

REVIEW ARTICLE

From incipient island arc to doubly-vergent orogen: A review of geodynamic models and sedimentary basin-fills of southern Central America

Christian Brandes  | Jutta Winsemann

Institut für Geologie, Leibniz Universität
Hannover, Callin Street 30, 30167, Hannover,
Germany

Correspondence

Christian Brandes and Jutta Winsemann,
Institut für Geologie, Leibniz Universität
Hannover, Callin Street 30, Hannover 30167,
Germany.

Email: brandes@geowi.uni-hannover.de;
winsemann@geowi.uni-hannover.de

Abstract

Southern Central America is a Late Mesozoic/Cenozoic island arc that evolved in response to the subduction of the Farallón Plate beneath the Caribbean Plate in the Late Cretaceous and, from the Oligocene, the Cocos and Nazca Plates. Southern Central America is one of the best studied convergent margins in the world. The aim of this paper is to review the sedimentary and structural evolution of arc-related sedimentary basins in southern Central America, and to show how the arc developed from a pre-extensional intra-oceanic island arc into a doubly-vergent, subduction orogen. The Cenozoic sedimentary history of southern Central America is placed into the plate tectonic context of existing Caribbean Plate models. From regional basin analysis, the evolution of the southern Central American island arc is subdivided into three phases: (i) non-extensional stage during the Campanian; (ii) extensional phase during the Maastrichtian-Oligocene with rapid basin subsidence and deposition of arc-related, clastic sediments; and (iii) doubly-vergent, compressional arc phase along the 280 km long southern Costa Rican arc segment related to either oblique subduction of the Nazca plate, west-to-east passage of the Nazca-Cocos-Caribbean triple junction, or the subduction of rough oceanic crust of the Cocos Plate. The Pleistocene subduction of the Cocos Ridge contributed to the contraction but was not the primary driver. The architecture of the arc-related sedimentary basin-fills has been controlled by four factors: (i) subsidence caused by tectonic mechanisms, linked to the angle and morphology of the incoming plate, as shown by the fact that subduction of aseismic ridges and slab segments with rough crust were important drivers for subduction erosion, controlling the shape of forearc and trench-slope basins, the lifespan of sedimentary basins, and the subsidence and uplift patterns; (ii) subsidence caused by slab rollback and resulting trench retreat; (iii) eustatic sea-level changes; and (iv) sediment dispersal systems.

KEYWORDS

Caribbean Plate, doubly-vergent orogen, island arc, sedimentary basins, southern Central America, subduction erosion, trench retreat

1 | INTRODUCTION

A major question in geoscience is to understand the evolution of continental crust (Polat, 2012), which represents the most complete archive for earth history (Hawkesworth et al., 2010). The formation of continental crust played a main role in the evolution of the earth by modifying the

composition of mantle and atmosphere as well as by providing habitats for life (Hawkesworth & Kemp, 2006). Subduction margins are the key locality to study how continents grow by terrane accretion (e.g. Korsch, Kositsin, & Champion, 2011; Tetreault & Buitier, 2012) and by magmatic rock emplacement (Polat, 2012). Sedimentary basins also provide archives for reconstructing the development of subduction margins. Their

sedimentary fill records the spatial and temporal evolution of the arc-trench system that is preserved on geological time scales (Ingersoll & Busby, 1995). Basin analysis (Busby, Smith, Morris, & Fackler-Adams, 1998) and studies of basin subsidence (Angevine, Heller, & Paola, 1990; Brandes, Astorga, Littke, & Winsemann, 2008; Struss, Artiles, Cramer, & Winsemann, 2008; Xie & Heller, 2009) are powerful tools to unlock these archives exposed along subduction margins, as also shown by Noda (2016).

Modern subduction margins are largely characterized by compressional mature and convergent arc-trench systems that developed at long-lived subduction zones, whereas early-stage systems are rare among modern arcs. Consequently, island-arc evolution has to be reconstructed from the geological record in order to understand the growth of continents at convergent margins (Busby, 2004; Vannucchi, Morgan, & Balestrieri, 2016).

The southern Central American island arc is one of the best studied subduction margins in the world and can therefore act as natural laboratory for analysing the development of arc-trench systems. Much research has been carried out since the 1980s, in the form of numerous publications in regional journals and unpublished master and PhD theses that collectively provide a large data set covering the onshore and offshore geology and geophysics. This excellent data set from different forearc and backarc basins in southern Central America forms the basis

for this study of the sedimentary record of this island arc, which is located in a key position along the western edge of the Caribbean Plate.

The objective of this paper is to review and synthesize the sedimentary and structural evolution of island arc-related sedimentary basins in southern Central America. Linking onshore and offshore geology will lead to a more comprehensive understanding of the basin development and the evolution of the subduction margin.

We will address three major questions related to the Central American arc system:

1. What are the first order, tectonic controls on basin evolution in Central America?
2. What controls the contractional doubly-vergent style of the Central American island arc in southeastern Costa Rica?
3. Can the evolution of the Central American island arc serve as a general model for the long term (> 100 Ma) evolution of all island arcs?

2 | GEOLOGICAL SETTING

The geology of Central America is presently characterized by the interaction of five lithospheric plates, including the oceanic Cocos, Nazca, and Caribbean plates and the continental North and South American plates (Figure 1). The Cocos and Nazca Plates, remnants of the oceanic Farallón

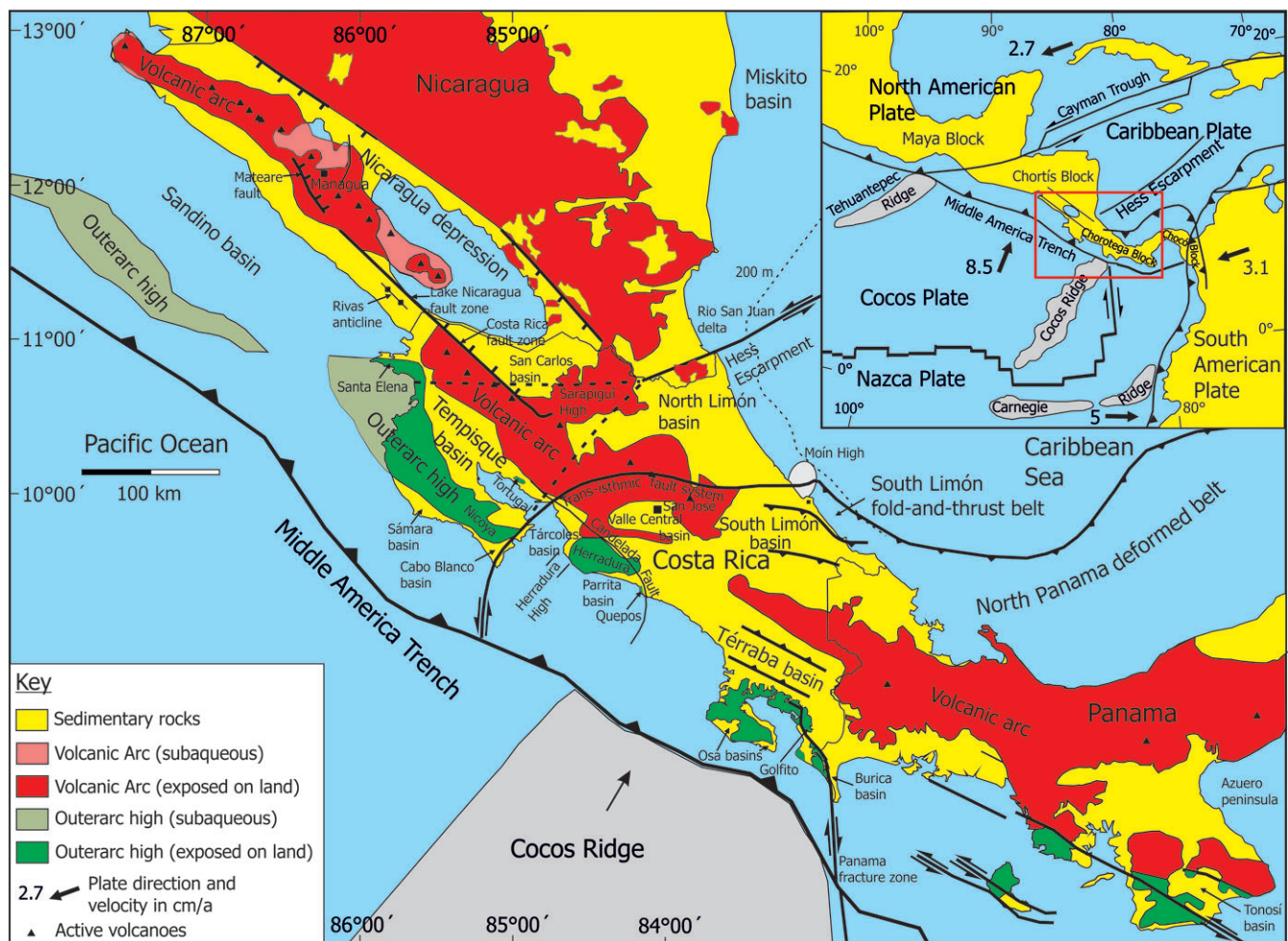


FIGURE 1 Geological map of Southern Nicaragua, Costa Rica, and western Panama, modified after Astorga (1997), Barboza, Barrientos, and Astorga (1995), Campos (2001), Coates, Collins, Aubry, and Berggren (2004), Donnelly (1989), Fernandez et al. (1997), J. J. Krawinkel (2003), Meschede and Frisch (1998), and Ross and Scotese (1988)

Plate, are subducted beneath the Caribbean Plate along the northwest-southeast trending Middle American trench. The present-day subduction velocity off Costa Rica, relative to the Caribbean Plate, is 8.5 cm/yr (DeMets, 2001). The Cocos Plate is characterized by a large northwest-southeast trending aseismic ridge, the Cocos Ridge, which is interpreted as representing a hotspot trace (e.g. Walther, 2003). The Cocos Ridge is more than 1 000 km long, roughly 200–250 km wide, about 2 km shallower than the adjacent basin. The 2 000 m bathymetric contour line is taken as the edge of the Cocos Ridge (Morell, 2016; Tomascak, Ryan, & Defant, 2000). The most recent studies (Vannucchi, Morgan, Silver, & Kluesner, 2016; Zeumann & Hampel, 2015, 2016, 2017) support an onset of ridge subduction in the Early Pleistocene at around 2 Ma.

2.1 | Plate tectonic evolution of the Caribbean region

The tectonic evolution of the southern Central American island arc is strongly connected to the geodynamics of the Caribbean Plate. The Caribbean Plate has an east-west extent of about 3 000 km. Its northern and eastern boundary is with the North American plate and its southern boundary with the South American Plate. Its boundaries to the west and southwest are with the Cocos and Nazca Plates. In contrast to other oceanic plates with an average crustal thickness of 6–8 km, the Caribbean Plate is 15–20 km thick (Burke, Fox, & Sengör, 1978; Diebold & Driscoll, 1999). There has been controversial discussion about the origin and evolution of the Caribbean region during the last two decades. All published ideas can be reduced to at least two different models summarized on Figure 2. Each model is based on a number of geological and geophysical observations. Comprehensive reviews of the different plate tectonic models either favor the inter-American model (James, 2006) or the Pacific model (Mann, 1999; Mann, Rogers, & Gahagan, 2007; J. Pindell et al., 2006; Pindell, Maresch, Martens, & Stanek, 2012). The most recent quantitative kinematic reconstruction of the Caribbean region since the Early Jurassic supports a modified Pacific model (Boschman, van Hinsbergen, Torsvik, Spakman, & Pindell, 2014).

2.1.1 | Pacific model

The Pacific model (Figure 2a) suggests an origin of the Caribbean Plate in the Pacific region and postulates a drift of the plate to its recent position (Astorga, 1994, 1997; Hoernle et al., 2002; Kerr, Iturralde-Vinent, Saunders, Babbs, & Tarney, 1999; Mann, 1999; Mann et al., 2007; J. Pindell et al. 2006, 2012; J. L. Pindell et al., 1988; J. L. Pindell & Kennan, 2009; Ross & Scotese, 1988). It is assumed that the Caribbean Plate represents an oceanic plateau (e.g. Kerr, Tarney, Marriner, Klaver, et al., 1996; Kerr, Tarney, Marriner, Nivia, et al., 1996; Hoernle et al., 2002), which was carried eastward with the Farallón Plate behind the east and northeast-facing Great Arc of the Caribbean (Burke, 1988). The databases for this assumption are petrological and geochemical similarities of the basalts of the Caribbean crust and the well known oceanic plateaus in the western Pacific. Also a similarity in the crustal structure and in the acoustic characteristics of the Caribbean crust and the oceanic plateaus was found (Bowland & Rosencrantz, 1988; Diebold & Driscoll, 1999; Mauffret & Leroy, 1997).

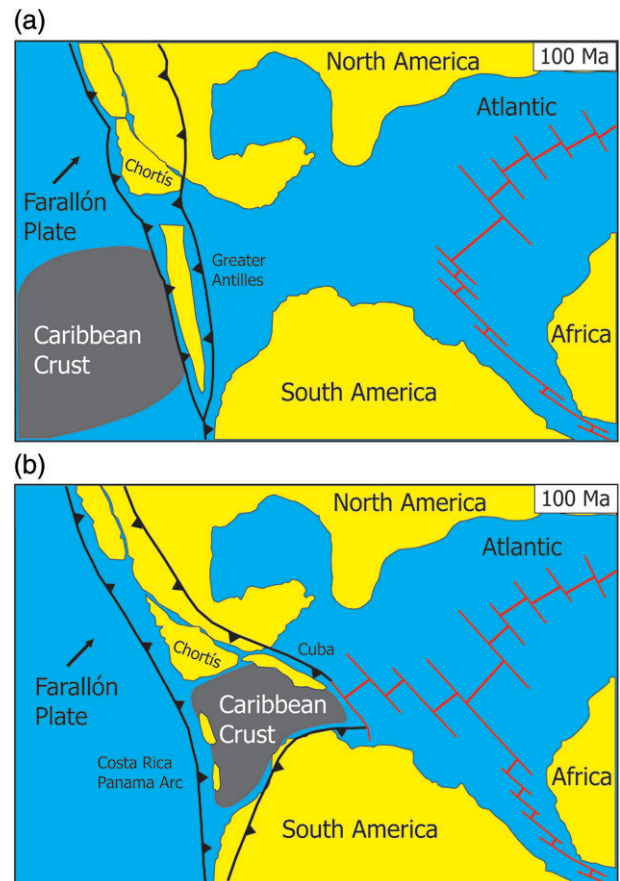


FIGURE 2 Plate tectonic models for the evolution of the Caribbean Plate. (a) Pacific model for the evolution of the Caribbean Plate. According to this model, the Caribbean Plate was formed in the eastern Pacific and later drifted into the gap between North and South America (J. L. Pindell et al., 1988; J. Pindell, Kennan, Stanek, Maresch, & Draper, 2006). (b) In situ model for the Caribbean Plate. Following this model, the Caribbean Plate evolved in place during the separating of North and South America. Modified after Meschede and Frisch (1998)

Cloos (1993) argued, based on isostasy calculations that oceanic plateaus with a crustal thickness greater than 17 km cannot be subducted. Therefore previous work assumed that the Caribbean Plate could not be subducted because of its thickness and buoyancy and therefore pushed the subduction zone eastward and moved successively into the gap between the North and South American Plate. However, more recent work of Mann and Taira (2004) shows that 80 % of the crustal thickness of the Ontong Java Plateau is subducted, therefore the previous buoyancy argument for the emplacement of the Caribbean Plate is probably not applicable.

2.1.2 | Inter-America model

This model (Figure 2b) implies that the Caribbean Plate evolved near its recent position between the North American and the South American plates (Frisch, Meschede, & Sick, 1992; James, 2009; Meschede, 1998; Meschede & Frisch, 1998; Meschede, Frisch, Chinchilla Chavez, López Saborio, & Calvo, 2000). During the break-up of Pangea, the North and South American plates were separated by a northwest-southeast striking rift-system that included both the Gulf of Mexico and the Caribbean. In Late Jurassic times this rift evolved

into a spreading center forming oceanic crust of the Proto-Caribbean Plate. During the Cretaceous, a mantle-plume established and induced a widespread basaltic volcanism, which affected the whole region (Diebold & Driscoll, 1999; Donnelly, 1994; Kroehler, Mann, Escalona, & Christeson, 2011). During this volcanic phase the Caribbean Large Igneous Province (CLIP) formed (previously also referred to as 'Mid Cretaceous sill-event'), which led to the significant increase in crustal thickness of the Caribbean Plate (Burke et al., 1978). This inter-American model is mainly based on paleomagnetic data, indicating a formation of the Caribbean Plate near the equator (Acton, Galbrun, & King, 2000; Frisch et al., 1992). Furthermore no significant latitudinal changes since Jurassic times could be observed and all documented motions of the plate correspond with the motions of South America. Therefore a juxtaposition of the Caribbean Plate with the South American Plate is likely. A link to the Farallón or to other Pacific plates is not supported by paleomagnetic data (Frisch et al., 1992). The plates clearly have moved independent of each other.

In a more recent data compilation, James (2009) pointed out that the Caribbean Plate consists of dispersed continental basement blocks and sedimentary rocks of Triassic to Cretaceous age, overlain by basalts that partly have formed subaerially that is interpreted as a Cretaceous, oceanic plateau by others (Diebold & Driscoll, 1999; Kroehler et al., 2011). This assumption is mainly based on a re-interpretation of seismic data and would imply an extensional and therefore in situ evolution of the Caribbean region, representing an area of rifted continental crust of Triassic and Jurassic age that is synchronous with the Gulf of Mexico.

2.1.3 | New quantitative plate kinematic reconstruction for the Caribbean region

A new kinematic plate tectonic reconstruction of Boschman et al. (2014) overcomes the major inconsistencies of the older models for the origin the Caribbean crust. The major outcome of this new

kinematic plate tectonic model is that the formation of the Caribbean Large Igneous Province (CLIP) cannot be related to the Galápagos hotspot, as previously assumed (e.g. Hauff, Hoernle, & van den Bogaard, 2000; Hoernle et al., 2002). The basalts probably originated from a separate plume, 2 000–3 000 km east of the modern Galápagos hotspot, as was already discussed by Meschede (1998). We therefore favor the new modified Pacific model from Boschman et al. (2014) because it best explains the early geological evolution of southern Central America.

The initiation of arc volcanism at around 75–70 Ma and the onset of volcanoclastic deposition within the forearc and backarc basins mark the establishment of a new subduction zone in front of the southern Chortís block and thickened crust of the CLIP.

3 | TECTONIC STRUCTURE AND TERRANE CONCEPT OF SOUTHERN CENTRAL AMERICA

Today's land-bridge above the subduction zone is a complex assemblage. From southeast Guatemala to northwest Colombia, the Maya, Chortís, Chorotega and Chocó blocks can be distinguished on the basis of age and lithologic differences of their Precambrian to Cretaceous basement types (Figures 2 and 3) (Campos, 2001; G. Dengo, 1962; Di Marco, Baumgartner, & Channell, 1995; Donnelly, 1989; Weinberg, 1992; Weyl, 1980). The Maya and Chortís blocks were previously thought to have an old continental basement (e.g. G. Dengo, 1962; Weyl, 1980). However, more recent work showed that the Chortís block consists of a complex assemblage of different terranes with accreted oceanic elements (Baumgartner et al., 2008; Mann et al., 2007; Rogers, Mann, & Emmet, 2007; Rogers, Mann, Emmet, & Venable, 2007) (Figure 3). The southern part of the Chortís block is a Late Cretaceous island arc that was attached to the central

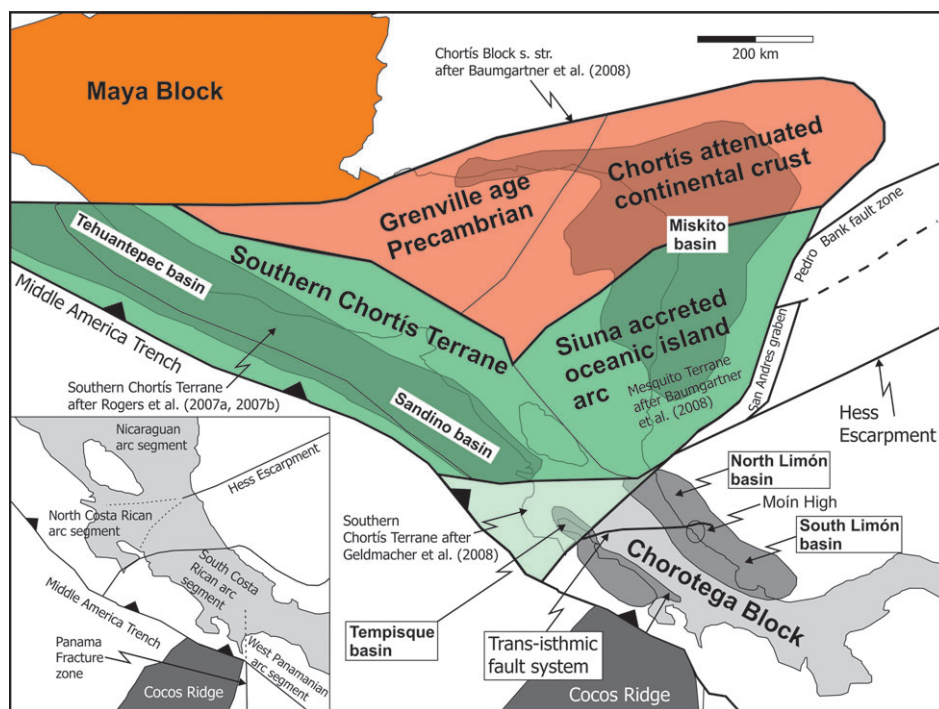


FIGURE 3 Structure of the Central American land-bridge between southern Mexico and Panama. The Chortís block consists of different tectonic terranes with a continental and oceanic origin. Based on Baumgartner, Flores, Bandini, Girault, and Cruz (2008), Carvajal-Arenas, Torrado, and Mann (2015), C. A. Dengo (2007), Geldmacher, Hoernle, van den Bogaard, Hauff, and Klügel (2008), Mann et al. (2007) and Rogers, Mann, and Emmet (2007), Rogers, Mann, Emmet, & Venable, 2007)

Chortís terrane in Late Cretaceous times and probably formed as the southeastern extension of the Guerrero arc of Mexico (Mann et al., 2007; Rogers, Mann, & Emmet, 2007; Rogers, Mann, Emmet, & Venable, 2007). Baumgartner et al. (2008) defined the Chortís block *sensu stricto* (comprising mainly Honduras and offshore areas towards the northeast) and the Mesquito Oceanic terranes (MOT) (comprising El Salvador, Nicaragua and the Nicaragua Rise). The Mesquito Oceanic terranes roughly correspond to the Siuna and the Southern Chortís terrane of Rogers, Mann, and Emmet (2007) and Rogers, Mann, Emmet, and Venable (2007) (Figure 3).

In contrast, the Chorotega and Chocó blocks comprise island arc segments underlain by Mesozoic oceanic crust (e.g. Baumgartner et al., 2008; Buchs, Arculus, Baumgartner, Baumgartner-Mora, & Ulianov, 2010; Buchs, Baumgartner, Baumgartner-Mora, Flores, & Bordini, 2011; G. Dengo, 1962; Escalante & Astorga, 1994; Flueh & von Huene, 2007; Hauff et al., 2000; Hoernle et al., 2002; Mann et al., 2007; Rogers, Mann, & Emmet, 2007; Sallarès, Danobeitia, Flueh, & Leandro, 1999; Seyfried et al., 1991; Weyl, 1980), which is interpreted to belong to the CLIP. Along the southwestern edge of the continental Chortís block, the Santa Rosa accretionary complex defines an intra-oceanic subduction zone with CLIP basement extending south of this belt (Escuder-Virueite & Baumgartner, 2014). The arc collision with the Chortís block occurred during the Late Cretaceous, resulting in the emplacement of the Santa Elena nappe in northern Costa Rica (Escuder-Virueite & Baumgartner, 2014; Geldmacher, Hoernle, van den Bogaard, Hauff, & Klügel, 2008; Sanchez, Mann, Emmet, 2016). Linkimer, Beck, Schwartz, Zandt, and Levin (2010) used a receiver function analysis to refine the terrane boundaries between the Chortís and Chorotega blocks. They suggest that the boundary between the Mesquito Oceanic terranes (Chortís block) and the Chorotega block corresponds with the western part of the Trans-isthmian fault system merging towards the northeast with the Hess Escarpment (Figure 3). A similar fault configuration has previously been proposed by Weinberg (1992).

James (2007) presented geological and geophysical hints for fragments of continental crust below the Chorotega and Chocó block. Main indicators are the occurrence of granulite xenoliths from the Arenal volcano, the composition of ignimbrites and the crustal thickness of 40–45 km in Costa Rica. In contrast to most other workers he concluded that parts of the Chorotega block consist of continental rocks that were offset from the Chortís block by rift processes in the Late Jurassic.

