1. Introduction

Forearc basins represent a key structural element of convergent margins because of their potential to alter the geometry of the upper plate and redistribute stresses between the incoming and overriding plates [Storti and McClay, 1995; Fuller et al., 2006; Simpson, 2010]. In traditional evolutionary models of subduction zones, forearc basins and their upper plate basement have been usually treated as separate and distinct elements, however, to dynamically interact and control forearc structure, deformation, and the behavior of plate boundary slip [McCaffrey, 1994; Song and Simons, 2003; Wells et al., 2003; Fuller et al., 2006; Cubas et al., 2013]. This conceptual separation has been motivated by the observed limited spatial extent and deformation within forearc basins [Mcintosh et al., 1993; von Huene and Klaeschen, 1999; Ranero et al., 2000; Strasser et al., 2009]. Accommodation space for the basin has been mainly attributed to permanent deformation of the overriding plate induced by the landward steepening of the slab dip [Fuller et al., 2006], temperature and strength-controlled changes [Zhao et al., 1986; Byrne et al., 1988; Saffer and Bekins, 2002], accumulation of coseismic crustal movements [Wells et al., 2003], uplift of a trench-slope break following thrust imbrication during subduction accretion [Seely et al., 1974; Sample and Fisher, 1986; Silver and Reed, 1988], and subduction erosion [Scholl et al., 1980; Vannucchi et al., 2001; von Huene et al., 2004]. Recent modeling of forearc basins highlights the importance of sediment loading and sedimentation rates in the basin, e.g., the influence of underfilled and overfilled basin conditions on forearc deformation [Fuller et al., 2006; Cassola, 2013]. In these, the forearc basin/upper plate basement is treated as a two-component system that allows forearc to sense and adjust to changes in many different geological conditions.

In such a two-component system, a forearc basin should always have an underlying forearc basement; this lower portion of the margin wedge should be composed either of an older accretionary prism or crystalline/ophiolitic/arc material. This previous conceptual framework appears to be incompatible with new observations from recent drilling and imaging of the southern Costa Rica forearc that are further discussed in section 2.2. In order to reconcile and interpret recent data collected in southern Costa Rica, we here propose a
simple conceptual model that removes a sometimes artificial differentiation between forearc basin and forearc basement, and introduces the concept of a depositionary forearc constructed at a depositionary subduction margin (Figure 1).

Our case study for a current depositionary margin is the Costa Rica margin offshore Osa Peninsula, an area recently studied in detail by ocean drilling and 3-D reflection seismics within CRISP (Costa Rica Seismogenesis Project) (Figure 2a).

2. Case Study: The Southern Costa Rica Subduction System

2.1. Tectonic Background

The CRISP IODP Exp. 334 and 344 transect is located at southern end of the Middle America Trench where the Cocos plate is being subducted beneath the Caribbean plate just north of the Cocos Ridge axis, the latter located below the Osa peninsula (Figure 2a). The NE-SW trending Cocos Ridge consists of thickened oceanic crust produced by Galapagos magmatism with a relief of 2.5 km above adjacent ocean floor. To the east of the Cocos Ridge, the Panama Fracture Zone separates the Cocos and the Nazca plates.

CRISP IODP Exp. 334 and 344 showed a pulse of subduction erosion revealed by $\approx 1$ km of uplift in $0.3 \text{ Ma}$ followed by $\approx 1.5 \text{ km}$ of subsidence in a similar time, based on changes in both benthic foraminifera and the sediment deposition environment offshore Osa peninsula that occurred between $\sim 2.2$ and $1.9 \pm 0.2 \text{ Ma}$ [Vannucchi et al., 2013] (see Figure 2b). This event correlates with the onset of subduction of the Cocos Ridge [MacMillan et al., 2004], which occurred immediately after the subduction of the Panama Fracture Zone system in this region. The uplift/subsidence evolution in Figure 2b agrees well with models of spatial distribution of ridge-induced vertical displacement [Zeumann and Hampel, 2015], where the maximum uplift value is located above the ridge tip and near the trench separated by an area of relative subsidence. Here, though, subsidence cannot be used to estimate upper plate thinning because of the subducting topography and the subsequent uplift. Ongoing subduction of the Cocos Ridge changed the geometry of the upper plate leading to a $\sim 350 \text{ km-long}$ 60 km-wide embayment extending from just southeast of the Nicoya Peninsula to the Panama Fracture Zone. Considering the volume missing from the forearc embayment, Vannucchi et al. [2013] concluded that roughly 120,000 km$^3$ of upper plate material was removed over 350 km of trench in 0.3 Ma with an upward migration of the plate boundary interface in the forearc of about 5.6 km.

