Demise of the Barra Honda carbonate shoal (Costa Rica) at the Paleocene-Eocene boundary linked to climate change and forearc tectonics

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Key Points

- U-Pb age, biostratigraphic, and stable isotope compositions show that the Barra Honda carbonate shoal ended at the Paleocene-Eocene boundary
- Ocean acidification and increased detrital/nutrient influx may be the primary causes of the demise
- High subsidence rates of the forearc basin during the early Eocene terminated the shallow carbonate sedimentation

Abstract

The latest Cretaceous(?)–Paleocene Barra Honda Formation represents one of the largest carbonate shoals (>900 km^2, 350 m thick) of the convergent margin of Costa Rica. Although the mode of formation of the carbonate shoal is well understood, how environmental and tectonic factors interacted to cause its demise near the Paleocene-Eocene boundary remains poorly constrained. Stable isotopic, biostratigraphic, mineralogical, and geochronologic analyses from the Barra Honda Formation and overlying siliceous Buenavista Formation provide new constraints on the timing and causes of the demise of the carbonate shoal. We report one new U–Pb zircon chemical abrasion, isotope dilution, thermal ionization mass spectrometry date (56.30 Ma ± 0.13 Ma, 2σ) obtained from an ash-rich layer at the boundary between the two formations. The sharp transition from Barra Honda massive limestones to Buenavista marl-chert alternations coincides with a negative shift in carbon isotope ($\delta^{13}C_{carb}$) values of about 3 to 5 ‰ and a 50 % decrease in carbonate contents. The timing of the combined lithological-mineralogical-isotopic change is coeval with the Paleocene-Eocene Thermal Maximum (PETM, 56 Ma). The onset of clay-rich sedimentation is consistent with a PETM-related increase of terrestrial influx of nutrients and detrital particles, which promoted eutrophication and decreased light availability in the photic zone. Combined with seawater acidification and warming, these environmental parameters were fatal to carbonate-producing benthic communities of Barra Honda. High subsidence rates of the

forearc basin and renewed arc volcanic activity must have closely followed the cessation of shallow carbonate production, preventing further formation of the carbonate shoal.

Plain Language Summary

The Barra Honda Formation in Costa Rica is a large area of carbonate rocks formed during the latest Cretaceous(?)–Paleocene interval. We wanted to understand why this carbonate shoal, which was formed by a favorable combination of environmental and tectonic factors, disappeared around the Paleocene–Eocene boundary. We studied different aspects, i.e., stable isotopes, microfossils, minerals, and ages of rocks from the Barra Honda Formation and the overlying Buenavista Formation. We present a new age date from zircons recovered from an ash layer between these formations, showing that the lithological change happened around 56 million years ago. At that time, there was a sudden shift in the types of sedimentary rocks deposited and in their carbon isotope values. This change coincides with a significant global event called the Paleocene–Eocene Thermal Maximum (PETM), known for causing environmental upheavals like ocean warming and increased ocean water acidity. These factors caused more nutrients to flow in from land and reduced light in the seawater, and likely led to the decline of benthic communities in the Barra Honda carbonate shoal. Additionally, the basin where these carbonate rocks formed started sinking rapidly after the PETM event, preventing the shoal from recovering.

1. Introduction

Oceanic Central America is composed of a puzzle of oceanic plateau and arc terranes that extend between the North America-derived, continental Chortis terrane, and the South American plate outcropping in the Columbian Andes (Figure 1a; Rogers et al., 2007; Baumgartner et al., 2008; Buchs et al., 2010; Andjić et al., 2019a, 2019b). No older continental basement is known to occur in these southern Central American terranes, that form the trailing edge of the Caribbean Plate (Mann, 2007; Pindell & Kennan, 2009). Sedimentation along the Central American convergent margin was dominated by arc-derived deep-water volcano-detrital deposits throughout the Late Mesozoic-Cenozoic (Escalante, 1991; Alvarado et al., 2007). Nevertheless, shallow-water carbonates do occur (Baumgartner-Mora & Baumgartner, 2016) and are characterized by: (i) sudden appearance and disappearance of conditions for chlorozoan carbonate production; (ii) modest size (1-100 km wide); and (iii) a geologically short period (1-10 Ma). These "punctuated chlorozoan carbonates" (Baumgartner-Mora et al., 2019) occur all along the Mid-American convergent margin and consist of short-lived carbonate banks and buildups, interstratified in generally deep-water turbiditic fore- and back-arc series. Hence, punctuated chlorozoan carbonates formed under overall unfavorable conditions: (i) a high input of suspended detrital particles was produced by tropical weathering of emerged oceanic terranes and superposed volcanic edifices, as well as airborne ashes from active volcanoes; (ii) the rise into the photic zone of any oceanic substrate suitable for punctuated chlorozoan carbonates was controlled either by accretion tectonics or by intra-oceanic volcanism (oceanic islands, plateaus, arcs). Carbonate production in long-lived (10-60 Ma), large carbonate shelves set along passive margins, is thought to be controlled primarily by paleoclimate and eustatic sea level change (e.g., Kemp & Sadler, 2014). In contrast, punctuated chlorozoan carbonates are the biotic response to convergent-margin endogenic processes, such as tectonic uplift related to the subduction/accretion of topographic relief on the subducting plate, that may result in a temporary arc gap (Andjić et al., 2018a, 2018b) and thus a reduction of detrital discharge (Andjić et al., 2019a).