3.1 | The basement of the Nicaraguan arc segment

The Nicaraguan arc segment belongs to the Chortís block. It is bounded in the south by the Hess Escarpment (Bowland, 1993; Rogers, Mann & Emmet, 2007; Sanchez et al., 2016; Seyfried et al., 1991; Weyl, 1980), a northeast–southwest trending bathymetric feature in the Caribbean Sea (Figures 1 and 3). It has previously been interpreted as a Late Mesozoic plate boundary, which acted as a strike-slip zone to compensate the movements between the Chortís block, Chorotega block and Caribbean plates (J. Krawinkel & Seyfried, 1994; Meschede & Frisch, 1998; Ross & Scotese, 1988). Bowland (1993) described the Hess Escarpment as a transcurrent fault that has a Late

Cretaceous to an Early Tertiary age. Alfaro, Barrera, and Rossello (2013) interpreted the Hess Escarpment as a positive flower structure with sinistral kinematics. Focal mechanisms shown in Alvarez-Gomez, Meijer, Martinez-Diaz, and Capote (2008) indicate that ongoing activity along the Hess Escarpment and the fault-plane solutions give evidence for oblique normal faulting and strike-slip kinematics.

The Cretaceous forearc basin of Nicaragua is probably underlain by older accreted island-arc rocks, which possibly can be correlated with the Mexican Guerrero terrane. The accretion of the Guerrero terrane to western Mexico occurred during the Cretaceous (Mann et al., 2007; Rogers, Mann & Emmet, 2007; Rogers, Mann, Emmet, & Venable, 2007). The absence of Paleozoic basement rocks is indicated by the geochemistry of Quaternary volcanic rocks (Mann et al., 2007; Rogers, Mann & Emmet, 2007).

The Siuna terrane of southeastern Nicaragua forms the basement of the Miskito backarc basin (Figure 3) and was probably produced by the collision between an intra-oceanic island arc and the continental margin of the Chortís block in the Late Cretaceous (Rogers, Mann, & Emmet, 2007; Rogers, Mann, Emmet, & Venable 2007; Sanchez et al., 2016). The Upper Rhaethian (*ca* 200 Ma) radiolarian assemblage has strong affinities with faunas described from Pacific North America (Baumgartner et al., 2008), pointing to a Pacific origin of the accreted terrane. The lead isotope values of the Siuna terrane cluster outside the Caribbean large igneous province and indicate that the Siuna arc is not underlain by Caribbean crust (Rogers, Mann, & Emmet, 2007). A subduction-related *mélange*, including thrust serpentinite and related ultramafic cumulates, is exposed near Siuna and marks the suture (Rogers, Mann, & Emmet, 2007). This *mélange* is unconformably overlain by Lower Cretaceous (Aptian/Albian) thin-bedded hemipelagic calcareous deposits and thin-bedded volcanoclastic turbidites, passing upwards into limestones, in which andesitic flows partly be intercalated (Baumgartner et al., 2008). New seismic data show that the entire fold-thrust belt extends offshore and underlies the northern or upper Nicaraguan Rise (Sanchez et al., 2016).

3.2 | The basement of the Costa Rican arc segments

The Costa Rican part of the island arc can be subdivided into a northern and a southern arc segment separated by the Trans-isthmian fault system (Figure 3) (Seyfried et al., 1991; Weyl, 1980). In the north the Hess Escarpment is the boundary. The Trans-isthmian fault system is an east–west trending lineament with major sinistral movements. Marshall, Fisher, and Gardner (2000) provided a comprehensive kinematic analysis of this fault system. They used the term Central Costa Rica Deformed Belt for the east–west trending diffuse fault zone. Driving mechanisms for the evolution of the Central Costa Rica Deformed Belt are basal traction from the shallow subduction, shear and horizontal shortening due to the subduction of the Cocos Ridge and uplift caused by seamount subduction (LaFemina et al., 2009; Marshall et al., 2000). The Trans-isthmian fault system (Figure 1) has probably been active since the Late Cretaceous (Seyfried et al., 1991) and has also been interpreted to represent a former plate boundary (Baumgartner et al., 2008; Weinberg, 1992). Data from J. L. Pindell and Kennan (2009) imply that this fault system is still active. This is supported by studies of the South Limón fold-and-thrust belt in the

backarc area. Brandes, Astorga, Blisniuk, Littke, and Winsemann (2007) showed that the northwestern edge of the South Limón fold-and-thrust belt has a strong bend and passes into the east-west trending Trans-isthmian fault system (Figure 1). Fault-scarps at the sea-floor visible on seismic lines indicate ongoing deformation in the leading edge of the fold-and-thrust belt (Brandes, Astorga, Back, Littke, & Winsemann, 2007a, 2007b; Brandes, Astorga, Blisniuk, et al., 2007). Mechanically, the northeastward propagation of the South Limón fold-and-thrust belt is compensated by sinistral strike-slip movements along the Trans-isthmian fault system (Brandes, Tanner, & Winsemann, 2016). Towards the south the South Costa Rican arc segment is bounded by the onland projection of the subducting Panama fracture zone (J. Krawinkel & Seyfried, 1994).

3.2.1 | The North Costa Rican arc segment

The northwestern part of the North Costa Rican arc segment probably belongs structurally to the Chortís block (e.g. Baumgartner et al., 2008; Geldmacher et al., 2008; Hauff et al., 2000; Linkimer et al., 2010; Weinberg, 1992) and is underlain by an assemblage of older accreted island arc rocks and/or relics of oceanic plateaus, aseismic oceanic ridges and seamounts that differ geochemically from the CLIP basalts (Alvarado, Denyer, & Sinton, 1997; Baumgartner et al., 2008; Buchs et al., 2013; Geldmacher et al., 2008; Hauff et al., 2000). These older ophiolitic basement rocks are intruded by younger basalts with a geochemical signature similar to that of the CLIP (Hauff et al., 2000), implying that the north Costa Rican arc segment was located at the northern edge of the Caribbean large igneous province (Baumgartner et al., 2008).

The oldest accreted seamounts are Jurassic in age (*ca* 175 Ma) and occur within the Early Cretaceous (*ca* 110 Ma) Santa Rosa accretionary complex, exposed at the southern coast of the Santa Elena Peninsula in northern Costa Rica (Buchs et al., 2013; Escuder-Viruet & Baumgartner, 2014). This accretionary complex probably forms the basement of the Santa Elena Peninsula and is overlain by a nappe of serpentinitized peridotite emplaced during the Cenomanian to Early Campanian (Frisch et al., 1992; Hauff et al., 2000; Tournon, 1994). It is the oldest known accretionary complex along the outer forearc zone of southern Central America and has probably been accreted to the convergent margin of the southern Chortís block (Buchs et al., 2013; Escuder-Viruet & Baumgartner, 2014).

Hauff et al. (2000) interpreted the Santa Elena complex as an uplifted mantle wedge of the Chortís subduction zone, originally located in front of Mexico. The Late Cretaceous exhumation of the peridotites coincides with the onset of displacement along the Motagua-Polochic fault. Similarities between the isotopic and trace element composition of ultramafic rocks exposed at Tortugal (89 Ma) and the Santa Elena Peninsula (Figure 1) suggests that they originated from the same source (Alvarado et al., 1997; Geldmacher et al., 2008; Hauff et al., 2000), implying that the boundary between the Chortís block and the Chorotega block could be located further south and merges into the Trans-isthmian fault system (Figure 3) (cf. Baumgartner et al., 2008; Linkimer et al., 2010; Weinberg, 1992). Stratigraphic and geochemical studies by Bandini, Flores, Baumgartner, Lockett, and Denyer (2008), Baumgartner et al. (2008), and Buchs et al. (2013)

carried out on the Nicoya Peninsula and in the Tempisque forearc basin confirm that the ophiolitic basement of this area also contains igneous rocks, which differ in age and geochemistry from those of the CLIP.

The development of late Campanian reefs on top of these uplifted ophiolitic basement blocks and the serpentinites of the Santa Elena Peninsula (e.g. Azéma, Bourgeois, Tournon, Baumgartner, & Desmet, 1985; Bandini et al., 2008; Jaccard, Münster, Baumgartner, Baumgartner-Mora, & Denyer, 2001; Seyfried et al., 1991; Seyfried & Sprechmann, 1986) postdate the collision of the Chortís block with the Chorotega block, which possibly has occurred therefore at around 75–71 Ma. The initiation of arc volcanism at around 75–70 Ma and the onset of volcanoclastic deposition within the forearc and backarc basins of southern Central America marks the establishment of a new subduction zone in front of the thickened Caribbean crust (e.g. Astorga et al., 1991; Baumgartner et al., 1984; Brandes et al. 2008; Buchs et al., 2010, 2011; Campos, 2001; Corrigan, Mann, & Ingle, 1990; Kumpulainen, 1995; Kumpulainen, Högdahl, Ólafsson, Muñoz, & Valle, 1999; Kutterolf, Rudolph, Schotters, & Deringer, 1997; K. D. McIntosh et al., 2007; Ranero, von Huene, Flueh, Duarte, et al., 2000; Ranero, von Huene, Flueh, Weinrebe, et al., 2000; Seyfried et al., 1991; Sprechmann, 1984; Struss et al., 2008; Winsemann, 1992; Winsemann & Seyfried, 1991). The eastern part of the North Costa Rican arc segment probably belongs to the Chorotega block and is underlain by CLIP basalts (Bowland, 1993; Bowland & Rosencrantz, 1988).

3.2.2 | South Costa Rican arc segment

The South Costa Rican arc segment is underlain by CLIP basalts and younger (70–20 Ma) accreted seamounts and aseismic ridges formed from the Galápagos hotspot (Appel, Wörner, Alvarado, Rundle, & Kussmaul, 1994; Buchs et al., 2011; Hauff et al., 2000; Hoernle et al., 2002; Hoernle, Hauff, & van den Bogaard, 2004; Wegner, Wörner, Harmon, & Jicha, 2011). Accretion has been the dominant process over the last 70 Ma, contributing to the growth of the forearc area (Buchs et al., 2011; Hoernle et al., 2002; Walther, Flueh, Ranero, von Huene, & Strauch, 2000).

In southern Costa Rica conditions change from steep subduction to gentler subduction related to the presence of the incoming Cocos Ridge (Corrigan et al., 1990; Gardner, Fisher, Morell, & Cupper, 2013; Lücke & Arroyo, 2015; Pratti, Güendel, & McNally, 1995a, 1995b). The island arc shows a deformed and uplifting forearc and backarc area, separated by the Talamanca Range with a height of 3.8 km and a width of ~ 80 km (Morell, Kirby, Fisher, & van Soest, 2012). This mountain range is a remarkable feature of the southern Central American land-bridge with the exposure of granites. These granites are Miocene in age and their occurrence corresponds with the highest elevations. MacMillan, Gans, and Alvarado (2004) assume an exhumation of the plutons with a rate of approximately 1 km/Ma for the Talamanca Range. Geological maps of Costa Rica show prominent thrust faults that trend northwest–southeast and run parallel to the mountain range (e.g. Fernandez et al., 1997). Along the southwestern range front, one of these thrusts separates the granitic rocks from the deformed sediments of the forearc basins. Gardner et al. (1992)

analysed the Quaternary uplift effects of the Cocos Ridge subduction. Young Plio-Pleistocene adakitic volcanism is possibly related to the partial melting of the Cocos Ridge ocean island basalts (Abratis & Wörner, 2001; Wegner et al., 2011).

A detailed analysis of the southern Costa Rican forearc kinematics was given by Sak, Fisher, Gardner, Marshall, and LaFemina (2009). The forearc area is characterized by a southwestward directed thrust system. The thrusts sole into a low angle detachment that lies at a depth of ~ 4 km (Fisher et al., 2004). Sitchler, Fisher, Gardner, and Protti (2007) and Morell, Fisher, and Gardner (2008) used balanced cross-sections to reconstruct the evolution of the forearc fold-and-thrust belt. Thrusting in the Fila Costeña is young and related to the subduction of the Cocos Ridge (Gardner et al., 2013; Morell et al., 2008; Vannucchi, Morgan, Balestrieri, et al., 2016). It probably started 1.5–1 Ma (Gardner et al., 2013). Sediments derived from the Talamanca Range were able to reach the trench-slope before 1.9 Ma. Later the Fila Costeña had become high enough to block a direct transport from the Talamanca Range into the trench-slope area offshore Osa (Vannucchi, Morgan, Balestrieri, et al., 2016).

The South Limón backarc basins are dominated by the Limón fold-and-thrust belt (Barboza et al., 1997; Brandes et al., 2007b; Brandes, Astorga, Blisniuk, et al., 2007). The internal part of this fold-and-thrust belt is characterized by thick-skinned tectonics. Deep earthquake loci provide evidence for active, deep seated thrusts (Suárez et al., 1995). In contrast, the external part of the Limón fold-and-thrust belt adjacent to the Caribbean coast is dominated by thin-skinned tectonics. Seismic reflection lines show that all thrusts sole into a common detachment at a depth of 3.7–4 km (Brandes et al., 2007b; Brandes, Astorga, Blisniuk, et al., 2007; Brande et al., 2008).

3.3 | The basement of the Panamanian arc segments

The area of Panama comprises three arc segments, bounded by major fault systems. From west to east these are the West Panamanian arc segment, Central Panamanian arc segment and East Panamanian arc segment (J. Krawinkel & Seyfried, 1994; Seyfried et al., 1991). The igneous basement of the Panamanian arc segments is composed of Cretaceous basalts of the Caribbean Large Igneous Province (CLIP), proto-arc related igneous rocks locally interbedded with late Campanian to Maastrichtian hemipelagic limestones, late Campanian to Eocene (71–40 Ma) arc-related igneous rocks and ocean island basalts, which were accreted along the forearc between 70–20 Ma. From the West Panamanian arc segment metamorphic rocks (greenschist to amphibolite facies) of unclear origins have been described (Buchs et al., 2011; Tournon, Triboulet, & Azéma, 1989).

The youngest phase of arc-related volcanism occurred from 19–5 Ma (Buchs et al., 2010, 2011; Wegner et al., 2011; Wörner, Harmon, & Wegner, 2009). Volcanism of adakitic composition in western and central Panama is possibly related to the change from orthogonal to oblique subduction at around 8.5 Ma (Rooney, Morell, Hidalgo, & Franceschi, 2015).

The igneous basement rocks are unconformably overlain by Eocene to Miocene shallow- and deep-water volcanoclastic rocks and shallow-water marine limestones (Barat et al., 2014; Kolarsky,

Mann, & Monechi, 1995; H. Krawinkel, Wozazek, Krawinkel, & Hellmann, 1999). Oblique collision between Panama and South America had probably started already at the end of the Middle Eocene (*ca* 40–38 Ma), which is indicated by the sudden appearance of transtensive and rotational deformation in the Panama Canal area, leading to the development of local extensional basins (Barat et al., 2014). Subsequently volcanism of adakitic composition was initiated in central Panama at around 29 Ma, which could be linked to slab tearing during break-up of the Farallón Plate (Barat et al., 2014). The oblique subduction beneath the South American Plate was mainly completed in early Miocene times, when compressional deformation started in eastern Panama (Farris et al., 2011). This collision was synchronous with a shut-off of the main volcanic arc in Panama and southern Central America. This area was then possibly fractured into the Chocó and Chorotega blocks, which rotated in different orientations (Barat et al., 2014).

The northern part of the West Panamanian arc segment is characterized by the North Panama deformed belt. This fold-and-thrust belt trends parallel to the Caribbean coast of Panama and developed due to oroclinal bending driven by the collision of Panama with South America (E. A. Silver, Reed, Tagudin, & Heil, 1990). Mann and Corrigan (1990) relate the buckling of the arc to strike-slip segmentation, rather than to ductile deformation. Internally the North Panama deformed belt is dominated by northward propagating thrust faults and related hanging wall anticlines as shown in E. A. Silver et al. (1990). Structural and seismological studies imply that the North Panama deformed belt extends into southeastern Costa Rica (Goes, Velasco, Schwartz, & Lay, 1993; E. A. Silver et al., 1990) and is linked by the Central Costa Rican deformed belt (by other authors referred to Trans-isthmian fault system) to the Middle America trench (Marshall et al., 2000). Therefore the South Limón fold-and-thrust belt analysed in Brandes et al. (2007b, 2008). Brandes, Astorga, Blisniuk, et al., 2007) can be regarded as the western prolongation of the North Panama deformed belt.

Continued plate convergence was possibly accommodated by movements along the Panama fracture zone and in the North Panama deformed belt (Mann & Kolarsky, 1995). The collision of the southern Central American island arc with South America led to widespread uplift at around 7 Ma (Barat et al., 2014) and a progressive closure of the Isthmus of Panama (Coates, Collins, Aubry, & Berggren, 2004; Hoernle et al., 2002; Montes et al., 2012). According to Montes et al. (2012, 2015) the Central American seaway probably disappeared at around 15–13 Ma. However, there is an ongoing debate on the timing of the closure of the Isthmus of Panama. Thermochronological data reveal four major cooling events in western and central Panama at 47–42 Ma, 32–28 Ma, 17–9 Ma and 9–0 Ma, which are consistent with the presence of emergent land areas and a reduction of the circulation between the Pacific Ocean and the Caribbean Sea (Ramírez et al., 2016). But the exchange of surface water between the oceans probably stopped much later at 2.76 Ma, indicated by palaeo-ecological data (O'Dea et al., 2016).

Rockwell, Bennert, Gath, and Franceschi (2010) presented a block model that explains the youngest fault movements along the Isthmus of Panama and the internal deformation caused by the

ongoing collision of Central America and South America during the Plio-Pleistocene.

4 | BASIN SYSTEMS OF THE SOUTHERN CENTRAL AMERICAN ISLAND ARC

The basin systems of the southern Central American island arc consist of a large range of elongate trench-slope, forearc, and backarc basins. In this section we will focus on the basins of the Nicaraguan and Costa Rican arc segments (Figure 4). The sedimentary evolution of these basins is summarized in Figure 5 and completed by the sedimentary record of the West Panamanian arc segment and the western Colombian basin.

4.1 | Forearc basins

The inner forearc area of the Nicaraguan and Costa Rican arc segments comprises three major basins, which are up to 12 km deep and mainly filled with volcanoclastic deep-water sediments. From north to south these are the Sandino basin, the Tempisque basin, and the Térraba basin (Figure 1).

4.1.1 | The Sandino basin

The Sandino basin (Nicaraguan arc segment) is characterized by at least 12 km thick Upper Cretaceous to Lower Miocene deep-water deposits (Figures 4 and 5; referred to as Rivas, Brito, and Masachapa formations), unconformably overlain by up to 1 300 m thick Middle Miocene to Pleistocene shallow-water and continental deposits (Baumgartner et al., 1984; Brandes, Struss, Vandr , & Winsemann, 2007; Kolb & Schmidt, 1991; H. Krawinkel & Kolb, 1994; Kumpulainen, 1995; Kumpulainen et al., 1999; Lang, Brandes, & Winsemann, 2017; K. D. McIntosh et al., 2007; Ranero, von Huene, Flueh, Duarte, et al., 2000; Struss, Blisniuk, Brandes, Kischkies, Winsemann, 2007; Struss, Brandes, Blisniuk, & Winsemann 2007; Struss, Brandes, Vandr , & Winsemann, 2007; Winsemann, 1992). It is bounded to the south by the Hess Escarpment and probably continues up to the Gulf of Fonseca in the north. Towards the west the basin is fronted by an outer arc. Today the Nicaragua Isthmus with the Rivas anticline forms the eastern boundary, which is interpreted as the footwall block of the Mateare-Lake Nicaragua fault zone (Funk, Mann, McIntosh, & Stephens, 2009) (Figure 1). The subsidence curve during the Late Cretaceous is relatively flat, implying low subsidence rates. From 68 Ma to 30 Ma a linear subsidence trend can be observed, followed by a short pulse of very rapid subsidence at the beginning of the Late Oligocene (Struss et al., 2008). After then, there was moderate subsidence at a relatively constant rate (Figure 6). Andjic, Baumgartner-Mora, and Baumgartner (2016) and Ranero, von Huene, Flueh, Duarte, et al. (2000) both postulated a Late Eocene deformation phase in the Sandino forearc basin. However, such a deformation phase cannot be verified by field data (Kumpulainen, 1995; Lang et al., 2017; Struss, Blisniuk, Brandes, et al., 2007; Struss, Brandes, Blisniuk, et al., 2007; Struss, Brandes, Vandr , et al., 2007; Winsemann, 1992), seismic data (Stephens, 2014) and basin modeling (Struss et al., 2008). The exposed Upper Eocene coarse-grained deep-

water channel-levee deposits of the Brito Formation are rich in reworked neritic fossils, neritic carbonates, and plant remains (Struss, Blisniuk, Brandes, et al., 2007; Struss, Brandes, Blisniuk, et al., 2007; Struss, Brandes, Vandr , et al., 2007; Winsemann, 1992) and display long-wavelength bedforms that resemble hummocky cross-stratification that might be misinterpreted as shallow-water deposits. However, these long-wavelength bedforms represent deposits of antidunes created by supercritical density flows (Lang & Winsemann, 2013; Lang et al., 2017). Deposits of supercritical density flows only have recently been recognized to form an important component of marine turbidite systems (e.g. Ito, Ishikawa, & Nishida, 2014).

During the Late Miocene, flexural uplift along the present-day coastal plain started and was accompanied by a westward shift of the basin depocenter (Ranero, von Huene, Flueh, Duarte, et al., 2000). The slow uplift continues along parts of the central coast until today and thickness variations across the main anticlines indicate ongoing deformation (Struss et al., 2008). Funk et al. (2009) proposed a footwall model that suggests an extensional deformational event of Oligocene and early Miocene age, which caused uplift and folding in the Nicaraguan Isthmus and the simultaneous folding and faulting in the offshore Sandino basin by a mechanism of out-of-syncline thrusting. This links the deformation of the Sandino basin to the formation of the Nicaragua Graben.

The modelled tectonic subsidence curve (Figure 6) differs from those of other forearc basins, which are commonly characterized by initial high rates of subsidence, followed by slower subsidence rates (Xie & Heller, 2009).

4.1.2 | The Tempisque basin

The fill of the Tempisque basin (North Costa Rican arc segment) is up to 6 km thick and consists of Upper Cretaceous to Eocene deep-water deposits (Astorga et al., 1991; Calvo & Bolz, 1994; Campos, 2001; Jaccard et al., 2001; Seyfried et al., 1991; Winsemann & Seyfried, 1991; Winsemann, 1992) unconformably overlain by shallow-water carbonates of the Barra Honda platform in the northern part of the basin (Jaccard et al., 2001; Seyfried et al., 1991).

It is bounded to the north by the Hess Escarpment and by the Trans-isthmic Fault zone towards the south. Towards the west it is bounded by the outer arc (Nicoya Peninsula) and towards the east by the volcanic arc (Astorga et al., 1991; Campos, 2001; Winsemann, 1992) (Figure 1).

