



## Abstract

The eastern part of the oceanic Cocos Plate presents a heterogeneous crustal structure due to diverse origins and ages as well as plate-hot spot interactions which originated the Cocos Ridge, a structure that converges with the Caribbean Plate in south-eastern Costa Rica. The complex structure of the oceanic plate directly influences the dynamics and geometry of the subduction zone along the Middle American Trench. In this paper an integrated interpretation of the slab geometry is presented based on three-dimensional density modeling of combined satellite and surface gravity data, constrained by available geophysical and geological data and seismological information obtained from local networks. The results show the continuation of steep subduction geometry from the Nicaraguan margin into Northwestern Costa Rica, followed by a moderate dipping slab under the Central Cordillera toward the end of the Central American Volcanic Arc. To the southeast end of the volcanic arc, our preferred model shows a steep, coherent slab that extends up to the landward projection of the Panama Fracture Zone. Overall, a gradual change in the depth of the intraplate seismicity is observed, reaching 220 km in the northwestern part, and becoming progressively shallower toward the southeast, where it reaches a terminal depth of 75 km. The changes in the terminal depth of the observed seismicity correlate with the increased density in the modeled slab. The absence of intermediate depth intraplate seismicity in the south-eastern section and the higher densities for the subducted slab in this area, support a model in which dehydration reactions in the subducted slab cease at a shallower depth, originating an anhydrous and thus aseismic slab.

## 1 Introduction

The southeastern end of the Middle American convergent margin is characterized by the segmentation of the subducting oceanic lithosphere and a heterogeneous crustal basement on the overriding plate. The oceanic Cocos Plate is composed of crustal

## SED

7, 1941–1977, 2015

### Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





created at the East Pacific Rise (EPR) and at the Cocos–Nazca Spreading Center (CNS) are present offshore Costa Rica (Barckhausen et al., 2001). The latter shows direct influence on the Galapagos Hot Spot, adding to the heterogeneous nature of the plate and resulting in three different morphotectonic domains recognized by von Huene et al. (2000): a northwestern section with smooth relief, which contrasts with a central seamount province outlining a Rough–Smooth Boundary, and a southeastern domain characterized by the Cocos Ridge. These morphotectonic domains correlate with significant changes in Moho depth for the Cocos Plate from 8 to 10 km for the EPR section (Sallarès et al., 2001), to 10 to 12 km for the seamount province (Walther, 2003; von Huene et al., 2000) and a maximum of 21 km for the crust of the Cocos Ridge (Sallarès et al., 2003).

The arrival of the Cocos Ridge to the trench and its effects on the subduction zone are still controversial subjects. Arrival time estimations range from 5–1 Ma, but the latest researches place the event at the early Pleistocene (Vannucchi et al., 2013) or late Pliocene (Morell et al., 2014). Hypothesis about the tectonic style include collision (LaFemina et al., 2009), flat subduction (Kolarsky et al., 1995), and steep angle subduction (Arroyo et al., 2003; Dzierma et al., 2011). Flat subduction is still commonly referred to explain forearc shortening, regional uplift, and Pleistocene decrease and termination of volcanic activity in southeastern Costa Rica (e.g. Fisher et al., 2004; Sitchler et al., 2007). However, tectonic reconstructions (MacMillan et al., 2004; Lonsdale, 2005) and recent results from local ocean drilling (Vannucchi et al., 2013) require further tectonic events – besides the arrival of the Cocos Ridge to the trench – to explain the evolution of this region.

Convergence rates are variable for the different domains with  $85 \text{ mm yr}^{-1}$  for the northwestern EPR section and  $90 \text{ mm yr}^{-1}$  for the Cocos Ridge domain (DeMets et al., 1994). Furthermore, oblique subduction along the MAT appears to take place in the region with a  $10^\circ$  counterclockwise difference in convergence direction relative to a trench normal vector (DeMets, 2001).

**Costa Rican  
subduction zone**O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



# SED

7, 1941–1977, 2015

## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Subduction related volcanism is present in the form of the Central American Volcanic Arc (CAVA), which begins at latitude 15° N and continues 1100 km parallel to the MAT, ending at the Irazu-Turrialba volcanic complex in central Costa Rica (Fig. 1). At this point, the CAVA is interrupted by a 190 km gap in the Quaternary volcanism in the Talamanca region. This gap ends at the Baru volcano, the only major Quaternary volcanic vent located in the eastern edge of the isthmus.

Seismic tomography studies were carried out in Nicaragua and Northwestern Costa Rica by Syracuse et al. (2008), DeShon et al. (2006), and in Central Costa Rica by Arroyo et al. (2009), Dinc et al. (2010); likewise, a comprehensive study of the Costa Rican subduction zone was performed by Husen et al. (2003a). A previous work on the geometry of the subduction zone based on earthquake hypocenters was published by Protti et al. (1994), who describe a segmentation of the subducting slab in Northwestern Costa Rica and interpret a change in its dipping angle as a sharp contortion. Moreover, those authors propose a termination of the deep intraslab seismicity in southeastern Costa Rica and interpret it as a shallow underthrusting of the Cocos Ridge. However, Husen et al. (2003a) observe a gradual decrease in the maximum depth of the intraslab seismicity from northern to southern Costa Rica. More recently, Dzierma et al. (2011) modeled a steeply dipping slab to a depth of approximately 70 to 100 km based on receiver function analysis for the northwestern part of the Talamanca region. Furthermore, local earthquake data from a temporal network show evidence of a steep slab down to ~ 70 km in southern Costa Rica (Arroyo, 2001; Arroyo et al., 2003).

Eastward from the PFZ, the boundary between the Caribbean and the Nazca plates in southern Panama is marked by a segment of the trench, which according to Lonsdale and Klitgord (1978), has transitioned since the Late Miocene to a strike-slip boundary after a period of 18 to 20 Ma of subduction. However, de Boer et al. (1988) propose a reactivation of the subduction 3.4 to 5.3 Ma ago, and consider the existence of a recent low angle subduction.

The Caribbean coast of Costa Rica appears segmented into a northwestern section extending to the Hess Escarpment and the slope of the Nicaragua Rise, and a south-eastern section defined by the North Panama Deformed Belt. According to Marshall et al. (2000), this fold-and-thrust belt is linked with the MAT through the Central Costa Rica Deformed Belt, a diffuse fault zone outlining the western boundary of the Panama Microplate.

### 3 Data

#### 3.1 Seismological data

Recent seismological studies (DeShon et al., 2003, 2006; Arroyo et al., 2009) have been used to constrain the slab geometry of the gravity model down to depths of ~ 40–50 km. In order to constrain the deepest parts of the model, earthquakes from four different data bases were used or relocated in this study, as will be described in Sect. 5.1: the catalogue from Husen et al. (2003a); the catalogue from the National Seismological Network (RSN in Spanish); the catalogue from the Arenal and Miravalles Seismological and Vulcanological Observatory (OSIVAM in Spanish); and the Boruca network catalogue.

The earthquake catalogue from Husen et al. (2003a) consists of nearly 4000 events recorded by the two permanent networks in Costa Rica, RSN and Costa Rican Vulcanological and Seismological Observatory at the National University (OVSI-CORI-UNA in Spanish). The data were used to derive a tomographic model of the whole country.

The RSN records seismic activity since the early 1980s, mainly with short-period, vertical-component stations up to 2010 (Fig. 3), when new broadband equipment was acquired. This research contemplates the 1991 (year when digital recording started) – 2004 period. Since the RSN network increased its number of stations in Central Costa Rica during that period, two additional local catalogues were examined in order to add to the amount of well-constrained seismicity toward the northwest and southeast.

