In-situ Mass Balance Estimates Offshore Costa Rica

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Abstract The Costa Rican convergent margin has been considered a type erosive margin, with erosional models suggesting average losses up to ∼153 km3/km/m.y. However, three-dimensional (3D) seismic reflection and Integrated Ocean Drilling Program data collected offshore the Osa Peninsula images accretionary structures and vertical motions that conflict with the forearc basal erosion model. Here we integrate such data to do an in-situ accounting of material transfer at the plate boundary across the outermost 10 km of the forearc, characterized by active and inactive megathrusts. Our in-situ budget finds an approximate balance between sediment recycling via accretion and underplating, 0.7–2.3 km3/km/m.y., and basal erosion, 0.7 km3/km/m.y., while subducting sediment volumes, 7.8 km3/km/m.y., greatly outpace either material transfer volumes. These budget results differ significantly from published estimates based on simple proxies of trench axis deflection and slope subsidence. These budget results are the summation of thin incoming hemipelagic sediments that variably accrete along the deformation front, underplating of hemipelagic sediments on the upthrown-side and basal erosion on the downthrown-side of active plate bending faulting landward of the trench axis, and sediment subduction primarily composed of pelagic sediments.

Plain Language Summary Subduction zones, where tectonic plates meet and dive under or over their neighbors, are environments of material exchange, where sediments and rocks are given, or taken away. Either of the converging plates, the one going under or over, can theoretically add or remove material depending on a number of conditions. Understanding what those conditions are and how much is added or removed is challenging, given these interactions occur offshore and deep in the earth. For decades, marine geoscientists have used proxies to estimate how much material is exchanged at subduction zones around the world. For the first time, new 3D imaging data allows us to directly estimate material exchange at a subduction zone. Using these data, we estimate the material exchange for a ∼10 km wide and ∼10 km long section of the subduction zone offshore Costa Rica, which has been considered an eroding continent. These new data show that for the footprint studied, the Costa Rican continent is not shrinking, but is balanced to slowly growing.

1. Introduction

Convergent margin forearcs (crust between trenches and volcanic arcs) are juxtaposed against subducting plates and contribute disproportionately to the growth and/or recycling of continental crust (Clift & Vannucchi, 2004). To constrain forearc mass budgets, many studies have used offshore drilling and two-dimensional (2D) marine geophysical imaging datasets, incorporated with the onshore record, to estimate mass budgets across the global ∼44,000 km of ocean-margin subduction zones (e.g., Vannucchi et al., 2013). From this work, the rate of convergence and thickness of incoming sediments seem to control whether forearcs grow (accrete) or recede (erode) over million year timescales (Clift & Vannucchi, 2004). However, such studies have been limited by (1) the one-dimensional (1D) and 2D nature of spatially sparse sampling and imaging, which limits the scale of structures that can be interpreted and is prone to spatial aliasing (Cartwright & Huuse, 2005), (2) the inability of 2D seismic imaging to migrate out-of-plane reflections from complex geologic structures inherent to convergent margin outer forearcs to their correct locations.
(Yilmaz, 2001) and (3) that anchoring to specific conceptual models most impacts interpretation outcomes on 2D seismic reflection data (Alcalde et al., 2019).