In the southern Tempisque basin, deep-water sedimentation prevailed until the Early Oligocene (Campos, 2001). From the Late Oligocene onwards, shallow-water and continental deposition occurred (Amann, 1993; Astorga et al., 1991; Bandini et al., 2008; Campos, 2001; Jaccard et al., 2001; H. Krawinkel, Seyfried, Calvo, & Astorga, 2000; Seyfried et al., 1991; Winsemann, 1992). The basin was probably repeatedly uplifted between the Early Paleocene to early Late Oligocene. More recent biostratigraphic data indicate that the Barra Honda platform carbonates formed during the Late Paleocene to Early Eocene (Jaccard et al., 2001), implying that the Barra Honda carbonates are partly brought onto Middle Eocene sediments, which corresponds to the Late Eocene to Early Oligocene deformation phase (Gursky, 1986; Jaccard et al., 2001; H. Krawinkel et al., 2000;

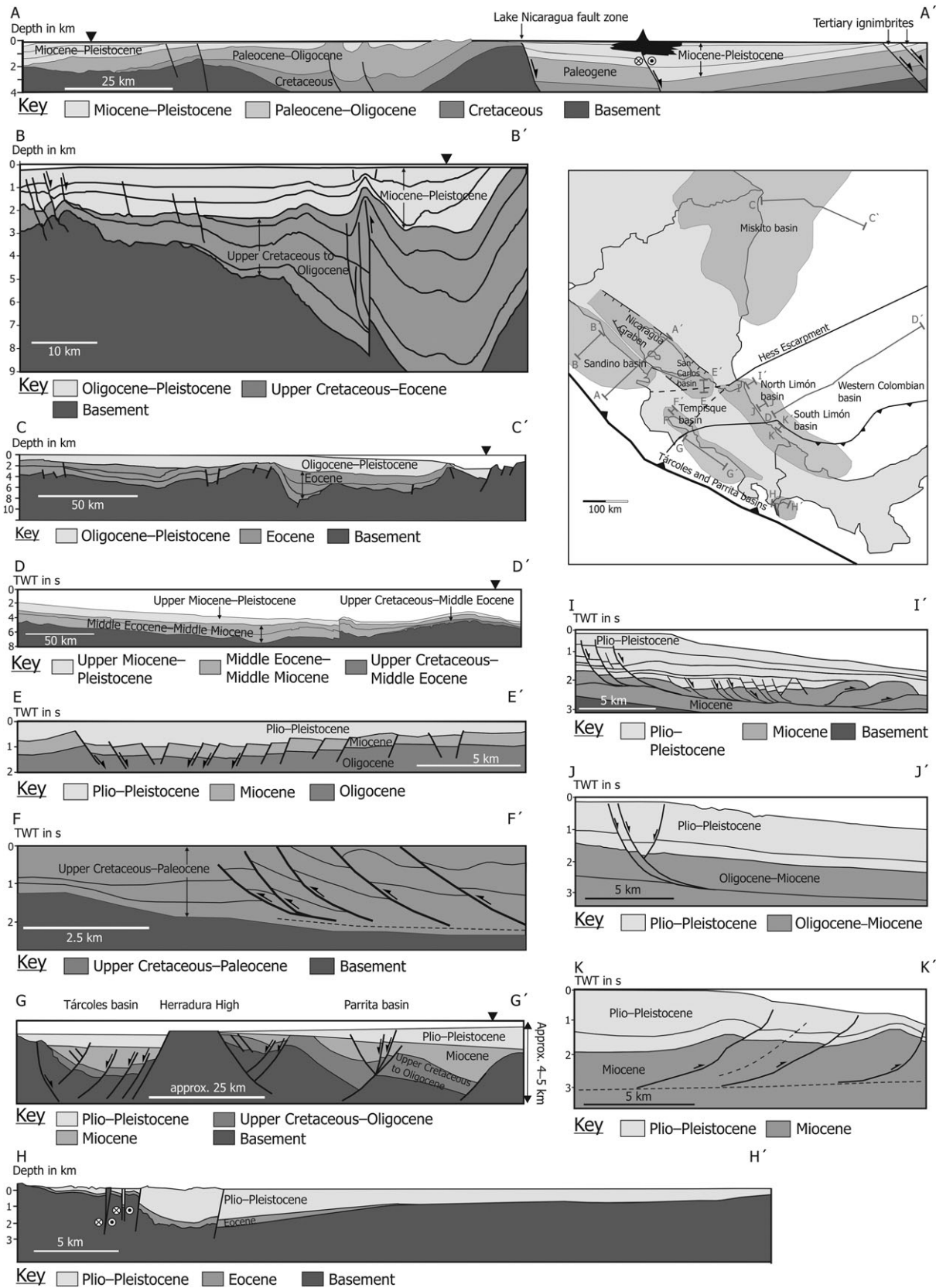


FIGURE 4 Cross-sections of the major sedimentary basins that are based on previously published sections. Section A–A', Sandino basin (modified after Funk et al., 2009); section B–B', Sandino basin (modified after Struss et al., 2008); section C–C', Miskito basin (modified after Muñoz et al., 1997); section D–D', Western Colombian basin (modified after Bowland, 1993); section E–E', San Carlos basin (modified after Astorga et al., 1991); section F–F', Tempisque basin (modified after Astorga et al., 1991); section G–G', Tárcoles and Parrita basins (modified after Campos, 2001); section H–H', Burica basin (modified after Kolarsky, Mann, & Monechi, 1995); section I–I', North Limón basin/Río San Juan Delta (modified after Brandes et al., 2007a, 2007b); section J–J', North Limón basin (modified after Brandes et al., 2007a, 2007b), section K–K', South Limón basin (modified after Brandes et al., 2008). Map is based on C. A. Dengo (2007)

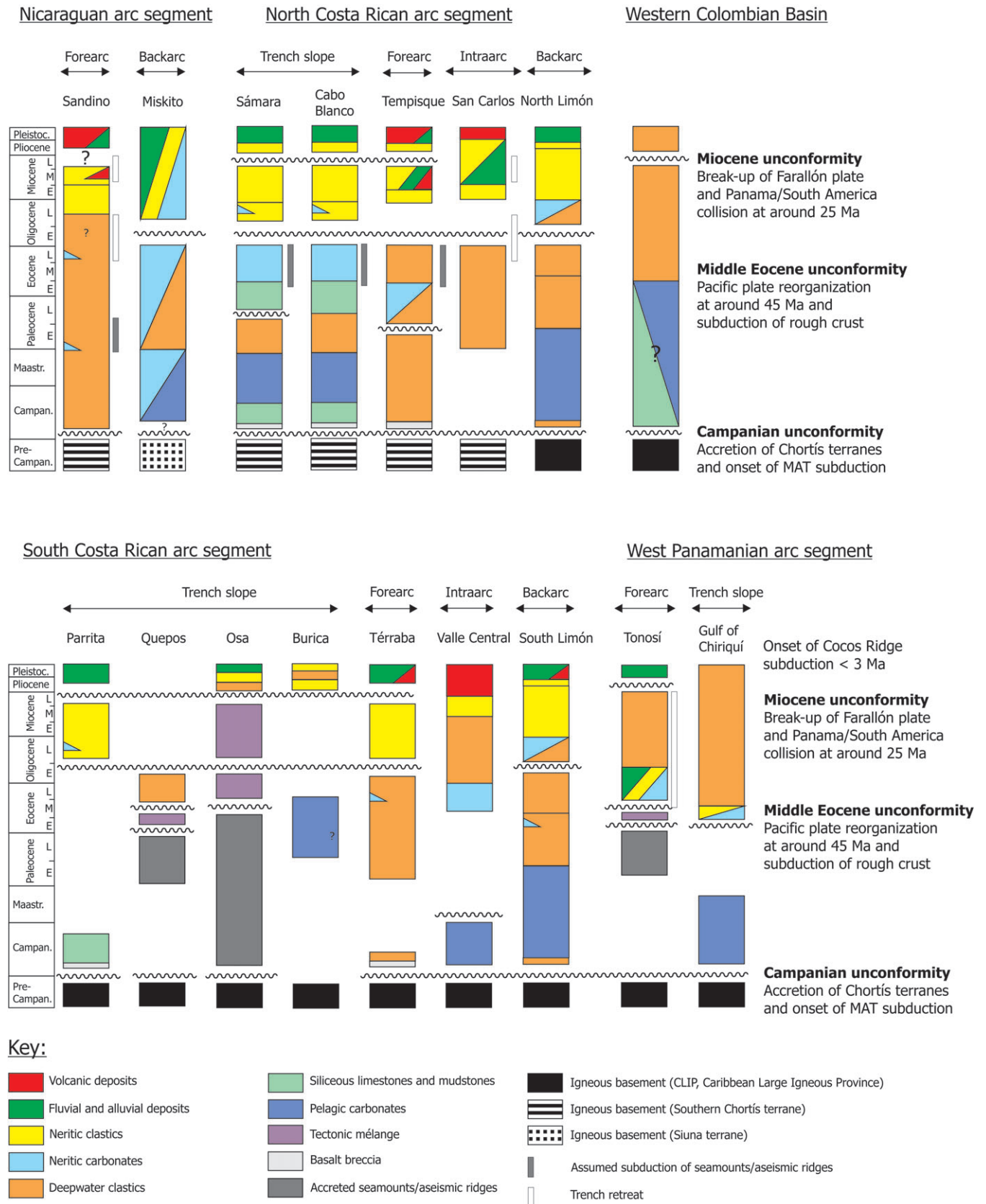
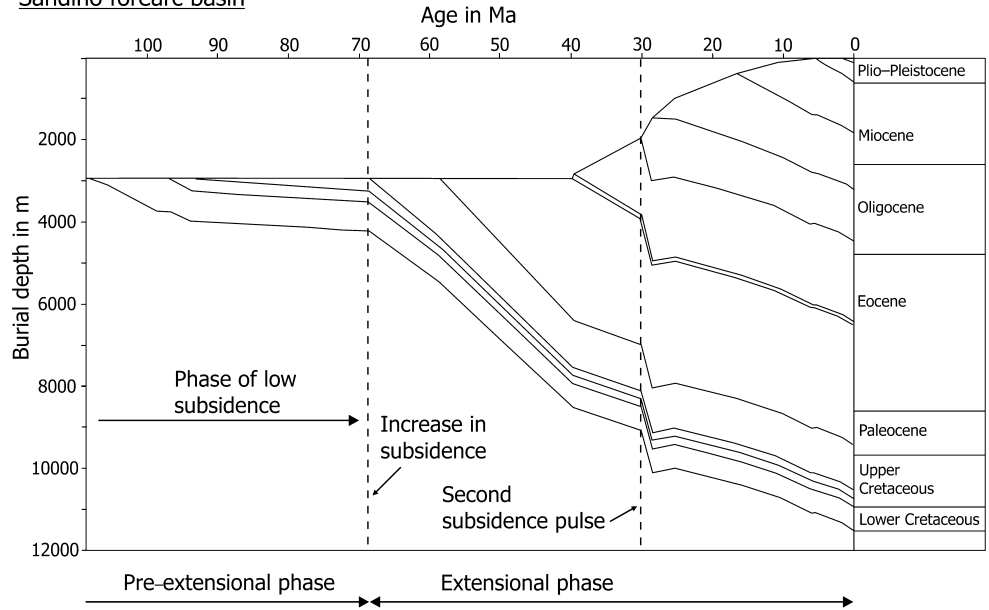
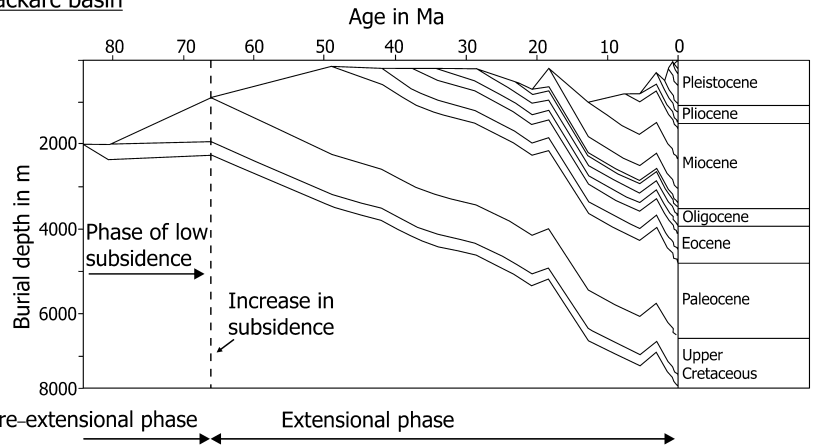


FIGURE 5 Sedimentary infill of island-arc related sedimentary basins. Modified after H. Krawinkel et al. (2000). Data are compiled from Alvarado et al. (1997), Amann (1993), Astorga et al. (1991), Baumgartner et al. (2008), Baumgartner et al. (1984), Bowland (1993), Brandes et al. (2008), Buchs et al. (2011), Campos (2001), Corrigan et al. (1990), Geldmacher et al. (2008), Hauff et al. (2000), Kolb and Schmidt (1991), Kolarsky, Mann and Monechi (1995), H. Krawinkel et al. (1999), Kumpulainen (1995), Mende (2001), Muñoz et al. (1997), Schlegel et al. (1995), Schmidt and Seyfried (1991), Struss (2008), Struss et al. (2008), Winsemann (1992), Winsemann and Seyfried (1991), Winsemann (1992), and von Eynatten et al. (1993). Campan., Campanian; E, Early; L, Late; M, Middle; Mastr., Maastrichtian; MAT, Middle America Trench; Pleistoc., Pleistocene

Sandino forearc basin



North Limón backarc basin



South Limón backarc basin

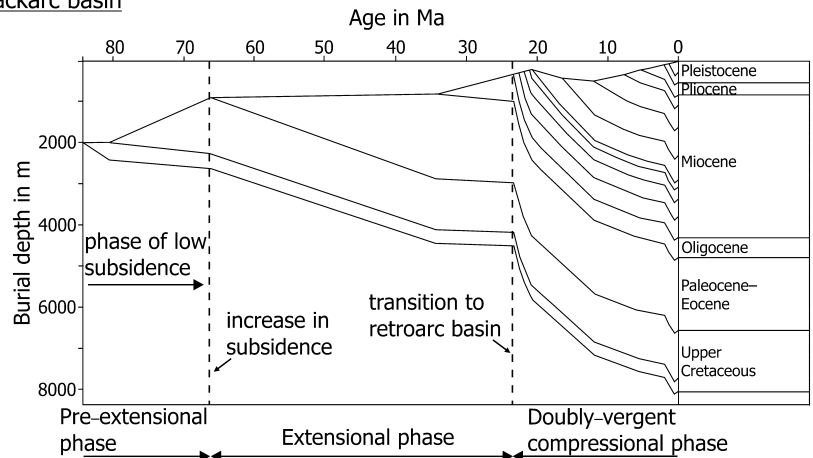


FIGURE 6 Geohistory curves of forearc and backarc basins of the Nicaraguan and North Costa Rican arc segments. The geohistory curves were extracted from 2D basin simulations published in Brandes et al. (2008) and Struss et al. (2008). The Sandino forearc basin is characterized by low subsidence during the period of 40 Myr. Since the Late Cretaceous the basin has a linear moderate subsidence with a short phase of accelerated subsidence in the Oligocene. In the North and South Limón backarc basins, subsidence started at approximately the same time as in the Sandino forearc basin. The North Limón backarc basin underwent continuous subsidence until today. The South Limón backarc basin was transformed into a retro-arc foreland basin in the Miocene as a result of the evolution of the South Limón fold-and-thrust belt. The strong increase in subsidence at around 23 Ma was probably related to the loading of the South Limón fold-and-thrust belt

Seyfried et al., 1991). The transport of the Barra Honda carbonates onto younger deep-water sediments has been explained by overthrusting (Jaccard et al., 2001). However, uplift of the outer structural high and the Barra Honda platform in combination with the subsequent gravitational sliding of large platform blocks into the deeper

part of the basin would be also a likely mechanism. The Late Eocene to Early Oligocene deformation started earlier in the northern part of the basin and propagated to the south (Campos, 2001) (Figure 4).

The different evolution of the Sandino and Tempisque forearc basin may be explained by a lower-angle subduction of oceanic crust

with a rough relief beneath the North Costa Rican arc segment (e.g. De Boer et al., 1995; H. Krawinkel et al., 2000) relative to the Sandino basin, leading to a differential uplift and subsidence of the outerarc and forearc area in northern Costa Rica. This uplift and subsidence pattern can be best explained by the subduction of a northeast–southwest trending aseismic ridge, which is consistent with modeling results of Zeumann and Hampel (2015).

4.1.3 | The Térraba basin

The Térraba basin is located on the South Costa Rican arc segment (Figure 1). It is bounded to the north by the Trans-isthmian fault system and ends to the southeast near the onland projection of the Panama fracture zone. Towards the west it is bounded by the outerarc (Osa and Burica Peninsula) and towards the east by the Talamanca Range. The fill of the Térraba basin is about 4–5 km thick and consists of Paleocene to Lower Miocene volcanoclastic turbidites, shallow-water ramp carbonates and bioclastic turbidites unconformably overlain by Miocene to Pleistocene shallow-water to terrestrial volcanoclastic sediments (Astorga et al., 1991; Corrigan et al., 1990; De Boer et al., 1995; Fisher et al., 2004; Kutterolf et al., 1997; Morell et al., 2008; Sitchler et al., 2007; Seyfried et al., 1991).

The basin is now a thrust-faulted coastal mountain range called the Fila Costeña that is dominated by southwest vergent thrusts (e.g. Gardner et al., 2013) with a minimum shortening of 17 km. The deformation is young. Sitchler et al. (2007) calculated a shortening of the inner forearc since the Middle Pliocene of about 58%. Thrusting in the Fila Costeña probably started at 1.5–1 Ma and was related to the subduction of the Cocos Ridge (Gardner et al., 2013). This assumption is supported by core data from offshore southern Costa Rica (Vannucchi, Morgan, Balestrieri, et al., 2016), indicating that sediments derived from the Talamanca Range were able to reach the trench-slope area before 1.9 Ma. Later the Fila Costeña had become high enough to block a direct transport from the Talamanca Range into the trench-slope area offshore Osa (Vannucchi, Morgan, Balestrieri, et al., 2016). There is ongoing deformation at shortening rates between 4–10 m/ky and uplift rates up to 1.5 m/ky (Fisher et al., 2004).

4.2 | Trench-slope basins

Several small trench-slope basins developed on the seaward margin of the outer structural high, which are commonly bounded by faults. Deposits of these trench-slope basins are exposed on the North Costa Rican arc segment (Sámara basin, Cabo Blanco basin) and the South Costa Rican arc segment (Tárcoles–Parrita basin, Quepos basin, Osa basins, and Burica basin; Figures 1, 4 and 5). On the Nicaraguan arc segment, an outer structural high developed during the Late Cretaceous and Paleogene (K. D. McIntosh et al., 2007; Ranero, von Huene, Flueh, Duarte, et al., 2000; Stephens, 2014; Struss et al., 2008).

Facies associations of the trench-slope basins vary considerably and strongly depend on local conditions, such as differential uplift/subsidence of the outer forearc area and size and location of feeder systems. In general basin-fills get younger towards the south. The oldest trench-slope deposits of Late Cretaceous to Eocene age are

exposed along the southwest coast of the Nicoya Peninsula (North Costa Rican arc segment), overlying pelagic deposits and ophiolitic basement rocks. These deep-water trench-slope deposits are up to 3 000 m thick. Very coarse-grained Lower Paleocene deep-water channel complexes of the Sámara trench-slope basin contain large rounded andesite boulders up to 1.5 m in diameter, indicating strong uplift of the adjacent forearc area, allowing for the transport of arc-derived material onto the trench-slope (Winsemann, 1992). The deep-water trench-slope deposits are unconformably overlain by Upper Eocene/Neogene shallow-water sediments. The lack of Lower Oligocene deposits suggests that the outerarc in north Costa Rica became uplifted and exposed again in the Early or early Late Oligocene. Subsequently only shallow-water deposits formed (Astorga et al., 1991; Baumgartner et al., 1984; Campos, 2001; H. Krawinkel et al., 2000; Lundberg, 1982; Seyfried et al., 1991; Winsemann, 1992).

During the Neogene rapidly subsiding extensional basins (Tárcoles and Parrita basins) developed (Barboza, Barrientos, & Astorga, 1995), where accommodation space was generated along listric normal fault arrays (Figures 4 and 5). These basins are bounded by major fault systems (Figure 4).

The volcanoclastic trench-slope deposits of the South Costa Rican and West Panamanian arc segments range in age from Paleocene to Plio-Pleistocene. In West Panama these are strike-slip basins controlled by trench-parallel strike-slip faults (Kolarksky, Mann, & Monechi, 1995). Initiation of strike-slip faulting and extension led to the development of rapidly subsiding basins, which were filled with shallow- and deep-water deposits (Figure 5). The highest rates of subsidence are recorded from the late Early Miocene to early Middle Miocene and the Plio-Pleistocene (e.g. Campos, 2001; Corrigan et al., 1990; Kolarksky, Mann, & Monechi, 1995; von Eynatten, Schmidt, & Winsemann, 1993). The onset of major strike-slip faulting could be related to the collision of the Central American island arc with South America and a related escape tectonics (LaFemina et al., 2009; J. L. Pindell & Kennan, 2009).

In southern Costa Rica a reversal of the subsidence pattern of the inner and outer forearc area occurred near the Miocene/Pliocene boundary. Before the Pliocene, the outerarc area of the Osa and Burica Peninsula was a topographic high that bounded the Térraba forearc basin towards the south. The Pliocene to Pleistocene marine sedimentation on the Osa and Burica Peninsula occurred in rapidly subsiding basins on a southward facing slope (Campos, 2001; Corrigan et al., 1990; Schlegel, Wortmann, Krawinkel, Krawinkel, & Winsemann, 1995; von Eynatten et al., 1993). The youngest Pleistocene complex uplift and subsidence pattern can be related to the subduction of the Cocos Ridge (cf. Vannucchi, Morgan, Balestrieri, et al., 2016; Zeumann & Hampel, 2015).

4.3 | Intraarc basins

Important features of the southern Central American land-bridge are the intraarc basins, represented by the Nicaragua Graben, the San Carlos basin and the Valle Central basin in Costa Rica (Figures 1 and 4).

The San Carlos basin can be regarded as the southeastern prolongation of the Nicaragua Graben (Figure 1). In southern Nicaragua this intraarc basin system is bounded to the west by the Mateare normal fault (Cailleau, LaFemina, & Dixon, 2007; Cowan et al., 2000; Funk et al., 2009) and the Lake Nicaragua fault zone and the Costa Rica fault zone (Stephens, 2014). Westward of these faults, the forearc area is located. The evolution of the faults in southern Nicaragua is probably related to the subduction parameters. GPS data imply that there is a northwest directed, trench-parallel movement of the forearc, relative to the Caribbean Plate, caused by strain partitioning as a consequence of oblique subduction (DeMets, 2001; Turner et al., 2007). Oblique subduction can lead to arc-parallel stretching and a forearc translation along strike-slip faults on the arc side (McCaffrey, 1996). The Nicaraguan forearc is interpreted to behave as such a rigid block (referred to as forearc sliver) that moves parallel to the arc (Turner et al., 2007). Trench-parallel movements of the forearc sliver can be compensated along arc-parallel strike-slip faults, which could act as basin bounding faults that separate the forearc basin from the arc. However, some authors state that such faults are not well developed in southern Nicaragua and therefore, LaFemina, Dixon, and Strauch (2002) introduced a model for southern Nicaragua, where the trench-parallel motion is compensated by the rotation of crustal blocks. The margin parallel shearing was accommodated in this model by bookshelf faulting along faults at high angles to the margin (LaFemina et al., 2002). However, the observations of Funk et al. (2009) do not support this idealized model in the lake area. Their study indicates that the Nicaragua depression is a strongly asymmetric half-graben, bounded by oblique normal faults. The evolution of the graben started in Late Oligocene times in the Lake Nicaragua area and extension propagated northward to the Gulf of Fonseca. Further research focused on the tectonic and volcanic activity of the Nicaragua Graben (e.g. Borgia & van Wyk de Vries, 2003; Freundt, Kutterolf, Wehrmann, Schmincke, & Strauch, 2006; LaFemina et al., 2002).

The San Carlos basin of the North Costa Rican arc segment (Figure 1) is only 4 km deep and 50 km wide. Cross-sections published in Astorga (1994) and Barboza, Fernández, Barrientos, and Bottazzi (1997) show that the basin-fill consists of up to 2 000 m Paleocene to Eocene fine-grained deep-water clastics overlain by Oligocene to Pleistocene shallow-water and continental deposits (Figure 5). A major extensional phase occurred in the Miocene (Barboza et al., 1997).

The Valle Central basin is an east–west trending strike-slip basin that is located in the Central Costa Rican arc platform (Figures 1 and 5). Rapid subsidence during the Neogene led to the deposition of up to 8 000 m thick deep- and shallow-water clastic sediments and lava flows (Campos, 2001).

4.4 | Backarc basins

Different backarc basins are developed on the Atlantic margin of the Central American land-bridge. From north to south these are: (i) the Miskito basin of the Nicaraguan arc segment; and (ii) the North and South Limón backarc basins, situated beneath the present-day coastal plain and shelf of eastern Costa Rica (Figure 1).

4.4.1 | The Miskito backarc basin

The Miskito backarc basin, also referred to as Mosquitia basin (C. A. Dengo, 2007; Sanchez et al., 2016) is underlain by the Siuna terrane (Figures 1 and 3), which is interpreted as an accreted oceanic element (Rogers, Mann, & Emmet, 2007). Towards the south the basin is bounded by the Hess Escarpment and probably extends approximately up to the Motagua-Pocholic fault zone in the north. After the terrane accretion probably a phase of post-collisional relaxation (sagging) occurred that controlled the overall subsidence pattern of sedimentary basins in the backarc area of Nicaragua (Sanchez et al., 2016). Increased extension processes probably started during the Early Eocene, leading to the development of numerous small, up to 7 km deep, basins. Older Cretaceous to Paleocene deposits are only patchily preserved (Muñoz, Baca, Artiles, & Duarte, 1997).

The Siuna Serpentinite Mélange is unconformably overlain by Lower Cretaceous (Aptian/Albian) thin-bedded hemipelagic calcareous deposits and thin-bedded volcanoclastic turbidites. The sedimentary succession shallows upwards and passes into thick-bedded Upper Cretaceous limestones in which andesitic flows are intercalated (Baumgartner et al., 2008; Muñoz et al., 1997). During the Paleocene to Middle Eocene turbidites of the Río Machuca Formation were locally deposited. On structural highs platform carbonates formed (Carvajal-Arenas, Torrado, & Mann, 2015). Within the rapidly subsiding pull-apart basins Lower Eocene to Recent deep-marine to continental clastic sediments and carbonates were deposited (Figure 4). The Lower Eocene carbonates are interbedded with lava flows and pyroclastic material. A major unconformity separates the Eocene from the Oligocene deposits (Carvajal-Arenas et al., 2015; Muñoz et al., 1997) marking a longer period of emergence. The late Cretaceous to Eocene sedimentary sequence is bounded by an upper erosional unconformity, probably indicating contemporaneous fault-block rotations and/or local uplifts (Sanchez et al., 2016). On the Nicaragua Rise, there is an important subsidence and depositional event during the Oligocene to Miocene in a westward tilted basin, possibly controlled by continued sagging. Depocenters display well-rounded shapes in map view that can be associated with a continued relaxation phase. The Upper Miocene to Pliocene sequence is thinner on the Nicaragua Rise and shows limited sediment accumulation. During the post-tectonic Pliocene-Pleistocene a stable carbonate platform established in the southwest. Since the Miocene a large delta wedge formed in the southern Miskito basin (Muñoz et al., 1997) that extends into the North Limón backarc basin (Brandes et al., 2007a, 2007b).