The uppermost Cretaceous(?)–Paleocene Barra Honda Formation (Fm.; Dengo, 1962), located in the Guanacaste Province of Costa Rica (Figure 1b), largely built of chloralgal carbonate mud, is a good example of a short-lived, moderately-sized (originally >900 km^2) chlorozoan carbonate shoal. Its age and stratigraphic setting were enigmatic for a long time, because of the scarcity of age-diagnostic fossils and its position sandwiched unconformably between Upper Cretaceous and Eocene deep-water clastic formations. Jaccard et al. (2001) re-mapped the formation and described occurrences of *Ranikothalia catenula* group and *Neodiscocyclina barkeri* from the upper Barra Honda Fm. and assigned it to a late Paleocene to early Eocene age. Facies models for the upper Barra Honda Fm. were proposed in Jaccard et al. (2001) and Baumgartner-Mora and Baumgartner (2016). The latter authors revised the systematics of *Ranikothalia* and gave a general account of upper Paleocene carbonates of Costa Rica and western Panama.

This study examines the stratigraphic top of the Barra Honda Fm. and the overlying pelagic cherts and limestones (Buenavista Fm.) that crop out in an active quarry 4.5 km east of the town of Nicoya (Figure 1b). In coeval, more distal, deep-water sections a pelagic cherty limestone series (Buenavista Fm.) records a break in the detrital forearc sedimentation between the underlying predominantly basaltic forearc turbidites (Curú Fm.) and the overlying, more andesitic turbidites of the Descartes Fm. (Baumgartner et al., 1984). The sediment petrologic change has been known for a long time (Lundberg, 1982) and the break has been interpreted by us as a possible regional, temporary arc gap between a primitive and a more evolved island arc (Andjić et al., 2018a). The birth and growth of the Barra Honda carbonate shoal has been previously discussed as a biotic response to the lack and/or bypassing of detrital input during the arc gap and uplift of the proximal forearc basin (Baumgartner-Mora & Baumgartner, 2016; Andjić et al., 2018a). In this study, we combine carbon stable isotope stratigraphy, bulk mineralogy analysis, zircon dating, and micropaleontology to test whether the sudden demise of the Barra Honda Fm. near the Paleocene–Eocene boundary may be primarily controlled by climate change during the PETM.

The abrupt shift from carbonate-rich to carbonate-poor layers–such as the Barra Honda–Buenavista boundary–has been described in marine PETM sections around the world. Centimeter- to meter-sized clay-rich layers coincide with the onset of the PETM, with examples from onshore sections (Schmitz et al., 2001; Aubry et al., 2007; Giusberti et al. 2007; Bralower et al., 2018) and offshore drillholes (Lyle et al., 2002; Zachos et al., 2004; Colosimo et al., 2006; Borneman et al., 2014; Penman, 2016; Wade et al., 2020). The interruption of carbonate-rich sedimentation in deep seas has been interpreted as the result of ocean acidification that accompanied the rapid release of large amounts of CO_2 (e.g., Dickens et al., 1997; Zachos et al., 2005; Zeebe & Zachos, 2007; Penman et al., 2014; Babila et al., 2018). The decrease or absence of carbonate accumulation and preservation in deep-water settings was primarily associated with the shallowing of the lysocline and carbonate compensation depth (Zachos et al., 2005; Gibbs et al., 2010; Murphy et al., 2010). The shallow-water, tectonically active, arc-proximal setting of the Barra Honda carbonate shoal requires a discussion on the interplay of local and global (e.g., ocean acidification) factors in its demise at the Paleocene–Eocene boundary.