Previous estimates of mass balance along subduction margins have utilized 2D seismic reflection and drilling to estimate subduction erosion, frontal accretion, underplating, and sediment by-passing (Clift & Vannucchi, 2004; Vannucchi et al., 2013; von Huene & Scholl, 1991; von Huene et al., 1980, 2004). Both 2D seismic reflection and drilling are able to partially characterize the vertical motions of the forearc, and many papers have come to the conclusion that subsidence must be caused by subduction erosion and uplift by subduction accretion. To the extent that these assumptions apply in a specific case, then 2D seismic reflection and drilling may provide interpolated estimates of subduction erosion and accretion across a margin. However, recent studies of the Japan and Costa Rica subduction margins suggest that forearc subsidence and uplift are not wholly linked to forearc mass balance changes but to plate kinematic changes, subducting topography and forearc-arc-backarc shortening (Edwards et al., 2018; Morell et al., 2019; Regalla et al., 2013). To resolve this difference in interpretation along the southern Costa Rican margin, we utilize IODP drilling combined with both post-stack time-migrated and a pre-stack depth-migrated three dimensional (3D) seismic reflection volumes to quantify an in-situ mass balance of material exchange across the outermost ∼10 km of the forearc (Figure 1), which mostly coincides with what is referred to as a frontal prism (Figure 2a; von Huene et al., 2000). Notably, the existence of the 3D seismic reflection data was only possible after decades of the previously mentioned offshore imaging studies and drilling campaigns along the entire Central American margin, making this a rare and unique dataset where surprises are to be expected.
From Costa Rica to Nicaragua, the outermost convergent margin appears to have a relatively continuous frontal prism, except where deformed and/or removed by subducting topography (von Huene et al., 2000). Even where the frontal prism is deformed or removed, the margin quickly restores itself to its former taper, either via a reincorporation of slope sediments (G. Kimura et al., 1997) and/or accretion of subducting sediments (Harris et al., 2013a). Thus, the frontal prism is a long-lived, margin-wide feature that is, part of a stable margin configuration. Our study area wholly encompasses the frontal prism and includes ~2–3 km downdip (landward) beyond its approximate end (Figure 2e). We quantify the exchange of material over this spatial domain, and we use this ~130 ka (77 km/My orthogonal convergence rate; DeMets et al., 2010) record to compare to previous mass balance estimates and investigate structural controls on material exchange.

1.1. Quantifying 100 KM$^2$ Mass Budget

The boundary along which a subducting plate dives under its neighbor can change its structural position due to new incoming sediments (Huiqi et al., 1992; Moore & Silver, 1987), variable rheology (Ikari et al., 2018) and/or changes in geometry due to plate bending (Boston et al., 2014). When the megathrust does change its structural position, there is an exchange of material between the plates; if the megathrust migrates up-section, material is transferred from the upper to the lower plate (basal erosion; Hilde, 1983), and conversely, if it drops down-section (underplating; H. Kimura et al., 2010), or if it steps seaward at the deformation front (accretion; Silver, 1971), material is transferred from the lower to the upper plate. The net material exchange is a sum of these megathrust positional changes, given by:

$$A + U - E = \Delta UP$$

where $A$ is accretion at the trench, $U$ is underplating, $E$ is basal erosion and $\Delta UP$ is the volume change of the upper plate. The total sediment subducted, $S$, is the sum of the remaining subducting sediments that bypass the upper plate.

2. Methods

2.1. Mapping A, E and S Volumes

We utilize pre-stack depth-migrated 3D seismic reflection data to constrain $A$, $E$ and $S$ volumes through detailed 3D mapping. We employed post-stack processing techniques that remove noise and aid amplitude-based tracking (Tingdahl & de Groot, 2003). Such post-stack processing relies principally on a secondary volume of inline and crossline dips, called a dip-steering volume, which contains for every sample in the volume a best fit dip to adjacent inline and crossline samples. The adjacency of inlines and crosslines included is controlled by the size of the moving 3D look window (often called a sub-cube) that the dip-steering volume is generated from, which controls both the resolution and noisiness of the dip-steering volume. A median amplitude filter, guided by the dip-steering volume, was then applied to the pre-stack depth-migrated reflection volume to generate a new filtered reflection volume. Amplitude-based horizon tracking was employed on this dip-steered median filtered reflection volume. Incorporating a dip-steered filtered volume and a secondary dip-steering volume makes it possible to map dipping reflections with semiautomated horizon tracking, which is required for mapping $A$, $E$ and $S$ bounding reflections.

