A recent phase of accretion along the southern Costa Rican subduction zone

Nathan L. Bangs¹, K. D. McIntosh¹, E. A. Silver², J. W. Kluesner² and César R. Ranero³

¹*Institute for Geophysics, University of Texas at Austin, PRC 196, 10100 Burnet Rd., Austin, TX*

²*Earth Sciences Department, University of California at Santa Cruz, Santa Cruz, CA*

³*Barcelona Center for Subsurface Imaging. ICREA at CSIC. ICM, Barcelona, Spain*

Corresponding author: Nathan Bangs, nathan@ig.utexas.edu

ABSTRACT

In 2011 we acquired a 3D seismic reflection volume across the Costa Rica margin NW of the Osa Peninsula to investigate the complex structure and the development of the seismogenic zone within the Costa Rica subduction zone in the vicinity of recent International Ocean Drilling Program (IODP) drilling. In contrast to previous interpretations, these newly acquired seismic images show that the margin wedge is composed of a layered fabric that is consistent with clastic sediments, similar to materials recovered from IODP drilling, that have been thrust and thickened into thrust-bounded folded sequences. These structures are consistent with a balanced sequence that has been frontally accreted in the context of an accretionary model. We interpret these sequences as sediment originally deposited on the subducting crust in a trench basin created by the southward migration of the Cocos-Nazca-Caribbean triple junction, and accreted

during recent margin subduction that also accelerated with passage of the triple junction. The margin is composed of relatively rapidly accreted sediment that was added to the margin during a phase of accretion within the last ~ 5 Ma that was probably preceded throughout the Neogene by periods of non-accretion or erosion.

1.0 Introduction

The Costa Rica margin is one among about half of the world's subduction zones that have been interpreted to be erosive (von Huene and Scholl, 1991; Clift and Vannucchi, 2004). These are convergent margins where trench sediment and upper plate material is tectonically removed and carried deeper into the subduction zone and ultimately brought into the mantle. The subduction erosion mechanism is globally significant because it can transport large volumes of upper plate material into the seismogenic zone, affecting frictional properties and hydrogeology and thus seismogenesis (von Huene, et al, 2004; Saffer and Tobin, 2011), and it can return continental crust material to the mantle (von Huene, et al, 2004). von Huene and Scholl (1991) estimate the volume of subducted material globally over the last 100 m.y. (1/2 to 2/3 due to tectonic erosion of upper plate materials), is sufficiently large to have offset the volume of igneous rocks that have been added to the Earth's terrestrial crust, resulting in zero net growth of Earth's continents since the Cretaceous.

Subduction erosion has primarily been interpreted and quantified from observation of large-scale, long-term margin subsidence (e.g. Clift and Vannucchi, 2004; von Huene and Scholl, 1991) and landward retreat of margins inferred from old volcanic arc rocks that formed 100s of km landward of the coast but now lie along coastal ranges or even under the continental slope (e.g. Yañez et al., 2001). Subsidence is presumed to be the result of basal erosion;

however, outer forearc subsidence can also be caused by changes in subduction geometry following changes in plate kinematics (e.g. Regalla et al., 2013).

Subduction erosion is also interpreted to generate distinctive margin structures (e.g. Ranero and von Huene, 2000, von Huene and Ranero, 2003); however, distinguishing erosional and accretionary margins from structural observations has been surprisingly difficult, despite the large difference in tectonic processes associated with subduction erosion and accretion (Ranero et al. 2007). This difficulty is in part due to the inherent loss of the geologic record with tectonic erosion, and structures within a margin might also be inherited from a geological process that is not presently operating and structures may not be representative of current tectonics along the margin. However, difficulty identifying tectonic erosion and accretion also stems from the inherent uncertainties with imaging and characterizing complex deformational structures associated with subduction zones.

The Middle America Trench convergent margin is believed to be a tectonically eroding margin (Ranero and von Huene. 2000; Ranero et al., 2000; Vannucchi et al., 2003, 2004, 2013) with both subsidence and structural observations supporting erosion. IODP Expedition 334 drilling samples from the mid slope of the Costa Rica margin NW of the Osa peninsula indicate margin subsidence from near shoreline to intermediate (800 – 1200 m) water depths during the last 3 m.y. of subduction history (Vannucchi, et al., 2013). Costa Rica has been interpreted as one of the most aggressively eroding margins, with estimates of average rates between 100 – 150 km³/m.y./km (compared to long-term average rates of 30 km³/m.y./km typical of erosive margins estimated by von Huene and Scholl, 1991), and with recent periods of extreme erosion estimated to be as much as 1,690 km³/m.y./km, near the Osa Peninsula, resulting from upper plate thinning due to tectonic erosion of 50 – 60 km of a preexisting forearc (Vannucchi et al., 2013).