4.4.2 | The North and South Limón backarc basins

The North and South Limón backarc basins developed on thickened oceanic crust (CLIP) and are structurally heterogeneous. An extensional backarc basin (North Limón basin) on the North Costa Rican arc segment and a compressional retro-arc foreland area (South Limón basin) on the South Costa Rican arc segment can be observed side by side. Both basins are separated by the Trans-isthmian fault system and the Moin High (Brandes et al., 2008; Brandes, Astorga, & Winsemann, 2009) (Figure 1). The North Limón basin is bounded to the north by the Hess Escarpment and towards the west by the

volcanic arc. The South Limón basin is bounded towards the west and south by the volcanic arc. The eastward extent is defined by the Limón fold-and-thrust belt (Brandes et al., 2008; Mende, 2001).

It is assumed that the evolution of the basins began as a non-extensional backarc basin (Mende, 2001). Pre-existing oceanic crust of the Caribbean Sea was brought into a backarc position due to the formation of the southern Central American island arc.

The North and South Limón basins have a widely similar 6–10 km thick fill, which consist of 1 280 m thick late Campanian to Maastrichtian pelagic limestones and intercalated volcanoclastic rocks, overlain by ~3 000 m thick Paleocene to Lower Eocene coarse-grained volcanoclastic turbidites, debris-flow deposits and lava flows (Figure 5). Early compressional deformation during Eocene to Oligocene times caused the formation of a significant anticline (Moín High), as implied by the simultaneous deposition of 150–200 m thick shallow-water limestones on local structural highs (Amann, 1993; Brandes et al., 2009; Mende, 2001), and of 700–900 m thick hemipelagic mudstones, calcareous turbidites, and carbonate debris-flow deposits in adjacent basin areas (Mende, 2001). From the margin of the backarc area, Amann (1993) described an angular unconformity overlain by an Upper Oligocene transgressive lag deposit. The unconformity was probably caused by uplift of the island arc in combination with a major sea-level fall (Amann, 1993; H. Krawinkel et al., 2000; Seyfried et al., 1991). Subsequently carbonate ramps were built on top of the uplifted areas. During the Plio-Pleistocene, piggy-back basins of the South Limón fold-and-thrust belt were filled with shallow-marine and continental rocks (Amann, 1993; Bottazzi, Fernandez, & Barboza, 1994; Fernandez, Bottazzi, Barboza, & Astorga, 1994; Mende, 2001).

The North Limón basin-fill is undeformed and probably is still subsiding today (Mende, 2001).

In contrast, the sedimentary rocks of the South Limón basin have been deformed by NE-directed folding and thrusting (Bowland, 1993; Brandes, Astorga, Blisniuk et al., 2007; Goes et al., 1993; E. A. Silver et al., 1990). The offshore part of the deformed belt is characterized by fault-propagation folds, where changes in fault-slip are compensated by folding in the hanging wall of the thrusts (Brandes & Tanner, 2014; Suppe & Medwedeff, 1990). Thin-skinned tectonics on a sub-horizontal detachment located within the sedimentary rocks is the prevailing deformation style (Brandes, Astorga, Blisniuk, et al., 2007).

Balanced cross-sections imply 8–9 % of horizontal shortening in Plio-Pleistocene times for the external part of the fold-and-thrust belt in the offshore area (Brandes et al., 2008, 2016). If out-of-sequence thrusting took place in the internal part of the fold-and-thrust belt, the horizontal shortening could be significantly higher. Geohistory curves provide important insights into the evolution of the North and South Limón basin.

The North and South Limón basins both show a linear subsidence trend (subsidence at a constant rate) in the Paleocene and Eocene (Figure 6; Brandes et al., 2008). This is probably typical for backarc basins, which evolve behind island arcs. The geohistory curve of the South Limón basin is more complex. In contrast to the northern backarc sub-basin, there is a pronounced increase in subsidence in the South Limón basin at the beginning of the Neogene at 23 Ma (Figure 6). The shape of the curve shares some characteristics with

geohistory curves derived from foreland basins (Angevine et al., 1990), but the subsidence of foreland basins (2–3 km) is generally much lower (Xie & Heller, 2009) than the 6 km of the South Limón basin. Based on the geodynamic position, the basin can be classified as a retro-arc foreland basin (cf. DeCelles & Giles, 1996). Because foreland basins evolve on continental crust, the best classification of the South Limón basin would be the one of an inverted backarc basin on thickened oceanic crust.

4.5 | Major basin-wide unconformities

Within the basin-fills major angular unconformities are developed (Figure 5), which can be traced along the forearc and backarc areas of Nicaragua, Costa Rica, and Panama. Gursky (1986), Seyfried et al. (1991) and H. Krawinkel et al. (2000) gave a comprehensive overview of main phases of deformation and uplift in the forearc area of Costa Rica and Nicaragua, which occurred during the Campanian, Middle Eocene to early Late Oligocene and Late Miocene.

4.5.1 | Campanian unconformity

The origin of the Campanian unconformity has been a source of controversy in the past and attributed to the establishment of a new subduction zone in the rear part of the Caribbean oceanic plateau (e.g. Buchs et al., 2010, 2011; H. Krawinkel et al., 2000; Seyfried et al., 1991). The data presented by Baumgartner et al. (2008), Escuder-Viruet and Baumgartner (2014), and Geldmacher et al. (2008) imply that the collision of an island arc (Guerreo terrane) with the southern Chortís block during the Late Cretaceous most likely caused this unconformity on the North Costa Rican arc segment. The development of late Campanian reefs on top of uplifted oceanic basement rocks and an accretionary complex (e.g. Azéma et al., 1985; Bandini et al., 2008; Denyer & Baumgartner, 2006; Jacard et al., 2001; Seyfried et al., 1991) postdate this collision. Subsequently the Middle American arc-trench system established, indicated by the initiation of arc volcanism at around 75–70 Ma and the onset of volcanoclastic deposition within the forearc and backarc basins of southern Central America (e.g. Astorga et al., 1991; Buchs et al., 2010, 2011, 2013; Campos, 2001; H. Krawinkel et al., 2000; Kutterolf et al., 1997; Seyfried et al., 1991; Winsemann, 1992).

4.5.2 | Middle Eocene to Oligocene unconformity

The Eocene to Oligocene unconformity can be best observed on the Nicoya Peninsula, where the unconformity deeply cuts into pre-Campanian rocks and uplifted Upper Cretaceous to Eocene deep-water sediments (e.g. Astorga et al., 1991; Baumgartner et al., 1984; Calvo, 1998; H. Krawinkel et al., 2000; Seyfried et al., 1991; Winsemann, 1992). As pointed out earlier this unconformity possibly resulted from the subduction of a northeast-southwest trending aseismic ridge, which caused a complex pattern of uplift and subsidence in the forearc area of the North Costa Rican arc segment.

Along the South Costa Rican and West Panamanian arc segments seamount accretion/subduction during the Eocene probably caused strong uplift and regional deformation (Buchs et al., 2011; Hauff et al., 2000; H. Krawinkel et al., 2000; Seyfried et al., 1991). The onset of oblique collision between Panama and South America at the

end of the Middle Eocene led to transtensive and rotational deformation in central Panama and probably caused the formation of the structural Chocó and Chorotega blocks, which rotated in different orientations (Barat et al., 2014).

As in the forearc basins, an important Middle Eocene to Late Oligocene unconformity is developed in the backarc area (e.g. Amann, 1993; Bowland, 1993; Brandes et al., 2009; Carvajal-Arenas et al., 2015; Mende, 2001; Muñoz et al., 1997). During this contractional phase the Moín High formed (Brandes et al., 2009).

The overall controlling factor for the Middle Eocene to Oligocene deformation phase probably was the Middle Eocene plate tectonic reorganization in the Pacific region, which led to major changes in subduction parameters along the Middle America trench (Buchs et al., 2011).

4.5.3 | The Miocene unconformity

The Miocene unconformity in the forearc basins is probably a composite result of (i) low-angle subduction of young oceanic lithosphere with rough relief on the downgoing slab; (ii) the accretion of seamounts and aseismic ridges (e.g. Buchs et al., 2011; De Boer et al., 1995; Hauff et al., 2000; H. Krawinkel et al., 2000), probably related to the break-up of the Farallón Plate at around 25 Ma and a related major change in plate vectors; and (iii) the onset of compressional deformation at around 25–23 Ma related to the completed oblique collision of Panama with South America between (Barat et al., 2014; Bowland, 1993; Farris et al., 2011; Winsemann, 1992).

In the forearc area of Costa Rica and western Panama small rapidly subsiding extensional basins formed during this time span that are bounded by fault systems (Amann, 1993; Campos, 2001; Kolarsky, Mann, & Monechi, 1995), indicating lateral movements along major strike-slip faults. These movements could be an effect of a forearc sliver or are a consequence of Middle Miocene lateral escape tectonics of the Panama block that was postulated by J. L. Pindell and Kennan (2009). In eastern Panama pop-up basins formed (Barat et al., 2014).

The Miocene unconformity also corresponds with uplift of southern Central America and increased volcanic activity. In response a thick prograding delta and turbidite fan system was deposited in the offshore backarc area of Costa Rica and the western Colombian basin (Bowland, 1993; Brandes et al., 2007a, 2007b; Muñoz et al., 1997).

5 | DISCUSSION

The structural and sedimentary evolution of the basin systems indicate that the development of the southern Central American island arc can be subdivided into three main stages (Figure 7):

1. A pre-extensional stage in the Campanian (Figure 7a).
2. The development of a tholeiitic island arc during the Maastrichtian to Paleogene in response to the subduction of the Farallón Plate beneath the thickened Caribbean plate. This extensional stage is characterized by rapidly subsiding sedimentary basins (Figure 7b), in which large amounts of volcanoclastic material were deposited.

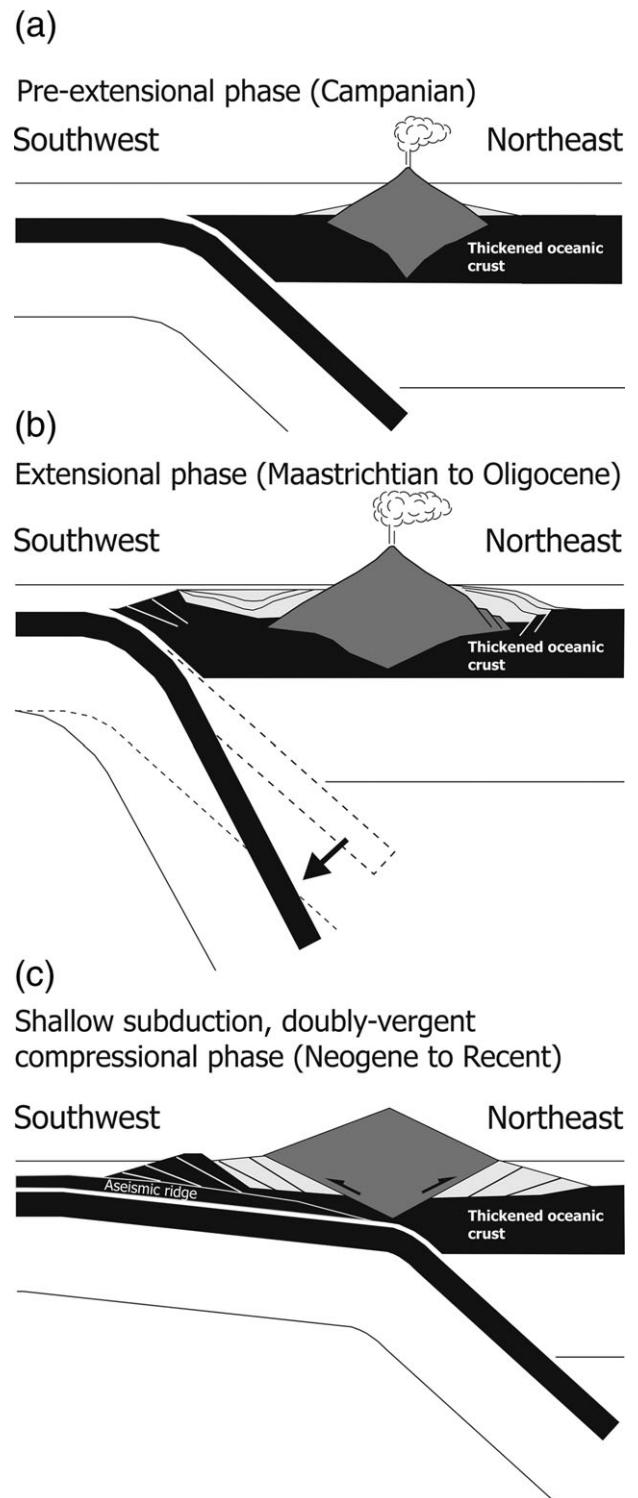


FIGURE 7 Schematic sketch of the island arc evolution. (a) The evolution of the island arc started with a pre-extensional arc in the Campanian. (b) Extensional stage during the Maastrichtian to Oligocene, characterized by rapidly subsiding sedimentary basins. Subduction erosion, slab rollback and resulting trench retreat are important drivers for basin subsidence in this phase. (c) During the Neogene, the southern part of the arc was shortened and transformed into a compressional arc. This transformation probably started already in the Miocene and the young Pleistocene subduction of the Cocos Ridge contributed to the contraction but was not the primary driver

3. The development of the South Costa Rican arc segment into a compressional arc (subduction orogen) during the Neogene (Figure 7c).

5.1 | The pre-extensional Late Cretaceous island arc

The pre-extensional stage is characterized by a phase of terrane accretion along the continental crust of the Chortís Block and the CLIP plateau. These accreted terranes and the CLIP basalts form the forearc and backarc basement of the southern Central American island arc.

The sedimentary record of the pre-extensional island arc comprises late Campanian hemipelagic calcareous deposits with some intercalations of rock-fall breccias and conglomerates. Clasts consist of partly well-rounded and weathered serpentinite and basalt blocks, reworked shallow-water carbonates and neritic fossils. Up-section thin-bedded volcanoclastic turbidites are intercalated (Astorga et al., 1991; Baumgartner et al., 1984; Calvo, 1998, 2003; Campos, 2001; Lundberg, 1982; Seyfried et al., 1991; Seyfried & Sprechmann, 1986; Winsemann, 1992).

5.2 | The extensional Maastrichtian to Paleogene evolution of the southern Central American island arc

Between 70 Ma and 60 Ma high sediment input started in the forearc basins, which is recorded by the rapid development of a tholeiitic island arc during the Maastrichtian to Paleogene (Baumgartner et al., 1984; Campos, 2001; Kumpulainen et al., 1999; Seyfried et al., 1991; Struss et al., 2008; Winsemann, 1992; Winsemann & Seyfried, 1991) that was accompanied by significant subsidence both in the forearc (Struss et al., 2008) and backarc area (Brandes et al., 2008) (Figure 6).

In the forearc area subduction erosion is very important (Vannucchi, Morgan, Balestrieri, et al. 2016; Vannucchi, Morgan, Silver, et al., 2016; Vannucchi, Scholl, Meschede, & Mcdougall-Reid, 2001), whereas slab rollback and trench retreat can affect both the forearc and backarc. Repeated phases of uplift and subsidence in the forearc area since the Paleocene can be best explained by changes in the subduction parameters. Uplift followed by subsidence can be a consequence of the subduction of aseismic ridges (Sak, Fisher, & Gardner, 2004; Zeumann & Hampel, 2015) or the accretion of oceanic plateaus (Walther et al., 2000) and oceanic islands (Buchs et al., 2011; H. Krawinkel et al., 2000).

Slab rollback can lead to significant changes in the stress field of an island arc. We used the term trench retreat for a seaward migration of the trench as used by e.g. Uyeda and Kanamori (1979). Experiments carried out by Funiello, Faccenna, Domenico, and Regenauer-Lieb (2003) indicate that trench retreat is an episodic process, controlled by the interaction of the slab and the mantle, leading to slab bending. It is a potential mechanism for backarc extension and backarc basin formation (Flower, Russo, Tamaki, & Hoang, 2001; Uyeda & Kanamori, 1979). Yamaji (2003) showed that the stress regime in the Ryukyu arc changed simultaneously in the forearc and backarc from compression to extension due to rollback. Slab rollback can lead to a significant trenchward migration of the volcanic chain

(Cadoux, Missenard, Martinez-Serrano, & Guillou, 2011; Faccenna, Funiello, Giardini, & Lucente, 2001; Ferrari, Petone, & Francalanci, 2001; Yamaji, 2003) and can cause decompression melting in the upper mantle (Schellart, 2010). A decrease in distance between source and sink and increased volcanism due to decompression melting would be a suitable explanation for the high sediment input into the forearc basins between 70 Ma and 60 Ma.

5.2.1 | Basin systems of the Nicaraguan arc segment

According to Walther et al. (2000) an oceanic plateau was subducted/accreted along the Nicaraguan arc segment during the latest Cretaceous and Paleocene. This collision is assumed to have led to a subsequent jump of the subduction zone by about 70 km to the southwest during the Eocene. Evidence is given by a mantle sliver in the subsurface of the Sandino basin, which is interpreted as a relic of a former subduction zone. There is no related perturbation in the geohistory curve (Figure 6). This implies that the observed mantle sliver below the Sandino forearc basin belongs to the older subduction zone, along which the Guerrero arc has been accreted to the Chortís block (e.g. Mann et al., 2007; Rogers, Mann, & Emmet, 2007) and would support the interpretation that remnants of the Guerrero arc form the basement of the Sandino basin. However, the input data for the early basin history are limited and therefore the modelled geohistory curve is uncertain for the early basin evolution.

The decrease in subsidence of the Sandino basin during the Late Eocene (Figure 6) could be explained with the model of Walther et al. (2000), where a slab break-off and the establishment of a new subduction zone further westward occurred, after the docking of an oceanic plateau. During the re-establishment of the subduction zone, a period of reduced subsidence prevailed. The deposition of very coarse-grained deep-water channel-levee complexes during the Late Eocene (Brandes, Struss et al., 2007; Kumpulainen, 1995; Struss, Blisniuk, Brandes, et al., 2007; Struss, Brandes, Blisniuk, et al., 2007; Struss, Brandes, Vandr , et al., 2007; Winsemann, 1992) could therefore be the result of the arc shift combined with reduced subsidence and a global sea-level fall. Evidence for another tectonic signal in the forearc area of southwest Nicaragua, which was probably related to slab detachment and subsequent trench retreat, is given by an increased subsidence pulse during the Early Oligocene at around 30 Ma and persisting deep-water sedimentation until the Early Miocene (Masachapa Formation; Struss et al., 2008; Figure 6). The observed Eocene extensional processes in the Miskito backarc basin, the related high sediment thickness (Mu oz et al., 1997) and the initial formation of the Nicaragua Graben during the Late Oligocene (Funk et al., 2009) could be also related to this trench retreat. A phase of crustal stretching affected the Miskito basin during the Oligocene to Miocene (Carvajal-Arenas et al., 2015; Mu oz et al., 1997), which could be related to trench retreat. On the Nicaragua Rise, increased subsidence during the Oligocene to Miocene was possibly controlled by continued sagging (Sanchez et al., 2016).

5.2.2 | Basin systems of the Costa Rican arc segments

The first important tectonic event in the forearc area of the North Costa Rican arc segment was most probably related to the

subduction of an aseismic ridge in front of the North Costa Rican arc segment during the Early Paleocene. The subduction of this ridge has caused strong uplift of the accretionary wedge and the Tempisque forearc basin in northern Costa Rica. Large resedimented shallow-water carbonate blocks, up to 150 m in diameter, embedded in Lower Paleocene deep-water turbidites of the Sandino forearc basin and the Tempisque forearc basin (Winsemann, 1992) indicate a related collapse of the Upper Campanian El Viejo carbonate platform (Jaccard et al. 2001) and vertical movements along the Hess Escarpment (Winsemann, 1992).

During the Early Paleocene the strong uplift of the inner forearc area possibly enabled the deposition of a thick and very coarse-grained volcanoclastic channel-lobe complex in the Sámara trench-slope basin on the western Nicoya Peninsula (Figure 1) (Lundberg, 1982; Winsemann, 1992) and the subsequent formation of the Late Paleocene to Early Eocene Barra Honda carbonate platform, which unconformably rests on deformed Upper Cretaceous to Paleocene deep-water sediments (Jaccard et al., 2001).

The subsequent Late Eocene to Early Oligocene uplift of the outer forearc area and the related collapse of the Barra Honda

carbonate platform probably reflect the onset of a renewed subduction of rough crust or an aseismic ridge that triggered the sliding of large platform blocks from the elevated basin margin over younger deposits in the deeper part of the basin (Figure 8). The different onset of the Late Eocene to Early Oligocene deformation and a related complex uplift and subsidence pattern imply an oblique subduction of this ridge.

The tectonic signal in the backarc area is less pronounced. Mende (2001) observed bimodal volcanism with dyke intrusions and the formation of pillow lavas that he interpreted as an indicator of a Paleocene to Eocene rifting event. The observed volcanism and subsidence are most likely the result of minor crustal stretching and extension with stretching factors below the typical rift values.

A Paleocene–Eocene extensional event in the South Limón backarc basin (Mende, 2001) possibly corresponds to the observed Eocene rifting processes in the Miskito backarc basin in Nicaragua (Muñoz et al., 1997). However, this extensional event is not visible in the geohistory curve of the North and South Limón basin and therefore was probably not very pronounced (Figure 6; Brandes et al., 2008). As in Nicaragua, the Neogene Costa Rican and

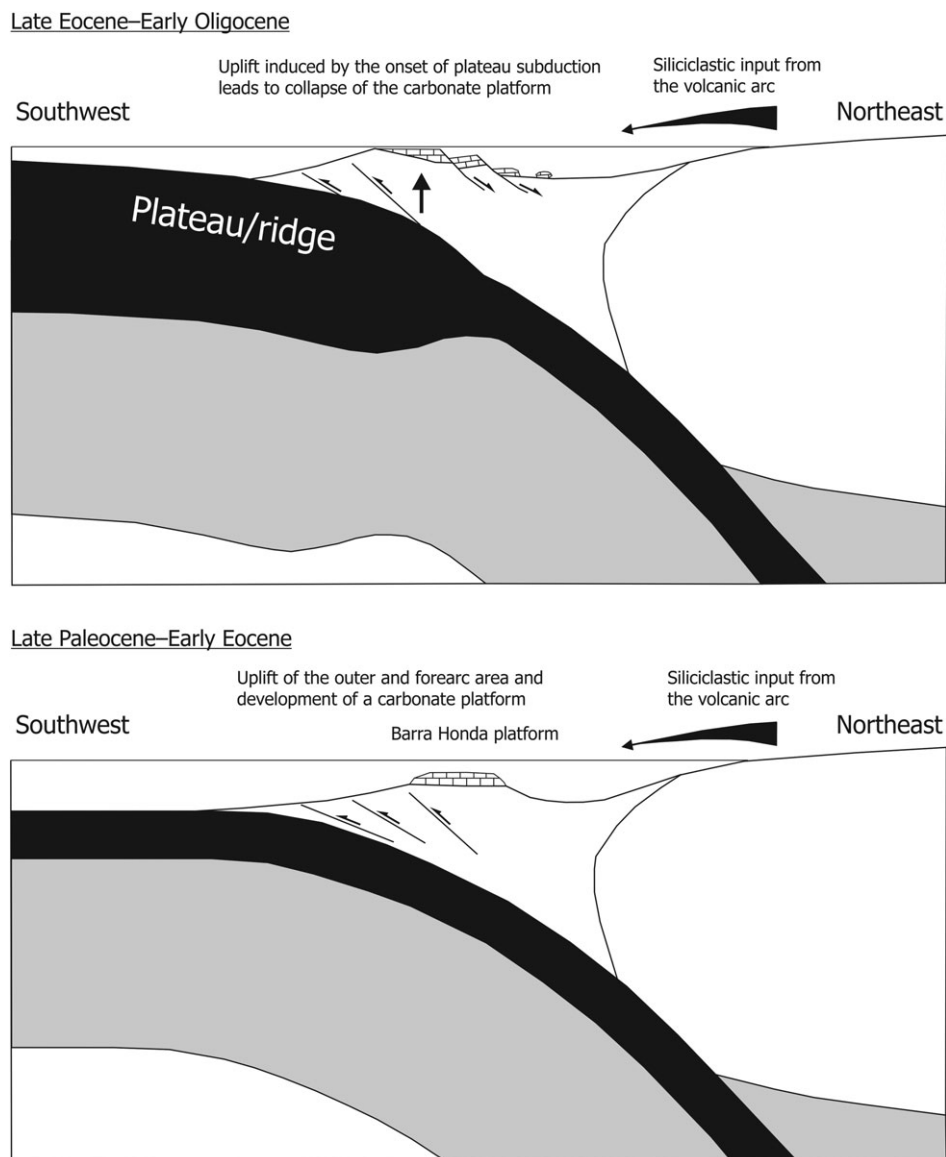


FIGURE 8 The subduction of oceanic plateaus or aseismic ridges caused strong uplift of the outer arc and the Barra Honda platform. Due to the uplift, the platform was mechanically destroyed and large shallow-water carbonate blocks became transported into the forearc basins, intercalated with clastic turbidites and rest on top of younger deposits. Subsequent trench retreat occurred and was an important driver for basin subsidence

Panamanian volcanic arc shifted towards the west, pointing to a trench retreat (Buchs et al., 2011; Hoernle et al., 2008). This implies that both the forearc and the backarc area of the southern Central American island arc were affected by ongoing slab detachment and subsequent trench retreat as a driver for the subsidence.