Sitchler et al. [2007] proposed that $\sim 35 \text{ km}$ out of the $\sim 60 \text{ km}$ of the width of the embayment is due to of underthrusting of the outer forearc (Osa Peninsula) under the inner forearc, driven by flat subduction of the Cocos Ridge. If half the embayment was formed by shortening, estimates of subduction erosion would be

![Figure 1. Conceptual model of a depositionary subduction margin. In this cartoon, the depositionary margin has a small frontal accretionary prism formed by oceanic sediments transferred from the incoming plate to the forearc. Inboard of the frontal prism the forearc is mostly formed by terrigenous sediments that accumulate on the top of the subsiding forearc that is eroding at its base. Subsidence in the forearc is rapid enough to capture all the upper plate-derived sediments, so that the trench and trench input in the subduction channel lack terrigenous sediments. If basal erosion consumes all the forearc material below the growing forearc basin, then overlying basin sediments can directly enter the subduction channel. Depositionary replacement of basement by basin material can vary downdip and along strike, leading to heterogeneous physical/rheological conditions along the plate boundary and in the forearc wedge.](image)
halved. However, recent seismic studies do not indicate flat subduction [Dinc et al., 2010; Dziema et al., 2011; Arroyo et al., 2014]. In addition, Quaternary deformation in the Osa Peninsula does not involve significant sub-horizontal shortening [Sak et al., 2009], while the inner forearc is actively deforming by folding and thrusting [Sitchler et al., 2007]. Finally, marine data constrain subduction erosion to have been a short-lived pulse, unlike shortening in the outer forearc fold-and-thrust belt which has been active since the Pliocene [Sitchler et al., 2007].

2.2. The CRISP Project
Seismic reflection images across the CRISP transect (Figure 3a) show a ~5 km wide frontal prism of deformed sediment immediately inland of the trench. The accretionary nature of the frontal prism was verified during IODP Exp. 344 which showed that the stratigraphy of the frontal prism is comparable to the stratigraphy of the incoming plate with a repetition of the sequence and age inversion implying the presence of a thrust [Harris et al., 2013].

Moving inboard across the margin, seismic reflection images show a high-amplitude reflection throughout the forearc from the middle slope to the shelf [Vannucchi et al., 2012; Bangs et al., 2015] (Figure 3a). It generally appears in the form of an angular unconformity. IODP drilling revealed that this unconformity is marked by the occurrence of a sharp lithological change dated at ~2.2 ± 0.2 Ma [Vannucchi et al., 2012; Harris et al., 2013; Vannucchi et al., 2013] (Figure 3b). On the shelf, at IODP Site U1379, the unconformity occurs at the base of the forearc basin sequence and indicates subaerial exposure followed by deposition from a shell-
rich beach to a nearshore sandstone [Vannucchi et al., 2013]. On the middle slope at IODP Site U1380, a shell-rich sand/stone unit is also present at the target depth of the unconformity (Figure 3b). Above the unconformity, the modern forearc basin sequence is ~1 km thick. It records a peak sediment accumulation rate of 1035 m/Ma in the last 0.6 Ma, i.e., 30 times faster than the accumulation rate of sediments in northern Costa Rica where the slope was not directly impacted by the Cocos Ridge [Kimura et al., 1997]. Interestingly, this rate is similar to trench accumulation rates at sediment-rich trenches, for example the accretionary Nankai margin [Moore et al., 2001], implying that the southern Costa Rica system is also characterized by abundant terrigenous sediment supply. Unlike its forearc, the southern Costa Rica trench is sediment-poor and lacks terrigenous sediments, containing only ~50 m of hemipelagic sediments from the Pleistocene to the Recent (Figure 3b). The terrigenous sediments have been efficiently captured by the forearc and have not reached the trench within the recent past (Figure 1). The rapid erosional event has, therefore, developed a positive feedback in which most of the volume of material being removed from the base of the upper plate has been replaced by new forearc sediment deposits within a rapidly subsiding forearc basin.
Below the \( \sim 2.2 \pm 0.2 \) Ma unconformity, CRISP drilling recovered poorly deformed fine to coarse-grained volcaniclastic turbidites, hemipelagites, and megabreccias typical of a deep-water environment (Figure 3b). Their early Pleistocene age (Calcareous nanofossil zone NN18-17) indicates a short or absent time gap.