We mapped $A$, $E$ and $S$ volumes by tracking the top and bottom bounding reflections and then calculating a thickness (vertical distance) per seismogram (Figure 2). Such reflection tracking in the pre-stack depth-migrated volume was indexed against reflection tracking in the time-migrated volume, where improved imaging of steeply dipping frontal prism reflections can locally be seen. The basal surface of $A$ volumes is marked by foreland nucleating thrusts (present, past and proto megathrusts) at the deformation front. These thrusts are reversed polarity reflections (relative to the seafloor reflection) immediately outboard of the principal deformation front that truncate incipient folding (i.e., stratal disruption; Figure 2). The top surface of accretionary volumes is the seafloor and/or the former, abandoned megathrust, which has been back-rotated to steeper angles (Figure 2). Eroded volumes ($E$) are seen where lower portions of imbricate stacks of steeply landward dipping reflections within the frontal prism are cut by a reversed polarity subhorizontal reflection
that links or bridges the megathrust up and down dip across high-angle, normal offset reflections (plate bending faults) orthogonal to the megathrust (Figure 2c; Edwards et al., 2018b). The top bounding surface is this subhorizontal reflection, and the bottom bounding surface is a subhorizontal reversed polarity reflection that separates subhorizontal reflections below (underthrusting sediments) from steeply dipping reflections above (deformed imbricate thrust stacks formerly of the upper plate). Subducted sediment (S) is bounded across its top by the megathrust or, where present, the base of E and across its bottom by the underthrusting lavas (Figure 2). Equivalent inlines from the post-stack time-migrated volume as seen in Figure 2 are provided in the supporting text. The top of the lavas was found by a well-to-seismic synthetic tie (IODP Site U1414 encountered lavas at 370 meters below seafloor; Figure 2e; Harris et al., 2013b), and is marked by a positive polarity reflection overlaying discontinuous and chaotic reflections.

Mapping A, E and S thicknesses (from the trench axis landward ∼10 km) utilized ∼450,000 depth converted seismograms. We summed respective A, E and S thicknesses and scaled them to volume per km², km³/km², by multiplying them by the nominal bin size in the 3D volume, ∼12.49 × 18.748 m, converting m² to km² and dividing the total by 100 km² (the trench parallel distance times the trench perpendicular distance of our study area). We then multiplied A, E and S rates (km³/km²) by 1—median porosity of similarly porous sediments encountered in IODP Sites U1412 and U1414 (solid portion of sediments). We used solid portions of 0.28 for A (median hemipelagic solid portion from IODP Site U1414; Figures 1 and 2e; Harris et al., 2013b), 0.4 for E (median frontal prism sediment solid portion from IODP Site U1412; Figure 1; Harris et al., 2013a), and 0.3 for S (median pelagic solid portion from IODP Site U1414; Figures 1 and 2e). We found A = 0.005 km³/km², E = 0.009 km³/km² and S = 0.1 km³/km².

### 2.2. Modeling Missing U

Because mapping is only capturing present-day accretion at the deformation front (Figures 2a–2d), it does not account for underplated or previously accreted volumes, (we include both in U), transferred during the previous ∼130 ka of subduction. This timeframe is estimated from a 77 km/m.y. orthogonal convergence rate over the ∼10 km of outermost forearc included in this study (DeMets et al., 2010). We see possible underplating associated with plate bending faults (e.g., Figure 3), but quantifying such a volume with mapping is not feasible given the difficulty in resolving reflection geometries within the frontal prism downdip from the accretionary front. Thus, we modeled underthrust porosities, restored thicknesses and estimated U by measuring the shift in the distribution of thicknesses before and after subduction (Figure 4). Because the megathrust does not interact with the pelagic reflection (top of the pelagic section) within ∼10 km of the trench (e.g., Figure 2a), we constrain our statistical approach to the hemipelagic section.

The distribution of hemipelagic thicknesses on the Cocos plate before subduction (Figure 1), extracted from ∼150,000 depth converted seismograms, has a range of 115–370 m (3σ from median; Figure 4), with a median thickness of 204 m. After subduction, hemipelagic thicknesses, extracted from ∼450,000 depth converted seismograms, shift to lower thicknesses (Figure 4), with minimum thicknesses down to <5 m and a median thickness of 82 m. Thinning is expected because a significant volume of sediments are scraped off at the deformation front and the overlying load increases rapidly, resulting in compaction-driven dewatering (Moore & Vrolijk, 1992). Since we have accounted for off-scraping at the deformation front with mapping, we can estimate U by modeling compaction, restoring uncompacted thicknesses and quantifying the shift in the distribution of uncompacted thicknesses pre- and post-subduction (see schematic workflow in Figure 5). This method assumes that the past ∼130 ka of incoming hemipelagic thicknesses is the same as at present, a reasonable assumption suggested by both the consistent hemipelagic thicknesses progressively outboard of the trench (Figure 2e) and the record of accretion of thin slices of sediments in the frontal prism (Figures 2a–2d).