5.3 | The Neogene evolution of the island arc and the development of the southern Costa Rican arc segment into a subduction orogen

5.3.1 | Forearc and intraarc basins of the Nicaraguan and Costa Rican arc segments

A second trench retreat event probably occurred in Miocene times. Modeling results of Cailleau and Oncken (2008) imply that today's arc-trench geometry cannot explain the Middle Miocene deformation pattern in the Sandino forearc basin. Field evidence for a Miocene trench retreat is given by the trenchward shift of the volcanic arc (Ehrenborg, 1996; Mann et al., 2007; Plank, Balzer, & Carr, 2002) and the onset of extensive crustal extension during the Late Miocene in the intraarc basins of Nicaragua and northern Costa Rica (e.g. Barboza et al., 1997; Funk et al., 2009). Today the crust has a reduced thickness below the depression in central Nicaragua. Directly beneath the Nicaraguan arc it has a thickness of only (24.6 ± 3.5) km (MacKenzie et al., 2008), which is most likely the result of the localized Neogene extension and graben formation. A phase of increased subsidence from 18 Ma to 13 Ma in the North Limón backarc basin and the Early Miocene phase of crustal stretching in the Miskito basin described by Muñoz et al. (1997) are possibly also related to this trench retreat. Striking evidence for a Miocene trench retreat also comes from the distribution of volcanic rocks. Exposed rocks from the volcanic arc in Nicaragua and Costa Rica are Oligocene to Pleistocene in age, getting successively younger towards the west (Appel et al., 1994; Ehrenborg, 1996; Hoernle et al., 2008; Plank et al., 2002), therefore indicating trench retreat during the Neogene. Remains of the older Late Cretaceous and Paleogene volcanic arc are not exposed and are either eroded or buried underneath younger deposits. A broad temporal change in magma compositions from tholeiitic to calc-alkaline occurred in the Oligocene (*ca* 30 Ma; Abratis & Wörner, 2001; Alvarado et al., 1992; De Boer et al., 1995). Between the Middle and Late Miocene a change from low-K calc-alkaline towards high-K calc-alkaline occurred (Gazel et al., 2009). During this time seamounts derived from the Galápagos hotspot were accreted along the Pacific margin of Central America (Alvarado et al., 1992; Hauff et al., 2000; Hoernle et al., 2002, 2004; Wegner et al., 2011).

The main controlling factor for the Neogene trench retreat was probably the break-up of the Farallón Plate into the Cocos and Nazca Plate at around 25 Ma (Mann et al., 2007). Differential subsidence of the forearc area possibly caused by fault activity along the Hess Escarpment and Trans-isthmian fault system as well as variations in subduction erosion due to seafloor roughness (Fisher, Gardner, Marshall, Sak, & Protti, 1998).

5.3.2 | Outerarc basins of the Costa Rican and West-Panamanian arc segments

Strike-slip movements and the increase in subduction erosion probably led to the formation of new basins in the outerarc area of Costa Rica and Panama (e.g. Kolarsky, Mann, & Monechi, 1995; Vannucchi, Morgan, Balestrieri, et al., 2016; Vannucchi, Morgan, Silver, et al., 2016; Vannucchi et al., 2001). Alvarado (2007) described a landward shift of the central and north Costa Rican volcanic arc during the Early Miocene as a result of the subduction of young lithosphere. These basins are relatively small, represent fault-bounded graben structures and are filled with deep-water or neritic siliciclastic deposits (Campos, 2001; Corrigan et al., 1990; Kolarsky, Mann, & Monechi, 1995; H. Krawinkel & Kolb, 1994; H. Krawinkel et al., 1999; Ranero, von Huene, Flueh, Weinrebe, et al., 2000; Schmidt & Seyfried, 1991; Seyfried, Krawinkel, & Aguilar, 1994; von Eynatten et al., 1993). The flooding of the Oligocene unconformity is well documented in the coastal areas of northern and central Costa Rica, indicating the development of plains of marine erosion and rapidly receding cliffs (Figure 5; Schmidt & Seyfried, 1991; Seyfried et al., 1991; H. Krawinkel & Kolb, 1994; H. Krawinkel et al., 2000). By the end of the Late Miocene most basins of the northern arc segments were completely filled and a third important unconformity formed that can be traced in the entire forearc area of Nicaragua and Costa Rica. In the outerarc area of the South Costa Rican arc segment (Osa and Burica Peninsula) and the West Panamanian arc segment (Gulf of Chiriquí) the highest rate of subsidence is recorded from the late Early Miocene to early Middle Miocene and the Plio-Pleistocene (Figure 5; Campos, 2001; Collins, Coates, Jackson, & Obando, 1995; Corrigan et al., 1990; Kolarsky, Mann, & Monechi, 1995; Schlegel et al., 1995; Vannucchi, Morgan, Balestrieri, et al., 2016; Vannucchi, Morgan, Silver, et al., 2016; von Eynatten et al., 1993). A reversal in the subsidence pattern of the inner and outer forearc area occurred near the Miocene/Pliocene boundary. Shallow marine and terrestrial sediments of the Térraba forearc basin indicate a complete filling by the Late Miocene (Corrigan et al., 1990; Kutterolf et al., 1997; H. Krawinkel et al., 2000; Seyfried et al., 1991). The Pliocene to Pleistocene marine sedimentation on the Osa and Burica Peninsula occurred in rapidly subsiding outerarc basins. Before the Pliocene, the outerarc area of Osa and Burica was a topographic high that bounded the Térraba forearc basin towards the southwest. On the Osa Peninsula, the formation of coarse-grained cone-shaped deltas indicates rapid drowning during the Pliocene (von Eynatten et al., 1993). On the Burica Peninsula an at least 3 500 m thick Plio-Pleistocene deep- to shallow-water trench-slope succession was deposited (Corrigan et al., 1990; Schlegel et al., 1995). In the Gulf of Chiriquí (offshore southwest Panama) up to 2 000 m thick sediments were deposited during the Plio-Pleistocene in a fault-bounded basin, which probably consists of deep-water turbidites (Kolarsky, Mann, & Monechi, 1995). Different studies have demonstrated the effects of subduction erosion along the Pacific margin of Costa Rica (Meschede, Zweigel, Frisch, & Völker, 1999; Ranero & von Huene, 2000; Vannucchi et al., 2001; Vannucchi, Morgan, Balestrieri, et al., 2016; Vannucchi, Morgan, Silver, et al., 2016). It is well known that the seafloor roughness (e.g. E. Silver, et al., 2004) has a strong influence on

vertical movements of the upper plate (Sak et al., 2009). Crust with a rough morphology, entering the subduction zone initially caused uplift of the upper plate, followed by increased subsidence due to enhanced subduction erosion (Sak et al., 2004; Zeumann & Hampel, 2015). This could explain the complex young subsidence and uplift history that is documented from the outerarc and the inner forearc at Osa.

5.3.3 | Backarc basins of the Costa Rican arc segments

The backarc basins of the Costa Rican arc segments differ in their Neogene evolution and their structural style. The North Limón basin (north of the Trans-isthmian fault system) still underwent subsidence as the geohistory curve shows (Brandes et al., 2008). The last 18 Myr are characterized by a linear subsidence trend, interrupted by a short pulse of uplift at around 4 Ma. The slight increase in subsidence at 18 Ma could be related to the Miocene trench retreat (cf. Cailleau & Oncken, 2008). In contrast, in the South Limón basin (Figure 6) there is an increase in subsidence at 23 Ma (Brandes et al., 2008), which probably indicates the point when the backarc basin was transformed into a retro-arc foreland basin. The rapid subsidence can be interpreted to have resulted from crustal loading due to the evolution of the South Limón fold-and-thrust belt. Farris et al. (2011) concluded that the tectonic collision between Panama and South America began at 25–23 Ma. The timing fits well to the onset of compressional deformation in eastern Panama, which possibly records the completion of oblique subduction between Panama and South America (cf. Barat et al., 2014; Farris et al., 2011). However, there is also the view that the collision between Panama and South America started around 14.8–12.8 Ma (Coates et al., 2004). The early onset at 25–23 Ma is near the time when the rapid subsidence in the South Limón basin started and persisting until today. It implies a strong connection of both the formation of the Panama deformed belt and the increase in subsidence in the South Limón basin. At around 25 Ma the break-up of the Farallón Plate into the Cocos and Nazca Plate occurred (Mann et al., 2007). This could also have influenced the subsidence in the South Limón basin. Therefore, the observed change in the subsidence pattern at around 23 Ma cannot be related to the subduction of the Cocos Ridge. In addition, MacMillan et al. (2004) state that important geodynamic factors like the oblique subduction of the Nazca Plate, the passage of the Nazca–Cocos–Caribbean triple junction and the subduction of rough crust shaped the southern Costa Rican arc segment and occurred before the onset of subduction of the Cocos Ridge. The increase of subsidence at around 2 Ma is probably related to the ongoing propagation of the Limón fold-and-thrust belt (Brandes et al., 2008), which possibly was enhanced by the subduction of the Cocos Ridge (cf. Morell, 2016; Morell, Gardner, Fisher, Idleman, & Zellner, 2013; Morell et al., 2012).

In contrast to the Nicaraguan and North Costa Rican arc segments, the South Costa Rican arc segment is characterized by deformed forearc and backarc basins. Integrating surface (Figure 9a) and subsurface data (Figure 9b), it is very likely that the geometry of this part of the island arc is very similar to that of doubly-vergent and asymmetric orogens. Recent work shows that doubly-vergent thrust wedges are a common feature of island arcs as shown by the work of

ten Brink, Marshak, and Granja Bruna (2009) and Kroehler et al. (2011). Especially the study of Kroehler et al. (2011) shows this doubly-vergent structure based on earthquakes hypocenters. All structural elements predicted by the models for doubly-vergent orogens as shown in Willett, Beaumont, and Fullsack (1993) can be found in the island arc segment of southern Costa Rica (Brandes & Winsemann, 2007). The deformed forearc can be regarded as pro-wedge and the Limón fold-and-thrust belt as retrowedge (Figure 9). The Talamanca Range in between can be interpreted as the central uplifted block. Similar to the model of Willett et al. (1993) this asymmetry is related to the polarity of subduction. In addition to the double vergence and the asymmetry, the model of Willett et al. (1993) also predicts a system of conjugate shear zones, which separates the central part of the orogen from the pro- and retrowedge. The northwest–southeast trending thrusts running parallel to both sides of the most elevated part of the Talamanca Range can be interpreted as part of such a step-up shear zone, similar to a subduction orogen like the Andes (Brandes & Winsemann, 2007). Based on its structure and geometry, the Talamanca Range can be compared to the uplifted triangular block in the orogen model of Willett et al. (1993) (Brandes & Winsemann, 2007). In addition, the Willett et al. (1993) model has a singularity, where the incoming plate detaches and subducts. The conjugate shear zones root in this singularity, consequently, the deformation occurs in the hanging wall. As shown in Fisher et al. (2004) and Morell et al., (2012, 2013), the leading edge of the Cocos Ridge is approximately below the center of the Talamanca Range and could represent such a singularity.

The Solomon Islands can serve as an analogue for the bivergent structure of the southern Central American island arc. Earthquake hypocenters illuminate the subducting slabs below the arc and seismic lines show the bivergent structure with two thrust systems that propagate into opposing directions (Mann & Taira, 2004). In case of the Solomon Islands, the doubly-vergent structure is caused by thickened crust entering from one side, forcing a flip in the subduction zone. However, data from the northeastern Caribbean region and sandbox models imply that a backarc fold-and-thrust belt can be regarded as retrowedge and a reversal of the subduction polarity or a mantle-driven trenchward motion of the overriding plate is not required to produce this structure (ten Brink et al., 2009). Grindlay, Mann, Dolan, and van Gestel (2005) show a comparable situation with a doubly-vergent arc structure at the Puerto Rico–Virgin Islands margin. Here, this doubly-vergent structure is produced by the thick Bahamas platform that entered the subduction zone, analogous to the situation at the Solomon Islands. This underlines the importance of the subduction of thick crust for the development of a doubly-vergent structure in an island arc setting.

Despite the formation of the Panama orocline, low-angle subduction of the Cocos Plate and the related basal traction also offers a possible driving mechanism for the evolution of the doubly-vergent mountain chain in southern Costa Rica. De Boer et al. (1995) proposed a decrease in the subduction angle since Late Miocene times. A transition from marine to continental deposits in the South Limón basin occurred at the end of the Late Miocene and fits to a phase of uplift that can be interpreted as the consequence of shortening and fold-belt formation. However, the dip angle of the slab in southern

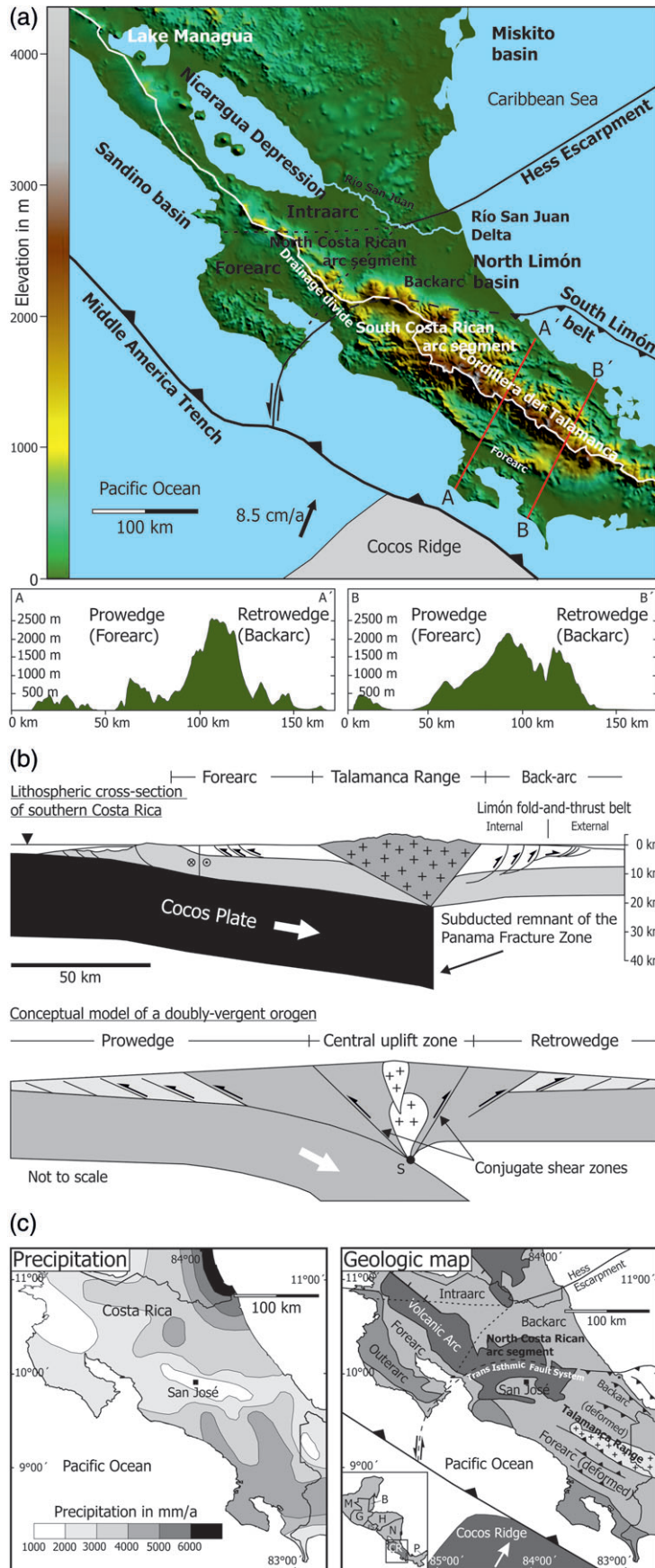


FIGURE 9 Doubly-vergent orogen of Costa Rica. (a) Digital elevation model of Costa Rica (based on GTOPO30 data, <http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html>) with extracted topographic profiles, indicating the surface expression of the doubly-vergent orogen. (b) Cross-section of the island arc showing the doubly-vergent orogen (modified after Bottazzi et al., 1994; Fisher et al., 2004; Fernandez et al., 1997; McClay & Whitehouse, 2004). (c) Distribution of the modern precipitation in Costa Rica and a geological map of Costa Rica (based on Portig, 1976), showing the two opposing thrust belts and the exposed granites in between. Deepest exposures of the granites coincide with highest rainfall areas

Central America is still under debate. For central Costa Rica, Zhu et al. (2009) derive an average dip angle of the Cocos Plate of 9.0°–9.1°, based on seismic data. Peacock et al. (2005) showed a slab angle

of 45° under central Costa Rica and a dip of 30° below southern Costa Rica. Based on earthquake hypocenters, Protti et al. (1995a) assume a flat slab below southern Costa Rica. More recent seismic

studies do not indicate flat subduction and propose dip angles of up to 80° present at least to a depth of 70–100 km (e.g. Arroyo, Greve-meyer, Ranero, & von Huene, 2014; Dzierma, Rabbel, & Thorwart, 2011; Vannucchi, Morgan, Silver, et al., 2016). Below the Talamanca area, Lücke and Arroyo (2015) assume a slab with a 50° in angle to a depth of 70 km and 64° for the final section to the depth of 200 km based on gravimetric data.

Another factor for the development of the doubly-vergent structure is the rigidity of the arc. In the work of ten Brink et al. (2009) it is shown that a doubly-vergent thrust system in an island arc setting develops in case that the island arc is relatively rigid. A rigid arc allows an effective stress transmission from the subduction zone into the backarc area (ten Brink et al., 2009). This possibly was enhanced by the thickened oceanic crust of the Caribbean Plate. With the high thickness this plate probably behaves like a continent leading to the formation of a mountain belt above the subduction zone, similar to the Andes further south.

The Plio-Pleistocene deformation of the southern Costa Rican arc segment is interpreted as an effect of the low-angle subduction of the Cocos Ridge (Corrigan et al., 1990; Gräfe, Frisch, Villa, & Meschede, 2002; Kolarsky, Mann, & Montero, 1995; Morell, 2016; Protti et al., 1995b; Protti & Schwartz, 1994; E. A. Silver, Galewsky, & McIntosh, 1995). Suárez et al. (1995) concluded that the Cocos Ridge does not subduct but collides with the trench. The present-day horizontal stress field in southern Costa Rica is consistent with an indenter (Kolarsky, Mann, & Montero, 1995; LaFemina et al., 2009; Montero, 1994). However, different opinions exist about the onset of subduction of the Cocos Ridge. They range from 8 Ma (Abratis & Wörner, 2001), 5 Ma (Kolarsky, Mann, & Montero, 1995), 3.6 Ma (Collins et al., 1995), 3–2 Ma (MacMillan et al., 2004) to < 3 Ma (Corrigan et al., 1990; Morell et al., 2012), and 1.5–1 Ma (Gardner et al., 2013) to 1 Ma (Lonsdale & Klitgord, 1978). These different ages are estimated from changes in magmatic activity, plate tectonic reconstructions, the analysis of upper plate deformation structures and additional thermochronological (Gräfe et al., 2002), and sedimentological data (Corrigan et al., 1990; Gardner et al., 1992; Kolarsky, Mann, & Monechi, 1995; Schlegel et al., 1995; Vannucchi, Morgan, Balestrieri, et al., 2016; Vannucchi, Morgan, Silver, et al., 2016; von Eynatten et al., 1993). The most recent field and modeling studies support an onset of Cocos Ridge subduction at around 2 Ma (Vannucchi, Morgan, Silver, et al., 2016; Zeumann & Hampel, 2015), which is consistent with the young subsidence pulse in the South Limón backarc basin (Brandes et al., 2008).

5.4 | Controlling factors for basin subsidence

5.4.1 | Forearc and outerarc basins

The geological data imply that subduction erosion, subduction of aseismic ridges and slab segments with rough crust as well as slab rollback and trench retreat were important drivers for subsidence in the arc-related basins of southern Central America. Subduction erosion, defined as the tectonic removal of material from the upper plate (Cloos & Shreve, 1988; von Huene & Scholl, 1991), subduction of aseismic ridges and slab segments with rough crust can cause short-term very rapid subsidence rates (Vannucchi, Morgan, Balestrieri,

et al., 2016; Vannucchi, Morgan, Silver, et al., 2016; Zeumann & Hampel, 2016). These factors shaped the forearc and controlled the lifespan/longevity of sedimentary basins. In the absence of major subduction erosion, larger, long-lived forearc basins with thick sedimentary fills developed. In contrast, smaller-scale, short-lived forearc and trench-slope basins with complex subsidence and uplift patterns formed, when subduction erosion was high due to the subduction of rough crust and aseismic ridges (Figure 4). An additional mechanism was strike-slip tectonics, caused by trench-parallel movements (e.g. Funk et al., 2009).

However, there are also other possible mechanisms that may have caused subsidence in the forearc area of southern Central America. As summarized in Dickinson (1995) four main subsidence mechanisms occur in forearc basins in general:

1. Flexure caused by the tectonic load of the subduction complex,
2. Flexure caused by sediment loading in the basin,
3. Bulk subsidence of the forearc region induced by the subduction of old and dense oceanic lithosphere and
4. Thermal subsidence.

It is possible that these mechanisms also played a role in southern Central America. The other side of the role of tectonic erosion for forearc subsidence in the forearc area of northwest Costa Rica may be underplating, changes in the basal shear stress, changes in slab dip or a pulse of subduction erosion as potential driving mechanisms (K. McIntosh, Silver, & Shipley, 1993). Fuller, Willett, and Brandon (2006) developed a model for forearc basin evolution that is based on the Coulomb-wedge theory. In their model, the forearc basin develops as a consequence of variations in the angle of the basal detachment (β) and the surface angle (α) of the wedge. An increase in the dip of the basal thrust leads to a decrease in the surface slope. When the surface slope becomes negative, a landward dipping surface evolves, creating a closed basin that traps sediments (Fuller et al., 2006). This mechanism could also have played a role in the evolution of the Sandino forearc basin. All proposed subsidence mechanisms could have acted in case of the Sandino basin. The lateral extent of the basin of more than 300 km and the thickness of the basin-fill of more than 12 km requires a long term driver for the subsidence like flexure, subduction erosion and trench retreat.

Regalla, Fisher, Kirby, and Furlong (2013) presented new insights into the influence of plate boundary kinematics on the subsidence of forearc basins. They were able to show, based on the example of the northeast Japan convergent margin that rapid tectonic subsidence in the outer forearc is contemporaneous with upper plate extension and an increase in the convergence rate at the trench. Furthermore, a relative uplift of the outer forearc area correlates with contraction of the arc and a decrease in the convergence rate. The driver for the forearc subsidence is most likely the shallow slab geometry. Acceleration in convergence rate can cause a broadening of the bending radius of the subducting plate (Regalla et al., 2013). This, in combination with a deep anchoring of the slab, can lead to a seaward retreat of the subduction hinge and the created space allows the forearc to subside (Regalla et al., 2013). Such a subsidence mechanism must be also considered for the forearc basins in southern Costa Rica, but

remains speculative because of the lack of knowledge in past subduction velocities and slab angles.

5.4.2 | Intraarc and backarc basins

Many different models have been developed for the evolution and subsidence mechanisms for intraarc and backarc basins. Both basin types evolve from extension of the arc. In general, an intraarc basin evolves into a backarc basin due to continued extension (Carey & Sigurdsson, 1985). Most of the models for intraarc/backarc evolution show that the extension behind the volcanic arc is caused by the mechanical or thermal influence of the related subduction zone. Karig (1971) published an early idea of a slab-induced mantle diapir. It is assumed that the subducted lithosphere becomes heated and produces a small rising thermal dome, which causes extension and a high heat flow in the overriding plate. In the mechanical models of Sleep and Toksöz (1971) and Hsui and Toksöz (1981) backarc spreading originates from special flows in the asthenosphere. The descending slab induces small circulating current cells in the overlying asthenosphere wedge, which lead to an extension of the crust behind the arc. This concept is commonly named the corner flow model. Other authors suggested different modes of slab rollback and trench retreat as possible driving mechanisms for backarc extension (Flower et al., 2001; Uyeda & Kanamori, 1979). As summarized in Nakakuki and Miura (2013) these slab-induced mechanisms of backarc basin formation can be subdivided into three groups on the basis of the plate kinematics:

1. The slab is anchored in the mantle and the overriding plate moves away from the trench.
2. Slab rollback controlled by mantle flow or asthenosphere injection.
3. Slab rollback controlled by gravity.

