



GR focus review

Subduction erosion, and the de-construction of continental crust: The Central America case and its global implications

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ABSTRACT

The relative rates of creation and destruction of continental crust at subduction zones are a key factor shaping the evolution of continental crust through time. Central America, arguably the best studied place where subduction erosion has been documented, is used here to assess past rates and modes of forearc recycling. Drilling from Guatemala to Costa Rica indicates that subduction erosion has been active since at least the early Miocene. Drilling also shows that the rates of subduction erosion have varied significantly both along strike and through time. The Integrated Ocean Drilling Program (IODP) Expedition 334 to southern Costa Rica documents unprecedented subduction erosion there – at rates larger than the fastest known rates of forearc accretion. In southern Costa Rica, accelerated subduction erosion of the upper plate initiated when the Panama Fracture Zone/Cocos Ridge, the latter being an over thickened aseismic ridge, arrived at the Middle America Trench. The forearc records this event with an unconformity at 2.2 ± 0.2 Ma. The recovered shelf sequence overlying the unconformity constrains a short (<2 Myr) interval of extreme subsidence (~ 1200 m) with a rapid pulse occurring during the first ~ 0.3 Myr. This event removed an estimated 1.2×10^6 km³ of forearc material at a rate of ~ 1125 km³/Myr/km of trench during a time of rapid (~ 1035 m/Myr) contemporaneous shelf sediment accumulation. Detrital apatite fission-track thermochronology on the sediments above the unconformity indicates the pattern of surficial sediment transport during this subduction erosion event. The fission track data show that sediments from the extinct and exhumed volcanic arc – the Cordillera de Talamanca – were able to immediately access the growing forearc basin after the onset of the 2.2 Ma subduction erosion event. The onset of subduction of an aseismic ridge as occurred at 2.2 Ma in southern Costa Rica is a fairly common tectonic event along a subduction margin. We suggest that similar rapid pulses of subduction erosion may punctuate the evolution of many margins, contributing disproportionately to crustal recycling at subduction zones. The (poorly) preserved geologic record of paleoforearcs needs to be reassessed with this mechanism in mind. It also implies that continental forearc material may be significantly consumed during short local bursts along a subduction margin, and furthermore, that margins abutting regions of frequent subduction of aseismic ridges, like the regions in the Western Pacific where the Darwin Rise currently subducts, should face disproportionate pulses of future subduction erosion and forearc recycling.

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1. Introduction

The quantification of the growth, destruction and recycling of continental crust across the geological eras is critical to understand not only the evolution of key tectonic processes, such as interactions between plates and other lithospheric geomechanics, but also the geochemical evolution of the mantle (Tatsumi and Kogiso, 2003; Tatsumi, 2005). Several authors have produced global models for crustal growth through time (cf. Rino et al., 2004). Most models imply net growth at differing rates through time. Their most significant contrasts lie in stressing the importance of continuous (Hurley and Rand, 1969; O’Nions et al., 1979; Veizer and Jansen, 1979; Allègre, 1982) vs. episodic growth (McCulloch and Bennett, 1994; Condie, 1998), or in arguing for rapid growth in the first 0.6–1 Ga after Earth’s origin, followed by a period with nearly constant crustal volume (Brown, 1979; Armstrong, 1981; Dewey and Windley, 1981; McLennan and Taylor, 1982; Reymer and Schubert, 1984) vs. a major phase of early continental crustal growth before ~3.8 Ga followed by a slow, steady reduction in the volume of continental crust since (Fyfe, 1978). One of the most-used approaches to address the rate of growth of continental crust through time has been through the compilation of U–Pb zircon ages in detrital and granitoid rocks (Condie et al., 2011). Zircon ages show a relatively small number of high-density age peaks distributed over the ~4.5 Ga of Earth’s existence. While these data have often been interpreted to imply phases of episodic crustal growth, they can also be interpreted to imply phases of preferential preservation of crust, orogeny and crustal metamorphism (for example zircon age-resets during Himalayan-style orogeny) (Condie et al., 2011; Cawood et al., 2012; Condie, 2014). The global importance of the destruction and mantle recycling of continental crust at subduction zones has captured the attention of geophysicists (Scholl and von Huene, 2007, 2009; Stern and Scholl, 2010) and, during the last few years, also isotope geochemists (Willbold and Stracke, 2006, 2010). Here we focus on observational evidence for the selective destruction and preservation of continental crust. Is it plausible for there to be periods with net destruction of continental crust? If so, what are reasonable magnitudes and timescales of the processes of net crustal destruction? Providing answers to these questions is the primary goal of this study, which is based on the approach of using constrained present-day rates as a key to better understand plausible past rates.

2. Subduction erosion and its controlling factors

Subduction erosion, i.e. the basal removal of upper plate material induced by subduction (von Huene and Scholl, 1991) is at present the largest-scale geological process destroying continental crust, with sediment subduction and continental delamination playing a lesser role (e.g. Clift et al., 2009a, 2009b). In this paper we assess the rates of subduction erosion and the net volume increase or decrease of continental crust where it is best measured offshore Central America, during the ~25 Ma time frame within which we can confidently track subduction erosion. We focus on Central America because this is the region that provides the biggest regional constraints to calculate a rate-time budget for this process of crustal destruction.

Several factors appear to shape subduction erosion. The topographic relief of seamounts on the subducting plate is one. This leads to directly

observable effects on the forearc slope of the overriding plate. In the southeast part of the Central America Trench offshore Costa Rica, the slope is punctuated by elongate depressions of roughly the same width as seamounts that are traceable up to 55 km inland, and parallel to the subduction vector (von Huene et al., 2000) (Fig. 1). At a bigger scale, still in Central America, the trench strike changes abruptly between Nicaragua and Costa Rica, describing a retreat that culminates at the axis of the subducting Cocos Ridge (Ranero et al., 2008) (Fig. 1). However, subduction erosion across Central America is not limited to areas where volcanic seafloor relief is subducting. Erosion is also measured for Guatemala (Vannucchi et al., 2004) and northern Costa Rica offshore Nicoya Peninsula (Vannucchi et al., 2001, 2003) where the seafloor is relatively smooth and seamount-poor. More generally, the controlling factors on the occurrence of subduction erosion or accretion appear to be primarily linked with the thickness of trench sediments and the subduction rate (Clift and Vannucchi, 2004). In particular, subduction erosion is favored by fast subduction >8 cm/yr – and thin <1 km – trench sediment fill.

In addition to the traces – ‘topographic shadows’ – that incoming plate relief can induce on the upper plate slope shortly after its subduction, in general subduction erosion can be directly detected by geologic observations in the forearc. Such observations include upper plate “basement” units – e.g. crystalline, ophiolitic, and fossil accretionary prisms – cropping out and forming the outer forearc (e.g. Straub et al., 2015), or the presence of a plate boundary shear zone that cuts through upper plate material (Vannucchi et al., 2008). Indirect evidence for subduction erosion involves a basal cut of imbricate thrusts and/or extensional faulting across the forearc that can be visible in reflection seismic images (Ranero and von Huene, 2000; Laursen et al., 2002), the progressive landward migration of the volcanic arc (Rutland, 1971; Bloomer et al., 1994; Vannucchi et al., 2001; Kay et al., 2005), and the subsidence of the forearc (von Huene et al., 1985; von Huene and Lallemand, 1990; Clift and MacLeod, 1999; Vannucchi et al., 2001, 2003). The latter can be detected through forearc drilling of unconformities with deposition of progressively deeper marine sediments on top of continental to shallow marine coastal facies, and sedimentary and paleo-ecological proxies. It is important to notice that subsidence in the forearc – in particular close to the trench – implies upper plate thinning, i.e. local removal of forearc material.

3. Subduction erosion in Central America

The Central America Trench was dredged offshore Nicaragua (Silver et al., 2000) and Mexico (de Lepinay et al., 1997). In both sites, upper plate basement was recovered from submarine outcrops located just a few km from the trench axis (Fig. 1). From Mexico to southern Costa Rica eight DSDP/ODP/IODP expeditions have recovered material from the forearc of the Central America Trench (Fig. 1). Here we concentrate on the temporal variability of subduction erosion along the margin that is shown by DSDP Leg 84 offshore Guatemala, ODP Leg 170 offshore Northern Costa Rica, and IODP Exp. 334 offshore southern Costa Rica (Fig. 2). These three areas also correspond to different “smoothnesses” of the subducting Cocos plate. Therefore, here they are considered type examples of what happens in smooth, seamount-dominated, and ridge-dominated subduction examples.

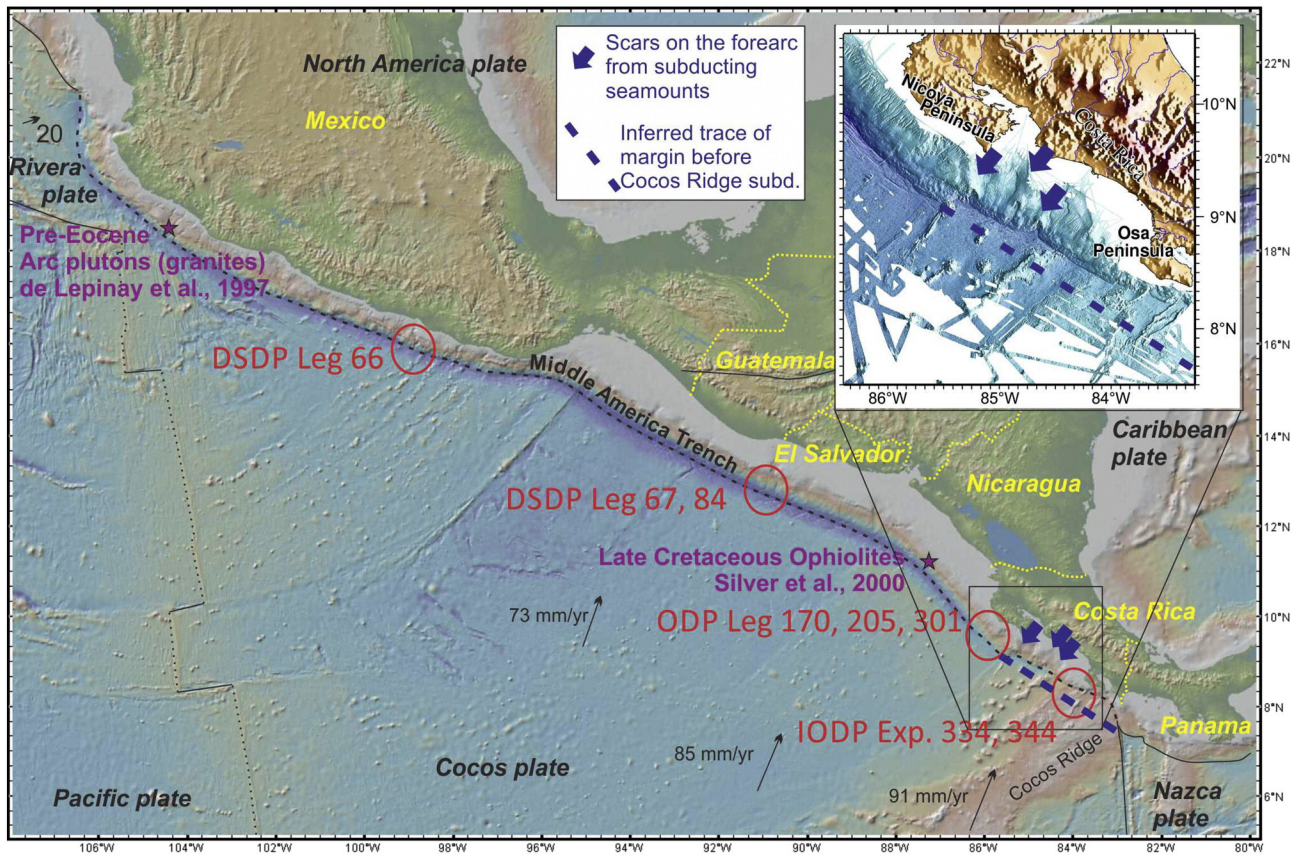


Fig. 1. Bathymetric and topographic map of the Middle America Trench and adjacent areas. Purple stars indicate the location of dredging that recovered igneous and ophiolitic material close to the trench. Blue arrows indicate scars left by subducted seamount on the forearc slope. The (minimum) margin retreat caused by Cocos Ridge subduction is also shown. In red the location of DSDP, ODP and IODP expeditions. Black arrows indicate the relative convergent rates (cm/year) between the oceanic and continental plates (DeMets, 2001).