SED

7, 1941–1977, 2015

### Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Costa Rican  
subduction zone**O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



tial model available is the EIGEN-6C (Shako et al., 2014), which additionally includes data from the LAGEOS and GOCE satellite missions. However, for purposes of consistency with regional lithospheric density modeling carried out for Central America (Lücke, 2014), and to resolve the shorter wavelengths obtained from a higher degree, the local density model was based on EGM2008.

In order to assess which individual dataset was adequate for the density modeling, different anomalies were calculated and compared with surface station data. A detailed analysis of a data subset for Costa Rica was carried out by Köther et al. (2012). To provide a dataset consistent with previous solid Earth modeling (Lücke et al., 2010; Lücke, 2014), in this study, the Bouguer anomaly was calculated from the gravity disturbance. The gravity disturbance is calculated for a given point on the Earth's surface; or the satellite derived gravity disturbance data used for this study, the downward continuation takes place between the orbit and the surface of the Earth. Li and Götze (2001) have discussed the use of gravity anomalies and disturbances in solid Earth modeling. Onshore, the effect of the Bouguer plate was subtracted from the value of the gravity disturbance, using the orthometric height at the topographic level as station elevation, which results in Bouguer anomaly values. For offshore data, values equivalent to the free air anomaly were obtained for stations located on the ocean surface. Figure 2 shows a compilation of the Bouguer anomaly onshore and the free air anomaly offshore for the study area.

## 4 Methods

### 4.1 Earthquake relocation

An analysis of relocation uncertainties is included in the tomography earthquake dataset from Husen et al. (2003a). The 3-D  $P$  wave velocity model from Husen et al. (2003a) and the minimum 1-D model for Costa Rica from Quintero and Kissling (2001), were used to relocate RSN, Boruca, and OSIVAM databases with the non-



dimensions to aid the interactive modeling. Recently, a regional model of Central America (Lücke, 2014) was achieved using 47 cross sections constructed from the Yucatan Peninsula to eastern Panama. This model is described in Sect. 5.2. From the regional density model, a subset was defined and further detailed by taking into account the  
5 constraining seismological data prepared for this research and the previously available geophysical data. For this area, 24 cross sections were considered and modeled in detail with emphasis on the subducting slab and the integration with the seismological results for Costa Rica.

In this study, the lithospheric density distribution was modeled in three dimensions  
10 for Costa Rica, to a depth of 200 km. Previous investigations by Tassara et al. (2006) achieved a 3-D lithospheric density model for the South American subduction zone through a similar method, from which the slab geometry and the density distribution were modeled to a depth of 400 km.

## 5 Results

### 15 5.1 Seismology

Analysis of probabilistic earthquake relocation uncertainties in 3-D velocity models (Husen et al., 2003b; Husen and Smith, 2004) show that, in general, hypocenter locations with less than six *P* wave observations are poorly constrained, even with a good azimuthal distribution of stations (coverage gap < 180°). In addition, focal depths are  
20 not well constrained without a station located within a distance similar to the focal depth, regardless of the total number of observations. These criteria were used in this study to select the datasets from the initial seismic catalogues. In total, 1145 events were selected, controlled, and relocated.

The RSN, OSIVAM, and Boruca datasets were relocated and classified into four  
25 quality classes using NonLinLoc. The 3-D *P* wave velocity model of Costa Rica from Husen et al. (2003a) was used for the first two datasets. However, the relocation of the

---

**Costa Rican  
subduction zone**

O. H. Lücke and  
I. G. Arroyo

---

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Boruca dataset with that velocity model was hindered because several Boruca-Panama stations are located out of its borders (Fig. 3). Instead, the minimum 1-D,  $P$  wave model for Costa Rica from Quintero and Kissling (2001) was used to relocate the events from southeastern Costa Rica. This 1-D model was chosen because it served as an initial model for the tomography by Husen et al. (2003a). In all three cases, only  $P$  wave readings were considered.

The October-Tree importance sampling algorithm included in NonLinLoc was used. This algorithm gives an accurate, efficient and complete mapping of the earthquake location PDF in the 3-D space. The October-Tree method uses recursive subdivision and sampling of cells in 3-D space to generate a cascade of sampled cells, where the density of those follows the PDF values of the cell center, leading to a higher density of cells in the areas of higher PDF (A. Lomax and A. Curtis, Oct\_tree importance sampling algorithm, available at <http://alomax.free.fr/nlloc/>, 2014).

Large differences between the maximum likelihood and the expectation hypocenter locations can result from an ill-conditioned location problem (Lomax et al., 2000). Husen and Smith (2004) found that a difference greater than 0.5 km between both hypocenter estimations cause large uncertainties of several kilometers in epicenter and focal depth. Numerous scatterplots were investigated in order to confirm this observation for our datasets. Further following Husen and Smith (2004), the average of the three axes of the 68 % confidence ellipsoid was taken into account to refine location quality. Figure 3 shows example scatterplots for each quality class used in this investigation.

Earthquakes in class D have an rms larger than 0.5 s and were not used. Events with location quality A, with well-defined PDFs, have differences between maximum-likelihood and expectation hypocenters of 0.5 km and lower, and maximum location uncertainties of 4 km. Differences above 0.5 km but under 3 km between both hypocenter estimations, and average uncertainties lower than 4 km define quality B. Their epicenters and focal depths are still relatively well defined. Earthquakes with a maximum rms of 0.5 s and differences in hypocenter estimations higher than 3 km are classified as

## SED

7, 1941–1977, 2015

### Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



C. They show large location uncertainties, of which the confidence ellipsoid is a poor approximation. From all the relocated datasets, 65 % of the events have quality A, 16 % quality B, and 19 % quality C.

## 5.2 Regional scale slab geometry as a reference density model

5 The geometry of the Central American subduction zone was modeled on a regional scale to serve as a reference model for the Costa Rican subset. In order to constrain the regional geometry of the subduction zone, hypocenters from the catalogue of the Central American Seismic Center (CASC) were taken into account. The CASC catalogue includes earthquakes with magnitudes above 3 and recorded by at least two  
10 national networks. The selected events have a minimum of 8 readings, a coverage gap of less than  $250^\circ$ , a maximum rms of 0.5 s and Gaussian uncertainties lower than 10 km in depth. Additionally, earthquake hypocenters from the catalogue of the National Earthquake Information Center of the US Geological Survey were considered to constrain the regional slab structure for depths greater than 110 km, which were not  
15 resolved by the CASC network.

The regional scale model is intended to provide the three-dimensional general framework for the detailed interpretation of the Costa Rican subduction segment presented here. This is necessary in order to eliminate edge effects in the 3-D modeling by extending the model outside of the area of interest up to a point in which the effect of  
20 the edges of the model is no longer significant for the modeled gravity in the area of interest. The regional scale model considers the segmentation of the Central American crustal basement and the regional Moho structure for the Caribbean Plate published by Lücke (2014). The geometry obtained from the regional model shows a uniformly dipping slab for the segment between  $91$  and  $86^\circ$  W. The subduction angle steepens  
25 for the southern Nicaragua segment and carries over to Northwestern Costa Rica. The largest heterogeneities in the geometry of the subduction zone are observed in the segment located eastward of the  $86^\circ$  W longitude and will be described in detail for the local scale model for the area.

## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 5.3 Detailed density model for the Costa Rican subduction zone

Using the regional density model of Central America (Lücke, 2014) as reference, a subset with enhanced detail was modeled for Costa Rica considering the better quality and availability of geophysical constraints. Offshore Costa Rica, the Cocos Plate was modeled with a density of  $2.80 \text{ Mg m}^{-3}$  for the crust,  $3.3 \text{ Mg m}^{-3}$  for the upper mantle and  $3.34 \text{ Mg m}^{-3}$  for the asthenospheric mantle. Density changes in the subducting slab were also modeled as an increase in density due to dehydration of the mantle and crust. The density of the crust of the subducting slab was constrained by petrological modeling by Bousquet et al. (2005), considering the lithostatic pressure on the plate interface and the temperature from thermal modeling by Peacock et al. (2005). A homogenous upper mantle with a density of  $3.32 \text{ Mg m}^{-3}$  and a  $3.34 \text{ Mg m}^{-3}$  asthenospheric mantle, were modeled for the overriding plate, setting the lithosphere-asthenosphere boundary at a depth between 75 and 85 km. The crustal basement for the Caribbean Plate in Costa Rica was divided into a southeastern block with a density of  $2.90 \text{ Mg m}^{-3}$  considering an overall basaltic composition of the basement related to the Caribbean Large Igneous Province (Hoernle et al., 2004), and a northwestern block with a density of  $3.00 \text{ Mg m}^{-3}$  for serpentinized ultramafic material related to the Mesquito Composite Oceanic Terrane (Baumgartner et al., 2008). Densities in the upper crust of the Caribbean Plate are variable and were modeled depending on local structures, such as predominant fore- and back-arc sedimentary basins ( $2.4\text{--}2.55 \text{ Mg m}^{-3}$ ), volcanic infill along the arc ( $2.6\text{--}2.7 \text{ Mg m}^{-3}$ ) and dioritoid intrusions in southeastern Costa Rica ( $2.75 \text{ Mg m}^{-3}$ ). The initial density of the crustal units of the Caribbean Plate was constrained by  $V_p$  values and the correlation with local geology and regional tectonic models. Lücke (2014) discusses in detail the constraints of the densities used for the 3-D model.

## SED

7, 1941–1977, 2015

### Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 5.4 Local integrated interpretation of slab geometry for Costa Rica

In order to achieve a three-dimensional interpretation of the geometry of the subducting slab, the earthquake hypocenter results were integrated into the density model. By means of three-dimensional visualization and projection of results onto two-dimensional cross sections (Fig. 4), the density model was modified interactively to achieve the best fit with the measured gravity data by considering the structure outlined by the seismicity. The joint interpretation allowed constraining the overall geometry of the density model, while simultaneously accounting for a more precise determination of the plate interface.

The results of this joint interpretation are shown in Figs. 4–6. Considerable changes in slab dip as well as in the density distribution of the subducted oceanic crust are observed. The Cocos Plate segmentation observed offshore Costa Rica (von Huene et al., 2000) carries over to the structure of the subducted slab. The northwestern section of the Cocos Plate (originated from the EPR and CNS) was modeled with a thickness of 6–8 km and subducts at a  $14^\circ$  angle to a depth of 30 km from which the slab dip steepens to a  $44^\circ$  angle to a depth of 80 km and finally  $71^\circ$  to the terminal depth of the model at 200 km (Fig. 4a). For Central Costa Rica, the slab dip transitions from a  $15^\circ$  angle for the section between the trench and a depth of 30 km,  $40^\circ$  to a depth of 80 km, and a relatively shallow angle for the final section with  $58^\circ$  to a depth of 200 km (Fig. 4b). This shallower section of the slab extends to the southwest, toward the end of the Quaternary volcanic arc, and corresponds to the subduction of the seamount province located between the Fisher Seamount and the Quepos Plateau on the oceanic plate.

At the southeastern end of the Quaternary volcanic arc, a change in the dip angle of the slab beneath 80 km depth is perceived, increasing from  $40$  to  $60^\circ$  (Fig. 4c). When observed as plotted depth contours (Fig. 5), this change in slab dip takes place 20 km to the northwest of the NE–SW axis formed by the Irazu and Turrialba volcanoes. This also coincides with the location of a feature in the gravity field, which separates

### Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





(LAB) modeled between 70 and 80 km, although it is located much deeper than the local LAB in the northwestern part of Costa Rica, between 130 and 160 km.

## 6 Discussion

The origin of the Wadati-Benioff seismicity has been a subject of discussion since its discovery, because at depths greater than  $\sim 30$  km, the pressure should prevent brittle or frictional processes. It is commonly believed that the intermediate-depth seismicity is enabled by slab dehydration (Kirby et al., 1996; Hacker et al., 2003). As the slab sinks, metamorphic reactions liberate fluids from hydrous phases. Dehydration increases pore pressure, thus reducing normal stress enough to bring the system into the brittle regime. Yet, the exact relationship between dehydration and earthquake nucleation is still not well understood. Earthquakes could be generated by dehydration embrittlement, creating new faults (Zhang et al., 2004) or reactivating pre-existing weak zones (Peacock, 2001), depending on where hydration occurred (Ranero et al., 2005).

Hydration of the downgoing slab seems to take place mainly near the trench, where water percolation and mineral alteration occur at extensional faulting in the crust and in the upper few kilometers of the mantle (Kirby et al., 1996), or even deeper, 15–30 km into the mantle (Peacock, 2001; Ranero et al., 2003). This bend faulting has been imaged offshore Middle America by high-resolution seafloor mapping, near-vertical reflection lines, and outer-rise seismicity (Hinz et al., 1996; von Huene et al., 2000; Ranero et al., 2005; Grevemeyer et al., 2007; Lefeldt and Grevemeyer, 2007).

Ranero et al. (2005) statistically compared the strike of bending-related faults in the oceanic plate with that of the nodal planes of intermediate-depth earthquakes ( $> 70$  km) along different segments of the Middle America and Chile subduction zones. The similarity they found supports previous studies from other subduction zones of the world (Jiao et al., 2000), attributing most of the intraslab seismicity to the reactivation of faults, rather than to the formation of new ones at the planes of maximum shear within the slab. Ranero et al. (2005) propose that seismicity starts between 60–80 km

# SED

7, 1941–1977, 2015

## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





with a geometry similar to that observed for the Nicaraguan section of the MAT (Syracuse et al., 2008). Between the northwestern part of the volcanic arc and the central region of Costa Rica, a change in slab dip is observed. For the central part, results show slab dip angles between 40 and 50° compatible with images from previous local earthquake tomographies by Arroyo et al. (2009) and Husen et al. (2003a). This section of the slab corresponds to the subduction of the seamount province of the Cocos Plate (von Huene et al., 2000). The northwestern and central regions are separated by a transition zone in which the slab dip beneath 40 km decreases from 75 to 45° (Fig. 5). A previous study from Protti et al. (1994) introduces a sharp contortion of the slab to accommodate this change in subduction angle. In the model presented here, however, the change in dip is observed but is achieved through a transition zone, by considering oblique subduction of the seamount section. For this region, the trend of the slab contours changes from trench parallel for the northwestern region, to a 17° offset from trench parallel for the transition zone. This change in the strike of the depth contours is consistent with the section of the margin where oblique subduction occurs, located to the southeast of the Rough–Smooth Boundary (Fig. 5).

Southeast of the Central mountain range, seismicity within a steep slab is observed to a depth of approximately 75 km, extending southwest to Uvita. The presence of a steeply subducting slab for this region is supported by seismic tomography results from Dinc et al. (2010), to a depth of 40 km and receiver functions results by Dzierma et al. (2011), where a steeply subducting slab is imaged to a depth of 100 km.