Structural details that reveal tectonic erosion and associated processes, however, are more equivocal and have been long debated along the Costa Rica margin. Using 3D seismic images, Shipley et al. (1992) argued that landward dipping structures within the frontal ~20 km of the margin wedge (the wedge shaped body of material that lies beneath the sediment cover of the margin slope) offshore the Nicoya peninsula are the manifestation of thrusting and thickening of material transferred from the subducting plate in an accretionary context. In contrast, von Huene et al. (2000) noted that weak and discontinuous reflectivity of the margin wedge imaged in a grid of 2D profiles and seafloor relief of regional swath bathymetry maps across Costa Rica and a segment of Nicaragua is consistent with fractured and faulted crystalline basement and not consistent with accreted sediments or out-of-sequence-thrusts typically associated with accretionary wedges. They argued that the seismic structure and high seismic velocities (3.5 – 5.5 km/s) of the margin wedge (Christeson et al., 1999) are more consistent with fractured crystalline rocks of the Nicoya complex and that the margin wedge is crystalline basement extending beneath the mid slope rather than an accretionary body. Drilling near the Osa peninsula has recovered well-cemented sediments with carbonate and zeolite cements that could explain the relatively high-velocity margin wedge along the 3D transect (4.0 – 4.8 km/s; Stavenhagen et al. 1998); however, the interpretation of the margin wedge remains equivocal due to poor imaging of highly deformed structures.

In 2011 we acquired a 3D seismic reflection volume across an 11 x 55 km² area of the Costa Rica margin, NW of the Osa Peninsula using the R/V Langseth to image the complex deformational structures of the subduction-zone's upper plate and the geometry and reflective characteristics of the subduction megathrust (Figure 1). The new 3D seismic reflection data show

the complex structure of the upper-plate's margin wedge in sufficient detail that it is now clear that at least the frontal 30-40 km of the margin wedge offshore Osa Peninsula has a layered structure consistent with clastic sediments that have been shortened and thickened by thrust faulting and folding in a fashion often seen in accretionary wedges. Consequently these structures raise the question: What are the structural manifestations of an erosional margin, and are they found along the southeastern Costa Rica margin, or are structures along this margin more consistent with a phase of accretion? Furthermore, can the tectonic history of this margin only be correctly interpreted with detail possible with high quality 3D images?

2. Structural elements of an erosive margin

Three key structural elements within erosive margins have been linked to erosional tectonics. First, a regional unconformity at the base of the margin-slope sediment cover is believed to form by gradual subsidence from near sea level associated with tectonic erosion. In Costa Rica, offshore Osa Peninsula drilling through the regional unconformity during Expeditions 334 and 344 recovered sands deposited in near shore conditions (< 100 m water depth) at the base of the slope cover sequence, near the top of the margin wedge (Vannucchi, et al., 2013; Expedition 344 Scientists, 2014). These sediments are currently at 600 m depth. If this is a surf-zone related unconformity between the base of the slope cover and the margin wedge, it is a structure that implies broad subsidence along all of Costa Rica and from beneath the shelf to the lower slope. It is a distinctive manifestation of subsidence potentially due to basal erosion. Similar unconformities are also seen beneath continental slopes of Nicaragua and Guatemala (Ranero et al., 2007), and along the Peru, north Chile and Japan Trench margins, all of which are thought to be erosive over a long time span (von Huene and Lallemand, 1990).