3.1. Guatemala–El Salvador – the “smooth” sector (Fig. 2)

DSDP Leg 84 drilled a transect of five sites distributed from the margin toe to the upper slope. Four of the five sites (Sites 566, 567, 568 and 570) recovered basic and ultrabasic upper plate basement, such as amphibolite and serpentinite (Aubouin and von Huene, 1985; von Huene et al., 1985), underlying the slope sediments. In the middle to upper slope sites, Sites 568, 569, and 570, the slope sediments on top of the basement showed limited reworking and provided good paleobathymetry data. In particular they revealed considerable subsidence that progressively migrated in time from the middle slope to the upper slope (Vannucchi et al., 2004). The record from Site 569 shows that subsidence started abruptly in the early Miocene – ≈ 19 Ma – in the middle slope, involved the middle-upper slope Site 568 at the Miocene–Pliocene boundary – ≈ 5 Ma –, and finally reached the upper slope at Site 570 in the Pliocene–Pleistocene boundary – ≈ 2 Ma. It is important to note that the subsidence calculated from seismic reflection images is much less than that resolved well by biostratigraphy (Vannucchi et al., 2004). The progression of subsidence shows that subduction erosion seems to be most efficient at basal depths which correspond to the region below the upper slope and shelf. The subduction erosion rates calculated for each of the sites have values between 11.3 and 13.4 $\text{km}^3/\text{Myr}/\text{km}$ of trench, with an average of 12 $\text{km}^3/\text{Myr}/\text{km}$ of trench or 0.03 Tg/yr (Vannucchi et al., 2004). This long-term steady-state subduction erosion has taken place at least since the middle Miocene and sets a minimum background value for Central American subduction erosion (Fig. 2).

3.2. Nicaragua–Northern Costa Rica – the “seamount-dominated” sector (Fig. 2)

About 600 km to the ESE offshore the Nicoya Peninsula in Costa Rica, Leg 170 drilled two sites to understand the nature of the upper plate basement. Here there was also a previous drilling attempt done during Leg 84. The base of the slope sediment succession and its underlying rocks were reached at Site 1042. The base of the slope sediment succession is formed by a middle Miocene – ≈ 16.5 Ma – carbonate breccia (Vannucchi et al., 2001, 2003). The breccia consists of well cemented carbonate sandstone clasts in a well cemented sandstone matrix. The sands of both clasts and matrix have the same composition with abundant neritic fossils, geopetal fillings, and vadose cement. Its characteristics, therefore, imply deposition in a beach environment (Vannucchi et al., 2001). This beach-rock is presently at about 4000 m depth – ≈ 3600 m of water + ≈ 400 m of sediments – and at about 4 km from the trench axis where the upper plate has an estimated thickness of about 2 km. Based on this data point the average subduction erosion rate offshore Nicoya Peninsula has been about 35 $\text{km}^3/\text{Myr}/\text{km}$ of trench or 0.10 Tg/yr (Vannucchi et al., 2001). Under this former beach-rock, drilling recovered basement material consisting of a basement ophiolitic breccia with clasts of cherts, basalt and ultramafic rocks (Kimura et al., 1997). Paleontological and geochemical analyses on the breccia showed its source rock to be the Nicoya Complex, the ophiolitic unit that crops out on the Nicoya Peninsula (Steiger et al., 2005). On the basis of coastal exposures in Nicoya Peninsula, the basement ophiolitic breccia is temporally and lithostratigraphically correlated with the basal breccia marking the regional angular unconformity

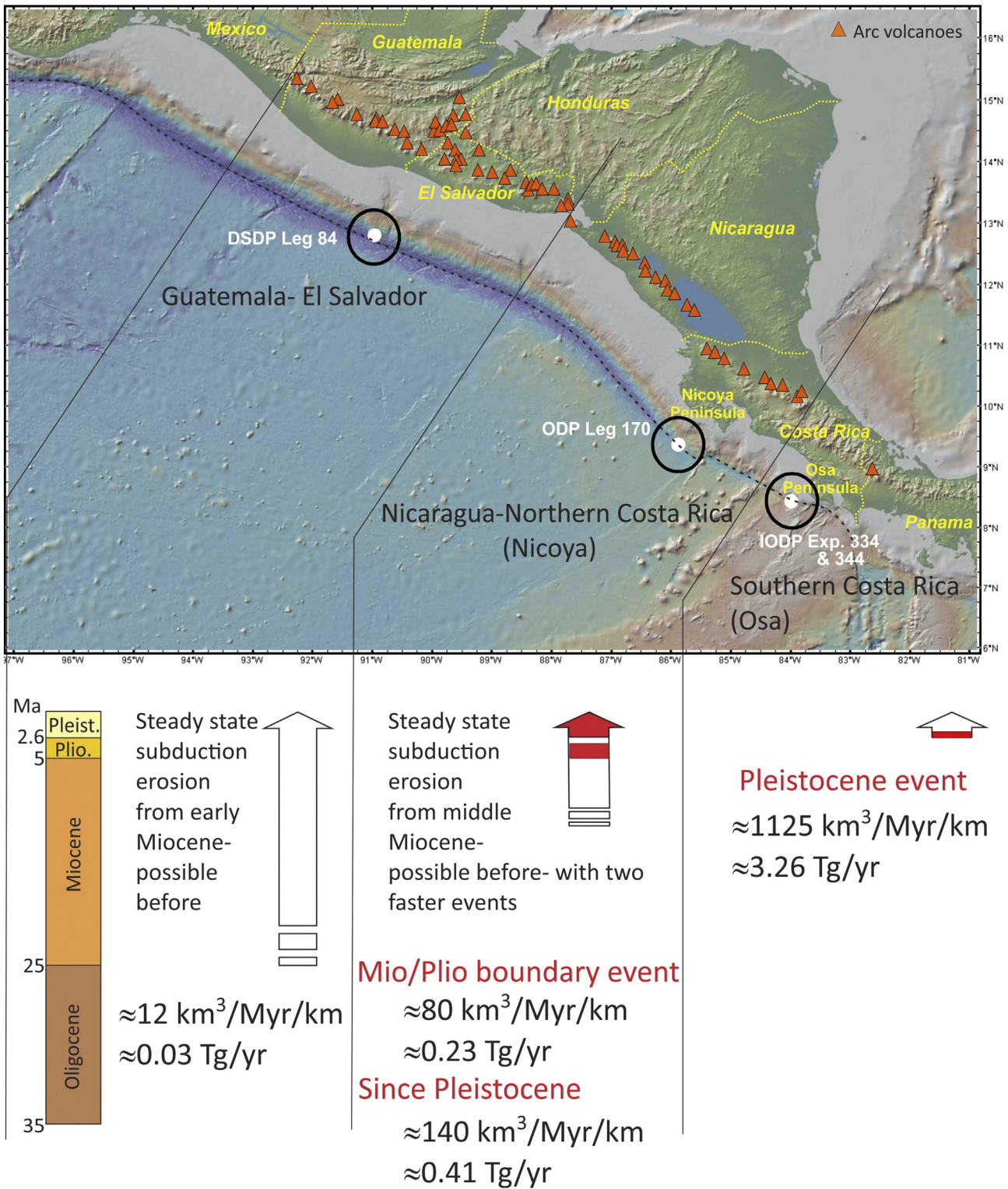


Fig. 2. Erosion rates calculated for the three sectors of the Central America subduction system considered in this study.

that separates the Neogene neritic to non-marine sequences from the underlying mafic units of the Mesozoic Nicoya Complex (Vannucchi et al., 2001). This interpretation is consistent with both the presence of ophiolite dredged from an outcrop offshore Nicaragua about 200 km to the NNW (Silver et al., 2000) (Fig. 1) and the acoustic properties of the forearc basement as measured by seismic reflection and refraction profiles (Hinz et al., 1996; Ye et al., 1996; Stavenhagen et al., 1998; Ranero and von Huene, 2000; Walther et al., 2000).

Above the beach-rock unit, sediments record continuous deposition since the middle Miocene (Vannucchi et al., 2003). The distribution of benthic foraminifera shows taxa common in bathyal (<2000 m water depth) settings at the base of the sequence, whereas taxa common in abyssal (>2000 m) settings dominate the most recent sediments. The deepening-upward trend confirms the trend indicated by the beach deposits found at its base. Careful analysis of the distribution of the benthic foraminifera shows that subsidence did not occur at a

constant rate, but, as already seen for Guatemala, it started quite abruptly at about the Miocene–Pliocene boundary (5.3 Ma) and continued to subside more rapidly until about 4 Ma when its rate slowed significantly, to increase again to an even higher rate at 2.5 Ma (Vannucchi et al., 2003). In this dataset, the first event starting at 6 Ma was responsible for the removal of about 200 km³ of forearc material corresponding to an erosion rate of 80 km³/Myr/km of trench or 0.23 Tg/yr, whereas the second event starting at 2.5 Ma was responsible for the removal of about 350 km³ of forearc material corresponding to an erosion rate of 140 km³/Myr/km of trench or 0.41 Tg/yr (Fig. 2).

3.3. Southern Costa Rica – the “ridge-subduction-dominated” sector (Fig. 2)

The Cocos Ridge is a 20–22 Ma aseismic ridge (Lonsdale and Klitgord, 1978). It is a 2000-m-high marine feature with a crustal thickness reaching >20 km whereas the adjacent crust of the Cocos plate at the trench is ~10 km-thick (Sallares et al., 2001). Three sites of IODP Exp. 334 and 344 focused on the upper slope and shelf inboard of the Cocos Ridge and offshore Osa Peninsula (Vannucchi et al., 2012; Harris et al., 2013). Two of them, Sites U1379 and U1380 (Fig. 3), sampled and penetrated beneath the acoustic reflector marking the base of slope/shelf sediments. Site U1379 exhibited a sharp unconformity, whereas Site U1380, located about 10 km trenchward from the other site, had a less well-defined unconformity marking the base of slope sequence. The erosional unconformity at Site U1379 is marked by a white calcium carbonate deposit that separates a Pliocene/Pleistocene – ≈2.5 Ma – hemipelagic mudstone from an overlying Pleistocene, 1.85 m-thick conglomerate–sandstone unit (Vannucchi et al., 2013). The age gap between the two sedimentary units is smaller than the age-uncertainties for biostratigraphic detection; this technique implies this unconformity formed between 2.5 Ma and 1.9 Ma (Vannucchi et al., 2013). With somewhat higher-precision tephrochronology, the unconformity is estimated to have an age of 2.2 ± 0.2 Ma (Schindlbeck et al., in press). The underlying mudstone presents some cracks a few mm thick that are filled with fine grained material coming from the overlying unit. The basal unit of the slope/shelf sequence is formed from a meter of pebble-conglomerate at its base transitioning upwards to carbonate-cemented sandstones with well-rounded lithic pebble-sized clasts and shells and shell fragments that often form cm-thick layers (Vannucchi et al., 2012, 2013). Most of the pebbles are basaltic, with minor cherts. Geochemical analyses of the basalts reveal their overall MORB affinity (Masaoki Uno, personal communication). The sedimentary structures of this basal unit suggest that its origin was a beach that evolved from pebbly to sandy to a nearshore environment (Vannucchi et al., 2013). Down-slope, at Site U1380, this unit transitions to an 11-m-thick deposit where medium- to coarse-grained sandstone layers rich in shell fragments alternate with minor clayey siltstone layers (Harris et al., 2013). The Site U1380 deposit has been dated between 2.1 and 1.9 Ma and it is located at a depth coincident with the acoustic reflector marking the base of slope sediment, but no visible unconformity is present at this location (Harris et al., 2013). At Site U1380 the underlying deposit is composed of siltstone, sandstone and minor conglomerate beds organized in two fining upward sequences (Harris et al., 2013). These cores suggest that in the middle slope the sedimentary environment didn't change quite so dramatically as it did in the shelf, but sedimentation was controlled by reworking of sediments deposited upslope where erosion was dominating a nearshore environment.

Both Sites U1379 and U1380 penetrated below the acoustic reflector marking the base of the slope/shelf sediments. In both cases the sediments recovered below the acoustic reflector were relatively undeformed hemipelagic and terrigenous sediments related to a forearc environment (Vannucchi et al., 2012; Harris et al., 2013). No upper plate basement was reached. This occurrence suggests multiple cycles of forearc basin sedimentation (Vannucchi et al., 2016).