The sediments below the unconformity are interpreted to have either been accreted from the Cocos plate or represent pre-Pleistocene Caribbean forearc deposits, based on three different lines of evidence [Vannucchi et al., 2012; Harris et al., 2013]:

1. Their faunal content and their lithostratigraphic characteristics do not resemble those of the sediments accumulating on the Cocos plate in this region;
2. Their state of deformation is not consistent with intraprism deformation. Deformation intensity decreases abruptly below the unconformity, in contrast with what has been observed for accretionary prisms such as the Nankai Trough forearc [Hayman et al., 2012] or Southern Mexico [Lundberg and Moore, 1982]. The sediments above the unconformity are characterized by a broad interval—from \( \approx 600 \) to \( 860 \) mbsf—of faults and fractures and by the development of discontinuous foliation domains. Deformation is accompanied by geochemical data suggesting lateral flow of a freshened fluid with elevated concentrations of thermogenic hydrocarbons and potassium [Vannucchi et al., 2012; Harris et al., 2013]. These data suggest the presence of one or more faults cutting through the sediments above the unconformity;
3. The oldest age for the thrust drilled at Site U1312 is \( \approx 1.9 \) Ma based on biostratigraphic age of the footwall sediments. Considering the age of the unconformity and the position of Site U1312 (Figure 3a), in a classic accretionary prism development the bulk of the forearc volume should have been off-scraped and accreted in \( 0.3 \pm 0.2 \) Ma. This would have required a thickness \( 2.3 \pm 0.5 \) km of sediment on the Cocos plate (without adjusting for porosity decrease for the accreted sediments).

The above points imply that the forearc basin contains at least two sedimentary cycles separated by a rapid event of uplift and subaerial exposure, which correlates with the onset of subduction of the Cocos Ridge at \( \approx 2.2 \pm 0.2 \) Ma following the subduction of the Panama Fracture zone in this region (Figure 3b).

### 2.3. The 3-D Reflection Seismic Project

Further insights into the internal wedge composition are given by seismic reflection imaging. Two-dimensional reflection lines across the area have been recently augmented by a 3-D reflection seismic data set acquired in an \( 11 \times 55 \) km\(^2\) area about 10 km to the NW of the drilling transect [Kluesner et al., 2013; Bangs et al., 2015]. The 3-D data set is located in a portion of the margin characterized by a bathymetric embayment of the shelf edge that, in comparison to other similar features along the margin and the projection of the Quepos Ridge, suggests that this might be an area where a seamount has recently subducted [Kluesner et al., 2013].

Prestack depth migration of the 3-D data produces a clearer image of the high-amplitude reflection marking the base of the Pleistocene to Recent slope cover [Bangs et al., 2015]. Prestack depth migration also produces a clearer image of internal structures within the margin wedge. Previous 2-D seismic sections already showed portions where tilted and deformed seismic layers alternated with more discontinuous and chaotic reflectivity. The new 3-D data set shows that the margin wedge volume consists of a folded layer sequence with faults displacing the layering. Faults dip both landward and seaward, and root at the plate interface (Figure 4). Deformation intensity increases with depth, but there are significant correlations in structural style between shallower and deeper portions of the forearc wedge. In particular, fold wavelengths increase landward while at the trench the deformation front shows regular stacked sediment packages. While the latter observation is consistent with a continuous outward advance of an accreted structure, the landward architecture is consistent with the folding of a landward-thickening wedge, but not with the sequential off-scraping seen at an accretionary wedge. Also the great thickness of the folds (\( \approx 4 \) km) is not consistent with the margin being formed from a thin—\( 100–400 \) m-thick—incoming sediment unit.