Secondly, structural evidence for tectonic erosion comes from studies of the basic structural elements within the margin, which reveal whether margins are largely the exposed remains of the eroded margin core or accreted materials, largely sediment, transferred from the subducting to the overriding plate (von Huene and Scholl, 1991). The Middle America Trench convergent margin is made up of three principal elements (Ranero, et al., 2007): 1) a comparatively high-seismic-velocity margin wedge (velocities of 4.5-5.5 km/s were measured within the margin wedge ~ 80 km to the NW of our survey; Ye et al, 1998; Stavenhagen et al. 1998) that forms the bulk of the margin structure, 2) an overlying slope cover sequence, and 3) a small frontal sediment prism with internal structures consistent with thrust faulting (< 10 km wide) that abuts the margin wedge (in this paper we interpret the “frontal prism” as an accretionary wedge as discussed below; Figure 2). This structural configuration has been interpreted as having been formed by tectonic erosion processes (Ranero et al., 2007). On the basis of the relatively high seismic velocity and the discontinuous seismic reflections within the margin wedge, the margin wedge has been interpreted to be a truncated (steeply tapered toward the trench) piece of upper-plate crystalline basement rocks formed by Nicoya Ophiolite Complex or crystalline and lithified rocks of the Osa Peninsula terranes (the Osa Igneous Complex and Osa Melange; Buchs et al., 2009) (Hinz et al., 1996; Ranero and von Huene, 2000; Ranero, et al., 2007). Ranero et al. (2007) infer that the core of the margin was exposed after landward retreat due to tectonic erosion along the base and seaward edge of the margin, consistent with structures associated with other erosional margins, e.g. Chile north of ~32°S (von Huene and Ranero, 2003, Ranero et al., 2006), the Aleutians (von Huene et al., 2012), Peru (von Huene and Lallemand, 1990; Clift et al., 2003), Ecuador (Sage et al., 2006). Along the Costa Rica margin, the margin wedge is buried beneath ~ 1 km of slope cover that extends from the shelf to the lower slope. Not

surprisingly erosional margins typically have thin trench sequences (< 500 m) that provide little material for frontal accretion and are prone to be completely subducted. Drilling along the Nicoya peninsula confirmed all but ~ 7 m of the ~ 500 m section is currently subducting (Kimura et al., 1997). A small frontal prism was interpreted as consistent with a lack of accretion because of ODP Leg 170 drilling near the Nicoya peninsula within the frontal prism that shows it is composed largely re-worked slope sediment derived from the shelf and deposited along the lower most trench slope (Kimura et al., 1997; Silver et al., 2000).

Thirdly, systems of normal faults that extend deep into the margin wedge are also a distinctive structure associated with tectonic erosion (von Huene et al., 2004). Normal faults are interpreted as a result of extension of the upper plate following removal of material along the base of the upper plate that leads to collapse of the margin. Normal faults through the margin wedge can be activated during interseismic periods when interseismic stress relaxation is sufficiently extreme (Wang et al., 2010). Normal faulting cutting into the top of the wedge has been mapped under the slope along the Nicaragua and Costa Rica margins (McIntosh et al., 1993; Ranero and von Huene, 2000) and is regionally collocated with the unconformity described above (Ranero et al., 2007).

3. Seismic data volume

We acquired the 3D seismic volume to the NW of the Osa Peninsula where the flank of the Cocos Ridge and Quepos guyot (produced by interaction of Galapagos Hot Spot and the Cocos-Nazca spreading center) are currently subducting (Figure 1). We used two 52.4 L (3200 in^3) airgun arrays fired alternately (each array was fired every 50 m) as our source, and recorded the arrivals on four six-km-long streamers towed with 150 m separation. We used a Kirchhoff

3D prestack depth migration algorithm and multiple iterations of 3D velocity analysis to produce high-quality, detailed images of the margin structure. Acquisition and processing details are described in Bangs et al. (2015). These results produce the best images to date of the complex structure of the overriding plate across the Costa Rican margin.

4. The 3D Seismic Structure NW of the Osa peninsula

4.1 Regional Unconformity

Figure 2 show an unconformity that separates the overlying slope cover from the underlying margin wedge sequence. The unconformity is evident from both the high reflection amplitude and terminations of underlying reflections at this horizon that are common throughout the volume (e.g. Figure 2). We can trace a high-amplitude reflection and the overlying slope cover sequence from beneath the shelf to the lower slope, although the strong seismic reflections or stratal relationships that define the unconformity are not seen everywhere. Along the lower slope the position of the unconformity is equivocal because of the greater conformity and low impedance contrast between the slope cover and margin wedge sequences. The seaward termination of the unconformity is also equivocal because of the greater deformation and disruption of more seaward structures. The unconformity is also recognizable from higher velocities and changes in seismic frequencies due to attenuation below the unconformity. By any measure the unconformity is identifiable and extends broadly across the shelf and slope.

4.2 Structural Elements within the Margin

The slope cover sequence is well imaged, and stratal relationships within it are generally interpretable throughout the volume. Despite moderate folding and fault displacement, slope sediment sequences are easily recognizable as continuous strata that can be correlated laterally

for 5 – 10 km (Figures 2-7) in both dip and strike directions. Drilling during Expeditions 334 and 344 penetrated these sequences at Sites 1380, 1379 (10 km southeast of the 3D volume) and 1413 (Figures 1b & 5), and recovered layered sequences of clastic sediments ranging in lithology from sands and sandstones to fine grained clays and claystones, with ages from recent to late Pleistocene (Vannucchi, et al., 2013; Expedition 344 Scientists, 2014; Figure 5).