The sedimentological and paleontological analysis of the slope/shelf sediments above the acoustic reflector – and the basal beach/nearshore

deposits for Site U1379 – shows subsidence to abyssal depths followed by uplift to the modern water depths of 127 m for Site U1379 and 500 m for Sites U1380 and U1381 (Vannucchi et al., 2013). This somewhat more complex trend offshore Osa Peninsula is anticipated to be a byproduct of the subduction of the Cocos Ridge. The onset time for Cocos Ridge subduction at Central America has been debated for decades (see next paragraph). Drilling data point that a major event occurred at 2.2 ± 0.2 Ma and was responsible for the sudden uplift of this forearc with erosion of forearc sediments (Vannucchi et al., 2013). This sudden phase of forearc uplift was followed by a pulse of fast forearc subsidence, in turn followed by further uplift. The uplift/subsidence effects of the initial phases of ridge subduction on the forearc have never been observed with the detail revealed by drilling offshore Osa Peninsula. The trend showed by these data agrees with patterns suggested by recent 3D finite-element modeling (Zeumann and Hampel, 2015). This study showed that subduction of aseismic ridges could lead to considerable uplift and indentation of the forearc, and also showed that in spite of the uniform ridge height, the predicted distribution of uplift along the ridge-axis was not uniform, but instead had two maxima near the tip of the ridge and near the trench, respectively. These model experiments suggested there should be a wave of subsidence followed by uplift trenchward of the trailing edge of the entering ridge, consistent with the geological record at this site.

The volume removed from the Osa forearc as a byproduct of Cocos Ridge subduction is more difficult to quantify than it is offshore Guatemala and Nicoya Peninsula, because the forearc profile is likely to have been completely modified by the ridge subduction, and the thickness of the upper plate offshore Osa remains somewhat controversial. As mentioned, the strike of the Central America Trench changes abruptly offshore Nicoya Peninsula (Fig. 1). The N140 E strike offshore Nicaragua changes to a N114 E strike offshore southern Costa Rica. The indentation culminates and ends inboard of the axis of the subducting Cocos Ridge. The indentation is asymmetric (Fig. 1), we suggest because the Cocos Ridge is cut on its SE flank by the NS oriented systems of fracture zones separating the Cocos plate from the Nazca plate. The pre-Cocos Ridge subduction geometry of the forearc can be reconstructed assuming no indentation (Vannucchi et al., 2013). The estimate leads to an inferred volume of missing material of 118,125 km³ removed in ≈2.5 Ma, which gives a loss rate over 350 km of trench of 153 km³/Myr/km or 0.44 Tg/yr offshore Osa. Based on the time-evolution of vertical tectonics, most removal occurred in a time-window <0.5 Ma during which erosion rates were 1125 km³/Myr/km or 3.26 Tg/yr (Vannucchi et al., 2013) (Fig. 2). These rates carry uncertainties linked to the original thickness of the upper plate, which would modify this rate by +9%/–9% for each km the actual thickness was more/less than our 15 km estimate, and the original length of the forearc, which would modify the estimate by +2%/–2% for each km the original length was more/less than the assumed 60 km length.

4. Controversies: the impact of the Cocos Ridge on the forearc

The Cocos Ridge example is a good case study with which to debate the nature of damage caused to a forearc by subduction of high bathymetric relief. Two of the major controversies regarding the results of IODP Exp. 334 and 344 involve: 1) subduction erosion rates offshore Osa Peninsula, and 2) the timing of subduction of the Cocos Ridge.

The issue of the subduction erosion rates offshore Osa Peninsula is linked to the origin of the trench's indentation: forearc shortening vs. forearc erosion. According to Sitchler et al. (2007), subduction of the Cocos Ridge induced a flat-slab that promoted the underthrusting of the outer forearc (Osa Peninsula) under the inner forearc resulting in major forearc shortening, ≥36 km, and thickening rather than net removal of upper plate material. This shortening resulted in the development of the Fila Costeña fold-and-thrust belt – a 1700-km-high mountain chain interposed between the offshore forearc/Osa Peninsula and the uplifted extinct volcanic arc of the Cordillera de Talamanca (Fig. 3). The postulated

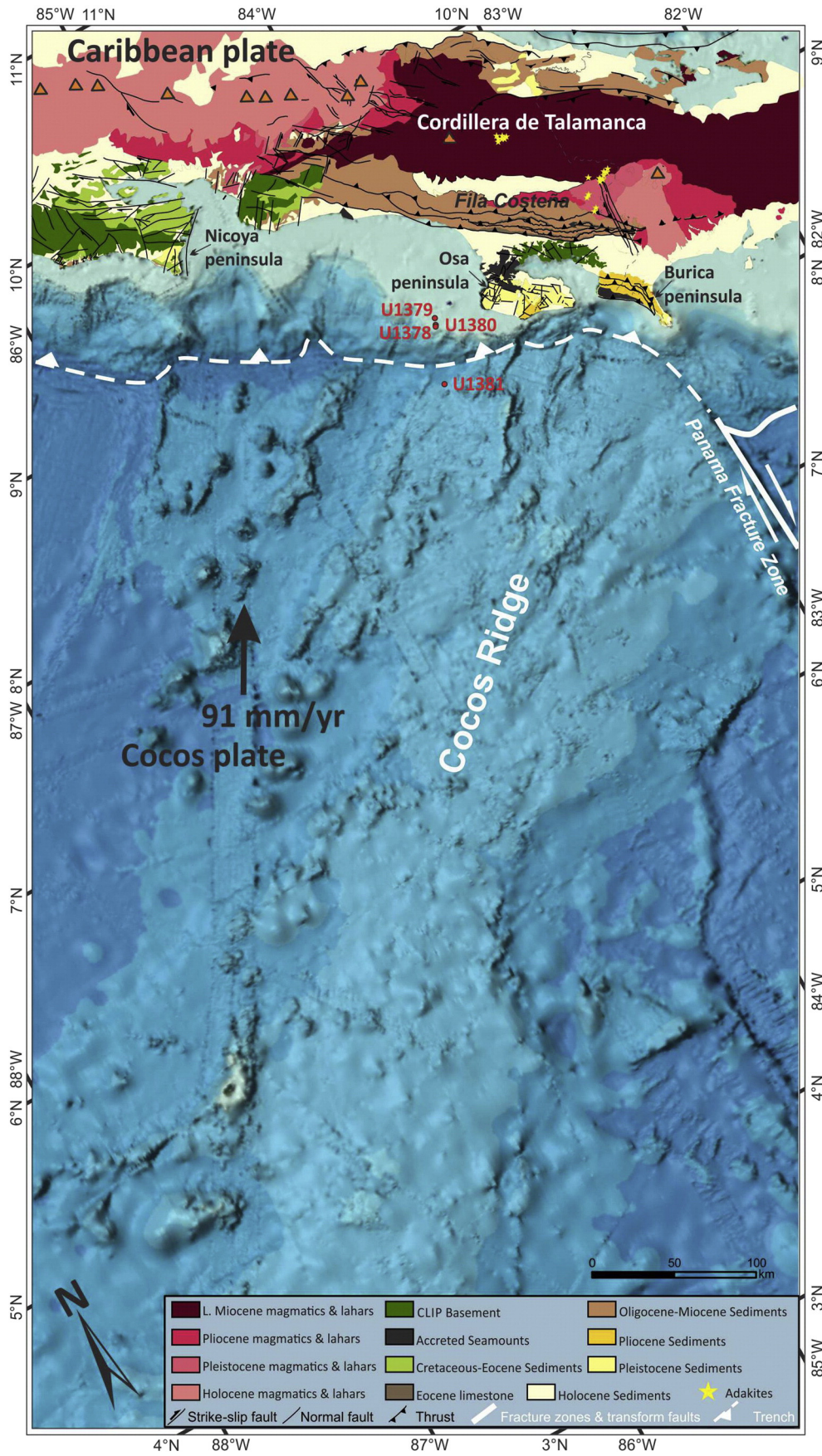


Fig. 3. Bathymetry of the Cocos Ridge subducting under southern Costa Rica. The geology of the onland areas has been modified from Morell (2016).

shortening rate distribution has the greatest shortening directly inboard of the Cocos Ridge axis (Fig. 3). However the Fila Costeña is a thin-skinned thrust-belt, i.e. its basement is not involved in the deformation, with a 4-km-deep décollement located at the base of Eocene–Miocene forearc basin units (Fisher et al., 2004; Sitchler et al., 2007). It is therefore evident that the development of the Fila Costeña, although strongly influenced by the Cocos Ridge subduction, does not seem to be able to account for the trench retreat inboard of the ridge itself. Moreover, the Quaternary deformation of the Plio-Pleistocene sediments of the Osa Peninsula does not involve significant sub-horizontal shortening (Sak et al., 2009) in spite of the numerous faults and fractures that cut the peninsula (Fig. 3). Instead, these faults and fractures accommodate vertical movements similar to the trends described at Site U1379. These observations imply the trench indentation was mostly associated with basement removal instead of shortening.

In the literature the timing of the beginning of subduction of the Cocos Ridge has been postulated to range from: a) 8 to 6.5 Ma based on the extinction of arc volcanism inboard of the ridge (De Boer et al., 1995), uplift of the Cordillera de Talamanca (Grafe et al., 2002), and the eruption of adakites within the Cordillera de Talamanca and at its southern end (Abratis and Worner, 2001) (Fig. 3); b) 4 to 2.5 Ma inferred from adakitic REE enrichment and Pd isotopic compositions (Goss and Kay, 2006); c) 3 to 2 Ma based on tectonic reconstructions (Lonsdale and Klitgord, 1978; MacMillian et al., 2004); and d) 1 Ma based on the emergence of the Osa Peninsula and deformation within the Fila Costeña (Gardner et al., 1992; Fisher et al., 2004).

The 8–6.5 Ma Cocos Ridge subduction hypotheses are based on ages for the shutoff of the volcanic arc and uplift of the Cordillera de Talamanca, a 3800 m-high mountain range of inactive volcanoes (Fig. 3). This uplift has commonly been ascribed to subduction of the buoyant Cocos Ridge. However, recent geophysical studies show that the Cordillera de Talamanca does not appear to lie on top of a buoyant, flat slab. Instead, earthquake locations, receiver functions and tomographic analyses suggest that the slab inboard of the NW flank of Cocos Ridge dips gently – $\approx 20^\circ$ – for approximately 100 km from the trench and then abruptly steepens – up to 80° – further downdip (Dinc et al., 2010; Dzierma et al., 2011; Arroyo et al., 2014). Recent gravity modeling and earthquake data extend this slab profile to the Panama Fracture Zone where the slab is thought to have a maximum dip of 65° (Lücke and Arroyo, 2015). Moreover, the youngest lavas in the Cordillera de Talamanca are ≈ 2.5 Ma – not ≈ 8 Ma (de Boer et al., 1991).

In the next paragraph we discuss new data that link the offshore and onshore forearc. This data further clarifies the relative timing between Cocos Ridge subduction, the development of the Cordillera de Talamanca, and deformation of the Fila Costeña fold-and-thrust belt.

4.1. New data on the onshore–offshore deformation associated with Cocos Ridge subduction

During IODP Exp. 334, Sites U1378 and U1379 (Figs. 3 and 4) were sampled for detrital apatite fission-track analysis. Detrital thermochronology is based on the comparison between cooling age patterns of detrital sediments with those of potential source areas (Garver et al., 1999; Bernet and Spiegel, 2004). The rationale behind the idea of applying detrital apatite fission-track thermochronology in this context lies in the different age signatures and thermal histories of the potential source units exposed in southern Costa Rica: the Osa Peninsula, Fila Costeña and Cordillera del Talamanca (Fig. 3). Apatites from the Cordillera de Talamanca, a mountain range that consists mainly of granitoid (i.e. rock fertile in apatite) which formed in a volcanic arc setting, are the only ones that may release a distinctive young age signature into adjacent sediments. These granitoid melts were emplaced at shallow levels between 12.8 and 7.8 Ma (K/Ar, $^{40}\text{Ar}/^{39}\text{Ar}$, Rb/Sr and Zr fission tracks), with their final cooling around 3 Ma (Drummond et al., 1995; Alvarado and Gans, 2012). Apatite fission-track ages for the granitoids range between 4.8 and 1.7 Ma with a mean weighted age of

3.0 ± 0.4 Ma (Grafe et al., 2002). Based on terrestrial alluvial deposits (i.e., lahars), pyroclastics, and lava flows of the Plio-Pleistocene – 4.3–1.2 Ma – Paso Real Formation in the Fila Costeña, the unroofing and initial exposure of the intrusive suite of the Cordillera de Talamanca are inferred to have occurred during the Quaternary (Marshall, 2007). The host rock of the volcanic arc and framework of the Caribbean plate in this region is the Caribbean Large Igneous Province – CLIP – formed at the Galapagos hotspot with ages ranging from 139 to 69 Ma – $^{40}\text{Ar}/^{39}\text{Ar}$ (Sinton et al., 1997; Hauff et al., 2000; Hoernle et al., 2004) (Fig. 3). CLIP lithologies – tholeiitic basalts, gabbros and subordinate plagiogranites – rarely contain apatite. More importantly, CLIP material was emplaced on the Caribbean plate during the Late Cretaceous–Paleocene. Since then, deformation of CLIP material in the region around southern Costa Rica has not been associated with temperature conditions able to reset fission-tracks in apatite (Pindell et al., 2006; Geldmacher et al., 2008).