Therefore, the new higher-resolution seismic images suggest not only a terrestrial sediment-dominated composition for the Osa margin wedge, but also an absence of past significant subduction accretion, in agreement with drilling observations (unless rapid sedimentation to the lower slope or trench occurred during the event of subduction erosion).
Among the structures within the margin wedge, Bangs et al. [2015] imaged a large-domed structure that thins laterally with seismic properties consistent with the adjacent material. Although Bangs et al. [2015] do not give a preferred interpretation for this feature; their analysis reinforces the variable 3-D structure of this margin. This inference is consistent with a scenario where the forearc offshore Osa Peninsula largely consists of deep basins filled with sediments coming from the continent that replace previous forearc "base ment" removed by basal tectonic erosion.

3. Southern Costa Rica Forearc as a Depositionary Margin

The replacement of the eroded forearc volume in Costa Rica was contemporaneous with, and we believe also triggered by, the onset of extreme subducting relief associated with the impact of the Cocos Ridge at the margin. This led to an intense, short-lived depositionary event associated with onset of subduction of the Cocos Ridge.

A depositionary margin develops when subduction erosion removes most of the original upper plate "base ment" within a section of the forearc, which is then replaced by terrigenous forearc basin/slope deposits. In contrast to an accretionary prism, where the terrigenous sediments are initially transported to and deposited on the incoming plate (at the trench and/or abyssal plain) and then off-scraped and accreted to the overriding plate, at a depositionary margin terrigenous sediments are deposited above the region of eroding forearc basement. If initial subduction erosion proceeds faster than sedimentation, the trench would step landward triggering an episode of fast sedimentation in the effort to restore the wedge-shaped forearc. This rapidly forming wedge would develop as a slope apron on top of a concurrently developing decollement. As a consequence of this different origin, depositionary margin sequences lack pelagic sediments. Also, although they can potentially deform in both compressional and extensional stress regimes, depositionary margin sediments do not present the tectonic stacking typical of thrust sequences in accretionary prisms. For the example detailed in this paper, extensional and compressional features are both present in the wedge (Figures 3a and 4). Compression with layer-parallel shortening and thickening is expressed by folds and growth thrust folds, while extensional episodes are recorded by complex network of faults in the mid to upper slope and shelf area that commonly do not penetrate through the entire wedge (Figure 1). The substantial internal deformation suggests the presence of a weak basal megathrust and/or mechanically weak sediments within the depositionary margin sequence and remaining basement.

Even though the Cocos Ridge is still subducting, changes in incoming plate relief associated with continued subduction of the Cocos Ridge have been much smaller than the changes associated with its onset. The
geological data show that in the Costa Rica forearc subduction erosion triggered by Cocos Ridge has coexisted with a frontal accretionary prism in the last ≈2 Ma. The frontal accretionary prism present in the CRISP area (Figure 3a) represents the effort of the wedge to regain an equilibrium profile as the frontal and basal erosion caused by the onset of Cocos Ridge subduction, a process particularly effective, if, as proposed above, the megathrust is weak [Davis et al., 1983]. The presence of the frontal accretionary prism in an erosive setting implies that forearcs and plate boundaries are dynamic features where downdip changes in net material transfer between the two plates can occur.

In the absence of sudden subduction erosion events, forearc basins can also grow to be large, slowly evolving, and ancient. For example, just north of Costa Rica the Sandino Basin offshore Nicaragua is 6–11 km thick over a total 15 km thick upper plate, with its oldest recovered sediments being Late Cretaceous, the same age as the initiation of subduction at this margin [Ranero et al., 2000]; and the Stevenson Basin in Alaska is 12 km thick over a total thickness of the upper plate of 15 km, with its oldest recovered sediments being middle Eocene in age [von Huene and Klaeschen, 1999]. The onset of subduction of a large-scale topographic feature could remove, even just locally, large volumes of upper plate basement and let the forearc sediments “touch” the plate boundary.