Along most of the 3D volume, the slope cover has been folded and faulted due to a series of underlying discrete landward dipping thrust faults with ~ 3-8 km spacing (fault spacing broadens progressively landward; Figures 2, - 5; see Bangs et al., 2015 for more details). Layers within the slope cover are not continuous across the entire sequence due to onlap and downlap of sequences following the development of the folds within the underlying margin wedge indicating the recent activity of these structures. However, through the middle of the volume (Figure 5), folding and faulting is not as intense as other parts of the volume and provides an interpretable window for the slope basin stratigraphy and insight into the recent deformation. Here, the deepest slope sequence (a in Figure 5) lies along the mid to lower slope and pinches out against the underlying margin wedge on the landward side (a_1), and against margin wedge sequences on the seaward side (a_2). On the basis of the geometry of the strata, the strata in the middle of this slope basin have been displaced vertically above the crest of the fold, inverting the center of the basin above the fold (Figure 6). The sequence (b) onlaps against the uplifted underlying sequence (a) and margin wedge, while the shallower sequence (c) extends farther seaward to the seaward edge of the basin (at c_2), where it onlaps the folded slope cover and underlying margin wedge. Assuming slope cover sequences (a-c) were deposited nearly horizontally, fault displacements within the underlying margin wedge can be estimated approximately (Figure 6).

All of these relationships reveal recent deformation that is consistent with the horizontal shortening and uplift along thrust ramps within the underlying margin wedge and slope cover.

4.2.1 Margin Wedge

The largest improvements to images along this transect are within the margin wedge. Despite persistent imaging difficulties due to reflector disruptions and discontinuities previously noted by von Huene et al. (2000), there is now sufficient reflection coherency and continuity in 3D to reveal the detailed relationships between the layered fabric within the margin wedge, faulting, and the overlying sediment strata, that was not previously interpretable in 2D sections. Packets of parallel seismic reflections are semi-continuous, closely-spaced, and generally have a landward dip (Figure 3). The layered sequences are folded into ridges with 3 - 8 km separation (A- D in Figures 3, 4, 5, 7& 8) that roughly parallel the margin and are bounded by thrust faults. These folds generally increase in width from the lower slope (A) to the upper slope (D). The folds and faults form a fault-propagation fold geometry with fold ramps parallel to layers near the base of the fault, and with overturned layers within the fold that become perpendicular to fault planes near the top of the fault (e.g. C in Figures 3 & 7).

Collectively these reflective horizons within the margin wedge appear as a series of imbricately stacked layered sequences (Figures 3-8). Faults bounding these folds generally have less displacement toward the trench (e.g. Figure 5), and, where we have been able to measure thicknesses of layers within thrust sequences reasonably well, there is a general thinning of layers (e.g. from ~ 1.8 km thick near (C) to ~ 1.2 km near (A) in Figure 7; similarly in Figure 3). We also note that the geometry of the fault propagation folds within the margin wedge parallels the tilted and folded geometry of the overlying slope cover indicating continuous shortening and thickening of the margin wedge during deposition of the slope cover.

The fault-propagation folds are sufficiently coherent that their broad variations as folded units are traceable along strike. The horizontal depth slice shown in Figure 4 intersects the margin wedge from its seaward extent near the base of the lower slope (near A) across the shelf break and shelf. The horizontal depth slice shows that the margin wedge beneath the slope is a series of synclines and anticlines with a slight plunge to the SE (as indicated in the horizontal slices by some terminations of the anticlines to the ESE, e.g. near D, and some termination of the synclines to the WNW, between B and C), with most of the folds extending across the entire 11 km of the 3D volume, and with some merging along strike into a broader fold (c.f. A and B along the crossline direction in Figure 4). The dip is slightly oblique to the convergence direction, which is parallel to the inline profiles (Figure 1).