For the Osa Peninsula and the Fila Costeña, the other sectors of the onshore bedrock in southern Costa Rica, apatite fission-track data are lacking. However both are composed by rocks significantly older than those exposed in the Cordillera de Talamanca, and these units also did not experience burial or deformation events since the Miocene that would have been able to reset their apatite fission-track clocks (Fisher et al., 2004; Sitchler et al., 2007). In particular, CLIP units were the source of sediments for the Oligo-Miocene turbidites and shallow marine formations that are folded and thrust in the Fila Costeña (Phillips, 1983). The Osa Peninsula and the Burica Peninsula, to the southeast expose an accreted seamount complex, the Osa Mélange (Vannucchi et al., 2006) (Fig. 3). This complex has ages ranging from Campanian to middle Eocene – 80 to 43.5 Ma – inferred with K/Ar, $^{40}\text{Ar}/^{39}\text{Ar}$, and radiolarian biostratigraphy (Di Marco, 1994; Di Marco et al., 1995; Hauff et al., 2000; Hoernle et al., 2002; Buchs et al., 2010). The Osa Mélange is mostly formed of basalts, gabbros and volcanoclastic sediments that have been accreted to the Caribbean plate and later exhumed (Vannucchi et al., 2006). The sediments that unconformably sit on top of the Osa Mélange constrain its accretion/exhumation to have occurred in the Eocene. These old sediments are irregularly distributed and nearly entirely composed of the underlying basaltic basement. Consistent deposition is recorded in the younger Plio-Quaternary sediments, whose provenance is still from the Mélange and CLIP material (Coates et al., 1992). These data constrain the fission-track age signature of Osa Mélange material to be significantly older than the record left by the Cordillera de Talamanca. These circumstances allow us to directly trace the inputs of erosional detritus (debris) from the Cordillera de Talamanca into offshore sediments.

Due to of the relatively small volume fraction of useful sandstone in the IODP cores, it was necessary to combine vertically adjacent samples to recover a sufficient number of apatite grains for analysis. Samples were combined in accordance with the lithostratigraphic units described for each site. A total of 4 combined samples were analyzed: three for Site U1379 and one for Site U1380 (Fig. 4).

4.1.1. Apatite fission tracks – results

Single-grain age distributions were decomposed into main grain components (Galbraith and Green, 1990; Brandon, 1992, 1996). Five age components were identified in the four samples (Table 1) (for the method see Supplementary Material). The youngest peak P1 (2.3 ± 0.4 Ma) is present only in sample CR1 that represents the oldest stratigraphic level – 1.9–2.5 Ma (Vannucchi et al., 2012). This peak is composed of 96% of the single grain ages. The other three intermediate peaks indicate source material ages of 10–15 Ma (P2), 20–30 Ma (P3), 50–70 Ma (P4) whereas P5 (ca. 100 Ma) is present only in the youngest sample UP1 where it is found within only 10% of the apatite grains. Fig. 4 shows results from the binomial decomposition of single grain age distributions.

In summary, the apatite fission-track single-grain age distributions for the younger offshore sediments – UP1, CR2 and CR3 < 1.9 Ma – in the forearc indicate that the Cordillera de Talamanca was not a sediment

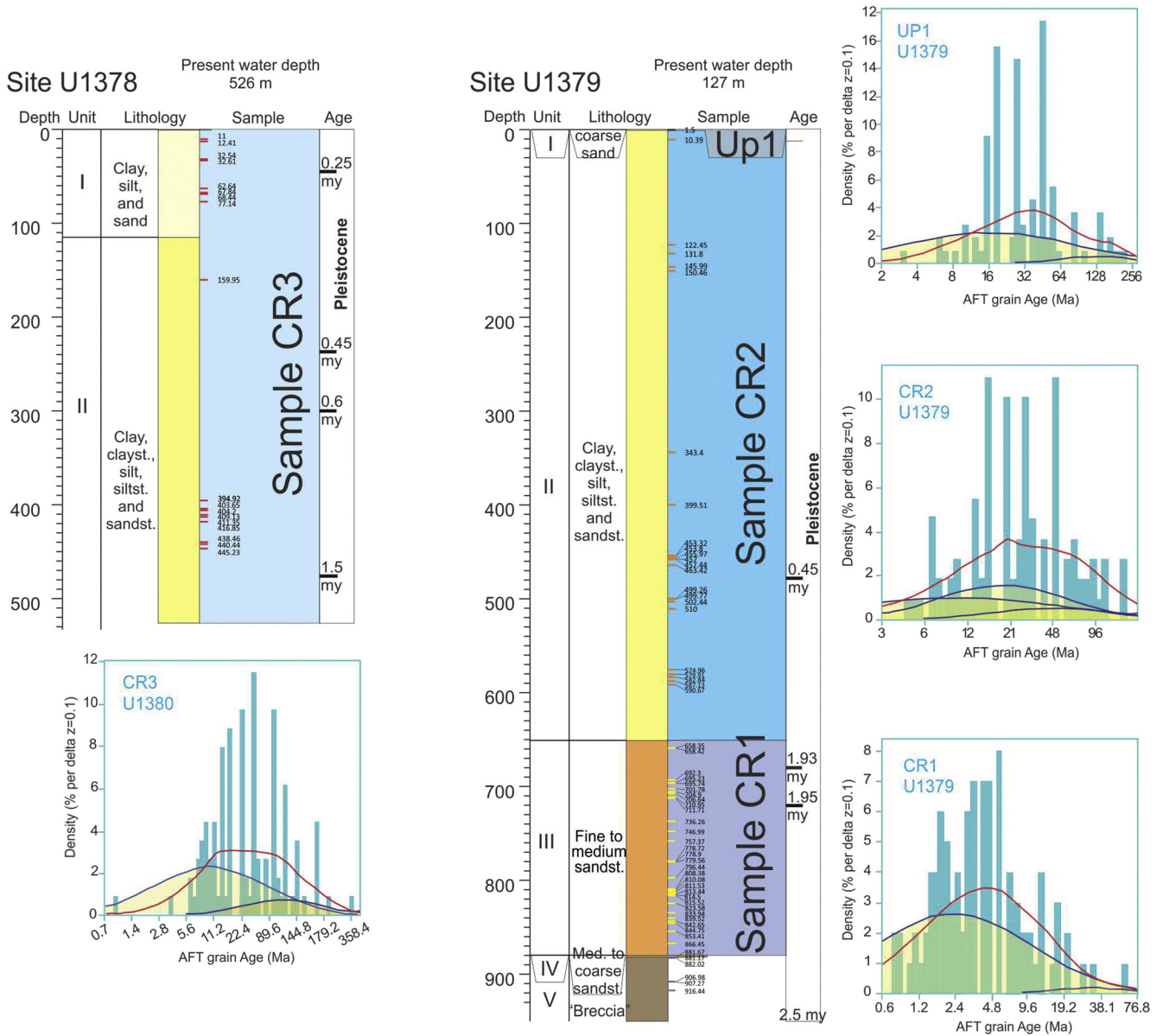


Fig. 4. Lithostratigraphic summaries of IODP Sites U1378 and U1379 showing the location of the single collected samples and how they were combined for fission track analysis. Results of the binomial decomposition of apatite fission track single-grain age distributions are shown for each sample. CR1 has the smallest age interval with no fission track ages older than 59.7 Ma and a clear peak at 2.3 Ma that is missing in the other diagrams.

source, although this source is present in oldest sediments recovered – CR1 – in which it represents the dominant sediment source (Frac 96%, Table 1). These data imply that areas of the Cordillera de Talamanca were already unroofing and exposing the intrusive granodioritic batholiths > 1.9 Myr ago. The strong predominance of peak P1 in CR1 is likely due to the much higher fertility in apatite of Cordillera de Talamanca with respect to the rocks composing the CLIP and seamount complex. Sediments derived from the erosion of the exposed Cordillera de Talamanca were able to reach the adjacent forearc before ~ 1.9 Ma. This became no longer possible after 1.9 Ma, when, in spite of the ongoing uplift/unroofing of the Cordillera de Talamanca – which at present is about 4000 m high – the source region for CR2 deposits switched to nearer-to-coast CLIP and seamount complexes. This switch is evidence that by ~ 1.9 Ma the Fila Costeña had become high enough to block direct transport of sediments from the Cordillera de Talamanca to the off-shore Osa forearc.

These analyses show that there is not a direct correlation between the timing of subsidence and uplift in the forearc and the development

of the two major physiographic provinces (Fila Costeña and Cordillera de Talamanca) inboard the Cocos Ridge. In particular, apatites sourced by the Cordillera de Talamanca (peak P1, age of 2.3 ± 0.4 Ma) indicate a rapid Talamanca exhumation event at 3 Ma (Grafe et al., 2002) that is recorded in sediments with stratigraphic age of ≈ 2 Ma. This finding reinforces reconstructions in which the Cordillera experiences a rapid unroofing event before the 2.2 ± 0.2 Ma unconformity that marks the onset of subduction of the Cocos Ridge. Therefore the extinction of the volcanic arc and the uplift of the Cordillera de Talamanca appear to be unrelated to the more recent subduction of the Cocos Ridge. Our preferred hypothesis is that the cessation of arc magmatism at the Cordillera de Talamanca was induced by the subduction beneath this region of an extinct section of the Cocos–Nazca spreading center (Johnston and Thorkelson, 1997).

The disappearance of the younger peak representing the Talamanca recorded in the younger sediments, < 1.9 Ma – samples CR2, CR3 and UP1 – is evidence that by this time the Fila Costeña began to represent an important barrier to material transport between the Talamanca and

Table 1
Apatite fission-track peak ages.

Sample	Depositional age [Ma]	ng	Age interval (Ma)	P1			P2			P3			P4			P5			Red. χ^2		
				Age (Ma)	63% CI	Frac %	Age (Ma)	63% CI	Frac %	Age (Ma)	63% CI	Frac %	Age (Ma)	63% CI	Frac %	Age (Ma)	63% CI	Frac %			
U1379																					
UPI	Recent	109	3.0–222.4				15.8	–2.3 + 2.7	90.5												
CR2	<1.9	109	4.6–150.7				10.0	–3.3 + 0.8	44												
CR1	1.9–2.5	100	0.7–59.7	2.3	–0.4 + 0.4	96				21.1	–4.7 + 6.0	42									
U1380										28.5	–12.9 + 23.5	4									
CR3	<1.9	113	1.0–348.4				10.4	–1.6 + 2.0	82												

Note: ng, number of grains analyzed for binomial peak fitting. 63% confidence level (CI) is approximately equal to $\pm 1\sigma$; Frac, fraction of the analyzed grains belonging to an age population in percent; red. χ^2 , reduced Chi-square test describing the probability of the fitting curve where a value of 1 coincides with a good fit.

this offshore site. The uplift of the Fila Costeña, therefore, is mostly younger than ~1.9 Ma. This records a detectable delay with respect to the main pulse of subduction erosion as recorded offshore, i.e. the 2.2 ± 0.2 Ma unconformity and its subsequent subsidence event. The development of an inland topographic barrier, the Fila Costeña, could be related to the progressive subduction of the Cocos Ridge. If this is the case, the inner and outer forearcs reacted and are still behaving differently in response to subduction of the ridge. The inner forearc does not record shortening along either the U1379–U1378 transect or in the Osa Peninsula (Fig. 3). Shortening is observed in the sediments along a 3D seismic reflection box across the forearc about 12 km to the NW from the U1379–U1378 drilling transect (Bangs et al., 2015), where it has been associated with local seamount subduction (Kluesner et al., 2013).

These data support the hypothesis that the onset of Cocos Ridge subduction is represented by the 2.2 ± 0.2 Ma unconformity and that the inner forearc reacted to the Cocos Ridge subduction by mass removal, rather than the shortening and thickening that is observed in the outer forearc.

5. Material fluxes along the Central America subduction system

Here we analyze the local continental crustal addition and removal during the recent evolution of the Central American subduction system.