#### 2.2.1. Restoring Subducted Thicknesses to Pre-subducted Thicknesses

We restore hemipelagic sediment thicknesses by removing the effects of compaction (i.e., porosity loss), with burial depths up to ∼2.5 km below seafloor (Figure 4b). Previous studies for these depths support our assumption that the volume of underthrust grains did not change by diagenesis and mineral dehydration.
We model underthrust porosities by two end-member approaches: (1) a simple 1D Athy logarithmic depth—porosity relation (Athy, 1930) and (2) a geostatistical conditional simulation (i.e., stochastic inversion) of acoustic impedances (Haas & Dubrule, 1994) from seismic reflectivity. We then calculate porosity from simulated impedances. Both the Athy and geostatistical simulation results are then used to restore thicknesses from their compacted state to an uncompacted state by the following porosity—thickness relation (Van Hinte, 1978),

$$T_o = \frac{(1 - \phi_o)T_u}{1 - \phi_o}$$  (2)

where $\phi_o$ is the median porosity (0.72) of incoming hemipelagics (Harris et al., 2013b) and $T_u$ and $\phi_o$ are the underthrust thickness and porosity (Figure 5). Restored, or uncompacted, thicknesses ($T_o$) are then compared to incoming sediment thicknesses ($T_i$; which are also considered uncompacted since they have not been subducted and underthrust), resulting in relative deficits ($T_i - T_o$; which in this study represent $U$).

Using the observed distribution of incoming, uncompacted thicknesses ($T_i$) to define our relative standards of comparison (Figure 4), resulted in lower (3σ; 115 m), median (204 m) and upper (3σ; 370 m) benchmark...
thicknesses. The resulting relative deficits are then scaled by the solid portions of hemipelagics observed in IODP site U1414, 0.28, resulting in estimates of $U$.

### 2.2.2. 1D Athy Depth—Porosity Model

We utilized the empirical relationship that porosity logarithmically decreases with depth of burial (Athy, 1930), such that,

$$\phi_o = \phi_v \exp(-bz)$$

(3)

**Figure 4.** a) Pre-subducted (light blue) and post-subducted (light green) hemipelagic thickness normalized probabilities. (b) Pre-subducted (light blue) overlain on post-subducted (light green) hemipelagic thicknesses spatial overlay. Pre-subducted thicknesses are plotted as distance seaward from trench and post-subducted thicknesses are plotted with thickness of overlying wedge, which is proportional to distance from trench. Interpretations of thicknesses due to compaction, compaction and/or lost to previous accretion and gained to basal erosion are annotated.

**Figure 5.** Schematic of workflow used to restore thicknesses and estimate material exchange underplated or previously accreted volumes from modeled porosities for hemipelagic sediments (shaded purple on seismograms). Inset of six example seismograms with crossline locations in depth-migrated volume (e.g., x2920, x2921, etc.). $T_n$ is underthrust thickness (observed post-subducted thickness at present), $T_o$ is restored thickness (modeled original pre-subducted thickness), $T_{cut}$ is benchmark thickness (either 115 m, 204 m, or 370 m; based on distribution of incoming hemipelagic thicknesses observed at present) and $U$ is the modeled underplated thickness, based on the deficit of a restored thickness relative to benchmark thicknesses.
where $\phi_0$ and $\phi_b$ are the original and buried porosities, $b$ is a constant linked to lithology and $z$ is depth below the seafloor. By utilizing the Athy model, we ignore excess pore pressures at depth, and as such, find end-member conservative estimates of $U$ (i.e., we overestimate compaction and restored thicknesses and therefore underestimate the shift in the distribution of thicknesses; Figure 4b). We applied a best fit between Equation 3 and the hemipelagic depth/porosity data from IODP Site U1414 to obtain the original porosity, 0.76, and $b$, $6.1 \times 10^{-4}$ (Figure 6), with $z$ being the top of the underthrusting sediments (i.e., megathrust). Modeled porosities gave uncompacted thickness deficits, using Equation 2, that summed to lower (115 m benchmark), median (204 m benchmark) and upper (370 m benchmark) estimates of $U_{athy} = 0.001 \text{ km}^3/\text{km}^2$, 0.009 km$^3$/km$^2$ and 0.03 km$^3$/km$^2$.