4.2.2 Accretionary wedge (frontal prism)

A small (< 10 km) frontal accretionary wedge along the toe of the slope forms from imbricate stacks of sediments scraped off of the incoming trench sequence with some slope cover material deposited on top of the accretionary wedge (Figures 2 & 9). This wedge was interpreted as a “frontal prism” because it was believed to be composed entirely of sediments shed from the shelf and slope and incorporated into the frontal wedge rather than sediments scraped off the subducting plate. In these new profiles, we see approximately half of the 400 - 450 m of sediment in the trench is accreted into the wedge and half lies beneath the decollement. The bulk of the accretionary wedge is accreted sediment and not slope cover sequences, which is consistent with observations of repeated trench sediment sequences recovered from drilling at Site 1412 ~ 10 km to the SE of the 3D volume (Expedition 344 Scientists, 2013).

4.3 Normal Faults

Sets of intersecting normal faults are pervasive throughout the slope cover sequences across the shelf and down the mid to lower slope (e.g. Figure 5; see Bangs et al. (2015) and Kluesner et al. (2013) for more examples). Normal faults typically have ~200 m spacing; however, they have very minimal offset < 25 m and can only be seen well in close up view (Figure 5a & 5b). A primary set has orientations generally NNE-SSW across the shelf (F-1 and F-2 in Figure 5b), and mid-slope, and possibly onto areas of the lower slope; however, they become increasingly more difficult to correctly identify in the disrupted lower slope strata. Other sets of normal faults and ENE-WSW (F-3 and F-4 in Figure 5b) have less offset and are harder to identify. The key observation within the 3D volume and not previously seen in 2D images is the shallow extent of the normal faults (Figure 5a). Nearly all of the normal faults penetrate no deeper than the slope cover sequences and few extend deeper than the top of the margin wedge (e.g. Figure 5a). The frontal ~20-30 km of the margin wedge at least is dominated by thrust or reverse faults only (Bangs et al., 2015). Normal faults across the shelf and upper slope are associated with regional stresses (Malinverno et al., 2015), but many of the normal faults along the mid to upper slope are shallow penetrating faults possibly caused by shallow extension above folds within the underlying margin wedge.

5.0 Tectonic history of the margin wedge

While structures associated with tectonic erosion, such as the regional unconformity, minimal trench sediment, and observations of normal faults, are certainly evident within the 3D volume, much of what appears in the 3D volume is actually inconsistent with structures associated with tectonic erosion. There is still considerable complexity beyond our resolution,

but two of the three key structures associated with tectonic erosion do not fit a model of continuous Neogene tectonic erosion.

First and foremost, the margin wedge beneath the slope and at least some portion of the outer shelf is made up of layered sequences that have been shortened by thrust faulting and folding and have been imbricately stacked (Figures 2-8). The long laterally continuous layering suggests these are clastic sediments; this is also consistent with sediment recovered during Expedition 344 at Site 1380. Drilling penetrated the entire Pleistocene slope sequence and an additional ~ 300 m into the Pliocene margin wedge, where coring recovered silts and clays, with occasional thin sand layers (Expedition 344 Scientists, 2013). We presume that these sediments were initially deposited on a stable basement in order for these clastic sediment layers to develop their broad (10's of km) lateral continuity shown in Figures 3-5, 7 & 8 and were then later subjected to compressional deformation and shortening. Based on the larger fault offsets and tighter folds of the margin wedge relative to the overlying slope cover (Figure 7), an extensive amount of shortening began prior to the development of the unconformity and slope cover sedimentation. Furthermore the coincident fold geometry of the slope cover suggests margin wedge shortening continued during slope sequence deposition and remains active currently, although activity in the last ~1 m.y. has declined and recent deformation is minimal. We presume the predominance of thrusting is in response to consistently strong basal tractions from the subducting plate and generally inconsistent with extension and collapse of the margin from basal erosion (e.g. von Huene et al. 2004). The general decrease in thrust fault displacement from landward to seaward is consistent with its growth as a coulomb wedge by frontal accretion as it maintained its critical wedge taper (Davis et al., 1983). The consequence of the compressional deformation is substantial shortening of up to at least 30 % (e.g. Figure 7) into a continuous

series of stacked sequences with no apparent breaks or discontinuities that might be associated with temporal changes from compressional to an extensional stress regime.

Secondly, there is an extensive normal fault system within the 3D volume; however, these faults are limited to the slope cover, exhibit small offsets, and rarely extend into the margin wedge. They are not through-going normal faults that extend through the overriding plate and do not appear to be associated with collapse of the margin. In fact, the margin wedge faults are almost all thrust faults consistent with continuous compression and there are no indications of periods of extension. Shallow normal faults are not unusual with accretionary systems as observed with the Nankai accretionary margin where uplift within the inner wedge leads to shallow extension (Moore et al., 2013); however, extension is broadly distributed across the Costa Rica margin and not localized along a splay fault system as it is in Nankai.