For the Nicaraguan arc-segment this rollback is indicated by the shift of the Neogene volcanic arc (Plank et al., 2002). These ideas are also underlined by the work of Faccenna et al. (2001), Morley (2001) and Sdrolias and Müller (2006), who showed the importance of slab rollback. The formation of backarc basins is an episodic process, where extension alternates with phases of tectonic quiescence. Driver for this episodicity are variations in motions of the trench and the upper plate (Clark, Stegman, & Müller, 2008).

Trench retreat is most likely the key process for the evolution of the intraarc and backarc basins in southern Central America. A Miocene trench retreat can be clearly reconstructed by field evidence (Ehrenborg, 1996; Mann et al., 2007; Plank et al., 2002) and modeling results (Cailleau & Oncken, 2008). The Eocene extensional processes in the Miskito backarc basin and the initial formation of the Nicaragua Graben during the Late Oligocene (Funk et al., 2009) emphasize the role of trench retreat. Chough and Sohn (2010) state that the weak coupling between the overriding and the subducting plate allows for backarc extension on the Korean peninsula. A similar weak coupling could have promoted backarc development in southern Central America. The young history of the Nicaraguan part of the arc is clearly characterized by extension. Morgan, Ranero, and Vannucchi

(2008) calculated an average arc-normal extension for Nicaragua in a range of ~ 6 mm/year during the last 15 my. This is probably accompanied by a weak plate coupling.

5.5 | Tectonics, Climate, and drainage systems

Little is known about the interplay of tectonics and drainage systems and their impact on the sediment supply of the arc-related basins in southern Central America. It becomes evident that the evolution of the drainage system and the catchment areas is closely related to the Neogene landscape evolution. In southern Costa Rica, the drainage divide is defined by the Talamanca Range, which evolved in Middle Miocene times (Campos, 2001; De Boer et al., 1995). The studies of Gräfe et al. (2002) and Morell et al. (2012, 2013) imply that increased uplift of the Talamanca Range started at around 3 Ma. In northern Costa Rica, the drainage divide is determined by the volcanoes of Guanacaste (Figure 9a). Marshall, Idleman, Gardner, and Fisher (2003) and Galve et al. (2016) showed the close relationship between the Plio-Pleistocene landscape evolution, sediment dispersal and the position of the volcanic arc. Shallowing of the subduction angle caused a migration of the volcanic arc and as a consequence, the fluvial network was reorganized (Marshall et al., 2003).

Southern Nicaragua has a very different topography where there are no major mountain ranges or continuous volcanic chains. This area is characterized by an active intraarc basin, occupied by Lake Nicaragua (Figure 1).

It can be assumed that the evolution of sediment transport systems had a direct effect on the sediment supply to the basins. As a result the sediment thicknesses between the forearc and backarc basins are remarkably different. In the North Limón backarc basin, the Neogene basin-fill is ~ 3 000–4 500 m thick whereas the Sandino forearc basin reveals ~ 1 900 m of Neogene sediments. Basin geometry or subsidence effects were probably not the only factors causing such a striking difference. We propose different rates of sediment supply as an additional important factor with higher sediment supply to the backarc basins. Our assumption is based on the location of the recent drainage divide in northern Costa Rica, which is close to the Pacific Ocean. From this we infer that the drainage area supplying the backarc basins is significantly larger than the area supplying the forearc basins. This configuration with the higher sediment accumulation in the backarc basins probably existed since the Late Miocene. Reasons for the higher sediment input into the backarc area are uplift due to the subduction of rough crust (Buchs et al., 2011; De Boer et al., 1995; Hauff et al., 2000; H. Krawinkel et al., 2000) and the collision of Panama with South America (Bowland, 1993; Farris et al., 2011). In addition, during the Late Oligocene–Early Miocene, rift processes and strike-slip processes occurred in southern Nicaragua and created the intraarc basin of the Nicaragua depression (Funk et al., 2009), which is drained by the Río San Juan leading to high sediment input into the backarc basins and the development of the Río San Juan Delta (Figure 4) (Brandes et al., 2007a, 2007b) and the related large deepsea fan in the western Colombian basin (Bowland, 1993).

In southern Costa Rica the doubly-vergent orogen and the related topography also have an influence on the surface processes. The climate of Costa Rica is influenced by the southwest directed

trade winds and a northeast directed wind system related to the inner tropical convergence zone (e.g. Sadler, Lander, Hori, & Oda, 1987). The area with the highest precipitation of 4 000–5 000 mm/year corresponds to the prowedge (Figure 9c). In the area of the inner retrowedge a precipitation of 3 000–4 000 mm/year occurs (Portig, 1976). In the external part of the South Limón fold-and-thrust belt, there is only 2 000–3 000 mm/year. The precipitation pattern shows an asymmetry that corresponds to the trend of the Talamanca Range (Portig, 1976). Due to orographic effects, the rainfall is focused on the prowedge area (Figure 9c). The consequence of this asymmetry is a prowedge denudation that led to an exhumation of the granitic rocks at high elevations in the interior of the mountain range (Figure 9c). These observations coincide with the predictions that were made by the model of Willett et al. (1993). The high precipitation in the prowedge area caused a significant sediment supply to the forearc region. High sedimentation rates during the Miocene are recorded from the Térraba forearc basin, where up to 800 m of shallow-water and terrestrial sediments accumulated (Mende, 2001), rapidly filling the basin. During the Pliocene and Early Pleistocene, more than 3 km thick volcanoclastic deep-water sediments were deposited in the Burica trench-slope basin, probably fed by a large delta as is indicated by abundant plant remains (Corrigan et al., 1990; Schlegel et al., 1995). The enhanced precipitation on the prowedge of the southern arc-segment possibly led to this significant increase in river discharge and sediment supply towards the Pacific coast.

5.6 | Comparison with other arc-trench systems

There are different arc-trench systems that have a similar structural and sedimentary evolution as the southern Central American island arc. Comparisons can be made from basin-scale to arc-trench system scale. The Great Valley forearc basin in California is a good analogue for the evolution of forearc basins in southern Central America. This basin evolved in a similar geodynamic position at the eastern rim of the Pacific Ocean and is also filled with thick coarse-grained deep-water clastics passing upwards into shallow-marine and continental deposits (Constenius, Johnson, Dickinson, & Williams, 2000; Williams & Graham, 2013). The most similar system with respect to the evolution of an entire arc-trench system is the Mesozoic island arc of Baja California, described by Busby et al. (1998). Like southern Central America, the Baja California arc evolved in three phases. A first intra-oceanic phase is characterized by small and steep-sided forearc and backarc basins that were fed with volcanoclastic detritus deposited on deep-water aprons (Busby et al., 1998). This is comparable to the early stage of island arc evolution in southern Central America during the Late Cretaceous. The second stage of the Baja California arc was classified as non-accretionary with a mildly extensional forearc area (Busby et al., 1998). Such a stage with rapidly subsiding basins developed also in southern Central America during the Maastrichtian to Oligocene. In the third stage the Baja California arc is a high-standing continental arc that became gradually compressional (Busby et al., 1998). Similarly, the South Costa Rican arc segment was transformed into a high stress system with deformed forearc and backarc areas during the Neogene that resemble the structure of a doubly-vergent orogen. This compressional stage of the island arc is

comparable to continental arc-trench systems like in the American Cordillera (Dickinson, 1976), where low-angle subduction caused deformation in the upper plate that can lead to the formation of retro-arc fold-and-thrust belts with related retro-arc foreland basins. Contractional deformation can be also observed in the Nicaraguan island arc segment. The fill of the Sandino forearc basin is characterized by two anticlines (Ranero, von Huene, Flueh, Duarte, et al., 2000; Struss et al., 2008) and there is also evidence for overthrusting in the contact zone of forearc basin and outer rise (Stephens, 2014). This fits to the general scheme of Busby et al. (1998), where mature island arcs tend to develop into more compressional systems. However, it has to be kept in mind that these structures can be also interpreted as footwall deformation caused by normal faulting during the formation of the Nicaragua Graben, as proposed by Funk et al. (2009). Noda (2016) proposed a new classification scheme of forearc basins based on the mass transfer between the lower and upper plate and the strain field in the basin. Key controlling factor for the type of forearc basin is the sediment flux at the subduction zone. Noda (2016) concluded that the Sandino forearc basin changed from compressional accretionary to non-accretionary during the middle Eocene to late Oligocene and identified extended subsidence that is attributed to trench retreat due to slab roll back or subduction erosion. This is consistent with the onset of increased subsidence during the Oligocene (Struss et al., 2008) and the persisting deposition of thick deep-water successions (Lang et al., 2017; Struss, Brandes, Blisniuk et al., 2007; Struss et al., 2008).

6 | CONCLUSIONS

The southern Central American island arc is a Mesozoic-Cenozoic arc-trench-system that serves as a general model for island arc evolution. The evolution can be subdivided into three major stages:

1. A pre-extensional phase in the Late Cretaceous characterized by terrane accretion along the continental crust of the Chortís Block and the CLIP plateau. These accreted terranes and CLIP basalts form the basement of the southern Central American island arc.
2. An extensional phase during the Maastrichtian to Oligocene, characterized by rapidly subsiding sedimentary basins, and deposition of thick arc-derived volcanoclastic material.
3. A compressional phase during the Neogene in southern Costa Rica, characterized by the transformation of the island arc into a compressional arc with a doubly-vergent geometry, dominated by fold-and-thrust belts in the forearc and backarc area.

6.1 | Extensional phase (Campanian to Oligocene)

The synthesis of the sedimentary and structural record of the southern Central America island arc can be linked to lithosphere processes to provide a deeper insight into first order factors controlling arc-related sedimentary basins and the temporal and spatial evolution of the island arc. Several pulses of seamount accretion and ridge subduction occurred since the Paleocene, interrupted by longer phases

of non-accretion and net subduction erosion. The subduction of aseismic ridges and slab segments with rough crust were important drivers for subduction erosion, controlled the shape of individual forearc and trench-slope basins, and affected the lifespan of sedimentary basins. In the absence of rough crust and major subduction erosion, larger, long-lived forearc basins with thick sedimentary fills developed (e.g. the Sandino forearc basin). In contrast, smaller-scale, short-lived forearc, and trench-slope basins with complex subsidence and uplift patterns formed, during subduction of rough crust and aseismic ridges. The structural and sedimentary evolution of the arc-related basins has therefore been strongly controlled by regional subduction parameters, especially the angle and morphology of the incoming plate.

Another important factor for basin subsidence was slab rollback and resulting trench retreat. From the sedimentary and tectonic record of the Nicaraguan and North Costa Rican arc segment it is evident that two periods of trench retreat occurred during the Cenozoic. The first trench retreat occurred during the Late Eocene to Oligocene and the second trench retreat during Miocene/Pliocene times, indicated by increased subsidence in the forearc and backarc basins, extension in the intraarc area and shift of the volcanic arc.

6.2 | Compressional phase (Neogene to Recent)

A compressional phase affected the South Costa Rican arc segment during the Neogene, characterized by the transformation of the island arc into a compressional arc (subduction orogen) with a doubly-vergent geometry due to subduction of younger crust resulting in shallowing of the slab angle. The driving mechanism for such deformation of an island arc setting is the rigidity of the arc and basal traction due to the lowering of the subduction angle. The young subduction of the Cocos Ridge at around 2 Ma, as shown by recent studies (Vannucchi, Morgan, Silver, et al., 2016; Zeumann & Hampel, 2015, 2016), contributed to the contraction but was not the primary driver.

6.3 | Basin-wide unconformities

Within the basins major unconformities are developed, which can be traced across the forearc and backarc areas of southern Central America. These unconformities formed during the Campanian, Middle Eocene to early Late Oligocene and Late Miocene. They have a complex composite tectonic origin and were partly enhanced by global sea-level changes. The Campanian unconformity is related to the collision of an island arc (Guerreo terrane) with the southern Chortís block and the subsequent establishment of a new subduction zone in the rear or western area of the Caribbean oceanic plateau. The Eocene to Oligocene unconformity possibly was caused by: (i) subduction and/or accretion of seamounts and aseismic ridges; and (ii) the onset of oblique collision between Panama and South America at the end of the Middle Eocene; or (iii) the plate tectonic reorganization in the Pacific region during the Middle Eocene, leading to major changes in subduction parameters along the Middle America trench. The Miocene unconformity is probably related to: (i) the break-up of the Farallón Plate at around 25 Ma and a related change in plate

vectors; and (ii) the onset of compressional deformation in southern Costa Rica and Panama, related to the completed oblique collision of Panama with South America.

ACKNOWLEDGEMENTS

The authors thank the Costa Rican Ministry of Environment and Energy (MINAE) and the Nicaraguan Institute of Energy (INE) for providing data. We are grateful to Paul Mann and five anonymous reviewers for constructive comments on the manuscript. M. Nakanishi and T. Muto are gratefully acknowledged for editorial handling. The manuscript benefited also from the discussion with A. Astorga, L. Campos, F. Holtz, A. Mende, M. Meschede, I. Struss, and D. Tanner. Special thanks go to V. Artilles, A. Astorga, L. Campos, M. Darce, M. Duarte, M. Montenegro, H. Seyfried, M. Solís, F. Wezel, and N. Zamora for support and hospitality during our stays in Central America.

ORCID

Christian Brandes  <http://orcid.org/0000-0003-2908-9259>

REFERENCES

- Abratis, M., & Wörner, G. (2001). Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm. *Geology*, 29, 127–130.
- Acton, G. D., Galbrun, B., & King, J. W. (2000). Paleolatitude of the Caribbean Plate since the Late Cretaceous. In R. M. Leckie, H. Sigurdsson, & G. Draper (Eds.), *Proceedings of the Ocean Drilling Program, scientific results* (Vol. 165, pp. 149–173). College Station, TX: Texas A&M University.
- Alfaro, E., Barrera, D. F., & Rossello, E. A. (2013). Diachronic Cenozoic wrenching in southwest of the Colombia Basin. *Comunicações Geológicas*, 1, 55–65.
- Alvarado, G. E. (2007, April 11–13). *Paleo and Neo Volcanic fronts in Central America* [Abstractbook]. 20th Colloquium on Latin American Earth Sciences, Kiel, Germany. pp. 8–9.
- Alvarado, G. E., Denyer, P., & Sinton, C. W. (1997). The 89 Ma Tortugal komatiitic suite, Costa Rica: Implications for a common geological origin of the Caribbean and Eastern Pacific region from a mantle plume. *Geology*, 25, 439–442.
- Alvarado, G. E., Kussmaul, S., Chiesa, S., Gillot, P. Y., Appel, H., Wörner, G., & Rundle, C. (1992). Re-sumenchronostratigráfico de las rocas ígneas de Costa Rica basadas en dataciones radiométricas. *Journal of South American Earth Sciences*, 6, 151–168.
- Alvarez-Gomez, J. A., Meijer, P. T., Martinez-Diaz, J. J., & Capote, R. (2008). Constraints from finite element modeling on the active tectonics of northern Central America and the Middle America Trench. *Tectonics*, 27, TC1008. <https://doi.org/10.1029/2007TC002162>
- Amann, H. (1993). Randmarine und terrestrische Ablagerungsräume des neogenen Inselbogensystems in Costa Rica (Mittelamerika). *Profil*, 4, 1–161.
- Andjić, G., Baumgartner-Mora, C., & Baumgartner, P. O. (2016). An upper Paleogene shallowing-upward sequence in the southern Sandino Forearc basin (NW Costa Rica): Response on tectonic uplift. *Facies*, 62. <https://doi.org/10.1007/s10347-016-0463-y>
- Angevine, C. L., Heller, P. L., & Paola, C. (1990). *Quantitative sedimentary basin modeling Course Note Series* (Vol. 32, pp. 1–247). Tulsa, OK: American Association of Petroleum Geologists.
- Appel, H., Wörner, G., Alvarado, G., Rundle, C., & Kussmaul, S. (1994). Age relations of igneous rocks from Costa Rica. *Profil*, 7, 63–69.
- Arroyo, I. G., Grevenmeyer, I., Ranero, C. R., & von Huene, R. (2014). Interplate seismicity at the CRISP drilling site: The 2002 Mw 6.4 Osa Earthquake at the southeastern end of the Middle America Trench.

- Geochemistry, Geophysics, Geosystems*, 15, 3035–3050. <https://doi.org/10.1002/2014GC005359>
- Astorga, A. (1994). El Mesozoico del sur de América Central: Consecuencias para el origen y evolución de la Placa Caribe. *Perfil*, 7, 171–233.
- Astorga, A. (1997). El puente-istmo de América Central y la evolución de la Placa Caribe (con énfasis en el Mesozoico). *Perfil*, 12, 1–201.
- Astorga, A., Fernández, J. A., Barboza, G., Campos, L., Obando, J., Aguilar, A., & Obando, L. G. (1991). Cuencas sedimentarias de Costa Rica: Evolución geodinámica y potencial de hidrocarburos. *Revista Geológica de América Central*, 13, 25–59.
- Azéma, J., Bourgeois, J., Tournon, J., Baumgartner, P. O., & Desmet, A. (1985). L'orogène pré-sénéonien supérieur de marge pacifique du Costa Rica/Amérique centrale. *Bulletin de la Société Géologique de France*, 8, 173–179.
- Bandini, A. N., Flores, K., Baumgartner, P. O., Jackett, S. J., & Denyer, P. (2008). Late Cretaceous and Paleogene radiolaria from the Nicoya Peninsula, Costa Rica: A tectonostratigraphic application. *Stratigraphy*, 5, 3–21.
- Barat, F., de Lépinay, B. M., Sosson, M., Müller, C., Baumgartner, P. O., & Baumgartner-Mora, C. (2014). Transition from the Farallon Plate subduction to the collision between South and Central America: Geological evolution of the Panama Isthmus. *Tectonophysics*, 622, 145–167.
- Barboza, G., Barrientos, J., & Astorga, A. (1995). Tectonic evolution and sequence stratigraphy of the central Pacific margin of Costa Rica. *Revista Geológica de América Central*, 18, 43–63.
- Barboza, G., Fernández, A., Barrientos, J., & Bottazzi, G. (1997). Costa Rica: Petroleum geology of the Caribbean margin. *The Leading Edge*, 16, 1787–1794.
- Baumgartner, P. O., Flores, K., Bandini, A. N., Girault, F., & Cruz, D. (2008). Upper Triassic to Cretaceous radiolaria from Nicaragua and northern Costa Rica—the Mesquito composite oceanic terrane. *Ofioliti*, 33, 1–19.
- Baumgartner, P. O., Mora, C. R., Butterlin, J., Sigal, J., Glacon, G., Azéma, J., & Bourgeois, J. (1984). Sedimentación y paleogeografía del Cretácico y Cenozoico del litoral pacífico de Costa Rica. *Revista Geológica de América Central*, 1, 57–136.
- Borgia, A., & van Wyk de Vries, B. (2003). The volcano-tectonic evolution of Concepción, Nicaragua. *Bulletin of Volcanology*, 65, 248–266.
- Boschman, L. M., van Hinsbergen, D. J. J., Torsvik, T. H., Spakman, W., & Pindell, J. L. (2014). Kinematic reconstruction of the Caribbean region since the Early Jurassic. *Earth-Science Reviews*, 138, 102–136.
- Bottazzi, G., Fernández, A., & Barboza, G. (1994). Sedimentología e historia tectono-sedimentaria de la cuenca Limón Sur. *Perfil*, 7, 351–389.
- Bowland, C. L. (1993). Depositional history of the western Colombian Basin, Caribbean Sea, revealed by seismic stratigraphy. *Geological Society of America Bulletin*, 105, 1321–1345.
- Bowland, C. L., & Rosencrantz, E. (1988). Upper crustal structure of the western Colombian Basin. *Geological Society of America Bulletin*, 100, 534–546.
- Brandes, C., Astorga, A., Back, S., Littke, R., & Winsemann, J. (2007a). Fault controls on sediment distribution patterns, Limón Basin, Costa Rica. *Journal of Petroleum Geology*, 30, 25–40.
- Brandes, C., Astorga, A., Back, S., Littke, R., & Winsemann, J. (2007b). Deformation style and basin-fill architecture of the offshore Limón back-arc basin (Costa Rica). *Marine and Petroleum Geology*, 24, 277–287.
- Brandes, C., Astorga, A., Blisniuk, P., Littke, R., & Winsemann, J. (2007). Anatomy of anticlines, piggy-back basins and growth strata: A case study from the Limón Fold-and-thrust belt, Costa Rica. In G. Nichols, E. Williams, & C. Paola (Eds.), *Sedimentary processes, environments and basins*, International Association of Sedimentologists Special Publication 38 (pp. 91–110). Oxford, England: Blackwell Science.
- Brandes, C., Astorga, A., Littke, R., & Winsemann, J. (2008). Basin modeling of the Limón Back-arc Basin (Costa Rica): Burial history and temperature evolution of an island arc-related basin-system. *Basin Research*, 20, 119–142.
- Brandes, C., Astorga, A., & Winsemann, J. (2009). The Moín High, East Costa Rica: Seamount, laccolith or contractional structure? *Journal of South American Earth Sciences*, 28, 1–13.
- Brandes, C., Struss, I., Vandr , C., & Winsemann, J. (2007). Architecture of proximal, midfan levee deposits, Punta Farallones La Flor, Nicaragua. In H. Nilsen, R. D. Shew, G. S. Steffens, & J. R. J. Studlick (Eds.), *Atlas of deep-water outcrops*. American Association of Petroleum Geologists Studies in Geology 56 (pp. 271–273). Tulsa, OK: AAPG.
- Brandes, C., & Tanner, D. C. (2014). Fault-related folding: A review of kinematic models and their application. *Earth Science Reviews*, 138, 352–370.
- Brandes, C., Tanner, D. C., & Winsemann, J. (2016). Kinematic 3-D retro-modeling of an orogenic bend in the South Limón fold-and-thrust belt, eastern Costa Rica: Prediction of the incremental internal strain distribution. *Pure and Applied Geophysics*, 173, 3341–3356.
- Brandes, C., & Winsemann, J. (2007). *Southern Costa Rica: An Island-arc Segment That Behaves like a doubly vergent orogen*. American Geophysical Union, Fall Meeting 2007 December 10–14, San Francisco, USA. abstract #T13C-1471.
- Buchs, D. M., Arculus, R. J., Baumgartner, P. O., Baumgartner-Mora, C., & Ulianov, A. (2010). Late Cretaceous arc development on the SW margin of the Caribbean Plate: Insights from the Golfito, Costa Rica, and Azuero, Panama, complexes. *Geochemistry, Geophysics, Geosystems*, 11, Q07S24. <https://doi.org/10.1029/2009GC002901>
- Buchs, D. M., Baumgartner, P. O., Baumgartner-Mora, C., Flores, K., & Bandini, A. N. (2011). Upper Cretaceous to Miocene tectonostratigraphy of the Azuero area (Panama) and the discontinuous accretion and subduction erosion along the Middle American margin. *Tectonophysics*, 512, 31–46.
- Buchs, D. M., Pilet, S., Baumgartner, P. O., Cosca, M., Flores, K. E., & Bandini, A. N. (2013). Low-volume intraplate volcanism in the Early/Middle Jurassic Pacific basin documented by accreted sequences in Costa Rica. *Geochemistry, Geophysics, Geosystems*, 14, 1552–1568. <https://doi.org/10.1002/ggge.20084>
- Burke, K. (1988). Tectonic evolution of the Caribbean. *Annual Review of Earth and Planetary Sciences*, 16, 201–230.
- Burke, K., Fox, P. J., & Seng r, A. M. C. (1978). Buoyant ocean floor and the evolution of the Caribbean. *Journal of Geophysical Research*, 83, 3949–3954.
- Busby, C. (2004). Continental growth at convergent margins facing large ocean basins: A case study from Mesozoic convergent-margin basins of Baja California, Mexico. *Tectonophysics*, 392, 241–277.
- Busby, C., Smith, D., Morris, W., & Fackler-Adams, B. (1998). Evolutionary model for convergent margins facing large ocean basins: Mesozoic Baja California, Mexico. *Geology*, 26, 227–230.
- Cadoux, A., Missenard, Y., Martinez-Serrano, R. G., & Guillou, H. (2011). Trenchward Plio-Quaternary volcanism migration in the Trans-Mexican Volcanic Belt: The case of the Sierra Nevada range. *Geological Magazine*, 148, 492–506.
- Cailleau, B., LaFemina, P. C., & Dixon, T. H. (2007). Stress accumulation between volcanoes: An explanation for intra-arc earthquakes in Nicaragua? *Geophysical Journal International*, 169, 1132–1138.
- Cailleau, B., & Oncken, O. (2008). Past forearc deformation in Nicaragua and coupling at the megathrust interface: Evidence for subduction retreat? *Geochemistry, Geophysics, Geosystems*, 9, Q03016. <https://doi.org/10.1029/2007GC001754>
- Calvo, C. (1998). Kretazische Subduktionsprozesse in S dzentralamerika. *Perfil*, 15, 1–161.
- Calvo, C. (2003). Provenance of plutonic detritus in cover sandstones of Nicoya Complex, Costa Rica: Cretaceous unroofing history of a Mesozoic ophiolite sequence. *Geological Society of America Bulletin*, 115, 832–844.
- Calvo, C., & Bolz, A. (1994). Der  lteste kalkalkaline Inselbogen-Vulkanismus in Costa Rica. *Marine Pyroklastika der Formation Loma Chumico (Alb bis Campan)*. *Perfil*, 7, 235–264.
- Campos, L. (2001). Geology and basins history of middle Costa Rica: An intraoceanic island arc in the convergence between the Caribbean and the central Pacific plates. *T binger Geowissenschaftliche Arbeiten, Reihe A*, 62, 1–138.
- Carey, S., & Sigurdsson, H. (1985). A model of volcanogenic sedimentation in marginal basins. In B. P. Kokelaar & M. F. Howells (Eds.), *Marginal basin geology. Volcanic and associated sedimentary and tectonic processes in modern and ancient marginal basins*. The Geological Society Special Publication 16 (pp. 37–58). Oxford, England: Blackwell Scientific Publications.