4. Implication for Wedge Stability and Seismogenesis

The shape of forearcs is observed to naturally evolve toward a wedge geometry. The geometric characteristics of this wedge have been successfully modeled by the Coulomb wedge theory to be a function of the friction along the megathrust and the wedge strength [Davis et al., 1983; Dahlen et al., 1984; Lallemand et al., 1994].

In the Coulomb wedge framework, the subsidence creating forearc basins is interpreted to be the consequence of increasing dip of the subducting plate [Fuller et al., 2006; Cassola, 2013]. If sediments keep filling the forearc basin as this occurs, the filled basin itself will tend to increase the stability of the wedge material beneath the basin. This has been shown in numerical modeling where a wedge with a filled forearc basin has low-strain rates and relatively little deformation, while an underfilled basin predisposes the entire wedge to high-strain rates and active deformation [Fuller et al., 2006; Cassola, 2013].

In the case of subduction due to localized basal erosion at an erosive margin, the Coulomb wedge theory must include the active removal of material from the base of the upper plate [Davis et al., 1983; Wang et al., 2010]. Furthermore, if, as in the case of a depositionary margin, the younger and weaker sediments replace older and more consolidated forearc material, the solution for the stress state of the wedge should include a two component system with time-dependent rheologies for each of them. The depositionary forearc in Costa Rica shows intense deformation throughout all its width and depth (Figure 4). Furthermore, the sediments above the ∼2.2 ± 0.2 Ma discontinuity are similarly deformed. Following the line of reasoning of Fuller et al. [2006], in this situation sedimentation, even for “geologically fast deposition,” does not keep up with subsidence so that the wedge deforms internally. In order for this deformation to occur within the Coulomb wedge theory, the new basin fill must be weaker than surrounding older material. When a portion of forearc basement is replaced from above by a depositionary forearc, this new forearc basin is likely to be a persistent weaker unit in the forearc. The removal and replacement of previous stronger and denser forearc basement by recent sediments might be anticipated to lead to overall rheological weakness. This weakening occurs because, in this portion of the forearc, the entire thickness of the forearc wedge has been created by the consolidation of forearc basin sedimentation instead of the seaward migration of continental crust, or the accumulation and progressive deformation and lithification of an accretionary forearc.

Unlike in accretionary prisms, the sediments of depositionary margins do not experience progressive horizontal transport, burial, and exhumation. Instead, they are mostly consolidated by burial, gravitational loading, and horizontal shortening (Figure 1). Therefore, while the subducting sediments and igneous rocks beneath the forearc can still be envisioned as the primary source of fluids along the megathrust and certainly can still contribute to fluid flow through the forearc wedge [Hensen et al., 2004; Ranero et al., 2008], in depositionary margins the forearc sediments can also be a key source of fluids that rise within the wedge. A massively dewatering and compacting section of a wedge can lead to much higher internal fluid pressures than those observed in accretionary prisms. This has important consequences on the strength of the wedge and its association to slow slip events versus earthquakes [Audet and Schwartz, 2013].
As noted above, an extreme event of subduction erosion can lead to the development of mechanically heterogeneous wedges, with fragments of "forearc basement" distributed along the base of the upper plate, separated by depositionary forearc sequences (Figure 1). In this case, the frictional properties of the megathrust are also likely to be heterogeneous, and linked to the geological history of the overlying forearc. Depositionary forearcs may differ from the classic landward − down dip increase of density assumed in classical models as they follow a different density + burial + compaction trajectory. These properties can all influence the seismogenic potential of different sections of the margin. In this regard, it is interesting that the anomalously shallow updip limit of plate interface seismogenesis at Osa [DeShon et al., 2003; Arroyo et al., 2014] is spatially correlated with the location of a recently formed depositionary forearc basin. This correlation needs to be tested to see if it is also noted at other forearcs.

5. Conclusions

The combined interpretation of offshore drilling and 3-D reflection seismic imaging reveals that the forearc in southern Costa Rica is composed of terrigenous sediments. These sediments can either be deposited directly on the upper plate as it is being removed from below by subduction erosion, or, in the most extreme scenario, the entire forearc could have been removed by a single subduction erosion event followed by depositionary replacement. In either case, this forearc did not grow by off-scraping and accretion, but rather by deposition of material from above to restore equilibrium profile of the wedge.