### 2.2.3. Geostatistical Conditional Simulation of Acoustic Impedance

We performed 90 non-unique inversions for acoustic impedance from the post-stack time-migrated 3D seismic reflection volume, by building an *a priori* model of impedances, estimating the source wavelet, computing semivariogram parameters, and using industry software provided to us (multi-point stochastic inversion tool [MPSI] from ArkCls Ltd./Earthworks Reservoir Ltd.). More information about the geostatistical simulation is provided in the supporting text.

We then calculated porosities from these impedances for all 90 simulations using an empirical best linear fit derived from IODP Site U1414 (Figure 7; Harris et al., 2013b). This process resulted in 90 simulated porosities per seismogram. We then quantified the probability of occurrence ($P_{10}$, $P_{50}$ and $P_{90}$) that the restored thicknesses, using Equation 2, were less than the lower, median and upper benchmark thicknesses for pre-subduction uncompacted thicknesses 115 m, 204 m and 370 m (e.g., if > 81 out of 90 uncompacted thicknesses were < 115 m, then that seismogram has a >90% probability of having lost solids to the upper plate according to the 115 m threshold; Figure 8). For those locations that meet such probability thresholds, we then took the median of the remaining restored thicknesses, summed their deficits relative to incoming benchmark thicknesses (115 m, 204 m, and 370 m) and scaled them to km$^3$/km$^2$ for each $U_{inv}$ iteration (Figure 7).

### 3. Results

Using the MORVEL plate velocity model (77 km/m.y. orthogonal convergence rate; DeMets et al., 2010), we scale our measurements to volume/km along trench/m.y. (km$^3$/km/m.y.) by multiplying our km$^3$/km$^2$ estimates by 77 km/m.y. We find that median estimates for $U$ (204 m; median benchmark thickness) significantly added to the accretionary volume, $A$, for a total median range of material transfer from the subducting to overriding plate of 0.7–2.3 km$^3$/km/m.y. (Table 1). Conversely, our mapped erosion volume, $E$, which is an estimation of material transfer from the overriding to subducting plate, scaled to 0.7 km$^3$/km/m.y. Between these additive and subtractive processes, we find a median estimate of the mass balance of the frontal prism, $\Delta UP$, to be 0–1.6 km$^3$/km/m.y., which is balanced to slightly additive (Table 1). Sediment subduction scaled to
Figure 8. Model results for U restored thicknesses from Athy (1930) and geostatistical conditional simulations with various probability of occurrences (P90, P50 and P10). Restored thicknesses for every seismogram from Athy (1930; leftmost column) and geostatistical conditional simulation for each probability of occurrence (10%, 50% and 90%) shown for benchmark thicknesses of 115 m (top row), 204 m (middle row) and 370 m (lower row). Red dashed line approximates the trench. White dashed lines approximate major plate bending faults. Restored thickness scales shown to the right. Subduction direction is generally perpendicular to the trench (to the NE).

7.8 km³/km/m.y. (Table 1). An upslope view along the plate interface of these results shows the spatial distribution of material exchange (Figure 9).

4. Discussion

By demonstrating that thin incoming sediments, ~0.3–0.5 km thicknesses, variably accrete and/or under-plate along strike (Figures 2, 7 and 9), we augment the findings from IODP Exp. 344, which recovered incoming sediments stacked and thrust within the frontal prism (Harris et al., 2013a). Within our volume, the megathrust does not seem to cut into the pelagic sediments within ~10 km of the trench (Figure 2a), possibly due to their increased frictional strength relative to hemipelagic sediments at frontal prism pressures and temperatures (Kurzawski et al., 2016). Regardless, if even thin incoming hemipelagic sediments accrete, then the frontal prism here is an accretionary prism, as suggested by Bangs et al. (2016).
Similar, but with greater spacing and thickness, imbricately stacked thrust packages are imaged in the middle prism of the outer forearc (Figures 2 and 10; the middle prism is considered to be extending landward from the frontal prism to the inner/outer wedge transition, which is approximately consistent with the shelf break; Bangs et al., 2016; Edwards et al., 2018; Martínez-Loriente et al., 2019). Such thrust packages continue variably along strike many kilometers and have decreasing offsets landward, making them consistent with the accretionary model. To account for their greater spacing and thicknesses, Bangs et al. (2016)