There is also evidence that at least the frontal 30 km of the margin-wedge structure within the 3D volume is more consistent with accretion during its formation than erosion. The structure of the slope cover is even clearer than the structures of the underlying margin wedge and it reveals recent tectonic history of the margin wedge. Since the development of the unconformity, the slope cover sequence records a history of uplift of the frontal sequence. The 3D images show a layered sequence currently being thrust under the downslope edge of the margin wedge. We interpret this thrust ramp (lower thrust in Figures 5 & 6) as the cause of uplift of the seaward most corner of the margin wedge. We note that the amount of uplift is approximately equal to the thickness of the section beneath the lower interpreted thrust fault and follows the approximate geometry of the thrust fault ramp. This coincident geometry is compelling evidence that deformation arises from uplift during thrusting along this ramp, which created the slope basin (between b1 and c2). Uplift by thrusting along this ramp began early in

the history of slope cover deposition, it continued episodically throughout the basin history, creating Ridge A/B in Figure 5, and it appears to continue today. These observations are consistent with an accretionary context.

6.0 Massive Erosion or episodic Accretion?

The critical new observation is that the margin wedge beneath the slope, imaged in the Costa Rica 3D seismic data, has long, continuous layers of clastic sediment and is not composed of crystalline basement. This observation must be accommodated in an interpretation of the tectonic history of this margin. Two likely end-member scenarios fit most of the observations.

The margin wedge could be composed of forearc basin sediments that were deposited on a stable forearc basement and have subsequently been thrust and thickened into the margin wedge. If this is the case, the forearc basement that formed the stable depositional platform would prevent or severely impede thrusting and thickening of any overlying forearc basin sediment unless the basement was thinned or removed, presumably by massive tectonic erosion (Vannucchi et al., 2013). If this happens by piecemeal erosion of a forearc basement in a fashion consistent with erosional models (von Huene et al., 2004), then it must have happened without producing many of the expected structures associated with tectonic erosion described above such as through-going normal faults. There is also no evidence for an older forearc basement, or other indications of tectonic disruption of the margin wedge during an episode of massive tectonic erosion of an underlying forearc basement. An alternative to piecemeal erosion of a forearc basement, tectonic erosion could have happened by rapid wholesale removal of a forearc basement, but again there is no structural evidence within the margin wedge for what most likely would be an even more massive tectonic disruption.

As an alternative to erosion, the margin wedge could be sediment that was recently and rapidly deposited in the trench and subsequently accreted. There is currently little sediment (~400 m) on the incoming plate or deposited in the trench along the 3D survey area (Figures 1 & 9; Bangs et al., 2015). This may be in large part due to the rapid subduction and the presence of the Cocos Ridge, which has created a very shallow trench. The current geometry is more favorable to sediment deposition on the shelf and slope rather than in the trench. While there currently is some frontal accretion, accretion is minimal because of the lack of trench sediment. However, past plate geometry was much more conducive to rapid sediment deposition and thick sediment accumulation in the trench and lower slope. As described by MacMillan et al., (2004), the southward migration of the Cocos-Nazca-Caribbean triple junction ~ 4.5 Ma (Figure 1a) resulted in ~ 2 km of subsidence of the trench and overriding plate. This occurred as the Panama-Coiba fracture zone system migrated south and the thick crust of the Nazca plate, possibly generated in the Miocene at the Samba Ridge (Morell, 2015) and associated with the fracture zones and the Coiba Ridge, was replaced with thinner crust. Passing of the triple junction also initiated rapid orthogonal convergence. A large sediment supply to the trench following rapid deposition of the trench basin created by the passing triple junction may have created an opportunity for frontal accretion of the trench sediments. Thick sediment sequences are currently deposited on the subducting crust in the Manila trench offshore Taiwan and accreted in thrust sequences with a geometry similar to the margin wedge thrust sequences in Costa Rica (Lester et al., 2013). The accretionary wedge along the lower slope of Taiwan margin also has a seaward decreasing fold spacing, which we see in Costa Rica (e.g. Figure 7b), and a seaward thinning of the incoming sediment section due to the geometry of the top of subducting ocean crust, which we speculate existed during accretion in southern Costa Rica prior to the approach of the Cocos Ridge.