Sediment subduction rates and, in particular, the terrigenous component of these sediments in the Middle America Trench contribute to the net removal of upper continental crust by subduction. Estimates need to account for the incoming plate trench fill sediments, but also for the possible amount of material not subducting because of accretion. Deep sea drilling and reflection seismics help to evaluate these rates. The Guatemala–El Salvador sector of the margin has a coastal plain about 30 km wide extending from the shoreline to the volcanic arc. High rainfall and high elevation of the volcanic arc contribute to a high sedimentation rate in the coastal area with volcanogenic deposits (Davies et al., 1979). The alluvium is discharged by rivers into the alluvial plain and from there to the forearc basin/slope and, finally, to the trench, where a variable thickness from 82 to 117 m of turbiditic deposits was drilled by DSDP Leg 67. It is interesting to note that the DSDP Leg 67 and 84 drill transects were located along a submarine canyon – the San José Canyon (Aubouin et al., 1982; von Huene et al., 1985) – which could be able to bypass the forearc, and directly deliver sediment into the trench. The hemipelagic/pelagic section varies from 74.5 to 428 m (Aubouin et al., 1982). Drilling in the lower slope at about 3 km from the trench axis showed no occurrences of thrusts, and no accreted trench turbidites, and the sediments have been interpreted as transported from upslope (Aubouin et al., 1982; von Huene et al., 1985). Considering a convergence rate of 73 mm/yr (DeMets, 2001), and calculating for the maximum thickness of turbidites (117 m at Site 67–499), hemipelagic sediments (171 m at Site 67–495), and pelagic sediments (257 m at Site 67–495), the total sedimentary input in the Guatemala–El Salvador sector is of order $40 \text{ km}^3/\text{Myr}/\text{km} - 0.11 \text{ Tg}/\text{yr}$, with $8.5 \text{ km}^3/\text{Myr}/\text{km} - 0.02 \text{ Tg}/\text{yr}$ – being the contribution of the terrigenous sediments (Fig. 5). In the Nicaragua–Northern Costa Rica sector, ODP Site 170–1039 recovered 400 m of sediments – 83 m hemipelagic and 317 m pelagic – from the trench. Remarkably, the turbiditic section was missing (Kimura et al., 1997). Sites 170–1040 and 1043 in the lower slope at 0.4–1.6 km from the trench showed no evidence for frontal accretion. For a convergence rate of 85 mm/yr (DeMets, 2001), the total sedimentary input is of order $34 \text{ km}^3/\text{Myr}/\text{km} - 0.10 \text{ Tg}/\text{yr}$ – without a terrigenous component (Fig. 5). Also the southern Costa Rica sector drilled during IODP Exp 334 and 344 did not recover any terrigenous sediment in the trench. The hemipelagic section here varies from 56 to 145 m while the pelagic section goes from 47 to 230 m (Vannucchi et al., 2012; Harris et al., 2013) accounting, with plate convergence at 91 mm/yr (DeMets, 2001), for a maximum sedimentary input of $34 \text{ km}^3/\text{Myr}/\text{km} - 0.10 \text{ Tg}/\text{yr}$. Site U1412 on the lower slope, though, revealed the presence of a frontal

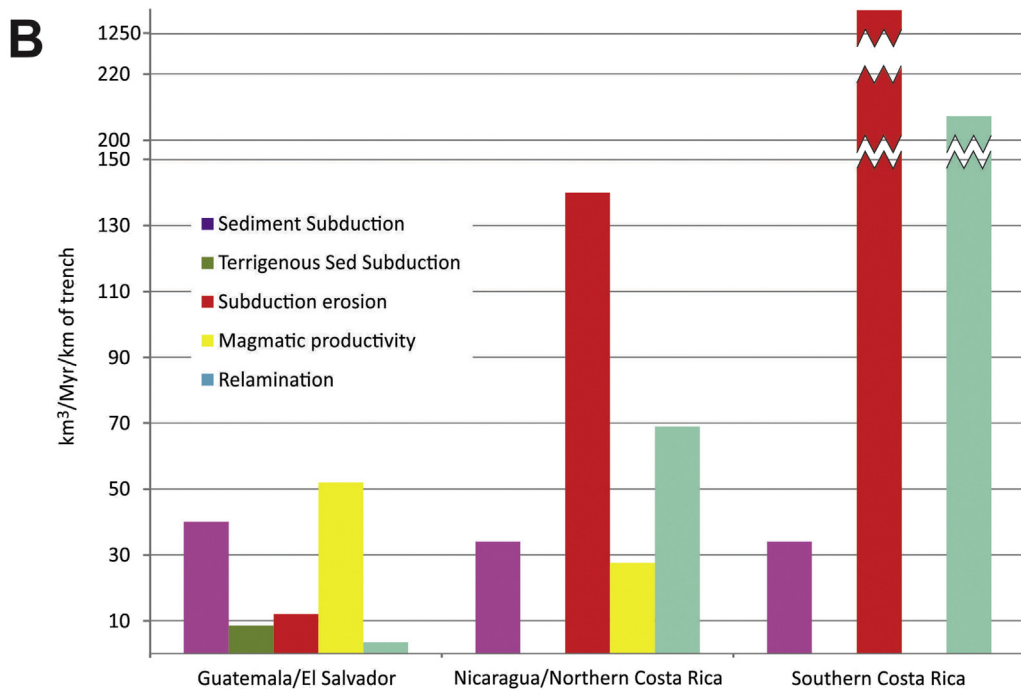
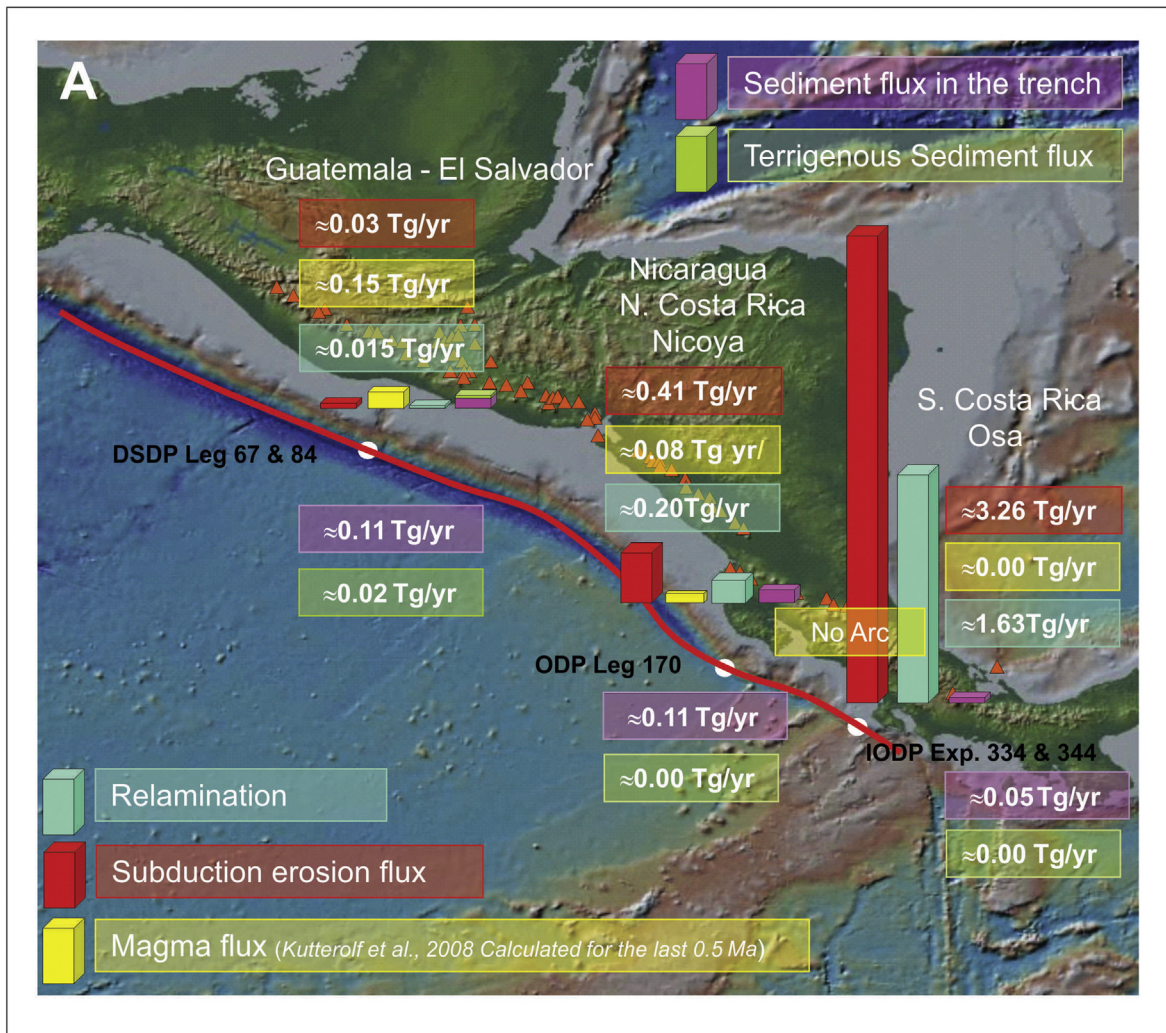


Fig. 5. Continental crust budget calculated for the three different sectors of the Central America Trench considered in this study. Different components of the budgets are calculated in Tg/yr (A) or km³/Myr/km (B).

accretionary prism able to capture about half of the input (Harris et al., 2013) (Fig. 5).

The overall arc productivity in Central America has been estimated to vary between 86 and 108 km³/Myr/km, slightly higher than the global arc average of 91 km³/Myr/km (Clift and Vannucchi, 2004). In Middle America, the recent productivity – <0.5 Ma – of its three sub-arc segments – Guatemala–El Salvador, Nicaragua–Northern Costa Rica (Nicoya), and southern Costa Rica (Osa) – has been recently reestimated by Kutterolf et al. (2008) for the last 0.5 Ma considering not only the erupted volumes – e.g. Carr et al. (2003) –, but also reassessing the plutonic component. These estimates are based on onland and offshore calculations of tephra volumes recalculated to erupted and fractionated cumulates in order to estimate the total magma mass. Kutterolf et al. (2008) note that magma production rates increase from southern Costa Rica, where the rate is 0 km³/Myr/km (0 Tg/yr) as the arc is extinct, to Guatemala, where the recent rate is 52 km³/Myr/km (\approx 0.15 Tg/yr) (Fig. 5).

Simply comparing subduction erosion rates + terrigenous sediment flux vs. arc magma production rates may not fully address the current continental crustal mass balance at a subduction zone (Fig. 5). In particular there is a further question that needs to be addressed (e.g. Stern, 2011): where does the material eroded by subduction erosion actually go?

The subduction factory initiative in Central America has mostly focused on the contribution to arc magmatism of sediments deposited on the incoming plate (Plank and Langmuir, 1998). In spite of a controversy between results on subduction inputs as revealed by drilling – subduction of the entire sedimentary section with no removal due to accretion (Kimura et al., 1997) – and magmatic outputs at the volcanic arc – showing the lowest contribution from the sediment to arc magmatism across the entire Central America Volcanic Arc, for example lowest contents of cosmogenic ¹⁰Be (Carr et al., 2003) –, subduction erosion has been rarely considered in Central America to be a process that could be responsible for significant geochemical variations in the material that reaches the arc. Often, a major hindrance to making clear distinctions with geochemical tracers is that eroded crust, trench sediments, and arc crustal basement can be all compositionally very similar, in which case the geochemical signal of eroded forearc basement material could be ambiguous. In the absence of a clearly visible chemical signal, geochemists have, therefore, advocated for underplating as the mechanism to ‘remove’ eroded material before it reaches the depth of magma generation. The uplift of the coastal area in Peru and Northern Chile (14°–18°S) inboard of a section of an eroding subduction system (Clift et al., 2003), has been interpreted to be due to underplating of material eroded from the outer forearc (Clift and Hartley, 2007).

In Costa Rica, underplating of seamounts was suggested to explain regionally focused coastal uplift in Nicoya and Osa Peninsula (Gardner et al., 2001; Sak et al., 2009). Although this mechanism can contribute to the increase of the upper plate’s overall volume, the actual estimate of how much material can be transferred from the incoming plate to the upper plate through seamount underplating is negligible. Underplating of eroded material at greater depths seems difficult as the slab is too steep to account for a simple mechanical transfer.