This type of highly disruptive subduction erosion event is unlikely to be "rare" in the geological record. Ocean basins contain a plethora of high relief bathymetric features. Volcanic rises, aseismic ridges, and seamount chains are commonly clumped, as they are often the by-product of hotspots or hotspot + mid-ocean ridge interaction, and therefore usually subduct in swarms along a given margin. As a consequence, the preservation potential for this heterogeneous geological process that occurs infrequently, but consistently operates on subduction forearcs appears to be relatively high.

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References

Allen, P. A., and J. R. Allen (1990), Basin analysis, principles and applications, Blackwell Scientific Publications, 451 pp., Oxford, U. K.
Arroyo, I. G., I. Greveinmeyer, C. R. Ranero, and R. von Huene (2014), Interplate seismicity at the CRISP drilling site: The 2002 Mw 6.4 Osa Earthquake at the southeastern end of the Middle America Trench, Geochim. Geophys. Geosyst., 15, 3035–3050, doi:10.1002/2014GC005359.
Audet, P., and S. Y. Schwartz (2013), Hydrologic control of forearc strength and seismicity in the Costa Rican subduction zone, Nat. Geosci., 6, 852–855, doi:10.1038/ngeo1927.
Bangs, N. L., K. D. McIntosh, E. A. Silver, J. W. Kluesner, and C. R. Ranero (2015), Fluid accumulation along the Costa Rica subduction thrust and development of the seismogenic zone, J. Geophys. Res. Solid Earth, 120, 67–86, doi:10.1002/2014JB01265.
Byrne, D. E., D. M. Davis, and L. R. Sykes (1988), Loc and maximum size of thrust earthquakes and the mechanics of the shallo region of subduction zones, Tectonics, 5, 403–421.
Cardozo, N. (2011), OSXBackstrip v. 2.9. [Available at http://mac.softpedia.com/get/Math-Scientific/OSXBackstrip.shtml.]
Cassola, T. (2013), Mechanics of forearc basins, PhD thesis, ETH-Zurich, 214 pp., Zurich, Switzerland.
Cubas, N., J. P. Avouac, P. Souloumiac, and Y. Leroy (2013), Megathrust friction determined from mechanical analysis of the forearc in the Maule earthquake area, Earth Planet. Sci. Lett., 381, 92–103.
Dahlen, F. A., J. Suppe, and D. Davis (1984), Mechanics of fold-and-thrust belts and accretionary wedges: Cohesive Coulomb theory, J. Geophys. Res., 89, 10,087–10,101.
Davis, D., J. Suppe, and F. A. Dahlen (1983), Mechanics of fold-and-thrust belts and accretionary wedges: Geologic Analysis of a Himalayan Accretionary Wedge, Professional Paper 1326, U.S. Geol. Survey.
DeMets, C. (2001), A new estimate for present-day Cocos-Caribbean plate motion: Implications for slip along the Central American volcanic arc, Geophys. Res. Lett., 28, 4043–4046.
DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1990), Current plate motions, Geophys. J. Int., 101(2), 425–478.
DeShon, H. R., S. Y. Schwartz, S. L. Bilek, L. M. Dormann, V. Gonzalez, J. M. Protti, E. R. Flueh, and T. H. Dixon (2003), Seismogenic zone structure of the southern Middle America Trench, Costa Rica, J. Geophys. Res., 108(B10), 2491, doi:10.1029/2002JB002294.
Dinc, A. N., I. Koulakov, M. Thorwart, W. Rabbel, E. R. Flueh, I. Arroyo, W. Taylor, and G. Alvarado (2010), Local earthquake tomography of Central Costa Rica: Transition from seamount to ridge subduction, Geophys. J. Int., 183, 286–302, doi:10.1111/j.1365-246X.2010.04717.x.
Dzierma, Y., W. Rabbel, M. Thorwart, E. R. Flueh, M. M. Mora, and G. E. Alvarado (2011), The steeply subducting edge of the Cocos Ridge: Evidence from receiver functions beneath the Northern Talamanca Range; south-central Costa Rica, Geochim. Geophys. Geosyst., 12, Q04530, doi:10.1029/2010GC003477.
Fuller, C. W., S. D. Willett, and M. T. Brandon (2006), Formation of forearc basins and their influence on subduction zone earthquakes, Geology, 34(2), 65–68.
Harris, R. N., A. Sakaguchi, K. Petronotis, and the Expedition 344 Scientists (2013), in Proceedings Integrated Ocean Drilling Program, vol. 344, Ocean Drill. Program, College Station, Tex., doi:10.2204/iodp.proc.344.2012.
Hayman, N. W., T. B. Byrne, L. C. McNeill, K. Kanagawa, T. Kanamatsu, C. M. Browne, A. M. Schleicher, and G. J. Hufnile (2012), Structural evolution of an inner accretionary wedge and forearc basin initiation, Nankai margin, Japan, Earth Planet. Sci. Lett., 353, 163–172.
Hensen, C., K. Wallmann, M. Schmidt, C. R. Ranero, and E. Sues (2004), Fluid expulsion related to mud extrusion off Costa Rica: A window to the subducting slab, Geology, 32(3), 201–204.

