleotopography on the major unconformity with basement rocks and the Osa group, and block faulting, with thickness of the Marenco formation ranging from 0 m on paleotopographic highs to nearly 300 m in fault-bounded basins.

The spatial distribution of deformation rates, topography, and structural fabric in the outer forearc are, to the first order, controlled by short-wavelength, high-relief bathymetric features on the downgoing Cocos Ridge. This is true, in part, because the upper plate is relatively thin, ~3 km to ~10 km, under the Osa Peninsula. The dominant set of active faults strike parallel (northwest) and perpendicular (northeast) to the trench and extend from the surface to the plate boundary. These faults cut the peninsula into a set of independently deforming blocks, ~5 km on a side, and have been active since the arrival of the Cocos Ridge at the Middle America Trench (ca. 1–3 Ma). Time-averaged uplift rates vary rapidly across individual blocks, ranging from 1.7 m/k.y. to
8.5 m/k.y. Variations in uplift amount, uplift rate, and topography on the Osa Peninsula are primarily tied to variations in the bathymetry of the Cocos Ridge. The deformation on the Osa Peninsula is ephemeral in the sense that topographic collapse and subsidence follow uplift –10 km

ca. 1-1.5 Ma; initial subduction of Cocos Ridge

Figure 9. (A–D) Tectonic evolution of the Panama microplate, in response to flat slab subduction of the Cocos Ridge. The line of section is parallel to the relative plate motion vector and passes through the Osa Peninsula and the culmination of the Fila Costeña thrust belt. Plate motion is relative to a fixed Caribbean plate in A because the Panama microplate has not formed yet. Plate motion rates are relative to the Panama microplate in B–D. Position of Panama fracture zone (PFZ) is based on migration rate of the Panama triple junction (Fig. 1, plate vector diagram) and the projected intersection of the Panama fracture zone with the line of section. Terraba basin is modeled after the modern Sandino basin in Nicaragua (after Ranero et al., 2000). Thickness for the Terraba basin is from Lowery (1982), Phillips (1983), Yuan (1984), and Sitchler et al. (2007). Shortening rates in the Fila Costeña are from Sitchler et al. (2007), and those in the outer forearc are from modern horizontal global positioning system (GPS) velocities (Norabuena et al., 2004; La Femia et al., 2009). Generalized scale is same for sections A–D. (E) Upper-plate deformation around an asperity is modeled as a hanging wall in a fault bend and is a function of the footwall geometry and upper-plate rheology [modified from Knipe, 1985; Fisher et al., 2004; Sak et al., 2004a]. Straining regions (in red) experience up- and down-shearing expressed as subvertical faults that extend from the plate boundary to the surface. Deformation is restricted to regions of curvature on the subducting plate. Hanging-wall shortcuts that may develop in these regions of curvature allow for subduction erosion of the upper plate. Increase in upper-plate thickness and strength downdip along the subduction zone facilitates shearing of the asperity and underplating. (F) Bathymetry from line C-C′ in Figure 8. Calculated, average long-term uplift rate and uplift event duration are calculated from the average slope of the asperity, length of the asperity slope parallel to the relative plate motion vector, and relative plate motion rate. MAT—Middle America Trench; ls—limestone.

APPENDIX 1

Laboratory and Analytical Procedures for OSL Analysis

The samples were processed under subdued red light, with the 90–125 µm quartz fraction extracted for dating using standard procedures (e.g., Galbraith et al., 1999). A single-aliquot regenerative-dose protocol was used to calculate equivalent doses (Murray and Roberts, 1998; Galbraith et al., 1999; Murray and Wintle, 2000).
Approximately 100 aliquots per sample, each composed of single grains of quartz, were preheated at 240 °C for 10 s and optically stimulated. The samples were then given applied doses using a calibrated 224Ra β-source and re-stimulated to record their regenerative OSL signals. OSL sensitivity changes in the quartz crystals between the natural and regenerative cycles were monitored after each optical stimulation, using test doses of 10 Gy following a 160 °C cut-off heat.

Output from the Risø apparatus was analyzed using Analyst version 3.2.1 software (Pirrie, 2006). OSL data were corrected for dark decay, and dose-response curves were constructed using six regenerative dose points. Estimates of equivalent dose were obtained from the intercept of the regenerative dose-response curve with the natural luminescence intensity. Optical ages were derived from weighted mean equivalent dose using the central age model of Galbraith et al. (1999). The maximum age model of Olley et al. (2006) was used to estimate the greatest finite equivalent dose for sample CR07–05.

RÖSNER, F. U. and ThOENI, C. A., 2003, Radiocarbon date calibrations were measured using instrumental neutron activation analysis (INAA) by Becquerel Laboratories, Mississauga, Ontario, Canada, and converted to dry values by oven drying sediment from the sample location for 8 h at 105 °C and CRID-4 calibration dose for samples CR07–05 and CR07–09 were derived from the INAA values using the conversion factors of Adanac and Atkin (1998).

Cosmic-ray dose rates were determined from established equations (Prescott and Hutton, 1994), allowing for sample depth, sediment density, and site altitude and latitude. Present-day field-moisture contents of the sediments were measured from oven drying sediment from the sample location for 8 h at 105 °C and sediments were considered broadly representative of long-term averages and used to correct attenuation of beta and gamma rays by water (Atkin, 1998).

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