Vannucchi et al. (2001) proposed that “dilution” of incoming sediments with eroded upper plate material could resolve some of these apparent controversies – they estimated the mass flux due to subduction erosion offshore was 95% of the total input into the subduction factory there since the Pliocene. Contamination of arc magmas with Cretaceous to Paleogene forearc material driven by subduction erosion was proposed by Goss and Kay (2006) to be critically involved in the appearance of adakitic magmas in Costa Rica and Panama. Subduction erosion crustal components can explain the steep REE pattern and enrichment in radiogenic Pb in the adakites in Central America (Goss and Kay, 2006), as well as in the central Andes (Kay et al., 2005; Goss et al., 2013; Risse et al., 2013). Also ‘enriched mantle’ components in magmas have been associated with recycling of continental crust

(Willbold and Stracke, 2006, 2010). Recently Straub et al. (2015) performed a thorough analysis on the central Mexican Volcanic Belt, a site where the eroded upper plate material is a geochemically distinctive Paleogene granodiorite. There, Sr–Nd–Pb–Hf and trace element data of this crustal input material were compared to Sr–Nd–Pb–Hf–He–O isotope chemistry of a well-characterized arc series of olivine-phyric, high-Mg# basalts to dacites. This work by Straub et al. (2015) was able to quantify the amount of upper plate material that needed to be recycled in the arc – 79–88 km³/Myr/km, 0.23–0.25 Tg/yr – and the results were strikingly similar to those estimated from the tectonic setting alone – 60–80 km³/Myr/km, 0.17–0.23 Tg/yr. In Mexico, therefore, it seems that most or all of the material removed by forearc subduction erosion reaches the depth of arc magma generation, where almost all of its incompatible elements are recycled back into arc magmas.

The conclusion that a significant proportion of the eroded forearc margin must be recycled in the mantle is reinforced by analyses of the southernmost central Andean volcanic zone as well as the backarc Puna plateau. Both volumetric considerations (Kay et al., 2005) and volcanic chemistry (Goss et al., 2013; Risse et al., 2013) suggest that most of the eroded material is recycled in the mantle. Goss et al. (2013) calculated a rate of recycling upper plate material in the mantle of 200 km³/Myr/km – 0.58 Tg/yr – in the interval between 3 and 8 Ma.

Finally, if the forearc material removed by subduction erosion could remain relatively buoyant (e.g. does not transform to a denser eclogitic phase), then the more felsic part of the eroded material has been proposed to be ‘relaminated’ back to the base of continental crust (Hacker et al., 2011). Sallares et al. (2001) and Hayes et al. (2013) observed relatively low average velocities in the lower crust of the volcanic arc in central Costa Rica and highly reflective crust–mantle transition zone. They interpreted these images as complex interactions of crust and mantle during crustal growth that can be interpreted to imply the occurrence of relamination. In the following estimates we do not consider the possible contribution of crustal shortening to volume and thickness estimates of the crust, which would further limit the possible amount of relamination (DeCelles et al., 2009). Indeed arc-normal extension in Central America, south of the North America–Caribbean plate boundary (Morgan et al., 2008), advocates against the occurrence of delamination. To be conservative in our calculations of continental crust loss, the following calculations define the maximum possible rate of eroded material that could be ‘relaminated’ (Hacker et al., 2011). Based on the eroded upper plate lithologies, one can estimate the volumes of felsic material that could possibly be relaminated \approx 0.01 Tg/yr (3.45 km³/Myr/km) in Guatemala, \approx 0.2 Tg/yr (69 km³/Myr/km) in northern Costa Rica, to \approx 1.6 Tg/yr (207 km³/Myr/km) in southern Costa Rica (Fig. 5).

Fig. 5 shows estimates of these potential fluxes in the three sectors of the Central America Trench based on the subduction erosion rates presented here, magma fluxes in the last 0.5 Ma following Kutterolf et al. (2008), and relamination following the approach by Hacker et al. (2011). Fig. 5 shows that the arc crust in the Guatemala–El Salvador segment is in net growth, in the Nicaragua–Northern Costa Rica (Nicoya) segment arc crust is in equilibrium or slightly decreasing in volume, whereas in the southern Costa Rica (Osa) arc crust is being destroyed.

6. Broader implications

Arc production in Central America is \approx 109 km³/Myr/km (0.31 Tg/yr), which is a typical value of magmatic productivity for an erosive subduction margin (Clift and Vannucchi, 2004). It is noteworthy that the average magmatic arc production at accretionary margins is only about half this value – \approx 55 km³/Myr/km (0.16 Tg/yr) (Clift and Vannucchi, 2004). This relatively high magmatic productivity at erosive subduction margins helps to prevent the overall destruction of continental crust at these margins. In the Guatemala–El Salvador sector, in fact, continental crust must grow as subduction erosion and terrigenous sediment subduction is

removing less material than the arc produces (Fig. 5). Moving toward the southeast, the balance becomes negative and subduction erosion is much faster than magmatic arc growth. Trading space for time, we envision the Guatemala–El Salvador sector as being representative of this margin for the situation before Cocos Ridge subduction.

The Central America Trench reveals clear along-strike tectonic and magmatic differences and characteristics, in large part because it has been studied in great detail in comparison to other subduction systems. The effects of the Cocos Ridge subduction in the southern Costa Rica sector can be inferred from two IODP expeditions and almost 40 years of offshore geophysical exploration. This level of detail simply does not exist at other subduction systems. Apart from the Cocos Ridge, at present high bathymetric relief subduction is occurring in Kamchakta – the Hawaii–Emperor seamount chain, in Tonga – the Louisville ridge, in Hikurangi – the Hikurangi Plateau, in South America – the Carnegie, Nazca, and Juan Fernandez Ridges, in the Solomon Islands – the Ontong-Java Plateau – and SW Japan – the Izu–Bonin volcanic arc, totaling ≈ 2400 km (Table 2) of subduction zones with high bathymetric relief subduction along the $\approx 40,000$ km-long global subduction system (Clift and Vannucchi, 2004), or 17% of the system. This estimate only considers the ongoing subduction of major bathymetric features – aseismic ridges, island arc massifs, oceanic plateaus, seamount clusters, spreading centers, and blocks of continental crust. A good aseismic ridge candidate for future subduction is the Ninetyeast Ridge in the Sumatra Trench. Note that all places where aseismic ridge subduction is occurring are erosive margins. Considering that the latter form 60% of the total trench length, $\sim 10\%$ of today's erosive margins are associated with aseismic ridge subduction. Note that the estimate for erosive margin length used here differs slightly from Clift and Vannucchi (2004) in that the Java Trench is now known to be an erosive margin (Kopp et al., 2006). If, as at present, $\frac{3}{4}$ of aseismic ridge subduction is oblique, (unlike the subducting Cocos or Carnegie Ridges), this would imply that this event occurs 7% of the time at a typical erosive margin. With these values and using current subduction erosion rates we found for the different sectors of the Central America Trench, this would imply that an estimate of the 'net' erosive margin rate is 7% times the $1125 \text{ km}^3/\text{Myr}/\text{km}$ southern Costa Rica (Osa) sector rate plus 93% times the average of Guatemala–El Salvador, which has a net rate of $12 \text{ km}^3/\text{Myr}/\text{km}$. This estimates the overall net rate to be $90 \text{ km}^3/\text{Myr}/\text{km}$, which is very similar to the average rate inferred by Clift et al. (2009a, 2009b), but our new estimate for this average is dominated by the effects of the strong subduction erosion associated with the onset of aseismic ridge subduction at a forearc. The implication is that aseismic ridge subduction is likely to be a globally significant destruction process for subduction forearcs.

It is also worth examining how the southern Costa Rica (Osa) sector is healing after the impact of the subduction of the Cocos Ridge. Recent work has compared the results of the IODP drilling Exp. 334 and 344 with 3D seismic reflection data from the same area. This reveals that there was a depositional mode of forearc evolution, with terrigenous sediments deposited directly on the forearc as it was being removed from below by subduction erosion (Vannucchi et al., 2016). A depositional margin takes full advantage of the terrigenous

sedimentary flux and grows without the occurrence of offscaping from the incoming plate (Vannucchi et al., 2016).

The material removed from the forearc by subduction erosion has the potential to follow a number of paths: it can be underplated back to the upper plate before reaching the depth of magma generation (Clift and Hartley, 2007), it can contribute to the arc magmatism (Straub et al., 2015) or it can be relaminated at depth (Hacker et al., 2011). The Central America example indicates that here eroded material has been subtracted from the crustal budget and is following the fate of the subducting slab.

7. Conclusions

Central America has a very useful role to play in our current understanding of the evolution of continental crust, because this arc is where arc material fluxes are best constrained at present. Here, subduction erosion has been documented to play a key role in the long-term evolution of continental crust, and the recycling of crust into the mantle.

Forearc evolution also appears to be more complex than a simple dichotomy between accretionary wedge addition of sediments vs. subduction erosion removal of forearc material. During subduction erosion, a 'replacive' depositional margin mode may operate, involving the rapid infill of forearc basins that overly the region of basal subduction erosion, and the development of a depositional margin segment within the eroding forearc. This mode can lead to the preservation of heterogeneous variable-age forearcs within the geologic record.

Finally, the Central American record shows that along strike variations in the growth/disruption of continental crust can be substantial. The net consumption of continental crust inboard of the Cocos Ridge subduction suggests that punctuated events of intense tectonic erosion lasting less than 1 Ma have a great effect over the continental crust budget through forearc removal and recycling of continental crust. In general, rates of subduction erosion appear to be quite variable in space and time, with sudden large-scale events having a significant influence on the long-term erosion rates through time. It will be important to keep in mind the importance of sudden, short-lived, extreme erosional and depositional margin events when assessing global rates of removal of continental crust at subduction zones, and surface-transport-linked lateral redistribution of mass during these rare intense events of subduction erosion.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.gr.2016.10.001>.

References

- Abratis, M., Worner, G., 2001. Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm. *Geology* 29 (2), 127–130.
- Allègre, C.J., 1982. Chemical geodynamics. *Tectonophysics* 81, 109–132.
- Alvarado, G.J., Gans, P.B., 2012. Síntesis geocronológica del magmatismo, metamorfismo y metalogenia de Costa Rica, America Central 2012, 46, 7–122. *Revista Geologica de America Central* 46, 7–122.
- Armstrong, R.L., 1981. Radiogenic isotopes: the case for crustal recycling on a near-steady state no-continental-growth. *Philosophical Transaction of the Royal Society A301*, 443–472.
- Arroyo, I.G., Grevemeyer, I., Ranero, C.R., von Huene, R., 2014. Interplate seismicity at the CRISP drilling site: the 2002 Mw 6.4 Osa Earthquake at the southeastern end of the Middle America Trench. *Geochemistry, Geophysics, Geosystems* 15 (7), 3035–3050.

Table 2
Length of trench with aseismic ridge subduction.

Hawaii–Emperor	635 km
Louisville	225 km
Hikurangi	140 km
Carnegie	330 km
Nazca	185 km
Cocos Ridge	185 km
Juan Fernandez	120 km
Java	450 km
Izu–Bonin	140 km