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Kimura, G., E. A. Silver, P. Blum, and the Expedition 170 Scientists (1997), *Proceedings of the Ocean Drilling Program, Initial Rep.*, vol. 170, 458 pp., Ocean Drill. Program, College Station, Tex., doi:10.2973/odp.proc.170.1997.

Kluessner, J. W., E. A. Silver, N. L. Bangs, K. D. McIntosh, J. Gibson, D. Orange, C. R. Ranero, and R. von Huene (2013), High density of structurally controlled, shallow to deep water fluid seep indicators imaged offshore Costa Rica, *Geochem. Geophys. Geosyst.*, 14, 519–539, doi: 10.1002/2016GC006259.

Lallemand, S. E., P. Schnurle, and J. Malavieille (1994), Coulomb theory applied to accretionary and nonaccretionary wedges: Possible causes for tectonic erosion and or frontal accretion, *J. Geophys. Res.*, 99, 12,033–12,055.

Lundberg, N., and J. C. Moore (1982), Structural features of the Middle America Trench slope off southern Mexico, *Deep Sea Drilling Project Leg 66*, in Initial Reports DSDP, vol. 66, edited by J. S. Watkins, and J. C. Moore, pp. 793–805, U.S. Gov. Print. Off., Washington, D.C.

MacMillan, L. P. B. Gans, and G. Alvarado (2004), Middle Miocene to present plate tectonic history of the southern Central American Volcanic Arc, *Tectonophysics*, 392(1–4), 325–348.

Mcaffrey, R. (1994), Global variability in subduction thrust zone fore-arc systems, *Pure Appl. Geophys.*, 142(1), 173–224.

Mcintosh, K., E. Silver, and T. Shipley (1993), Evidence and mechanisms for fore-arc extension at the accretionary Costa-Rica convergent margin, *Tectonics*, 12, 1380–1392.

Moore, G. F., A. Taara, A. Klaus, and the Expedition 190 Scientists (2001), *Proceedings of the Ocean Drilling Program, Initial Rep.*, vol. 190 Ocean Drill. Program, College Station, Tex., doi:10.2973/odp.proc.ir.190.2001.

Ranero, C. R., R. von Huene, E. Fluhe, M. Duarte, D. Baca, and K. McIntosh (2000), A cross section of the convergent Pacific margin of Nicaragua, *Tectonics*, 19, 335–357.

Ranero, C. R., I. Grevemeyer, H. Sahling, U. Barckhausen, C. Hensen, K. Wallmann, W. Weinrebe, P. Vannucchi, R. von Huene, and K. McIntosh (2008), Hydrogeological system of erosional convergent margins and its influence on tectonics and interplate seismogenesis, *Geochem. Geophys. Geosyst.*, 9, Q03S04, doi:10.1029/2007GC001679.

Ryan, W. B. F., et al. (2009), Global multiresolution topography synthesis, *Geochem. Geophys. Geosyst.*, 10, Q03014, doi:10.1029/2008GC002332.

Saffer, D. M., and B. A. Bekins (2002), Hydrologic controls on the morphology and mechanics of accretionary wedges, *Geology*, 30(3), 271–274.