Despite the lack of significant incoming sediment now, the fact that we see long continuous sequences within the margin wedge is consistent with an accretionary context. Furthermore, the observation that margin wedge stratigraphic sequences are progressively thinner toward the trench is consistent with thinning of more recent incoming trench sediment sequences. We speculate that a thick incoming section existed since the passage of the triple junction, which led to a brief (~ 4.5 to ~2.0 Ma) episode of accretion along this margin. After the passage of the triple junction and the Coiba ridge, the trench basin became elevated with the advance of the Cocos Ridge, trench sedimentation declined, and trench sequences progressively thinned causing accretion to progressively cease almost completely to what is actively accreting at the toe now. This may have occurred simultaneously with trench retreat from Cocos Ridge collision that Fisher et al (2004) attribute to inner forearc shortening along the Fila Costeña thrust belt.

What remains unclear for an accretionary scenario is how the unconformity developed and how the uplift and subsidence associated with the unconformity fit into an accretionary context. Dynamic changes in plate boundary geometry (Regalla et al., 2013) are a possible mechanism for generating a broad unconformity. Uplift and subsidence could also be a result of aseismic ridge or seamount subduction; however, we have no direct evidence for subduction of any specific feature. Local aseismic ridge subduction is certainly possible or maybe even expected within the 3D volume depending on the downdip continuity of the incoming bathymetric ridges on the Cocos plate (e.g. the Quepos ridge in Figure 1). A ridge subducted 2 Ma would have passed completely through our survey area by ~1.5 Ma and be difficult to detect now, but it would only have local uplift or erosional effects and any resulting unconformity would be localized. It could explain the unconformity within the 3D volume, but then it would not be part of a broader unconformity related to tectonic erosion. With limited age control and

poor along strike correlation it is unclear if there is a genetic link between the unconformities across broad regions of the Middle America margin or if localized unconformities due to aseismic ridge subduction are more likely than a broader regional unconformity. In any case, the structure within the southern Costa Rica margin seen in 3D images is consistent with a period of margin accretion. This relatively brief phase of accretion has constructed a proportionally large volume along the margin in a relatively brief period of the margin's history. This observation implies that the recent phase of accretion was not sustained throughout the Neogene, and the history of the margin likely includes other periods of accretion, non-accretion or erosion.

It remains to be seen whether there are more areas of accretion along the Middle America margin, or if this is a localized characteristic of southern Costa Rica. Erosion along Costa Rica broadly may be localized and limited to effects of aseismic ridge or seamount subduction rather than broadly extensive. Answering this question will require high-quality images like the 3D images shown here, to provide a more complete picture of the Middle America convergent margin structure.

7.0 Acknowledgments

We thank Don Fisher for helpful comments on an earlier version of this manuscript. We appreciate EPSL reviewers Kristin Morell and Lisa McNeill for providing constructive and thorough reviews that helped the manuscript greatly. We thank Paradigm Geophysical for Geodepth and Echos software packages used for data processing and interpretation. We thank Repsol in the Woodlands, TX for assistance with data processing and generous contributions of computer resources for 3D prestack depth migration. This work was supported by National Science Foundation grant numbers 1435386 and 1457221. This is UTIG contribution # _____.

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FIGURE CAPTIONS

Figure 1a. Regional map of the Central America margin showing the Leg 170 and Leg 205 drill
sites near the Nicoya Peninsula, the 3D survey area near the Osa Peninsula, and the IODP
Expedition 334 and 344 drilling transect. Also shown is the intersection of the Coiba fracture
zone and the trench through time (black line) with approximated ages (white circles) (from

MacMillan et al. 2004). Note that the trench Coiba FZ. formed the Cocos-Nazca-Caribbean plate triple junction until the formation of the Panama FZ ~ 2 Ma. 1b.) Bathymetric map showing 3D seismic survey (red rectangle) location offshore of Osa Peninsula, Costa Rica. Stars locate two recent thrust earthquakes. Orange and green circles mark the Expedition 334 and 344 drill sites respectively.

Figure 2 Perspective overview of the 3D volume to show the major margin structures. The main elements of the upper plate are: 1) an accretionary wedge (equivalent to the frontal prism in Ranero et al., 2000); 2) the margin wedge, which is the wedge shaped body extending from beneath the shelf, across the shelf break to the base of the slope (white arrow) and merges gradually into the accretionary wedge; 3) the slope cover sediments that have been shed from the margin and deposited on top of the margin wedge.