- Aubouin, J., von Huene, R., 1985. Summary: Leg 84, Middle America Trench transect off Guatemala and Costa Rica. In: von Huene, R., Aubouin, J. (Eds.), Initial Reports, DSDP, 84. U.S. Government Printing Office, Washington, D.C., pp. 939–956.
- Aubouin, J., von Huene, R., Azema', J., Coulbourn, W.T., Cowan, D.S., Curiale, J.E., Dengo, C.A., Faas, R.W., Harrison, W., Hesse, R., Ladd, J.W., Mudylov, N., Shiri, M., Thompson, P.R., Westberg, M.J., 1982. Proceedings of the Deep Sea Drilling Program, Initial Report, 67. U.S. Government Printing Office, Washington D.C. (967 p.).
- Bangs, N.L., McIntosh, K.D., Silver, E.A., Kluesner, J.W., Ranero, C.R., 2015. Fluid accumulation along the Costa Rica subduction thrust and development of the seismogenic zone. *Journal of Geophysical Research: Solid Earth* 120 (1).
- Bernet, M., Spiegel, C., 2004. Detrital Thermochronology: Provenance Analysis, Exhumation, and Landscape Evolution of Mountain Belts. Geological Society of America, Special Papers, Boulder, Colorado.
- Bloomer, S.H., Ewart, A., Hergt, J.M., Bryan, W.B., 1994. Geochemistry and origin of igneous rocks from the outer Tonga forearc (Site 841). In: Hawkins, J., Parson, L., Allan, J. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results vol. 135. Ocean Drilling Program, College Station, TX, pp. 625–646.
- Brandon, M.T., 1992. Decomposition of fission-track grain-age distributions. *American Journal of Science* 292, 535–564.
- Brandon, M.T., 1996. Probability density plot for fission-track grain-age samples. *Nuclear Tracks and Radiation Measurements* 26, 663–676.
- Brown, G.C., 1979. The changing pattern of batholith emplacement during earth history. In: Atherton, M.P., Tarney, J. (Eds.), Origin of Granite Batholiths. Shiva, Nantwich, UK, pp. 106–115.
- Buchs, D.M., Arculus, R.J., Baumgartner, P.O., Baumgartner-Mora, C., Ulianov, A., 2010. Late Cretaceous arc development on the SW margin of the Caribbean Plate: insights from the Golfo, Costa Rica, and Azuero, Panama, complexes. *Geochemistry, Geophysics, Geosystems* 11.
- Carr, M.J., Feigenson, M.D., Patino, L.C., Walker, J.A., 2003. Volcanism and geochemistry in Central America: progress and problems. Inside the Subduction Factory 138, 153–179.
- Cawood, P.A., Hawkesworth, C.J., Dhuime, B., 2012. The continental record and the generation of continental crust. *Geological Society of America Bulletin* 125, 14–32.
- Clift, P.D., Hartley, A., 2007. Slow rates of subduction erosion along the Andean margin and reduced global crustal recycling. *Geology* 35, 503–506.
- Clift, P.D., MacLeod, C.J., 1999. Slow rates of subduction erosion estimated from subsidence and tilting of the Tonga forearc. *Geology* 27 (5), 411–414.
- Clift, P., Vannucchi, P., 2004. Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. *Reviews of Geophysics* 42 (2), RG2001 (doi:10.1029/2003RG000127).
- Clift, P.D., Pecher, I., Kukowski, N., Hampel, A., 2003. Tectonic erosion of the Peruvian forearc, Lima Basin, by subduction and Nazca Ridge collision. *Tectonics* 22 (3) (p. art. no.-1023).
- Clift, P., Schouten, H., Vannucchi, P., 2009a. Arc-continent collisions, sediment recycling and the maintenance of the continental crust. In: Cawood, P., Kroener, A. (Eds.), *Accretionary Orogens in Space and Time* vol. 318. Geological Society, London, pp. 75–103.
- Clift, P.D., Vannucchi, P., Morgan, J.P., 2009b. Crustal redistribution, crust–mantle recycling and Phanerozoic evolution of the continental crust. *Earth-Science Reviews* 97, 80–104.
- Coates, A.G., Jackson, J.B.C., Collins, L.S., Cronin, T.M., Dowsett, H.J., Bybell, L.M., Jung, P., Obando, J.A., 1992. Closure of the Isthmus of Panama – the near-shore marine record of Costa-Rica and western Panama. *Geological Society of America Bulletin* 104 (7), 814–828.
- Condie, K.C., 1998. Episodic continental growth and supercontinents: a mantle avalanche connection? *Earth and Planetary Science Letters* 163, 97–108.
- Condie, K.C., 2014. Growth of continental crust: a balance between preservation and recycling. *Mineralogical Magazine* 78 (3).
- Condie, K.C., Bickford, M.E., Aster, R.C., Belousova, E., Scholl, D.W., 2011. Episodic zircon ages, Hf isotopic composition, and the preservation rate of continental crust. *Geological Society of America Bulletin* 123 (5–6), 951–957.
- Davies, D.K., Almon, W.R., Bonis, S.B., Hunter, B.E., 1979. Deposition and diagenesis of Tertiary-Holocene volcanoclastics, Guatemala. In: Scholl, P.A., Schugler, P.R. (Eds.), *Aspects of Diagenesis*. Soc. Econ. Paleontol. Mineral. Spec. Publ. vol. 26, pp. 281–306.
- De Boer, J.Z., Defant, M.J., Stewart, R.H., Bellon, H., 1991. Evidence for active subduction below western Panama. *Geology* 19, 649–652.
- De Boer, J.Z., Drummond, M.S., Bordelon, M.J., Defant, M.J., Bellon, H., Mauri, R.C., 1995. Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca). In: Mann, P. (Ed.) *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America* vol. 295, pp. 35–55.
- de Lepinay, B.M., Michaud, F., Calmus, T., Bourgeois, J., Poupeau, G., SaintMarc, P., 1997. Large neogene subsidence event along the Middle America Trench off Mexico (18 degrees–19 degrees N): evidence from subsurface observation. *Geology* 25 (5), 387–390.
- DeCelles, P.G., Duca, M.N., Kapp, P., Zandt, G., 2009. Cyclicity in Cordilleran orogenic systems. *Nature Geoscience* 2, 251–257. <http://dx.doi.org/10.1038/ngeo469>.
- DeMets, C., 2001. A new estimate for present-day Cocos-Caribbean plate motion: implications for slip along the Central American volcanic arc. *Geophysical Research Letters* 28 (21), 4043–4046.
- Dewey, J.F., Windley, B.F., 1981. Growth and differentiation of continental crust. *Philosophical Transactions of the Royal Society A* 301, 189–206.
- Di Marco, G., 1994. Les terrains accrétés du sud du Costa Rica: Evolution tectonostratigraphique de la marge occidentale de la plaque Caraïbe Mémoires de Géologie (Lausanne), vol. 20. Université de Lausanne, Switzerland, p. 184.
- Di Marco, G., Baumgartner, P.O., Channell, J.E.T., 1995. Late Cretaceous–early Tertiary paleomagnetic data and revised tectonostratigraphic subdivision of Costa Rica and western Panama. In: Mann, P. (Ed.), *Geologic and Tectonic Development of the Caribbean Plate Boundary in Southern Central America*, Volume 295. Geological Society of America Special Paper, Boulder, Colorado, pp. 1–27.
- Dinc, A.N., Koulakov, I., Thorwart, M.M., Rabbel, W., Flueh, E.R., Arroyo, I.G., Taylor, W., Alvarado, G., 2010. Local earthquake tomography of central Costa Rica: transition from seamount to ridge subduction. *Geophysical Journal International* 183 (1), 286–302.
- Drummond, M.S., Bordelon, M., de Boer, J.Z., Defant, M.J., Bellon, H., Feigenson, M.D., 1995. Igneous petrogenesis and tectonic setting of plutonic and volcanic rocks of the Cordillera de Talamanca, Costa Rica–Panama, Central American Arc. *American Journal of Science* 295, 875–919.
- Dzierma, Y., Rabbel, W., Thorwart, M.M., Flueh, E.R., Mora, M.M., Alvarado, G.E., 2011. The steeply subducting edge of the Cocos Ridge: evidence from receiver functions beneath the northern Talamanca Range, south-central Costa Rica. *Geochemistry, Geophysics, Geosystems* 12.
- Fisher, D.M., Gardner, T.W., Sak, P.B., Sanchez, J.D., Murphy, K., Vannucchi, P., 2004. Active thrusting in the inner forearc of an erosive convergent margin, Pacific coast, Costa Rica. *Tectonics* 23 (2) (p. art. no.-TC2007).
- Fyfe, W.S., 1978. The evolution of the Earth's crust: modern plate tectonics to ancient hot spot tectonics. *Chemical Geology* 23, 89–114.
- Galbraith, R.F., Green, P.F., 1990. Estimating the component ages in a finite mixture. *Nuclear Tracks and Radiation Measurements* 17, 197–206.
- Gardner, T.W., Verdonck, D., Pinter, N.M., Slingerland, R., Furlong, K.P., Bullard, T.F., Wells, S.G., 1992. Quaternary uplift astride the aseismic Cocos Ridge, Pacific coast, Costa Rica. *Geological Society of America Bulletin* 104 (2), 219–232.
- Gardner, T., Marshall, J., Merritts, D., Bee, B., Burgette, R., Burton, E., Cooke, J., Kehrwald, N., Protti, M., Fisher, D., Sak, P., 2001. Holocene forearc block rotation in response to seamount subduction, southeastern Peninsula de Nicoya, Costa Rica. *Geology* 29 (2), 151–154.
- Garver, J.L., Brandon, M.T., Roden-Tice, M., Kamp, P.J.J., 1999. Erosional denudation determined by fission-track ages of detrital apatite and zircon. In: Ring, U., Brandon, M.T., Willett, S., Lister, G. (Eds.), *Exhumation Processes: Normal Faulting, Ductile Flow, and Erosion*, Volume 154. Geological Society of London Special Publication, London, pp. 283–304.
- Geldmacher, J., Hoernle, K., Van den Bogaard, P., Hauff, F., Kluegel, A., 2008. Age and geochemistry of the Central American forearc basement (DSDP Leg 67 and 84): insights into Mesozoic arc volcanism and seamount accretion on the fringe of the Caribbean IAP. *Journal of Petrology* 49 (10), 1781–1815.
- Goss, A.R., Kay, S.M., 2006. Steep REE patterns and enriched Pb isotopes in southern Central American arc magmas: evidence for fore-arc subduction erosion? *Geochemistry, Geophysics, Geosystems* 7.
- Goss, A.R., Kay, S.M., Mpodozis, C., 2013. Andean adakite-like high-Mg andesites on the northern margin of the Chilean-Pampean flat-slab (27–28.5°S) associated with frontal arc migration and fore-arc subduction erosion. *Journal of Petrology* 54, 2193–2234.
- Grafe, K., Frisch, W., Villa, I.M., Meschede, M., 2002. Geodynamic evolution of southern Costa Rica related to low-angle subduction of the Cocos Ridge: constraints from thermochronology. *Tectonophysics* 348 (4), 187–204.
- Hacker, B.R., Kelemen, P.B., Behn, M.D., 2011. Differentiation of continental crust by remelting. *Earth and Planetary Science Letters* 307, 501–516.
- Harris, R.N., Sakaguchi, A., Petronotis, K., the Expedition 344 Scientists, 2013. *Proceeding IODP, Volume 344*. Integrated Ocean Drilling Program, College Station, TX.
- Hauff, F., Hoernle, K., Bogaard, P.V.D., Alvarado, G.E., Garbe-Schönberg, D., 2000. Age and geochemistry of basaltic complexes in western Costa Rica: contributions to the tectonic evolution of Central America. *Geochemistry, Geophysics, Geosystems* 1 (5).
- Hayes, J.L., Holbrook, W.S., Lizarralde, D., van Avendonk, H.J.A., Bullock, A.D., Mora, M., Ramirez, C., Harder, S., Alvarado, G.E., 2013. Crustal structure across the Costa Rican Volcanic Arc. *Geochemistry Geophysics Geosystems* 14 (4), 1087–1103.
- Hinz, K., VonHuene, R., Ranero, C.R., Flueh, E., Klaeschen, D., Leinbach, J., Ruoff, O., Bargehlo, H.O., Block, M., Fritsch, J., Kewitsh, P., Meyer, H., Schreckenberger, B., Mrázek, I., 1996. Tectonic structure of the convergent Pacific margin offshore Costa Rica from multichannel seismic reflection data. *Tectonics* 15 (1) (p. 54–8).
- Hoernle, K., van den Bogaard, P., Werner, R., Lissinna, B., Hauff, F., Alvarado, G., Garbe-Schönberg, D., 2002. Missing history (16–71 Ma) of the Galapagos hotspot: implications for the tectonic and biological evolution of the Americas. *Geology* 30 (9), 795–798.
- Hoernle, K., Hauff, F., van den Bogaard, P., 2004. 70 m.y. history (139–69 Ma) for the Caribbean large igneous province. *Geology* 32 (8), 697–700.
- Hurley, P.M., Rand, J.R., 1969. Pre-drift continental nuclei. *Science* 164, 1229–1242.
- Johnston, S.T., Thorkelson, D.J., 1997. Cocos-Nazca slab window beneath Central America. *Earth And Planetary Science Letters* 146 (3–4), 465–474.
- Kay, S.M., Godoy, E., Kurtz, A., 2005. Episodic arc migration, crustal thickening, subduction erosion, and magmatism in the south-central Andes. *Geological Society of America Bulletin* 117 (1–2), 67–88.
- Kimura, G., Silver, E.A., Blum, P., et al., 1997. Proceedings of the Ocean Drilling Program, Initial Report, 170. College Station (TX), Ocean Drilling Program (458 p.).
- Kluesner, J.W., Silver, E.A., Gibson, J., Bangs, N.L., McIntosh, K.D., Orange, D., Ranero, C.R., von Huene, R., 2013. High density of structurally controlled, shallow to deep water fluid seep indicators imaged offshore Costa Rica. *Geochemistry, Geophysics, Geosystems* 14 (3).
- Kopp, H., Flueh, E.R., Petersen, C.J., Weinreb, R.W., Wittwer, A., Scientists, M., 2006. The Java margin revisited: evidence for subduction erosion off Java. *Earth and Planetary Science Letters* 242, 130–142.
- Kutterolf, S., Freundt, A., Pérez, W., 2008. Pacific offshore record of plinian arc volcanism in Central America: 2. Tephra volumes and erupted masses. *Geochemistry, Geophysics, Geosystems* 9, Q02502.
- Laursen, J., Scholl, D.W., von Huene, R., 2002. Neotectonic deformation of the central Chile margin: deepwater forearc basin formation in response to hot spot ridge and seamount subduction. *Tectonics* 21 (5).