- Carvajal-Arenas, L. C., Torrado, L., & Mann, P. (2015). Early and Late Eocene/Oligo-Miocene (!) petroleum system on the Nicaraguan Rise: Insights from basin and three-dimensional petroleum system modeling. In C. Bartolini & P. Mann (Eds.), *Petroleum geology and potential of the Colombian Caribbean margin*. American Association of Petroleum Geologists Memoir, 108 (pp. 615–646). Tulsa, OK: APPG.
- Chough, S. K., & Sohn, Y. K. (2010). Tectonic and sedimentary evolution of a Cretaceous continental arc-backarc system in the Korean peninsula: New view. *Earth-Science Reviews*, 101, 225–249.
- Clark, S. R., Stegman, D., & Müller, R. D. (2008). Episodicity in back-arc tectonic regimes. *Physics of the Earth and Planetary Interiors*, 171, 265–279.
- Cloos, M. (1993). Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. *Geological Society of America Bulletin*, 105, 715–737.
- Cloos, M., & Shreve, R. L. (1988). Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins: 2. Implications and discussion. *Pure and Applied Geophysics*, 128, 501–545.
- Coates, A. G., Collins, L. S., Aubry, M.-P., & Berggren, W. A. (2004). The geology of the Darien, Panama, and the late Miocene-Pliocene collision of the Panama arc with northwestern South America. *Geological Society of America Bulletin*, 116, 1327–1344.
- Collins, L. S., Coates, A. G., Jackson, J. B. C., & Obando, J. A. (1995). Timing and rates of emergence of the Limón and Bocas del Toro basins: Caribbean effects of Cocos Ridge subduction? In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*. Geological Society of America Special Paper, 295 (pp. 263–289). Boulder, CO: GSA.
- Constenius, K. N., Johnson, R. A., Dickinson, W. R., & Williams, T. A. (2000). Tectonic evolution of the Jurassic-Cretaceous Great Valley forearc, California: Implications for the Franciscan thrust-wedge hypothesis. *Geological Society of America Bulletin*, 112, 1703–1723.
- Corrigan, J., Mann, P., & Ingle, J. C. (1990). Forearc response to subduction of the Cocos Ridge, Panama-Costa Rica. *Geological Society of America Bulletin*, 102, 628–652.
- Cowan, H., Machette, M. N., Amador, X., Morgan, K. S., Dart, R. L., & Bradley, L.-A. (2000). *Map and Database of Quaternary Faults In the Vicinity of Managua, Nicaragua* (U.S. Geological Survey Open-File Rep. 00-0437). (released January 2002).
- De Boer, J. Z., Drummond, M. S., Bordelon, M. S., Defant, M. J., Bellon, H., & Maury, R. C. (1995). Cenozoic magmatic phases of the Costa Rican island arc (Cordillera de Talamanca). In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*. Geological Society of America Special Paper, 295 (pp. 35–55). Boulder, CO: GSA.
- DeCelles, P. G., & Giles, K. A. (1996). Foreland basin systems. *Basin Research*, 8, 105–123.
- DeMets, C. (2001). A new estimate for present-day Cocos-Caribbean plate motion: Implications for slip along the Central American volcanic arc. *Geophysical Research Letters*, 28, 4043–4046.
- Dengo, C. A. (2007). Petroleum geology. In J. Bundschuh & G. E. Alvarado (Eds.), *Central America, geology, resources and hazards* (pp. 895–916). London, England: Taylor and Francis.
- Dengo, G. (1962). *Estudio geológico de la region de Guanacaste, Costa Rica*. San José, Costa Rica: Instituto Geográfico de Costa Rica.
- Denyer, P., & Baumgartner, P. O. (2006). Emplacement of Jurassic-Lower Cretaceous radiolarites of the Nicoya Complex (Costa Rica). *Geologica Acta*, 4, 203–218.
- Di Marco, G., Baumgartner, P. O., & Channell, J. E. T. (1995). Late Cretaceous-early Tertiary paleomagnetic data and a revised tectonostratigraphic subdivision of Costa Rica and western Panama. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*. Geological Society of America Special Paper, 295 (pp. 1–27). Boulder, CO: GSA.
- Dickinson, W. R. (1976). Sedimentary basins developed during evolution of Mesozoic-Cenozoic arc-trench system in western North America. *Canadian Journal of Earth Sciences*, 13, 1268–1287.
- Dickinson, W. R. (1995). Forearc basins. In C. J. Busby & R. V. Ingersoll (Eds.), *Tectonics of sedimentary basins* (pp. 221–261). Oxford, England: Blackwell Science.
- Diebold, J. B., & Driscoll, N. W. (1999). New insights on the formation of the Caribbean basalt province revealed by multichannel seismic images of volcanic structures in the Venezuelan Basin. In K.J. Hsü (Ed.), *Sedimentary Basins of the World, Caribbean Basins* (Vol. 4, pp. 561–589) Amsterdam: Elsevier.
- Donnelly, T. W. (1989). Geologic history of the Caribbean and Central America. In A. W. Bally & A. R. Palmer (Eds.), *The geology of North America - an overview*. Geological Society of America Special Paper A (pp. 299–321). Boulder, CO: GSA.
- Donnelly, T. W. (1994). The Caribbean Cretaceous basalt association: A vast igneous province that includes the Nicoya Complex of Costa Rica. *Profil*, 7, 17–45.
- Dzierma, Y., Rabbel, W., & Thorwart, M. M. (2011). The steeply subducting edge of the Cocos Ridge: Evidence from receiver functions beneath the northern Talamanca Range, south-central Costa Rica. *Geochemistry, Geophysics, Geosystems*, 12. <https://doi.org/10.1029/2010GC003477>
- Ehrenborg, J. (1996). A new stratigraphy for the Tertiary volcanic rocks of the Nicaraguan Highland. *Geological Society of America Bulletin*, 108, 830–842.
- Escalante, G., & Astorga, A. (1994). Geología del este de Costa Rica y el norte de Panama. *Revista Geológica de América Central, Terremoto de Limón*, 1–14.
- Escuder-Viruet, J., & Baumgartner, P. O. (2014). Structural evolution and deformation kinematics of a subduction-related serpentinite-matrix mélangé, Santa Elena peninsular, northwest Costa Rica. *Journal of Structural Geology*, 66, 356–381.
- Faccenna, C., Funicello, F., Giardini, D., & Lucente, P. (2001). Episodic back-arc extension during restricted mantle convection in the Central Mediterranean. *Earth and Planetary Science Letters*, 187, 105–116.
- Farris, D. W., Jaramillo, C., Bayona, G., Restrepo-Moreno, S. A., Montes, C., Cardona, A., ... Valencia, V. (2011). Fracturing of the Panamanian Isthmus during initial collision with South America. *Geology*, 39, 1007–1010.
- Fernandez, J. A., Alvaro, A., Guillermo, B., Bottazzi, G., Campos, L., Obando, J., ... Valerio, A. (1997). *Mapa geológico de Costa Rica*. San Jose, Costa Rica: Ministerio del Ambiente y Energía.
- Fernandez, J. A., Bottazzi, G., Barboza, G., & Astorga, A. (1994). Tectónica y estratigrafía de la Cuenca Limón Sur. *Revista Geológica de América Central, Terremoto de Limón*, 15–28.
- Ferrari, L., Petrone, C. M., & Francalanci, L. (2001). Generation of oceanic-island basalt-type volcanism in the western Trans-Mexican volcanic belt by slab rollback, asthenosphere infiltration, and variable flux melting. *Geology*, 29, 507–510.
- Fisher, D. M., Gardner, T. W., Marshall, P., Sak, P. B., & Protti, M. (1998). Effect of subducting seafloor roughness on forearc kinematics, Pacific coast, Costa Rica. *Geology*, 26, 467–470.
- Fisher, D. M., Gardner, T. W., Sak, P. B., Sanchez, J. D., Murphy, K., & Vannucchi, P. (2004). Active thrusting in the inner forearc of an erosive convergent margin, Pacific coast, Costa Rica. *Tectonics*, 23, TC2007. <https://doi.org/10.1029/2002TC001464>
- Flower, M. F. J., Russo, R. M., Tamaki, K., & Hoang, N. (2001). Mantle contamination and the Izu-Bonin-Mariana (IBM) "high-tide mark": Evidence for mantle extrusion caused by Tethyan closure. *Tectonophysics*, 333, 9–34.
- Flueh, E. R., & von Huene, R. (2007). Crustal structure. In J. Bundschuh & G. E. Alvarado (Eds.), *Central America, geology, resources and hazards* (pp. 268–276). London, England: Taylor and Francis.
- Freundt, A., Kutterolf, S., Wehrmann, H., Schmincke, H.-U., & Strauch, W. (2006). Eruption of the dacite to andesite zoned Mateare Tephra, and associated tsunamis in Lake Managua, Nicaragua. *Journal of Volcanology and Geothermal Research*, 149, 103–123.
- Frisch, W., Meschede, M., & Sick, M. (1992). Origin of the Central American ophiolites: Evidence from paleomagnetic results. *Geological Society of America Bulletin*, 104, 1301–1314.
- Fuller, C. W., Willett, S. D., & Brandon, M. T. (2006). Formation of forearc basins and their influence on subduction zone earthquakes. *Geology*, 34, 65–68.

- Funiciello, F., Faccenna, C., Giardini, D., & Regenauer-Lieb, K. (2003). Dynamics of retreating slabs: 2. Insights from three-dimensional laboratory experiments. *Journal of Geophysical Research*, 108(B4), 2207. <https://doi.org/10.1029/2001JB000896>
- Funk, J., Mann, P., McIntosh, K., & Stephens, J. (2009). Cenozoic tectonics of the Nicaraguan depression, Nicaragua, and Median Trough, El Salvador, based on seismic-reflection profiling and remote-sensing data. *Geological Society of America Bulletin*, 121, 1491–1521.
- Galve, J. P., Alvarado, G. E., Pérez-Peña, J. V., Mora, M. M., Booth-Rea, G., & Azañón, J. M. (2016). Megafan formation driven by explosive volcanism and active tectonic processes in a humid tropical environment. *Terra Nova*, 28, 427–433.
- Gardner, T. W., Fisher, D. M., Morell, K. D., & Cupper, M. L. (2013). Upper-plate deformation in response to flat slab subduction inboard of the aseismic Cocos Ridge, Osa Peninsula, Costa Rica. *Lithosphere*, 5, 247–264.
- Gardner, T. W., Verdonck, D., Pinter, N. M., Slingerland, R., Furlong, K. P., Bullard, T. F., & Wells, S. G. (1992). Quaternary uplift astride the aseismic Cocos Ridge, Pacific coast, Costa Rica. *Geological Society of America Bulletin*, 104, 219–232.
- Gazel, E., Carr, M. J., Hoernle, K., Feigenson, M. D., Szymanski, D., Hauff, F., & van den Bogaard, P. (2009). Galapagos-OIB signature in southern Central America: Mantle refertilization by arc-hot spot interaction. *Geochemistry, Geophysics, Geosystems*, 10, Q02S11. <https://doi.org/10.1029/2008GC002246>
- Geldmacher, J., Hoernle, K., van den Bogaard, P., Hauff, F., & Klügel, A. (2008). Age and geochemistry of the Central American forearc basement (DSDP Leg 67 and 84): Insights into Mesozoic arc volcanism and seamount accretion on the fringe of the Caribbean LIP. *Journal of Petrology*, 49, 1781–1815.
- Goes, S. D. B., Velasco, A. A., Schwartz, S. Y., & Lay, T. (1993). The April 22, 1991, Valle de la Estrella, Costa Rica (Mw=7.7) earthquake and its tectonic implications: A broadband seismic study. *Journal of Geophysical Research*, 98(B5), 8127–8142.
- Gräfe, K., Frisch, W., Villa, I. M., & Meschede, M. (2002). Geodynamic evolution of southern Costa Rica related to low-angle subduction of the Cocos Ridge: Constraints from thermochronology. *Tectonophysics*, 348, 187–204.
- Grindlay, N. R., Mann, P., Dolan, J. F., & van Gestel, J.-P. (2005). Neotectonics and subsidence of the northern Puerto Rico–Virgin Islands margin in response to the oblique subduction of high-standing ridges. In P. Mann (Ed.), *Active tectonics and seismic hazards of Puerto Rico, the Virgin Islands, and offshore areas*. Geological Society of America Special Paper, 385 (pp. 31–60). Boulder, CO: GSA.
- Gursky, M. M. (1986). *Tektonische und thermische deformation im ophiolithischen Nicoya-Komplex und seinem sedimentären Auflager (Nicoya-Halbinsel, Costa Rica) und ihre Bedeutung für die geodynamische Entwicklung im südlichen Zentralamerika*. (PhD thesis) (pp. 230). Marburg, Germany: University of Marburg.
- Hauff, F., Hoernle, K., & van den Bogaard, P. (2000). Age and geochemistry of basaltic complexes in western Costa Rica: Contributions to the geotectonic evolution of Central America. *Geochemistry, Geophysics, Geosystems*, 1. <https://doi.org/10.1029/1999GC000020>
- Hawkesworth, C. J., Dhuime, B., Pietranik, A. B., Cawood, P. A., Kemp, A. I. S., & Storey, C. D. (2010). The generation and evolution of the continental crust. *Journal of the Geological Society, London*, 167, 229–248.
- Hawkesworth, C. J., & Kemp, A. I. S. (2006). Evolution of the continental crust. *Nature*, 443, 811–817.
- Hoernle, K., Abt, D. L., Fischer, K. M., Nichols, H., Hauff, F., Abers, G. A., ... Strauch, W. (2008). Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua. *Nature*, 451, 1094–1097.
- Hoernle, K., Hauff, F., & van den Bogaard, P. (2004). 70 m.y. history (139–69 Ma) for the Caribbean large igneous province. *Geology*, 32, 697–700.
- Hoernle, K., van den Bogaard, P., Werner, R., Lissinna, B., Hauff, F., Alvarado, G., & Garbe-Schönberg, D. (2002). Missing history (16–71 Ma) of the Galápagos hotspot: Implications for the tectonic and biological evolution of the Americas. *Geology*, 30, 795–798.
- Hsui, A. T., & Töksöz, M. N. (1981). Back-arc spreading: Trench migration, continental pull or induced convection? *Tectonophysics*, 74, 89–98.
- Ingersoll, R. V., & Busby, C. J. (1995). Tectonics of sedimentary basins. In C. J. Busby & R. V. Ingersoll (Eds.), *Tectonics of sedimentary basins* (pp. 1–51). Oxford, England: Blackwell Science.
- Ito, M., Ishikawa, K., & Nishida, N. (2014). Distinctive erosional and depositional structures formed at a canyon mouth: A lower Pleistocene deep-water succession in the Kazusa forearc basin on the Boso Peninsula, Japan. *Sedimentology*, 61, 2042–2062.
- Jaccard, S., Münster, M., Baumgartner, P. O., Baumgartner-Mora, C., & Denyer, P. (2001). Barra Honda (Upper Paleocene–Lower Eocene) and El Viejo (Campanian–Maastrichtian) carbonate platforms in the Tempisque area (Guanacaste, Costa Rica). *Revista Geológica de América Central*, 24, 9–28.
- James, K. H. (2006). Arguments for and against the Pacific origin of the Caribbean Plate: Discussion, finding for an inter-American origin. *Geologica Acta*, 4, 279–302.
- James, K. H. (2007). Structural geology: From local elements to regional synthesis. In J. Bundschuh & G. E. Alvarado (Eds.), *Central America, geology, resources and hazards* (pp. 277–321). London, England: Taylor and Francis.
- James, K. H. (2009). In situ origin of the Caribbean: Discussion of data. In K. H. James, M. A. Lorente, & J. L. Pindell (Eds.), *The origin and evolution of the Caribbean Plate*. Geological Society of London Special Publication 328 (pp. 77–125). Bath, England: The Geological Society Publishing House.
- Karig, D. E. (1971). Origin and development of marginal basins in the western Pacific. *Journal of Geophysical Research*, 76, 2542–2561.
- Kerr, A. C., Iturralde-Vinent, M. A., Saunders, A. D., Babbs, T. L., & Tarney, J. (1999). A new plate tectonic model of the Caribbean: Implications from a geochemical reconnaissance of Cuban Mesozoic volcanic rocks. *Geological Society of America Bulletin*, 111, 1581–1599.
- Kerr, A. C., Tarney, J., Marriner, G. F., Klaver, G. T., Saunders, A. D., & Thirlwall, M. F. (1996). The geochemistry and petrogenesis of the late-Cretaceous picrites and basalts of Curaçao, Netherlands Antilles: A remnant of an oceanic plateau. *Contributions to Mineralogy and Petrology*, 124, 29–43.
- Kerr, A. C., Tarney, J., Marriner, G. F., Nivia, A., Klaver, G. T., & Saunders, A. D. (1996). The geochemistry and tectonic setting of late Cretaceous Caribbean and Colombian volcanism. *Journal of South American Earth Sciences*, 9, 111–120.
- Kolarsky, R. A., Mann, P., & Monechi, S. (1995). Stratigraphic development of southwestern Panama as determined from integration of marine seismic data and onshore geology. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*. Geological Society of America Special Paper, 295 (pp. 159–200). Boulder, CO: GSA.
- Kolarsky, R. A., Mann, P., & Montero, W. (1995). Island arc response to shallow subduction of the Cocos Ridge, Costa Rica. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*. Geological Society of America Special Paper, 295 (pp. 235–262). Boulder, CO: GSA.
- Kolb, W., & Schmidt, H. (1991). Depositional sequences associated with equilibrium coastlines in the Neogene of southwestern Nicaragua. In D. I. M. MacDonald (Ed.), *Sedimentation, tectonics and eustasy: Sea-level changes at active margins*. International Association of Sedimentologists Special Publication, 12 (pp. 259–272). Oxford, England: Blackwell Science.
- Korsch, R. J., Kositsin, N., & Champion, D. C. (2011). Australian island arcs through time: Geodynamic implications for the Archean and Proterozoic. *Gondwana Research*, 19, 716–734.
- Krawinkel, H., & Kolb, W. (1994). Sequential aspects of the Neogene El Fraile formation (Nicaragua Trough, SW-Nicaragua). *Profil*, 7, 325–333.
- Krawinkel, H., Seyfried, H., Calvo, C., & Astorga, A. (2000). Origin and inversion of sedimentary basins in southern Central America. *Zeitschrift für Angewandte Geologie, SH*, 1, 71–77.
- Krawinkel, H., Wozazek, S., Krawinkel, J., & Hellmann, W. (1999). Heavy-mineral analysis and clinopyroxene geochemistry applied to provenance analysis of lithic sandstones from the Azuero-Soná Complex (NW Panama). *Sedimentary Geology*, 124, 149–168.

- Krawinkel, J., & Seyfried, H. (1994). A review of plate-tectonic processes involved in the formation of the southwestern edge of the Caribbean Plate. *Profil*, 7, 47–61.
- Krawinkel, J. J. (2003). Struktur und Kinematik am konvergenten Plattenrand der südlichen Zentralamerikanischen Landbrücke (Zentral- und Süd-Costa Rica, West-Panamá). *Profil*, 20, 1–36.
- Kroehler, M. E., Mann, P., Escalona, A., & Christeson, G. L. (2011). Late Cretaceous-Miocene diachronous onset of back thrusting along the South Caribbean deformed belt and its importance for understanding processes of arc collision and crustal growth. *Tectonics*, 30, TC6003. <https://doi.org/10.1029/2011TC002918>
- Kumpulainen, R. A. (1995). Stratigraphy and Sedimentology in Western Nicaragua. *Revista Geologica de América Central*, 18, 91–94.
- Kumpulainen, R. A., Högdahl, K., Ólafsson, G., Muñoz, A., & Valle, M. (1999). Sedimentology and stratigraphy of the fore-arc basin in southwestern Nicaragua. In S. Å. Elming, L. Widenfalk, & D. Rodrigues (Eds.), *Geoscientific research in Nicaragua: Swedish-Nicaraguan joint project during the period 1981-1991* (pp. 107–116). Luleå, Sweden: Luleå Technical University.
- Kutterolf, S., Rudolph, M., Schotters, N., & Deringer, A. (1997). Strukturelle und sedimentäre Entwicklung eines Forearc-Beckens (Tertiär, Térraba-Trog, Costa Rica). *Profil*, 12, 203–248.
- LaFemina, P. C., Dixon, T. H., Govers, R., Norabuena, E., Turner, H., Saballos, A., ... Strauch, W. (2009). Fore-arc motion and Cocos Ridge collision in Central America. *Geochemistry, Geophysics, Geosystems*, 10, Q05S14. <https://doi.org/10.1029/2008GC002181>
- LaFemina, P. C., Dixon, T. H., & Strauch, W. (2002). Bookshelf faulting in Nicaragua. *Geology*, 30, 751–754.
- Lang, J., Brandes, C., & Winsemann, J. (2017). Erosion and deposition by supercritical density flows during channel avulsion and backfilling: Field examples from coarse-grained deepwater channel-levee complexes (Sandino Forearc Basin, southern Central America). *Sedimentary Geology*, 349, 79–102.
- Lang, J., & Winsemann, J. (2013). Lateral and vertical facies relationships of bedforms deposited by aggrading supercritical flows: From cyclic steps to humpback dunes. *Sedimentary Geology*, 296, 36–54.
- Linkner, L., Beck, S. L., Schwartz, S. Y., Zandt, G., & Levin, V. (2010). Nature of crustal terranes and the Moho in northern Costa Rica from receiver function analysis. *Geochemistry, Geophysics, Geosystems*, 11, Q01S19. <https://doi.org/10.1029/2009GC002795>
- Lonsdale, P., & Klitgord, K. (1978). Structure and tectonic history of the eastern Panama Basin. *Geological Society of America Bulletin*, 89, 981–999.
- Lücke, O. H., & Arroyo, I. G. (2015). Density structure and geometry of the Costa Rican subduction zone from 3-D gravity modeling and local earthquake data. *Solid Earth*, 6, 1169–1183.
- Lundberg, N. (1982). Detrital record of the early Central American magmatic arc: Petrography of intraoceanic forearc sandstones, Nicoya Peninsula, Costa Rica. *Geological Society of America Bulletin*, 103, 905–915.
- MacKenzie, L., Abers, G. A., Fischer, K. M., Syracuse, E. M., Protti, J. M., Gonzalez, V., & Strauch, W. (2008). Crustal structure along the southern Central American volcanic front. *Geochemistry, Geophysics, Geosystems*, 9, Q08S09. <https://doi.org/10.1029/2008GC001991>
- MacMillan, I., Gans, P. B., & Alvarado, G. (2004). Middle Miocene to present tectonic history of the southern Central American Volcanic Arc. *Tectonophysics*, 392, 325–348.
- Mann, P. (1999). Chapter 1 Caribbean sedimentary basins: Classification and tectonic setting from Jurassic to present. *Caribbean Basins. Sedimentary Basins of the World*, 4(C), 3–31.
- Mann, P., & Corrigan, J. (1990). Model for late Neogene deformation in Panama. *Geology*, 18, 558–562.
- Mann, P., & Kolarsky, R. A. (1995). East Panama deformed belt: Structure, age, and neotectonic significance. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*. Geological Society of America Special Paper, 295 (pp. 111–130). Boulder, CO: GSA.
- Mann, P., Rogers, R. D., & Gahagan, L. (2007). Overview of plate tectonic history and its unresolved tectonic problems. In J. Bundschuh & G. E. Alvarado (Eds.), *Central America, geology, resources and hazards* (pp. 205–241). London, England: Taylor and Francis.
- Mann, P., & Taira, A. (2004). Global tectonic significance of the Solomon Islands and Ontong Java Plateau convergent zone. *Tectonophysics*, 389, 137–190.
- Marshall, J. S., Fisher, D. M., & Gardner, T. W. (2000). Central Costa Rica deformed belt: Kinematics of diffuse faulting across the western Panama block. *Tectonics*, 19, 468–492.
- Marshall, J. S., Idleman, B. D., Gardner, T. W., & Fisher, D. M. (2003). Landscape evolution within a retreating volcanic arc, Costa Rica, Central America. *Geology*, 31, 419–422.
- Mauffret, A., & Leroy, S. (1997). Seismic stratigraphy and structure of the Caribbean igneous province. *Tectonophysics*, 283, 61–104.
- McCaffrey, R. (1996). Estimates of modern arc-parallel strain rates in fore arcs. *Geology*, 24, 27–30.
- McClay, K. R., & Whitehouse, P. S. (2004). Analog modeling of doubly vergent thrust wedges. In K. R. McClay (Ed.), *Thrust tectonics and hydrocarbon systems*. American Association of Petroleum Geologists Memoir 82 (pp. 184–206). AAPG: Tulsa, OK.
- McIntosh, K., Silver, E., & Shipley, T. (1993). Evidence and mechanisms for forearc extension at the accretionary Costa Rica convergent margin. *Tectonics*, 12, 1380–1392.
- McIntosh, K. D., Silver, E. A., Ahmed, I., Berhorst, A., Ranero, C. R., Kelly, R. K., & Flueh, E. R. (2007). The Nicaragua Convergent Margin: Seismic reflection imaging of the source of a tsunami earthquake. In T. H. Dixon & J. C. Moore (Eds.), *The seismogenic zone of subduction thrust faults* (pp. 257–287). New York, NY: Columbia University Press.
- Mende, A. (2001). Sedimente und Architektur der Forearc- und Backarc-Becken von Südost-Costa Rica und Nordwest-Panamá. *Profil*, 19, 1–130.
- Meschede, M. (1998). The impossible Galapagos connection: Geometric constraints for a near-Andean origin of the Caribbean plate. *Geologische Rundschau*, 87, 200–205.
- Meschede, M., & Frisch, W. (1998). A plate tectonic model for the Mesozoic and Early Cenozoic history of the Caribbean Plate. *Tectonophysics*, 296, 269–291.
- Meschede, M., Frisch, W., Chinchilla Chavez, A. L., López Saborio, A., & Calvo, C. (2000). The plate tectonic evolution of the Caribbean Plate in the Mesozoic and Early Cenozoic. *Zeitschrift für Angewandte Geologie*, 51, 275–281.
- Meschede, M., Zweigel, P., Frisch, W., & Völker, D. (1999). Mélange formation by subduction erosion: The case of the Osa mélange in southern Costa Rica. *Terra Nova*, 11, 141–148.
- Montero, W. (1994). Neotectonics and related stress distribution in a subduction-collisional zone: Costa Rica. *Profil*, 7, 125–141.
- Montes, C., Bayona, G., Cardona, A., Buchs, D. M., Silva, C. A., Morón, S., ... Valencia, V. (2012). Arc-continent collision and orocline formation: Closing of the Central American seaway. *Journal of Geophysical Research*, 117, B04105. <https://doi.org/10.1029/2011JB008959>
- Montes, C., Cardona, A., Jaramillo, C., Pardo, A., Silva, J. C., Valencia, V., ... Niño, H. (2015). Middle Miocene closure of the Central American Seaway. *Science*, 348, 226–229.
- Morell, K. D. (2016). Seamount, ridge and transform subduction in southern Central America. *Tectonics*, 35, 357–385. <https://doi.org/10.1002/2015TC003950>
- Morell, K. D., Gardner, T. W., Fisher, D. M., Idleman, B. D., & Zellner, H. M. (2013). Active thrusting, landscape evolution and late Pleistocene sector collapse of Barú Volcano above the Cocos-Nazca slab tear, southern Central America. *Geological Society of America Bulletin*, 125, 1301–1318.
- Morell, K. D., Fisher, D. M., & Gardner, T. W. (2008). Inner forearc response to subduction of the Panama fracture zone, southern Central America. *Earth and Planetary Science Letters*, 265, 82–95.
- Morell, K. D., Kirby, E., Fisher, D. M., & van Soest, M. (2012). Geomorphic and exhumational response of the Central American volcanic arc to Cocos Ridge subduction. *Journal of Geophysical Research*, 117, B04409. <https://doi.org/10.1029/2011JB008969>
- Morgan, J. P., Ranero, C. R., & Vannucchi, P. (2008). Intra-arc extension in Central America: Links between plate motions, tectonics, volcanism, and geochemistry. *Earth and Planetary Science Letters*, 272, 365–371.
- Morley, C. K. (2001). Combined escape tectonics and subduction rollback-back arc extension: A model for the evolution of Tertiary rift