| Sediment delivery (km³/km/m.y.) | Basal erosion (km³/km/m.y.) | Subduction (km³/km/m.y.) | Accretion (km³/km/m.y.) | ΔUpper plate (no magma; km³/km/m.y.) |
|---------------------------------|-----------------------------|--------------------------|-------------------------|-------------------------------------|
| Frontal Prism (this study)      |                             |                          |                         |                                     |
| 7–12                            | 0.7                         | 7.8                      |                         |                                     |
|                                 | A + Uαthy (*benchmark thickness) |                        |                         |                                     |
|                                 | 0.4 (*115 m)                 |                          |                         | −0.3                                |
|                                 | 0.7 (*204 m)                 |                          |                         | 0                                   |
|                                 | 2.4 (*370 m)                 |                          |                         | 1.7                                 |
|                                 | A + Uinv                     |                          |                         |                                     |
|                                 | 1.2 (*115 m)                 |                          |                         | 0.5                                 |
|                                 | 2.3 (*204 m)                 |                          |                         | 1.6                                 |
|                                 | 5.1 (*307 m)                 |                          |                         | 4.3                                 |
| Forearc (offshore Nicoya Peninsula; Vannucchi et al., 2003) |                             |                          |                         |                                     |
| 17                              | 105                          | 122                      | 0                       | −105                                |
| Forearc (offshore Osa Peninsula; Vannucchi et al., 2013) |                             |                          |                         |                                     |
| 17                              | 153                          | 122                      | 0                       | −153                                |

*Benchmark incoming thicknesses of 115 m, 204 m and 370 m (3σ below median, median, and 3σ above median of present-day incoming hemipelagic thicknesses) are used to estimate restored hemipelagic thickness deficits (U; accreted/underplated thicknesses not accounted for in A).

Figure 9. Upslope perspective of accretion and underplating (A + U; labeled accretion), basal erosion (E; labeled erosion) and sediment subduction (S; labeled bypass). Purples denote incoming sediment thicknesses. Inlines 2600 and 2050 shown for reference. Dash white line marks trench axis. White (accretion), gray (sediment subduction) and dark gray (basal erosion) shown overlaying megathrust horizon.
suggested that the passage of the Panama Triple Junction could have augmented greater trench fill than observed today. Landward of this accretionary front, Vannucchi et al. (2016) proposed an abrupt change to rapid basal erosion that drives rapid subsidence, which would capture sediments headed to the trench (a margin type they named “depositionary”). However, Edwards et al. (2018) presented evidence that rapid Early Pleistocene subsidence (∼1 km) extended across the entire outer forearc imaged by the 3D seismic reflection volume (including the accretionary portion of the middle prism), conflicting with the depositionary margin model that competing processes and megathrust conditions were partitioned at some distance from the trench. The findings from Edwards et al. (2018) that very little outer forearc subsidence (∼100 m) has occurred during the last ∼1.3 Ma parallels our findings that during the last ∼130 ka, the outermost ∼10 km of the outer forearc has been approximately balanced.

Basal erosion is co-located with the downthrown side of plate-bending faults under the frontal prism. If a high-angle bending fault is landward-dipping, basal erosion occurs down dip, whereas if it is seaward-dipping, then basal erosion occurs up dip (Figure 2a vs. Figures 2b–2d). Several lines of evidence suggest plate-bending faulting here originates landward of the trench, including the lack of horst and graben structures outboard of the trench and a lack of outer rise seismicity (DeShon et al., 2003). The nearest horst and graben structures seaward of the trench are >150 km along strike to the northwest (von Huene et al., 2000). Delayed plate-bending faulting may be related to the encroachment of the buoyant and thick Cocos Ridge (Figure 1), which seismic images show the dip angle of subduction to be initially shallow (Lucke & Arroyo, 2015). Delayed plate-bending faulting that drives basal erosion deviates from Hilde (1983), who proposed that horst and graben structures that are carried into the subduction system abrade the basal portions of the prism. Delayed plate-bending faulting negates any trench/graben filling sediments by offsetting the megathrust after subduction, rather than the seafloor before subduction. It is unlikely that abrading (i.e., high basal friction) is the driving mechanism, as basal erosion also occurs on seaward-dipping plate-bending faults where the nascent megathrust propagates to shallower depths (Figures 2a, 2e and 9). We also do not see evidence for a thick subduction channel, where an incremental migration of megathrusts up dip by hydrofracturing (i.e., very low basal friction) would overprint the landward dipping fabric of the base of the upper plate (von Huene et al., 2004).