Sak, P. B., D. M. Fisher, T. W. Gardner, J. S. Marshall, and P. C. LaFemina (2009), Rough crust subduction, forearc kinematics, and Quaternary uplift rates, Costa Rican segment of the Middle America Trench, *Geol. Soc. Am. Bull.*, 121, 992–1012, doi:10.1130/0091-7613(2009)121<992::AID-GSAB>3.0.CO;2-A.

Sample, J. C., and D. M. Fisher (1986), Duplex accretion and underplating in an ancient accretionary complex, Kodiak Islands, Alaska, *Geol. J.*, 14(2), 160–163.

Scholl, D. W., R. von Huene, T. L. Vallier, and D. G. Howard (1980), Sedimentary masses and concepts about tectonic processes at underthrust oceanic margins, *Geology*, 8, 564–568.

Seely, D. R., P. R. Vail, and G. G. Walton (1974), Trench slope model, in *The Geology of Continental Margins*, edited by C. Burck, and C. Drake, pp. 249–260, Springer, Berlin.

Silver, E. A., and D. L. Reed (1988), Backthrusting in accretionary wedges, *J. Geophys. Res.*, 93, 3116–3126.

Silver, E. A., J. W. Kluesner, J. H. Edwards and P. Vannucchi (2014), A thick, deformed sedimentary wedge in an erosional subduction zone, *Tectonics*, 33(4), 2014TC002631.

Simpson, G. D. H. (2010), Formation of accretionary prisms influenced by sediment subduction and supplied by sediments from adjacent continents, *Geology*, 38(2), 131–134.

Stitchler, J. C., D. M. Fisher, T. W. Gardner, and M. Protti (2007), Constraints on inner forearc deformation from balanced cross sections, *Fila Costena thrust belt, Costa Rica, Tectonics*, 26, TC6012, doi:10.1029/2006TC001949.

Storti, F., and K. McClay (1995), Influence of syntectonic sedimentation on thrust wedges in analogue models, *Geology*, 23(11), 999–1002.

Strasser, M., et al. (2009), Origin and evolution of a splay fault in the Nankai accretionary wedge, *Nat. Geosci.*, 2, 648–652.

Vannucchi, P., D. W. Scholl, M. Meschede, and K. McDougall-Reid (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, 649–668.

Vannucchi, P., K. Ujiie, N. Stroncik, and the Expedition 334 Scientists (2012), *Proceedings of Integrated Ocean Drilling Program*, vol. 334, Ocean Drill. Program Manage. Inc., Tokyo, doi:10.2204/iodp.proc.334.2012.

Vannucchi, P., P. B. Sak, J. P. Morgan, K. Ohkushi, K. Ujiie, and I. E. S. Scientists (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.

von Huene, R., and D. Klaeschen (1999), Opposing gradients of permanent strain in the accretion zone and elastic strain across the seismogenic zone of the Kodiak shelf and slope, *Alaska, Tectonics*, 18, 248–262.

von Huene, R., C. R. Ranero, and P. Vannucchi (2004), Generic model of subduction erosion, *Geology*, 32(10), 913–916.

Wang, K., Y. Hu, R. von Huene, and K. Kukowski (2010), Interplate earthquakes as a driver for shallow subduction erosion, *Geology*, 38, 431–434, doi:10.1130/G30597.1.

Wells, R. E., J. R. Blakely, Y. Sugiyama, D. W. Scholl, and P. A. Dintelman (2003), Basin-centered asperities in great subduction zone earthquakes: A link between slip, subsidence, and subduction erosion?, *J. Geophys. Res.*, 108(B10), 2507, doi:10.1029/2002JB002072.

Zeumann, S., and A. Hampsell (2015), Deformation of erosive and accretive forelands during subduction of migrating and non-migrating asesmic ridges: Results from 3-0 finite element models and application to the Central American, Peruvian, and Ryukyu margins, *Tectonics*, 34, 1769–1791, doi:10.1002/2015TC003867.

Zhao, W. L., D. M. Davis, F. A. Dahlen, and J. Suppe (1986), Origin of convex accretionary wedges: Evidence from Barbados, *J. Geophys. Res.*, 91, 10,246–10,258.