- basins in Thailand, Malaysia and Laos. *Journal of the Geological Society*, 158, 461–474.
- Muñoz, A., Baca, D., Artiles, V., & Duarte, M. (1997). Nicaragua: Petroleum geology of the Caribbean margin. *The Leading Edge*, 16, 1799–1805.
- Nakakuki, T., & Mura, E. (2013). Dynamics of slab rollback and induced back-arc basin formation. *Earth and Planetary Science Letters*, 361, 287–297.
- Noda, A. (2016). Forearc basins: Types, geometries, and relationships to subduction zone dynamics. *GSA Bulletin*, 128, 879–895.
- O'Dea, A., Lessios, H. A., Coates, A. G., Eytan, R. I., Restrepo-Moreno, S. A., Cione, A. L., ... Jackson, J. B. C. (2016). Formation of the Isthmus of Panama. *Science Advances*, 2, e1600883. <https://doi.org/10.1126/sciadv.1600883>
- Peacock, S. M., van Keken, P. E., Holloway, S. D., Hacker, B. R., Abers, G. A., & Ferguson, R. L. (2005). Thermal structure of the Costa Rica – Nicaragua subduction zone. *Physics of the Earth and Planetary Interiors*, 149, 187–200.
- Pindell, J., Kennan, L., Stanek, K. P., Maresch, W. V., & Draper, G. (2006). Foundations of Gulf of Mexico and Caribbean evolution: Eight controversies resolved. *Geologica Acta*, 4, 303–341.
- Pindell, J., Maresch, W. V., Martens, U., & Stanek, K. (2012). The Greater Antillean Arc: Early Cretaceous origin and proposed relationship to Central American subduction mélanges: Implications for models of Caribbean evolution. *International Geology Review*, 54, 131–143.
- Pindell, J. L., Cande, S. C., Pitman, W. C., Rowley, D. B., Dewey, J. F., Labrecque, J., & Haxby, W. (1988). A plate-kinematic framework for models of Caribbean evolution. *Tectonophysics*, 155, 121–138.
- Pindell, J. L., & Kennan, L. (2009). Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: An update. In K. H. James, M. A. Lorente, & J. L. Pindell (Eds.), *The origin and evolution of the Caribbean Plate*. Geological Society of London Special Publication 328 (pp. 1–55). Bath, England: The Geological Society Publishing House.
- Plank, T., Balzer, V., & Carr, M. (2002). Nicaraguan volcanoes record paleo oceanographic changes accompanying closure of the Panama gateway. *Geology*, 30, 1087–1090.
- Polat, A. (2012). Growth of Archean continental crust in oceanic island arcs. *Geology*, 40, 383–384.
- Portig, W. (1976). The climate of Central America. In W. Schwertfeger (Ed.), *Climates of Central and South America*. World Survey of Climatology, 12 (pp. 405–478). Amsterdam, The Netherlands: Elsevier.
- Protti, M., Gündel, F., & McNally, K. (1995a). The geometry of the Wadati-Benioff zone under southern Central America and its tectonic significance: Results from a high-resolution local seismographic network. *Physics of the Earth and Planetary Interiors*, 84, 271–287.
- Protti, M., Gündel, F., & McNally, K. (1995b). Correlation between the age of the subducting Cocos plate and the geometry of the Wadati-Benioff zone under Nicaragua and Costa Rica. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*. Geological Society of America Special Paper, 295 (pp. 309–326). Boulder, CO: GSA.
- Protti, M., & Schwartz, S. Y. (1994). Mechanics of back arc deformation in Costa Rica: Evidence from an aftershock study of the April 22, 1991, Valle de la Estrella, Costa Rica, earthquake ($M_w=7.7$). *Tectonics*, 13, 1093–1107.
- Ramírez, D. A., Foster, D. A., Min, K., Montes, C., Cardona, A., & Sadove, G. (2016). Exhumation of the Panama basement complex and basins: Implications for the closure of the Central American seaway. *Geochemistry, Geophysics, Geosystems*, 17, 1758–1777.
- Ranero, C. R., & von Huene, R. (2000). Subduction erosion along the Middle America convergent margin. *Nature*, 404, 748–752.
- Ranero, C. R., von Huene, R., Flueh, E., Duarte, M., Baca, D., & McIntosh, K. (2000). A cross section of the convergent Pacific margin of Nicaragua. *Tectonics*, 19, 335–357.
- Ranero, C. R., von Huene, R., Flueh, E. R., Weinrebe, W., Hinz, K., Leandro, G., ... Duarte, M. (2000). Lower plate control on subduction erosion processes along the middle America convergent margin. *Zeitschrift für Angewandte Geologie, SH*, 1, 291–296.
- Regalla, C., Fisher, D. M., Kirby, E., & Furlong, K. P. (2013). Relationship between outer forearc subsidence and plate boundary kinematics along the Northeast Japan convergent margin. *Geochemistry, Geophysics, Geosystems*, 14(12), 5227–5243. <https://doi.org/10.1002/2013GCO05008>
- Rockwell, T. K., Bennett, R. A., Gath, E., & Franceschi, P. (2010). Unhinging an indenter: A new tectonic model for the internal deformation of Panama. *Tectonics*, 29, TC4027. <https://doi.org/10.1029/2009TC002571>
- Rogers, R. D., Mann, P., & Emmet, P. A. (2007). Tectonic terranes of the Chortís block based on integration of regional aeromagnetic and geologic data. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate Boundary in northern Central America*. Geological Society of America Special Paper, 428 (pp. 65–88). Boulder, CO: GSA.
- Rogers, R. D., Mann, P., Emmet, P. A., & Venable, M. E. (2007). Colon fold belt of Honduras: Evidence for Late Cretaceous collision between the continental Chortís block and intraocenaic Caribbean arc. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate Boundary in northern Central America*. Geological Society of America Special Paper, 428 (pp. 129–149). Boulder, CO: GSA.
- Rooney, T. O., Morell, K. D., Hidalgo, P., & Franceschi, P. (2015). Magmatic consequences of the transition from orthogonal to oblique subduction in Panama. *Geochemistry, Geophysics, Geosystems*, 16, 4178–4208.
- Ross, M. I., & Scotese, C. R. (1988). A hierarchical tectonic model of the Gulf of Mexico and the Caribbean region. *Tectonophysics*, 155, 139–168.
- Sadler, J. C., Lander, M. A., Hori, A. M., & Oda, L. K. (1987). *Tropical marine climatic atlas. Volume II: Pacific Ocean*. National Oceanic Administration. Tropical Ocean and Atmosphere and Equatorial Pacific Ocean Climate Studies. Honolulu, Hawaii: Department of Meteorology, University of Hawaii.
- Sak, P. B., Fisher, D. M., Gardner, T. W., Marshall, J. S., & LaFemina, P. C. (2009). Rough crust subduction, forearc kinematics, and Quaternary uplift rates, Costa Rican segment of the Middle America Trench. *Geological Society of America Bulletin*, 121, 992–1012.
- Sak, P. B., Fisher, D. M., & Gardner, T. W. (2004). Effects of subducting seafloor roughness on upper plate vertical tectonism: Osa Peninsula, Costa Rica. *Tectonics*, 23, TC1017. <https://doi.org/10.1029/2002TC001474>
- Sallarès, V., Danobeitia, J. J., Flueh, E. R., & Leandro, G. (1999). Seismic velocity structure across the middle American landbridge in northern Costa Rica. *Journal of Geodynamics*, 27, 327–344.
- Sanchez, J., Mann, P., & Emmet, P. A. (2016). Late Cretaceous–Cenozoic tectonic transition from collision to transtension, Honduran Borderlands and Nicaraguan Rise, NW Caribbean Plate boundary. In M. Nemčok, S. Rybár, S. T. Sinha, S. A. Hermeston, & L. Ledvényiová (Eds.), *Transform margins: Development, controls and petroleum systems*. Geological Society of London Special Publication 431 (pp. 273–297). Bath, England: The Geological Society Publishing House.
- Schellart, W. P. (2010). Mount Etna-Iblean volcanism caused by rollback-induced upper mantle upwelling around the Ionian slab edge: An alternative to the plume model. *Geology*, 38, 691–694.
- Schlegel, R., Wortmann, U., Krawinkel, H., Krawinkel, J., & Winsemann, J. (1995). Architecture and facies associations of Plio-Pleistocene trench-slope deposits, Burica Peninsula, Central America. In K. T. Pickering, F. Ricci Lucchi, R. Smith, R. N. Hiscott, & N. Kenyon (Eds.), *An atlas of deep-water systems* (pp. 63–66). Dordrecht, The Netherlands: Springer Science.
- Schmidt, H., & Seyfried, H. (1991). Depositional sequences and sequence boundaries in forearc coastal embayments: Case histories from Central America. In D. I. M. MacDonald (Ed.), *Sedimentation, tectonics and eustasy: Sea-level changes at active margins*. International Association of Sedimentologists Special Publication 12 (pp. 241–258). Oxford, England: Blackwell Science.
- Sdrolias, M., & Müller, R. D. (2006). Controls on back-arc basin formation. *Geochemistry, Geophysics, Geosystems*, 7, Q04016. <https://doi.org/10.1029/2005GCO01090>
- Seyfried, H., Astorga, A., Amann, H., Calvo, C., Kolb, W., Schmidt, H., & Winsemann, J. (1991). Anatomy of an evolving Island Arc: Tectonic and eustatic control in the south Central American forearc area. In D. I. M. MacDonald (Ed.), *Sedimentation, tectonics and eustasy: Sea-level changes at active margins*. International Association of Sedimentologists Special Publication 12 (pp. 273–292). Oxford, England: Blackwell Science.

- Seyfried, H., Krawinkel, H., & Aguilar, T. (1994). Significance of stratigraphic bounding surfaces in a shallow marine, sand-swamped forearc basin: A case study from the Punta Judas Formation (Miocene, Costa Rica). *Profil*, 7, 293–323.
- Seyfried, H., & Sprechmann, P. (1986). Über die Frühgeschichte (Campan bis Eozän) der südlichen mittelamerikanischen Landbrücke. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte*, 1, 38–55.
- Silver, E., Costa Pisani, P., Hutnak, M., Fisher, A., DeShon, H., & Taylor, B. (2004). An 8–10 Ma tectonic event on the Cocos Plate offshore Costa Rica: Result of Cocos Ridge collision? *Geophysical Research Letters*, 31, L18601. <https://doi.org/10.1029/2004GL020272>
- Silver, E. A., Galewsky, J., & McIntosh, K. D. (1995). Variation in structure, style, and driving mechanism of adjoining segments of the North Panama deformed belt. In P. Mann (Ed.), *Geologic and tectonic development of the Caribbean Plate boundary in southern Central America*. Geological Society of America Special Paper, 295 (pp. 225–233). Boulder, CO: GSA.
- Silver, E. A., Reed, D. L., Tagudin, J. E., & Heil, D. J. (1990). Implications of the north and south Panama thrust belts for the origin of the Panama orocline. *Tectonics*, 9, 261–281.
- Sitchler, J. C., Fisher, D. M., Gardner, T. W., & Protti, M. (2007). Constraints on inner forearc deformation from balanced cross sections, Fila Costena thrust belt, Costa Rica. *Tectonics*, 26, TC6012. <https://doi.org/10.1029/2006TC001949>
- Sleep, N. H., & Toksöz, M. N. (1971). Evolution of marginal basins. *Nature*, 233, 548–550.
- Sprechmann, P. (1984). *Manual de geología de Costa Rica, 1: Estratigrafía*. San José, Costa Rica: Edition Universitaria.
- Stephens, J. H. (2014). Tectonic and depositional history of an active forearc basin, Sandino Basin, offshore Nicaragua (PhD thesis). Austin, Texas: The University of Texas at Austin.
- Struss, I. (2008). The petroleum potential of the Sandino Forearc Basin, Western Nicaragua. (PhD thesis) (pp. 176). Hannover, Germany: Leibniz Universität Hannover.
- Struss, I., Artilés, V., Cramer, B., & Winsemann, J. (2008). The petroleum system in the Sandino Forearc Basin, offshore western Nicaragua. *Journal of Petroleum Geology*, 31, 221–244.
- Struss, I., Blisniuk, P., Brandes, C., Kischkies, M., & Winsemann, J. (2007). Channel geometries and internal deformation patterns of the Playa Las Tablas channel-levee system, Nicaragua. In H. Nilsen, R. D. Shew, G. S. Steffens, & J. R. J. Studlick (Eds.), *Atlas of deep-water outcrops*. American Association of Petroleum Geologists Studies in Geology 56 (pp. 265–267). AAPG: Tulsa, OO.
- Struss, I., Brandes, C., Blisniuk, P. M., & Winsemann, J. (2007). Eocene deep-water channel-levee deposits, Nicaragua: Channel geometries and internal deformation patterns of six outcrops. In H. Nilsen, R. D. Shew, G. S. Steffens, & J. R. J. Studlick (Eds.), *Atlas of deep-water outcrops*. American Association of Petroleum Geologists Studies in Geology 56, CD Rom, 31 p. Tulsa, OK: AAPG.
- Struss, I., Brandes, C., Vandr , C., & Winsemann, J. (2007). Lithofacies and depositional architecture of an upper fan channel complex, Punta Naranjo, Nicaragua. In H. Nilsen, R. D. Shew, G. S. Steffens, & J. R. J. Studlick (Eds.), *Atlas of deep-water outcrops*. American Association of Petroleum Geologists Studies in Geology 56 (pp. 268–270). Tulsa, OK: AAPG.
- Su rez, G., Pardo, M., Dom nguez, J., Ponce, L., Montero, W., Boschini, I., & Rojas, W. (1995). The Lim n, Costa Rica earthquake of April 22, 1991: Back arc thrusting and collisional tectonics in a subduction environment. *Tectonics*, 14, 518–530.
- Suppe, J., & Medwedeff, D. A. (1990). Geometry and kinematics of fault-propagation folding. *Eclogae Geologicae Helvetica*, 83, 409–454.
- ten Brink, U. S., Marshak, S., & Granja Bruna, J. L. (2009). Bivergent thrust wedges surrounding oceanic island arcs: Insight from observations and sandbox models of the northeastern Caribbean plate. *Geological Society of America Bulletin*, 121, 1522–1536.
- Tetreault, J. L., & Buitter, S. J. H. (2012). Geodynamic models of terrane accretion: Testing the fate of island arcs, oceanic plateaus, and continental fragments in subduction zones. *Journal of Geophysical Research*, 117, B08403. <https://doi.org/10.1029/2012JB009316>
- Tomascak, P. B., Ryan, J. G., & Defant, M. J. (2000). Lithium isotope evidence for light element decoupling in the Panama subarc mantle. *Geology*, 28, 507–510.
- Tournon, J. (1994). The Santa Elena Peninsula: An ophiolitic nappe and a sedimentary volcanic relative autochthonous. *Profil*, 7, 87–96.
- Tournon, J., Triboulet, C., & Az ma, J. (1989). Amphibolites from Panama: Anticlockwise P–T paths from a Pre-upper Cretaceous metamorphic basement in Isthmian Central America. *Journal of Metamorphic Geology*, 7, 539–546.
- Turner, H. L., LaFemina, P., Saballos, A., Mattioli, G. S., Jansma, P. E., & Dixon, T. (2007). Kinematics of the Nicaraguan forearc from GPS geodesy. *Geophysical Research Letters*, 34, L02302. <https://doi.org/10.1029/2006GL027586>
- Uyeda, S., & Kanamori, H. (1979). Back-arc opening and the mode of subduction. *Journal of Geophysical Research*, 84, 1049–1061.
- Vannucchi, P., Morgan, J. P., & Balestrieri, M. L. (2016). Subduction erosion, and the de-construction of continental crust: The Central America case and its global implications. *Gondwana Research*, 40, 184–198.
- Vannucchi, P., Morgan, J. P., Silver, E. A., & Kluesner, J. W. (2016). Origin and dynamics of depositional subduction margins. *Geochemistry, Geophysics, Geosystems*, 17, 1966–1974.
- Vannucchi, P., Scholl, D. W., Meschede, M., & McDougall-Reid, K. (2001). Tectonic erosion and consequent collapse of the Pacific margin of Costa Rica: Combined implications from the ODP leg 170, seismic offshore data, and regional geology of the Nicoya Peninsula. *Tectonics*, 20, 649–668.
- von Eynatten, H., Schmidt, H., & Winsemann, J. (1993). Plio-Pleistocene outer arc basins in southern Central America. In L. Frostick & R. Steele (Eds.), *Sedimentation and tectonics*. International Association of Sedimentologists Special Publication 20 (pp. 399–414). Oxford, England: Blackwell Science.
- von Huene, R., & Scholl, D. W. (1991). Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust. *Reviews of Geophysics*, 29, 279–316.
- Walther, C. H. E. (2003). The crustal structure of the Cocos Ridge off Costa Rica. *Journal of Geophysical Research*, 108, B3. <https://doi.org/10.1029/2001JB000888>
- Walther, C. H. E., Flueh, E. R., Ranero, C. R., von Huene, R., & Strauch, W. (2000). Crustal structure across the Pacific margin of Nicaragua: Evidence for ophiolitic basement and a shallow mantle sliver. *Geophysical Journal International*, 141, 759–777.
- Wegner, W., W rner, G., Harmon, R. S., & Jicha, B. R. (2011). Magmatic history and evolution of the Central American Land Bridge in Panama since Cretaceous times. *Geological Society of America Bulletin*, 123, 703–724.
- Weinberg, R. F. (1992). Neotectonic development of western Nicaragua. *Tectonics*, 11, 1010–1017.
- Weyl, R. (1980). *Geology of Central America*. Berlin, Germany: Borntraeger.
- Willett, S. D., Beaumont, C., & Fullsack, P. (1993). Mechanical model for the tectonics of doubly vergent compressional orogens. *Geology*, 21, 371–374.
- Williams, T. A., & Graham, S. A. (2013). Controls on forearc basin architecture from seismic and sequence stratigraphy of the Upper Cretaceous Great Valley Group, central Sacramento Basin, California. *International Geology Review*, 55, 2030–2059. <https://doi.org/10.1080/00206814.2013.817520>
- Winsemann, J. (1992). Tiefwasser-sedimentationsprozesse und -produkte in den Forearc-Becken des mittelamerikanischen Inselbogensystems: Eine sequenzstratigraphische Analyse. *Profil*, 2, 1–218.
- Winsemann, J., & Seyfried, H. (1991). Response of deep-water forearc systems to sea-level changes, tectonic activity and volcanoclastic input in Central America. In D. I. M. MacDonald (Ed.), *Sedimentation, tectonics and eustasy: Sea-level changes at active margins*. International Association of Sedimentologists Special Publication 12 (pp. 217–240). Oxford, England: Blackwell Science.
- W rner, G., Harmon, R. S., & Wegner, W. (2009). Geochemical evolution of igneous rock and changing magma sources during the evolution and closure of the Central American Landbridge. In S. M. Kay, V. A. Ramos, & W. R. Dickinson (Eds.), *Backbone of the Americas: Shallow subduction, plateau subduction, plateau uplift, and ridge and terrane*

- collision*. Geological Society of America Memoir, 2004 (pp. 183–196). Boulder, CO.
- Xie, X., & Heller, P. L. (2009). Plate tectonics and basin subsidence history. *Geological Society of America Bulletin*, 121, 55–64.
- Yamaji, A. (2003). Slab rollback suggested by latest Miocene to Pliocene forearc stress and migration of volcanic front in southern Kyushu, northern Ryukyu Arc. *Tectonophysics*, 364, 9–24.
- Zeumann, S., & Hampel, A. (2015). Deformation of erosive and accretive forearcs during subduction of migrating and non-migrating aseismic ridges: Results from 3-D finite-element models and application to the Central American, Peruvian and Ryukyu margins. *Tectonics*, 34, 1769–1791.
- Zeumann, S., & Hampel, A. (2016). Three-dimensional finite-element models on the deformation of forearcs caused by aseismic ridge subduction: The role of ridge shape, friction coefficient of the plate interface and mechanical properties of the forearc. *Tectonophysics*, 684, 76–91.
- Zeumann, S., & Hampel, A. (2017). Impact of Cocos Ridge (Central America) subduction on the forearc drainage system. *Geology*, 45, 907–910.
- Zhu, J., Kopp, H., Flueh, E. R., Klaeschen, D., Papenberg, C., & Planert, L. (2009). Crustal structure of the central Costa Rica subduction zone: Implications for basal erosion from seismic wide-angle data. *Geophysical Journal International*, 178, 1112–1131.

How to cite this article: Brandes C, Winsemann J. From incipient island arc to doubly-vergent orogen: A review of geodynamic models and sedimentary basin-fills of southern Central America. *Island Arc*. 2018;27:e12255. <https://doi.org/10.1111/iar.12255>