Plate-bending faults maintain a consistent spacing of a few kilometers and have similar offsets (up to several hundred meters) at greater depths (Kirkpatrick et al., 2020), up to a significant plate-bending fault ∼30 km from the trench (∼6 km below seafloor; Figure 11), which is located below the inner/outer wedge transition (approximately the shelf break; Edwards et al., 2018). Plate-bending faults landward of ∼30 km from the trench can have larger offsets, with several up to > 1 km (Figure 10). This potential step change increase in offsets coincides with the transition to a more steeply dipping megathrust below the shelf/inner wedge (∼9°–20°; Figure 10). Intraplate seismicity in the region increases at and beyond ∼30 km landward of the trench as well, within the seismogenic zone (DeShon et al., 2003). If plate-bending fault offsets are proportional to the volumes of basal erosion, then our basal erosion rates observed under the frontal prism (up to ∼10 km landward of the trench) extends across the middle prism, up to ∼30 km landward of the trench,

Figure 10. Model of trench perpendicular length of megathrust across forearc crust. First 30 km dip is constrained by three-dimensional depth converted seismic reflection volume, remaining length of interface is constrained by 35 km thickness of crust and 19° plate dip (shown with red line; DeShon et al., 2003). Seismogenic zone is highlighted in red and frontal prism in purple. Tick marks along figure edges denote depth and length in kilometers.
covering ~1/3-1/4 of the forearc system (Figures 10–11). Previous basal erosion estimates along the southern Costa Rican margin, which used the proxies of shelf and slope subsidence recorded across both the inner and middle prisms and the deflection of the trench axis landward relative to the trench axis offshore the Nicoya Peninsula (Figure 1), are >150 km$^3$/km/m.y. (Vannucchi et al., 2013), much greater than our findings of 0.7 km$^3$/km/m.y. To get to greater forearc basal erosion rate estimates, the margin may require either greater basal erosion occurring landward of the middle prism, such as from increased subducting plate bending and faulting landward of the inner/outer wedge transition, or from episodic processes (Clift et al., 2005) that are not documented within our ~130 ka time window. However, new studies propose other models that may invalidate greater basal erosion rates estimated from proxies, such as the proxy of outer forearc subsidence, which may instead be linked to subducting topography (Edwards et al., 2018) and/or plate kinematic changes (Edwards et al., 2018; Regalla et al., 2013), and the proxy of trench axis landward deflection, which may instead be linked to significant forearc-arc-backarc shortening (Morell et al., 2019).

5. Conclusions

Our in-situ assessment of material transfer within the first 10 km of subduction offshore the Osa Peninsula, Costa Rica shows that even thin subducting sediments (<0.5 km thicknesses) are variably accreted along strike and that active plate-bending faulting under the upper plate variably drives both underplating on its upthrown-side and basal erosion on its downthrown-side. Our in-situ budget finds an approximately balanced to slowly growing outermost forearc (within ~10 km of the trench) that facilitates wholesale sediment subduction of pelagic sediments. We find that the frontal prism mass balance budget possibly extends
across the middle prism (up to ∼30 km landward of the trench axis), covering ∼1/3–1/4 of the forearc system. These results differ significantly from previous mass balance estimates of material transfer based on simple proxies of upper plate vertical motions and geomorphic features and support more recent studies that do not find evidence of large forearc net mass loss.

Data Availability Statement

Datasets for this research are available through Kluesner et al., 2013 and Bangs et al., 2014 and are hosted in the data repository at http://www.marine-geo.org/collections/#/collection/Seismic#dataSets, with identifier https://doi.org/10.1594/IEDA/500204. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Acknowledgments

This work was supported by US National Science Foundation grants OCE-0851380 and OCE-1154635. We thank the crew of the R/V Marcus G. Langseth and scientists on board for the collection of the 3D seismic reflection data. We also thank dGB Earth Sciences for free access to OpenTest Pro and ArkCLS and Earthworks Reservoir for free access to the multi-point stochastic inversion commercial plugin.

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