Figure 3. 3D perspective view of the margin wedge across the mid-slope region. Black line marks the unconformity separating the slope cover from the underlying margin wedge. Ridges A-C (also shown in Figures 4,5,7 & 8) are fault-propagation folds that form thrust ridges. Blue dashed lines marks the folded and faulted layered fabric within the margin. Red lines show thrust faults separating thrust ridges. Note the continuity of layering along strike, the structural continuity between thrust ridges of the margin wedge and overlying slope cover, and the progressive decrease in shortening between the margin wedge and younger and younger slope cover. Also note the absence of normal faults or extensional structures through the margin wedge.

Figure 4. Chair cut of the 3D volume with a depth slice through the margin wedge from the lower slope to beneath the shelf showing the along strike continuity of folded stratigraphic layers. Stratigraphic layers (blue dashed lines) are folded within thrust ridges (A-C; shown in profile Figures 3,5,7 & 8) that extend along strike across the 11 km width of the 3D volume and plunge slightly to the NE (into the page). An unconformity (black line) separates the slope cover from the underlying margin wedge. The main faults (red lines) are thrust faults and separate thrust ridges (e.g. near C) or intersect ridges (near D)

Figure 5. a) Enlargement of slope cover sequences along line 2320 showing small offset normal faults across the upper slope. Note the small offsets (<25 m) and the shallow depth extent of these faults. The normal faults terminate above the top of the margin wedge. These normal faults are typical of all of the normal faults observed within the 3D volume. b) Three-dimensional perspective view of the normal slope cover normal faults showing their orientation. Faults are recognizable in both profile and horizontal depth slices. These faults form two sets of conjugate normal fault pairs oriented ENE-WSW (F-1&2) and ENE-WSW (F-3&4). Note the shallow unconformity within the slope cover is not the regional unconformity at the top of the margin wedge. The normal faults terminate below the shallow unconformity and above the top of the margin wedge.

c) Inline 2320 (dip line) through the middle of the 3D volume showing the relationship between thrusting within the margin wedge and slope sediment sequence stratigraphy (see text and Figure 6 for interpretation). Box shows locations of enlargements shown in a) and b).

d) Interpreted section shown in c). Slope cover sequences (a-c) are separated by light blue lines. An unconformity separating slope cover from the margin wedge produces a large amplitude

seismic reflection (black line). Thrust sequences are bounded by faults (red lines). Dashed blue lines show continuous, deformed stratigraphic horizons. Sediment ages are approximated by projection from roughly equivalent sequences in nearby Expedition 344 drill sites.

Figure 6. Schematic cartoon of kinematic movement within the margin wedge along Inline 2320 (Figure 5) to show a possible deformation history within the margin wedge. Movement is based on the constraint that slope cover stratigraphic sequences (a-c) were deposited approximately horizontally and subsequently deformed by shortening within the margin wedge (brown shading) by slip along discrete thrusts (red lines). Dashed blue lines are stratigraphic horizons within the margin wedge. Light blue lines are stratigraphic horizons within the slope cover (yellow shading). Red arrows show slip displacement necessary to produce a nearly horizontal seafloor deposition surface. Note that slip is distributed across the margin wedge, although it has been limited to the lower slope in recent years.

Figure 7. Two profiles from the mid-slope region showing the slope cover, margin wedge, and subducting crust through the middle of the 3D volume and through the SE edge of the volume. Blue dashed lines follow stratigraphic horizons within the slope cover and underlying margin wedge. Red lines are two faults that show the extent of slip is substantially larger within the older, deeper, and more landward portions of the margin wedge. The margin wedge stratigraphic layers thin toward the trench. Folds within the margin wedge shorten toward the trench, which is typical throughout the 3D volume. Percentages are the amount of shortening along the respective horizons assuming they formed straight lines initially. Arrows show layering within the margin wedge that is interpreted as layered clastic sediment.

599

600 Figure 8.

601 Three-dimensional perspective view of thrust and fold sequences within the margin wedge.

602 Letters show folds corresponding to those shown in Figures 3,4,5, & 7. Folds B and C are folded

603 in both dip and strike directions as indicated by the dipping strata within the thrust sequence

604 (between blue lines).

605

606 Figure 9.

607 Seismic Inline 2098 (with interpreted section) from the trench, across the deformation front, the

608 accretionary wedge and the seaward most part of the margin wedge. Note the decollement

609 initiates midway down the ~400 m thick incoming trench section. Consequently, ~ 200 m

610 sections are accreted at the toe to form the frontal accretionary wedge. Red lines follow thrust

611 faults and the decollement. Blue lines follow stratigraphic horizons. Green line follows the top of

612 the ocean crust.

613

Figure 1a

Figure 1b

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9