The results from the Boruca seismic network in southeastern Costa Rica (Arroyo, 2001) show a subducting slab dipping at a 50° angle for the Dulce Gulf region to a depth of 70 km (Figs. 4c and 5). These results, along with the receiver functions and seismic tomography data immediately to the northwest, were included as constraints into the density model. Regarding the slab geometry, the results from the three-dimensional density modeling agree with the seismological observations. Furthermore, the density model shows no large scale lateral segmentation of the subducting oceanic lithosphere for the area in which a gap in the seismicity is observed (inland of the Coronado Bay,

## SED

7, 1941–1977, 2015

### Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Fig. 5). This suggests that a continuous subducting slab is present for the margin from Central Costa Rica to the Panama Fracture Zone.

Lateral changes in the density structure of the slab are limited to the section of the subducted oceanic crust with a density of  $3.15 \text{ Mg m}^{-3}$  (Fig. 4). Taking into account the maximum depth of the seismicity, this three-dimensional polyhedron was modeled to represent the zone in which dehydration reactions occur, contrasting with a  $3.3 \text{ Mg m}^{-3}$  zone for an anhydrous slab. From the joint seismological-density modeling and interpretation, an overall trend is observed in which the maximum depth for the dehydrating oceanic crust decreases toward the southeast, starting at 160 km in the northwest, following with 125 km for the Central region and reaching a depth of 75 km for southeastern Costa Rica. This trend may be related to the extent of hydration of the upper mantle in the subducting oceanic plate in the form of serpentinization. Petrological models by Husen et al. (2003a) place the boundary in which the subducted crust transforms to anhydrous eclogite at 100 km for southeastern Costa Rica and at 130 km for Northwestern Costa Rica, thus showing a similar trend. The depth of the  $3.15\text{--}3.3 \text{ Mg m}^{-3}$  boundary in the subducted crust of the density model shows a good correlation between the termination of the seismicity and the depth (Fig. 4).

Within the conceptual model from Ranero et al. (2005), the degree of bend faulting occurring in the outer rise would directly influence the characteristics of the intraslab seismicity by determining both the extent of hydration through serpentinization of the upper mantle, and the segmentation of the slab by means of fragile deformation. In this sense, the Costa-Rican subduction zone provides a wide spectrum of environments with different degrees of bending-related faulting.

A smooth segment in which the oceanic plate presents pervasive, trench-parallel, bending-related faulting, subducts off Central America and Northwestern Costa Rica (Hinz et al., 1996; von Huene et al., 2000; Ranero et al., 2003; Grevemeyer et al., 2007; Lefeldt and Grevemeyer, 2007). In the Central Pacific (seamount) segment, however, the thicker oceanic crust promotes a smaller outer rise and less-developed faulting (von Huene et al., 2000), while the Cocos Ridge section in the southeast lacks

## SED

7, 1941–1977, 2015

### Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion













## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Barckhausen, U., Ranero, C. R., von Huene, R., Cande, S. C., and Roeser, H. A.: Revised tectonic boundaries in the Cocos Plate off Costa Rica: implications for the segmentation of the convergent margin and for plate tectonic models, *J. Geophys. Res.*, 106, 19207–19229, 2001.

5 Baumgartner, P., Kennet, F., Bandini, A., Girault, F., and Cruz, D.: Upper Triassic to Cretaceous radiolaria from Nicaragua and northern Costa Rica – the Mesquito composite oceanic terrane, *Ophioliti*, 33, 1–19, 2008.

10 Bindeman, I. N., Eiler, J. M., Yogodzinski, G. M., Tatsumi, Y., Stern, C. R., Grove, T. L., Portnyagin, M., Hoernle, K., and Danyushevsky, L. V.: Oxygen isotope evidence for slab melting in modern and ancient subduction zones, *Earth Planet. Sc. Lett.*, 235, 480–496, doi:10.1016/j.epsl.2005.04.014, 2005.

Bousquet, R., Goffé, B., deCapitani, C., Chopin, C., Le Pichon, X., and Henry, P.: Comment on “Subduction factory: 1. Theoretical mineralogy, densities, seismic wave speeds, and H<sub>2</sub>O contents” by Bradley, R. Hacker, Geoffrey, A. Abers, and Simon, M. Peacock, *J. Geophys. Res.*, 110, 3, doi:10.1029/2004JB003450, 2005.

15 Coffinn, M. F., Gahaga, L. M., and Lawyer, L. A.: Present-day Plate Boundary Digital Data Compilation, Technical Report, 5, University of Texas Institute for Geophysics, Austin Texas USA, 1998.

20 de Boer, J. Z., Defant, M. J., Stewart, R. H., Restrepo, J. F., Clark, L. F., and Ramirez, A. H.: Quaternary calc-alkaline volcanism in western Panama: regional variation and implication for the plate tectonic framework, *J. S. Am. Earth Sci.*, 1, 275–293, 1988.

de Boer, J. Z., Defant, M. J., Stewart, R. H., and Bellon, H.: Evidence for active subduction below western Panama, *Geology*, 24, 649–652, 1991.

25 DeMets, C.: 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, doi:10.1029/2001GL013518, 2001.

DeMets, C., Gordon, R. G., Argus, D. F., and Stein, S.: Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, 21, 2191–2194, doi:10.1029/94gl02118, 1994.

30 DeMets, C., Gordon, R. G., and Argus, D. F.: Geologically current plate motions, *Geophys. J. Int.*, 181, 1–80, doi:10.1111/j.1365-246X.2009.04491.x, 2010.

**Costa Rican  
subduction zone**O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- DeShon, H. R., Schwartz, S. Y., Bilek, S. L., Dorman, L. M., Gonzalez, V., Protti, J. M., Flueh, E. R., and Dixon, T. H.: Seismogenic zone structure of the southern Middle America Trench, Costa Rica, *J. Geophys. Res.*, 108, 2491, doi:10.1029/2002JB002294, 2003.
- DeShon, H. R., Schwartz, S. Y., Newman, A. V., González, V., Protti, M., Dorman, L. R. M., Dixon, T. H., Sampson, D. E., and Flueh, E. R.: Seismogenic zone structure beneath the Nicoya Peninsula, Costa Rica, from three-dimensional local earthquake P- and S-wave tomography, *Geophys. J. Int.*, 164, 109–124, doi:10.1111/j.1365-246X.2005.02809.x, 2006.
- Dinc, A. N., Koulakov, I., Thorwart, M., Rabbel, W., Flueh, E., Arroyo, I. G., Taylor, W., and Alvarado, G. E.: 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, 2010.
- Drummond, M. S., Bordelon, M., de Boer, J. Z., Defant, M. J., Bellon, H., and Feigenson, M. D.: Igneous petrogenesis and tectonic setting of plutonic and volcanic rocks of the Cordillera de Talamanca, Costa Rica-Panama, Central American arc, *Am. J. Sci.*, 295, 875–919, 1995.
- Dzierma, Y., Thorwart, M. M., Rabbel, W., Flueh, E. R., Alvarado, G. E., and Mora, M. M.: Imaging crustal structure in south central Costa Rica with receiver functions, *Geochem. Geophys. Geosy.*, 11, Q08S26, doi:10.1029/2009GC002936, 2010.
- Dzierma, Y., Rabbel, W., Thorwart, M. M., Flueh, E. R., Mora, M. M., and Alvarado, G. E.: The steeply subducting edge of the Cocos Ridge: evidence from receiver functions beneath the northern Talamanca Range, south-central Costa Rica, *Geochem. Geophys. Geosy.*, 12, Q04S30, doi:10.1029/2010GC003477, 2011.
- Fisher, D. M., Gardner, T. W., Sak, P. B., Sanchez, J. D., Murphy, K., and Vannucchi, P.: Active thrusting in the inner forearc of an erosive convergent margin, Pacific coast, Costa Rica, *Tectonics*, 23, TC2007, doi:10.1029/2002tc001464, 2004.
- Gazel, E., Hoernle, K., Carr, M. J., Herzberg, C., Saginor, I., van den Bogaard, P., Hauff, F., Feigenson, M., and Swisher III, C.: Plume-subduction interaction in southern Central America: mantle upwelling and slab melting, *Lithos*, 121, 117–134, doi:10.1016/j.lithos.2010.10.008, 2011.
- Götze, H. J.: Ein numerisches Verfahren zur Berechnung der gravimetrischen und magnetischen Feldgrößen für dreidimensionale Modellkörper, PhD Thesis, TU Clausthal, Clausthal, Germany, 1976.
- Götze, H. J. and Lahmeyer, B.: Application of three-dimensional interactive modeling in gravity and magnetics, *Geophysics*, 53, 1096–1108, 1988.

## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Grevemeyer, I., Ranero, C. R., Flueh, E. R., Kläschen, D., and Bialas, J.: Passive and active seismological study of bending-related faulting and mantle serpentinization at the Middle America trench, *Earth Planet. Sc. Lett.*, 258, 528–542, doi:10.1016/j.epsl.2007.04.013, 2007.
- 5 Hacker, B. R., Peacock, S. M., Abers, G. A., and Holloway, S. D.: Subduction factory 2: Are intermediate depth earthquakes in subducting slabs linked to metamorphic dehydration reactions?, *J. Geophys. Res.*, 108, 2030, doi:10.1029/2001jb001129, 2003.
- Hey, R.: Tectonic evolution of the Cocos-Nazca spreading center, *Geol. Soc. Am. Bull.*, 88, 1404–1420, 1977.
- 10 Hinz, K. R., von Huene, R., Ranero, C. R., and PACOMARWorkingGroup: Tectonic structure of the convergent margin offshore Costa Rica from multichannel seismic reflection data, *Tectonics*, 15, 54–66, 1996.
- Hoernle, K., Hauff, F., and van den Bogaard, P.: A 70 m.y. history (139–69 Ma) for the Caribbean large igneous province, *Geology*, 32, 697–700, 2004.
- 15 Hoernle, K., Abt, D., Fischer, K., Nichols, H., Hauff, F., Abers, G. A., van den Bogaard, P., Heydolph, K., Alvarado, G. E., Protti, M., and Strauch, W.: Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua, *Nature*, 451, 1094–1097, doi:10.1038/nature06550, 2008.
- Husen, S. and Smith, R. B.: Probabilistic earthquake relocation in three-dimensional velocity models for the Yellowstone National Park region, Wyoming, *B. Seismol. Soc. Am.*, 94, 880–896, 2004.
- 20 Husen, S., Quintero, R., Kissling, E., and Hacker, B.: Subduction-zone structure and magmatic processes beneath Costa Rica constrained by local earthquake tomography and petrological modelling, *Geophys. J. Int.*, 155, 11–32, doi:10.1046/j.1365-246X.2003.01984.x, 2003a.
- 25 Husen, S., Kissling, E., Deischmann, N., Wiemer, S., Giardini, D., and Baer, M.: Probabilistic earthquake location in complex three-dimensional velocity models: application to Switzerland, *J. Geophys. Res.*, 108, 2077, doi:10.1029/2002jb001778, 2003b.
- Jiao, W., Silver, P. G., Fei, Y., and Prewitt, C. T.: Do intermediate- and deep-focus earthquakes occur on preexisting weak zones? An examination of the Tonga subduction zone, *J. Geophys. Res.*, 105, 125–138, 2000.
- 30 Johnston, S. T. and Thorkelson, D. J.: Cocos-Nazca slab window beneath Central America, *Earth Planet. Sc. Lett.*, 146, 465–474, 1997.

## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Kirby, S., Engdahl, E. R., and Denlinger, R.: Intermediate-depth intraslab earthquakes and arc volcanism as physical expressions of crustal and uppermost mantle metamorphism in subducting slabs, in: Subduction: Top to Bottom: American Geophysical Union Geophysical Monograph 96, edited by: Bebout, G. E., Scholl, D. W., Kirby, S. H., and Platt, J. P., American Geophysical Union, Washington D.C., USA, 195–214, doi:10.1029/GM096, 1996.

Kolarsky, R. A., Mann, P., and Montero, W.: Island arc response to shallow subduction of the Cocos Ridge, Costa Rica, *Geol. S. Am. S.*, 295, 235–262, doi:10.1130/SPE295-p235, 1995.

Köther, N., Götze, H. J., Gutknecht, B. D., Jahr, T., Jentzsch, G., Lücke, O. H., Mahatsente, R., Sharma, R., and Zeumann, S.: The seismically active Andean and Central American margins: Can satellite gravity map lithospheric structures?, *J. of Geodyn.*, 59–60, 207–218, 2012

LaFemina, P., Dixon, T. H., Govers, R., Norabuena, E., Turner, H., Saballos, A., Mattioli, G., Protti, M., and Strauch, W.: Fore-arc motion and Cocos Ridge collision in Central America, *Geochem. Geophys. Geosy.*, 10, 21, doi:10.1029/2008gc002181, 2009.

Lefeldt, M. and Grevemeyer, I.: Centroid depth and mechanism of trench-outer rise earthquakes, *Geophys. J. Int.*, 172, 240–251, doi:10.1111/j.1365-246X.2007.03616.x 2007.

Li, X. and Götze, H.-J.: Ellipsoid, geoid, gravity, geodesy, and geophysics, *Geophysics*, 66, 1660–1668, 2001.

Lomax, A., Virieux, J., Volant, P., and Berge-Thierry, C.: Probabilistic earthquake location in 3D and layered models, in: *Advances in Seismic Event Location*, edited by: Thurber, C. H., and Rabinowitz, N., Kluwer Academic Publishers, Dordrecht, the Netherlands, 101–134, 2000

Lonsdale, P.: Creation of the Cocos and Nazca plates by fission of the Farallon plate, *Tectonophysics*, 404, 237–264, doi:10.1016/j.tecto.2005.05.011, 2005.

Lonsdale, P. and Klitgord, K. D.: Structure and tectonic history of the eastern Panama Basin, *B. Seismol. Soc. Am.*, 89, 981–999, 1978.

Lücke, O. H.: Moho structure of Central America based on three-dimensional lithospheric density modelling of satellite-derived gravity data, *Int. J. Earth Sci.*, 103, 1733–1745, doi:10.1007/s00531-012-0787-y, 2014.

Lücke, O. H., Götze, H.-J., and Alvarado, G. E.: A constrained 3D density model of the upper crust from gravity data interpretation for central Costa Rica, *International Journal of Geophysics*, 2010, 1–9, doi:10.1155/2010/860902, 2010.

MacMillan, I., Gans, P. B., and Alvarado, G.: Middle Miocene to present plate tectonic history of the southern Central American Volcanic Arc, *Tectonophysics*, 392, 325–348, doi:10.1016/j.tecto.2004.04.014, 2004.

## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Marshall, J. S., Fisher, D. M., and Gardner, T. W.: Central Costa Rica deformed belt: kinematics of diffuse faulting across the western Panama block, *Tectonics*, 19, 468–492, 2000.
- Morell, K. D., Kirby, E., Fisher, D. M., and van Soest, M.: Geomorphic and exhumational response of the Central American Volcanic Arc to Cocos Ridge subduction, *J. Geophys. Res.*, 117, B04409, doi:10.1029/2011jb008969, 2014.
- Moser, T. J., van Eck, T., and Nolet, G.: Hypocenter determination in strongly heterogeneous Earth models using the shortest path method, *J. Geophys. Res.*, 97, 6563–6572, doi:10.1029/91jb03176, 1992.
- Pavlis, N. K., Holmes, S. A., Kenyon, S. C., and Factor, J. K.: The development and evaluation of the Earth Gravitational Model 2008 (EGM2008), *J. Geophys. Res.-Sol. Ea.*, 117, B04406, doi:10.1029/2011jb008916, 2012.
- Peacock, S. M.: Are the lower planes of double seismic zones caused by serpentine dehydration in subducting oceanic mantle?, *Geology*, 29, 299–302, 2001.
- Peacock, S. M., vanKeken, P. E., Holloway, S. D., Hacker, B. R., Abers, G. A., and Fergason, R. L.: Thermal structure of the Costa Rica–Nicaragua subduction zone, *Phys. Earth Planet. In.*, 149, 187–200, doi:10.1016/j.pepi.2004.08.030, 2005.
- Protti, M., Gundel, F., and McNally, K.: The geometry of the Wadati-Benioff Zone under southern Central America and its tectonic significance – results from a high-resolution local seismographic network, *Phys. Earth Planet. In.*, 84, 271–287, doi:10.1016/0031-9201(94)90046-9, 1994.
- Quintero, R. and Kissling, E.: An improved P-wave velocity reference model for Costa Rica, *Geofis. Int.*, 40, 3–19, 2001.
- Ranero, C. R., Phipps Morgan, J., McIntosh, K., and Reichert, C.: Bending-related faulting and mantle serpentinization at the Middle America Trench, *Nature*, 425, 367–373, doi:10.1038/nature01961, 2003.
- Ranero, C. R., Villaseñor, A., Phipps Morgan, J., and Weinrebe, W.: Relationship between bend-faulting at trenches and intermediate-depth seismicity, *Geochem. Geophys. Geosy.*, 6, Q12002, doi:10.1029/2005gc000997, 2005.
- Rüpke, L., Phipps Morgan, J., Hort, M., and Connolly, J. A. D.: Are the regional variations in Central American arc lavas due to differing basaltic versus peridotitic slab sources of fluids?, *Geology*, 30, 1035–1038, doi:10.1130/0091-7613(2002)030<1035:ATRVIC>2.0.CO;2, 2002.
- Ryan, B. F., Carbotte, S. M., Coplan, J. O., O’Hara, S., Melkonian, A., Arko, R., Weis- sel, R. A., Ferrini, V., Goodwillie, A., Nitsche, F., Bonczkowski, J., and Zemsky, R.:

## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Global multi-resolution topography synthesis, *Geochem. Geophys. Geosy.*, 10, Q03014, doi:10.1029/2008gc002332, 2009.

Sallarès, V., Dañobeitia, J. J., and Flueh, E. R.: Lithospheric structure of the Costa Rican Isthmus: effects of subduction zone magmatism on an oceanic plateau, *J. Geophys. Res.*, 106, 621–643, 2001.

Sallarès, V., Charvis, P., Flueh, E. R., and Bialas, J.: Seismic structure of Cocos and Malpelo Volcanic Ridges and implications for hot spot-ridge interactions, *J. Geophys. Res.*, 108, 2564, doi:10.1029/2003JB002431, 2003.

Schmidt, S., H. J. Götze, C. Fichler, and Alvers, M.: IGMAS+ – a new 3D Gravity, FTG and Magnetic Modeling Software, in: *GEO-INFORMATIK Die Welt im Netz*, edited by: Zipf, A., Behncke, K., Hillen, F., and Scheffermeyer, J., Akademische Verlagsgesellschaft AKA GmbH, Heidelberg, Germany, 57–63, ISBN 978-3-89838-335-6, 2010

Shako, R., C. Förste, O. Abrikosov, S. Bruinsma, J.-C. Marty, J.-M. Lemoine, F. Flechtner, H. Neumayer, and Dahle, C.: EIGEN-6C: a high-resolution global gravity combination model including GOCE data, in: *Observation of the System Earth from Space – CHAMP, GRACE, GOCE and Future Missions*, *Advanced Technologies in Earth Sciences*, edited by: Flechtner, F., Sneeuw, N., and Schuh, W.-D., Springer Verlag, Berlin Heidelberg, 155–161, 2014.

Siebert, L. and Simkin, T.: *Volcanoes of the World: An Illustrated Catalogue of Holocene Volcanoes and their Eruptions*, Smithsonian Institution, Global Volcanism Program Digital Information Series, GVP-3, available at: <http://volcano.si.edu> (last access: 08 July 2015), 2002.

Sitchler, J. C., Fisher, D. M., Gardner, T. W., and Protti, M.: Constraints on inner forearc deformation from balanced cross sections, Fila Costeña thrust belt, Costa Rica, *Tectonics*, 26, TC6012, doi:10.1029/2006tc001949, 2007.

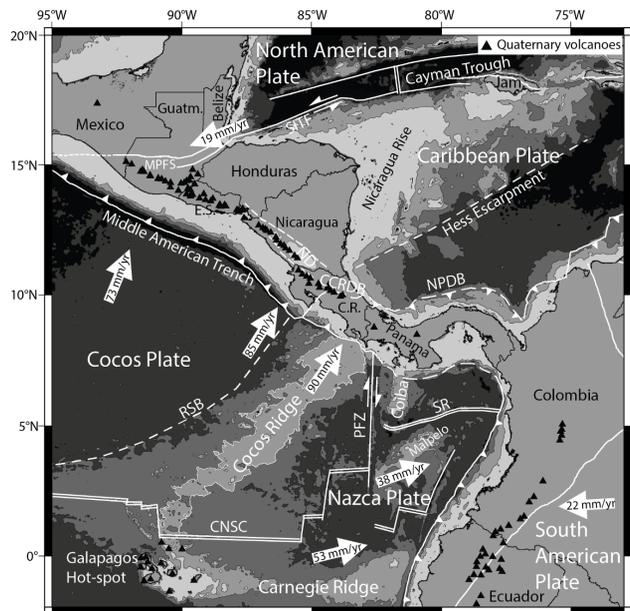
Syracuse, E. M., Abers, G. A., Fischer, K., MacKenzie, L., Rychert, C., Protti, M., González, V., and Strauch, W.: Seismic tomography and earthquake locations in the Nicaraguan and Costa Rican upper mantle, *Geochem. Geophys. Geosy.*, 9, Q07S08, doi:10.1029/2008gc001963, 2008.

Tarantola, A. and Valette, B.: Inverse problems = quest for information, *J. Geophys.*, 50, 159–170, doi:10.1038/nrm1011, 1982.

Tassara, A., Götze, H.-J., Schmidt, S., and Hackney, R.: Three-dimensional density model of the nazca plate and the andean continental margin, *J. Geophys. Res.*, 111, B09404, doi:10.1029/2005JB003976, 2006.