- Lonsdale, P., Klitgord, K.D., 1978. Structure and tectonic history of the eastern Panama Basin. *Geological Society of America Bulletin* 89, 981–999.
- Lücke, O.H., Arroyo, I.G., 2015. Density structure and geometry of the Costa Rican subduction zone from 3-D gravity modeling and local earthquake data. *Solid Earth* 6, 1169–1183.
- MacMillan, I., Gans, P.B., Alvarado, G., 2004. Middle Miocene to present plate tectonic history of the southern Central American Volcanic Arc. *Tectonophysics* 392 (1–4), 325–348.
- Marshall, J.S., 2007. The geomorphology and physiographic provinces of Central America, in Central America. In: Bunschuh, J., Alvarado, G., Alvarez, L., Alvarez, W., Asaro, F., Michel, H. (Eds.), *Geology, Resources and Hazards*. Taylor & Francis, London, UK, pp. 1–51.
- McCulloch, M.T., Bennett, V.C., 1994. Progressive growth of the Earth's continental-crust and depleted mantle – geochemical constraints. *Geochimica et Cosmochimica Acta* 58 (21), 4717–4738.
- McLennan, S.M., Taylor, S.R., 1982. Geochemical constraints on the growth of the continental crust. *Journal of Geology* 90, 342–361.
- Morell, K.D., 2016. Seamount, ridge, and transform subduction in southern Central America. *Tectonics* 35 (2), 357–385.
- Morgan, J.P., Ranero, C.R., Vannucchi, P., 2008. Links between plate motions, arc-normal extension and the tectonics, volcanism, and geochemistry of the Middle American Arc. *Earth and Planetary Science Letters* 272, 365–371.
- O'Nions, R.K., Evensen, N.M., Hamilton, P.J., 1979. Geochemical modeling of mantle differentiation and crustal growth. *Journal of Geophysical Research* 84, 6091–6101.
- Phillips, J.S., 1983. *Stratigraphy, Sedimentology and Petrologic Evolution of Tertiary Sediments in Southern Costa Rica* Master's thesis Louisiana State University.
- Pindell, J., Kennan, L., Stanek, K.P., Maresch, W.V., Draper, G., 2006. Foundations of Gulf of Mexico and Caribbean evolution: eight controversies resolved. *Geologica Acta* 4 (1–2), 303–341.
- Plank, T., Langmuir, C.H., 1998. The chemical composition of subducting sediment and its consequences for the crust and mantle. *Chemical Geology* 145 (3–4), 325–394.
- Ranero, C.R., von Huene, R., 2000. Subduction erosion along the Middle America convergent margin. *Nature* 404 (6779), 748–752.
- Ranero, C.R., Grevemeyer, I., Sahling, U., Barckhausen, U., Hensen, C., Wallmann, K., Weinrebe, W., Vannucchi, P., Von Huene, R., McIntosh, K., 2008. The hydrogeological system of erosional convergent margins and its influence on tectonics and interplate seismogenesis. *Geochemistry, Geophysics, Geosystems* 9, Q03. <http://dx.doi.org/10.1029/2007GC001679>.
- Reymer, A., Schubert, G., 1984. Phanerozoic addition rates to the continental crust and crustal growth. *Tectonics* 3, 63–77.
- Rino, S., Komiya, T., Windley, B.F., Katayama, I., Motoki, A., Hirata, T., 2004. Major episodic increases of continental crustal growth determined from zircon ages of river sands; implications for mantle overturns in the Early Precambrian. *Physics of the Earth and Planetary Interiors* 146 (1–2), 369–394.
- Risse, A., Trumbull, R.B., Kay, S.M., Coira, B., Romer, R.L., 2013. Multi-stage evolution of Late Neogene mantle-derived magmas from the central Andes back-arc in the southern Puna Plateau of Argentina. *Journal of Petrology* 54, 1963–1995.
- Rutland, R.W.R., 1971. Andean orogeny and ocean floor spreading. *Nature* 233, 252–255.
- Sak, P.B., Fisher, D.M., Gardner, T.W., Marshall, J.S., LaFemina, P.C., 2009. Rough crust subduction, forearc kinematics, and Quaternary uplift rates, Costa Rican segment of the Middle American Trench. *Geological Society of America Bulletin* 121 (7–8), 992–1012.
- Sallares, V., Danobeitia, J.J., Flueh, E.R., 2001. Lithospheric structure of the Costa Rican Isthmus: effects of subduction zone magmatism on an oceanic plateau. *Journal of Geophysical Research-Solid Earth* 106 (B1), 621–643.
- Schindlbeck, J.C., Kutterolf, S., Freundt, A., Alvarado, G., Wang, K.-L., Straub, S.M., Hemming, S.R., Frische, M., 2016. Late Cenozoic tephrostratigraphy offshore southern Central America: 1. Applications of tephrochronostratigraphy. *Geochemistry, Geophysics, Geosystems* (in press).
- Scholl, D.W., von Huene, R., 2007. Crustal recycling at modern subduction zones applied to the past-issues of growth and preservation of continental basement, mantle geochemistry, and supercontinent reconstruction. In: Hatcher, R.D.J., Carlson, M.P., McBride, J.H., Martínez Catalá, N.J.R. (Eds.), *4D Framework of Continental Crust*. Geological Society of America, Memoirs vol. 200, pp. 9–32.
- Scholl, D.W., von Huene, R., 2009. Implications of estimated magmatic additions and recycling losses at the subduction zones of accretionary (non-collisional) and collisional (suturing) orogens. In: Cawood, P., Kroener, A. (Eds.), *Accretionary Orogens in Space and Time*, Volume 318. Geological Society, London, pp. 105–125.
- Silver, E.A., McIntosh, K.D., Ranero, C., 2000. Influence of lower plate structure on the overriding slope offshore Nicaragua: new geophysical observations and first dredge samples of basement rocks. *Eos, Transactions American Geophysical Union* 81, T12D–T103.
- Sinton, C.W., Duncan, R.A., Denyer, P., 1997. Nicoya Peninsula, Costa Rica: a single suite of Caribbean oceanic plateau magmas. *Journal of Geophysical Research* 102 (B7), 15507–15520.
- Sitchler, J.C., Fisher, D.M., Gardner, T.W., Protti, M., 2007. Constraints on inner forearc deformation from balanced cross sections, Fila Costena thrust belt, Costa Rica. *Tectonics* 26 (6), TC6012 (v, no.).
- Stavenhagen, A.U., Flueh, E.R., Ranero, C.R., McIntosh, K.D., Shipley, T., Leandro, G., Schulze, A., Dañoibeitia, J.J., 1998. Seismic wide-angle investigations in Costa Rica – a crustal velocity model from the Pacific to the Caribbean. *Zentralblatt für Geologie und Paläontologie* 1 (3–6), 393–408.
- Steiger, T., Meschede, M., Gawlick, H., 2005. Evidence of Nicoya ophiolite material drilled at ODP Site 1042: *Eos* (trans.). *American Geophysical Union* 86 (52), T33C–0579.
- Stern, C.S., 2011. Subduction erosion: rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle. *Gondwana Research* 20, 284–308.
- Stern, R.J., Scholl, D.W., 2010. Ying and yang of continental crust creation and destruction by plate tectonic processes. *International Geology Review* 52, 1–31.
- Straub, S.M., Gomez-Tuena, A., Bindeman, I.N., Bolge, L.L., Brandl, P.A., Espinosa-Perena, R., Solari, L., Stuart, F.M., Vannucchi, P., Zellmer, G.F., 2015. Crustal recycling by subduction erosion in the central Mexican Volcanic Belt. *Geochimica et Cosmochimica Acta* 166, 29–52.
- Tatsumi, Y., 2005. The subduction factory: how it operates in the evolving Earth. *GSA Today* 15 (7).
- Tatsumi, Y., Kogiso, T., 2003. The subduction factory: its role in the evolution of the Earth's crust and mantle. *Geological Society, London, Special Publications* 219 (1), 55–80.
- Vannucchi, P., Scholl, D.W., Meschede, M., McDougall-Reid, K., 2001. 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 (5), 649–668.
- Vannucchi, P., Ranero, C.R., Galeotti, S., Straub, S.M., Scholl, D.W., McDougall-Ried, K., 2003. Fast rates of subduction erosion along the Costa Rica Pacific margin: implications for nonsteady rates of crustal recycling at subduction zones. *Journal of Geophysical Research* 108 (B11), 2511 (doi:10.1029/2002JB002207).
- Vannucchi, P., Galeotti, S., Clift, P.D., Ranero, C., von Huene, R., 2004. Long term subduction erosion along the Middle America Trench offshore Guatemala. *Geology* 32 (7), 617–620.
- Vannucchi, P., Fisher, D.M., Gardner, T.W., Bier, S., 2006. From seamount accretion to tectonic erosion: formation of Osa Mélange and the effects of Cocos Ridge subduction in southern Costa Rica. *Tectonics* 25, TC2004.
- Vannucchi, P., Remitti, F., Bettelli, G., 2008. Geological record of fluid flow and seismogenesis along an erosive subducting plate boundary. *Nature* 451 (7179), 699–703.
- Vannucchi, P., Ujiie, K., Stronck, N., the Expedition 334 Scientists, 2012. *Proceeding IODP, Volume 334. Integrated Ocean Drilling Program Management International, Inc., Tokyo*.
- Vannucchi, P., Sak, P.B., Morgan, J.P., Ohkushi, K., Ujiie, K., Scientists, I.E.S., 2013. Rapid pulses of uplift, subsidence, and subduction erosion offshore Central America: implications for building the rock record of convergent margins. *Geology* 41, 995–998.
- Vannucchi, P., Morgan, J.P., Silver, E.A., Kluesner, J.W., 2016. Origin and dynamics of depositional subduction margins. *Geochemistry, Geophysics, Geosystems*.
- Veizer, J., Jansen, S.L., 1979. Basement and sedimentary recycling and continental evolution. *Journal of Geology* 87, 341–370.
- von Huene, R., Lallemand, S., 1990. Tectonic erosion along the Japan and Peru convergent margins. *Geological Society of America Bulletin* 102 (6), 704–720.
- von Huene, R., Scholl, D.W., 1991. Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental-crust. *Reviews of Geophysics* 29 (3), 279–316.
- von Huene, R., Aubouin, J., Arnott, R.J., Baltuck, M., Bourgeois, J., Helm, R., Ogawa, Y., Kvenvolden, K.A., McDonald, T.J., Taylor, E., McDougall, K., Filewicz, M.V., Winsborough, B., Lienert, B., 1985. *Proceedings of the Deep Sea Drilling Program, Initial Report, 84*. U.S. Government Printing Office, Washington D.C. (967 p.).
- von Huene, R., Ranero, C.R., Weinrebe, W., Hinz, K., 2000. Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos Plate, and Central American volcanism. *Tectonics* 19 (2), 314–334.
- Walther, C.H.E., Flueh, E.R., Ranero, C.R., von Huene, R., Strauch, W., 2000. Crustal structure across the Pacific margin of Nicaragua: evidence for ophiolitic basement and a shallow mantle sliver. *Geophysical Journal International* 141 (3), 759–777.
- Willbold, M., Stracke, A., 2006. Trace element composition of mantle end-members: implications for recycling of oceanic and upper and lower continental crust. *Geochemistry, Geophysics, Geosystems* 7, Q04004.
- Willbold, M., Stracke, A., 2010. Formation of enriched mantle components by recycling of upper and lower continental crust. *Chemical Geology* 276, 188–197.
- Ye, S., Bialas, J., Flueh, E.R., Stavenhagen, A., vonHuene, R., Leandro, G., Hinz, K., 1996. Crustal structure of the Middle American Trench off Costa Rica from wide-angle seismic data. *Tectonics* 15 (5), 1006–1021.
- Zeumann, S., Hampel, A., 2015. Deformation of erosive and accretive forearcs during subduction of migrating and non-migrating aseismic ridges: results from 3-D finite element models and application to the Central American, Peruvian, and Ryukyu margins. *Tectonics* 2015TC003867.



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Maria Laura Balestrieri is responsible for the fission-track laboratory of the Institute of Geosciences and Earth Resources, CNR, Italy. Her main research interests are the fission-track and (U–Th)/He method thermochronometry. Her skills are devoted to quantify exhumation and erosion in bedrock and provenance in the detrital fraction and more in general in the application of low temperature thermochronology in the different geodynamic environments (rift and passive margin: Nubian margin, Transantarctic Mountains, Ethiopian rift, Gulf of California; Orogenic belts such as the Northern Apennines of Italy, and the Peloritani Mts in Sicily).