**Costa Rican  
subduction zone**O. H. Lücke and  
I. G. Arroyo[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

- Vannucchi, P., Sak, P. B., Phipps Morgan, J., Ohkushi, K. I., Ujiie, K., and the I. E. S. S.: Rapid pulses of uplift, subsidence, and subduction erosion offshore Central America: implications for building the rock record of convergent margins, *Geology*, 41, 995–998, doi:10.1130/G34355.1, 2013.
- 5 von Huene, R., Ranero, C. R., Weinrebe, W., and Hinz, K.: Quaternary convergent margin tectonics of Costa Rica, segmentation of the Cocos Plate, and Central American volcanism, *Tectonics*, 19, 314–334, 2000.
- Walther, C. H. E.: The crustal structure of the Cocos Ridge off Costa Rica, *J. Geophys. Res.*, 108, 2136, doi:10.1029/2001JB000888, 2003.
- 10 Zhang, J., Green II, H. W., Bozhilov, K., and Jim, Z.: Faulting induced by precipitation of water at grain boundaries in hot subducting oceanic crust, *Nature*, 428, 633–636, 2004.



**Figure 1.** Tectonic setting of the Central American Isthmus. White lines show plate boundaries and major tectonic structures. Location of Quaternary volcanoes modified from Siebert and Simkin (2002). White arrows show direction and rate of plate motions relative to the Caribbean Plate (fixed) according to: DeMets et al. (1994, 2010), and DeMets (2001). Plate boundaries modified from Coffin et al. (1998) and Lonsdale (2005). Black lines depict the coastline and international borders. C.R.: Costa Rica; E.S.: El Salvador; Guatm.: Guatemala; Jam.: Jamaica; CCRDB: Central Costa Rica Deformed Belt; MPFS: Motagua-Polochic Fault System; ND: Nicaragua Depression; NPDB: North Panama Deformed Belt; PFZ: Panama Fracture Zone; RSB: Rough–Smooth Boundary modified from Hey (1977); SITF: Swan Islands Fault; SR: Sandra Rift (de Boer et al., 1988). White contour represents the  $-2000$  m bathymetric level outlining the Cocos Ridge, bathymetric data from Global Multi-Resolution Topography by Ryan et al. (2009).

## SED

7, 1941–1977, 2015

### Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

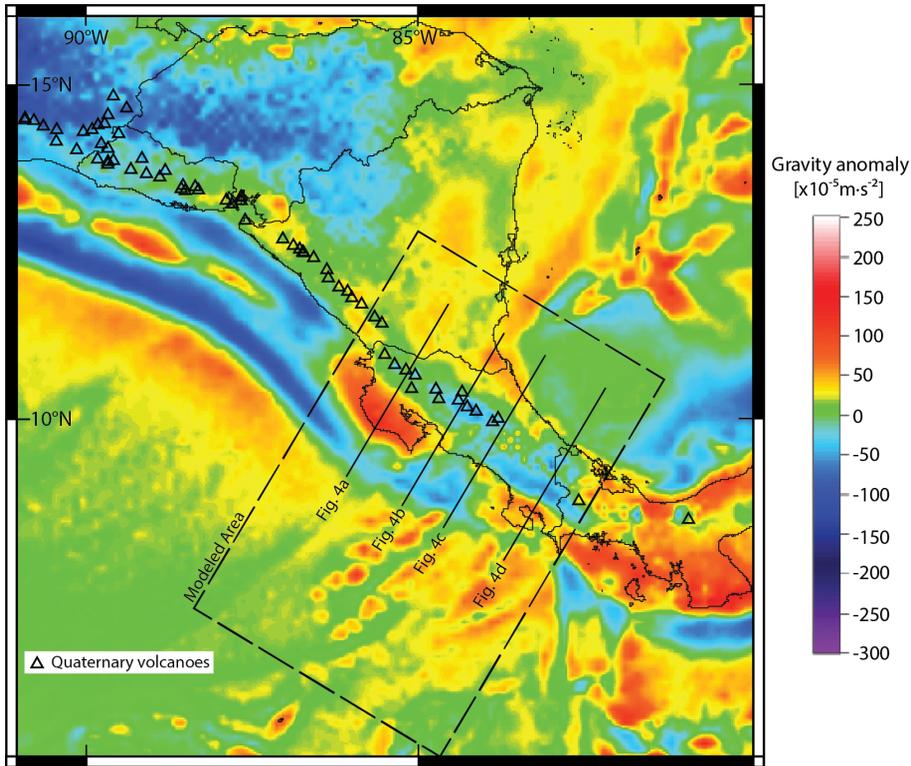
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Figure 2.** Gravity field data for the Central American isthmus and surrounding areas. Bouguer anomaly onshore and free-air anomaly offshore calculated for this study from gravity disturbance data from EGM2008 (Pavlis et al., 2012). Location of the cross sections shown in Fig. 4 and the area of the local scale density model for Costa Rica are indicated in black. Location of Quaternary volcanoes modified from Siebert and Simkin (2002). International borders and coastline are shown as black lines.

**Costa Rican  
subduction zone**

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

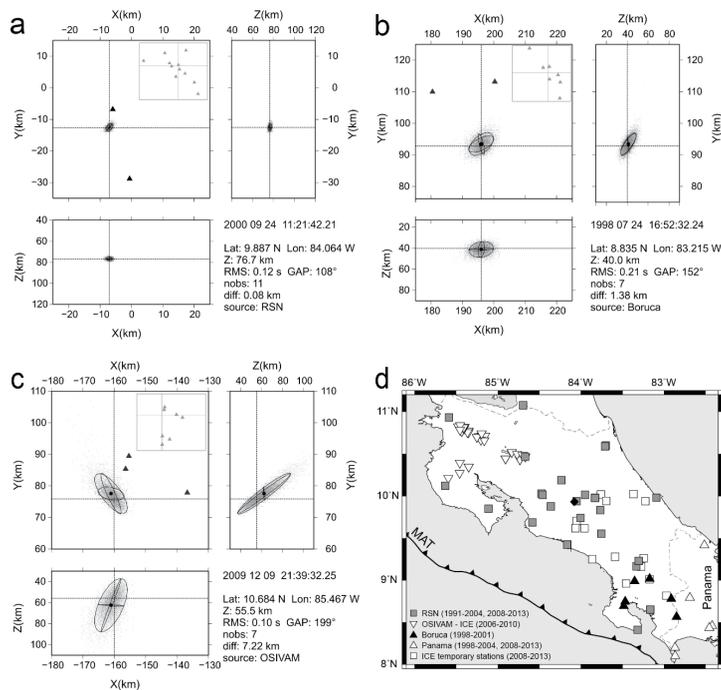
Back Close

Full Screen / Esc

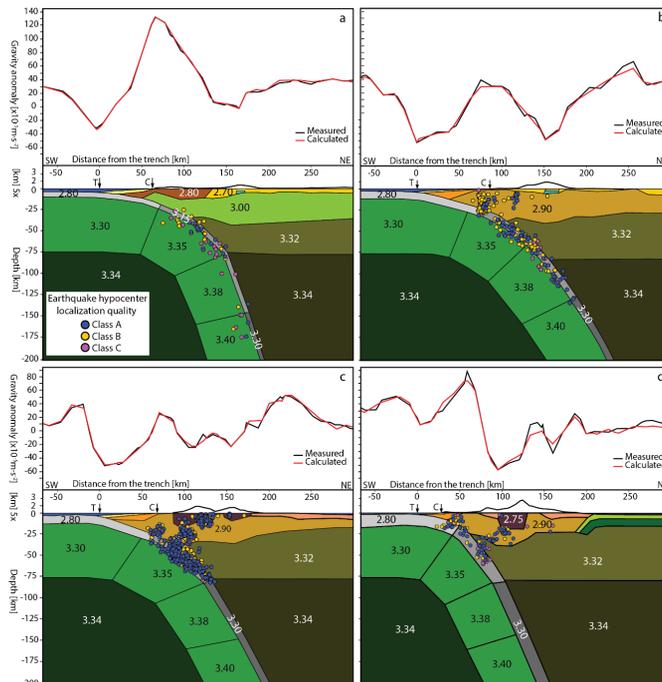
Printer-friendly Version

Interactive Discussion





**Figure 3.** Density scatter plots (**a–c**) of representative earthquakes for each quality class used in this study (see text) and seismic stations map (**d**). In the map, squares represent RSN stations, inverted triangles OSIVAM stations and black triangles Boruca stations (see text for network descriptions). The black dashed line marks the MAT axis. Scatter plots: plan view in  $x$ – $y$  direction and cross sections in  $x$ – $z$  and  $y$ – $z$  directions are shown. The intersection of the dashed lines marks the maximum likelihood hypocenter locations. Black circles denote expectation hypocenter locations. Projection of the 68 % confidence ellipsoid is shown by black lines. The insets include all the seismological stations (triangles) used to locate the earthquakes (intersection of bold lines). Nobs: number of observations, diff: difference between maximum likelihood and expectation hypocenter locations.

Costa Rican  
subduction zoneO. H. Lücke and  
I. G. Arroyo

**Figure 4.** Vertical cross sections from the local scale 3-D density model and relation to the integrated earthquake hypocentre locations for this study. The upper panels show the fit between the measured (black) and calculated (red) gravity anomaly. Circles show the earthquake hypocenters color coded for classes: A (blue), B (yellow), C (magenta). The modeled density distribution of the subducted oceanic crust is depicted in grey tones:  $2.80 \text{ Mg m}^{-3}$  (light grey),  $3.15 \text{ Mg m}^{-3}$  (medium grey),  $3.30 \text{ Mg m}^{-3}$  (dark grey). Location of the cross-sections is shown in Fig. 2.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

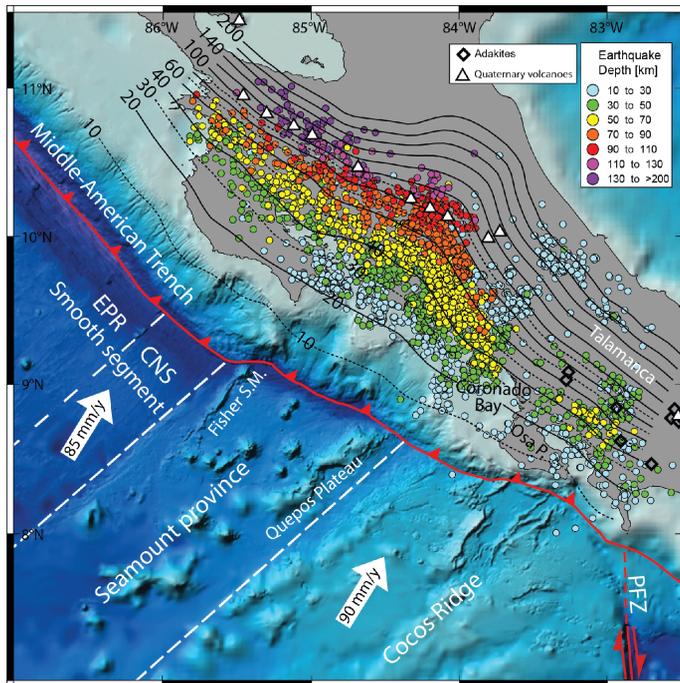
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Figure 5.** Slab depth contours for Costa Rica from the integrated interpretation of seismological and density modeling results. White arrows indicate direction and rate of plate motion from DeMets (2001) and DeMets et al. (1994). Earthquake depths are indicated in the inset. Tectonic features on the oceanic plate after von Huene et al. (2000) and Barckhausen et al. (2001). The red dented line represents the axis of the Middle American Trench. EPR: East-Pacific Rise, CNS: Cocos–Nazca Spreading Centre, PFZ: Panama Fracture Zone. Bathymetric data from Global Multi-Resolution Topography by Ryan et al. (2009). Open diamond symbols show the location of adakite samples from Hoernle et al. (2008) and Gazel et al. (2011).

Costa Rican subduction zone

O. H. Lücke and I. G. Arroyo

Title Page

Abstract Introduction

Conclusions References

Tables Figures

◀ ▶

◀ ▶

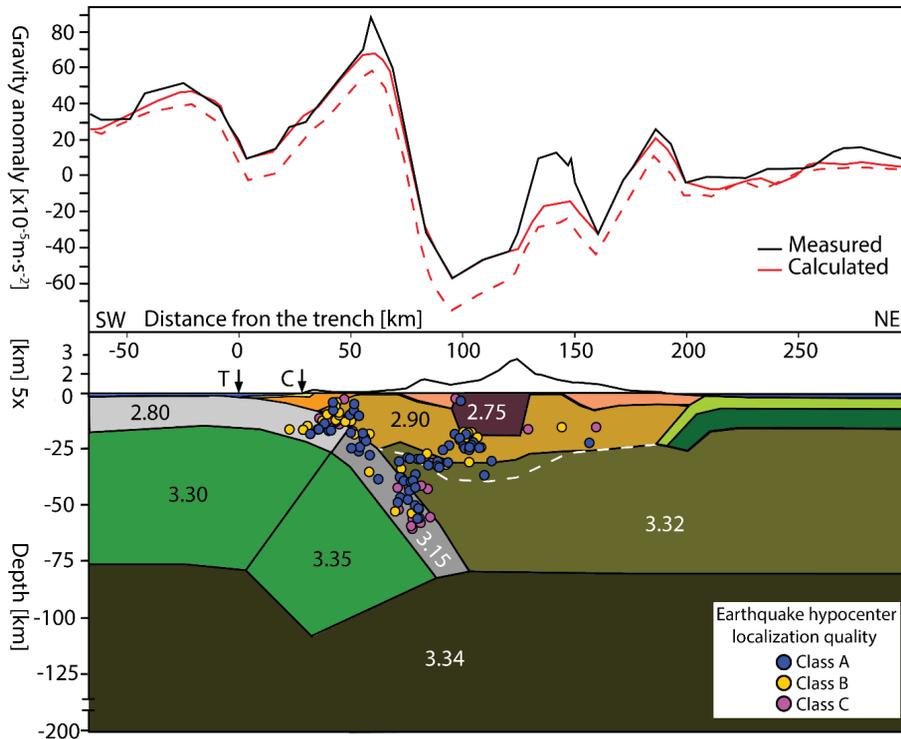
Back Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Figure 6.** Cross section of the alternative density model considering a slab detachment at 80 km for the Cocos ridge. The upper box shows the fit between the measured (black) and calculated (red) gravity anomalies, the red stippled line shows the calculated gravity anomaly for the alternate slab detachment model with the Moho structure from Lücke (2014). The lower box shows the alternative model assuming a slab detachment at a depth of 70 to 80 km under the Talamanca region. White stippled line represents the location of the Moho from Lücke (2014) constrained by receiver function results from Dzierma et al. (2010). Color circles show the location of earthquake hypocenters obtained for this study.

# SED

7, 1941–1977, 2015

## Costa Rican subduction zone

O. H. Lücke and  
I. G. Arroyo

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