1.1. Margin response to rough crust subduction

The subduction of bathymetric reliefs influences the structural and magmatic evolution of convergent margins (Cloos, 1993). Whether accretion occurs or not, the primary response of the upper plate is to accommodate the colliding object by kilometric surface uplift in the forearc (Spikings & Simpson, 2014). Hence, the amplitude of vertical tectonic motions may be of up to two orders of magnitude higher than eustatic variations (Gardner et al., 2013). Short-lived, shallow-water and sub-aerial environments appear in the inner and/or outer forearc and replace previous long-lived, deep-water domains (Dorobek, 2008). Except in the case of stationary subduction of an aseismic ridge or hotspot track (~1000 km length scale), the duration of forearc uplift is generally shorter than 5 Ma (Meffre & Crawford, 2001; Tetreault & Buiter, 2012; Vogt & Gerya, 2014). Once the colliding bathymetric feature is subducted, the forearc seafloor subsides to its previous water depth; if rough crust subduction caused tectonic erosion of the upper plate, the forearc basin subsides to deeper water depths than in its pre-collisional state (von Huene & Suess, 1988).

A possible secondary response of the upper plate to the collision of bathymetric relief is cessation of the volcanic activity, which occurs after the initial stage of collision at shallow depths. Spatial gaps in volcanism develop when the leading edge of the object, or its remaining root, reaches greater depth where it may promote flat slab subduction, slab break-off, or modification of dehydration processes in the mantle wedge (McGeary et al., 1985; Rosenbaum & Mo, 2011; Bishop et al., 2017). In the latter case, considering orthogonal convergence rates comprised between ~3.5 and 12 cm/yr (e.g., Young et al., 2019), volcanic arc cessation in response to the arrival of the object at the depth of major slab dehydration and arc magmagenesis (~100 km; Ranero et al., 2005) may occur between ~0.8 and 3 Ma after the onset of collision. If the object is long enough (>100 km), a magmatic lull occurs while surface uplift is sustained by the subduction of the object trailing edge.

The identification of arc gaps in ancient volcanic formations is uncertain, because igneous rocks are often discontinuously preserved. Drawing mainly on examples from Central America, Andjić et al. (2018a) have recently shown that forearc sedimentary rocks can record lulls in the magmatic history of arcs (Figure 2). In particular, the abrupt interruption of volcaniclastic sedimentation in forearc basins and its replacement by pelagic sedimentation indicate a demise in the production of arc-derived material. After the collision of the bathymetric relief, renewed subduction of normal oceanic crust in the window of major fluid release and related volcanic activity resume the supply of detrital material to the forearc basin. Interestingly, Andjić et al. (2018a) have identified delays between the onset/end of forearc uplift and onset/end of volcanic activity in past collision episodes of oceanic plateau in Costa Rica (middle Campanian and late Paleocene). Here, shallow-water carbonates (i.e., middle Campanian El Viejo and late Paleocene Barra Honda formations; Figure 1b) deposited in response to forearc uplift formed earlier than pelagic sedimentation (i.e., Piedras Blancas and Buenavista formations) resulting from the cessation of volcanic arc activity: this may be the consequence of the colliding object interacting first with shallow levels of the upper plate before being subducted to greater depths and modifying dehydration processes in the mantle wedge (Figure 2). In contrast, the demise of shallow-water carbonate factories intervened earlier than the termination of pelagic sedimentation: this may result from the tail of the colliding object interacting with the mantle wedge later than it was the case with the shallow upper plate (Figure 2d). Because it occurred near the Paleocene–Eocene boundary, the demise of the Barra Honda shoal may not be solely attributed to local factors (e.g., forearc tectonics and/or volcaniclastic input) and calls for a test of a causal link with the PETM.

2. The Barra Honda Formation: previous work

The Barra Honda carbonate shoal crops out in the Tempisque and Nicoya areas as erosional remnants in karstified hills representing anticlines, covering today less than 60 km^2 (Denyer et al., 2014a), but originally had a surface of >900 km^2 (Baumgartner-Mora & Baumgartner, 2016; Figure 3a). It was defined as a formation by Dengo (1962). Mora (1981) described two subunits in the Cerro Barra Honda area: a lower, poorly stratified, massive white limestone composed of algal boundstones and some peloid wackestones, largely composed of micrite, and an upper stratified unit of peloidal packstones and oolitic grainstones. Geological mapping (Rivier, 1983; Jaccard et al., 2001; Flores et al., 2003a, 2003b; compilation by Denyer et al., 2014b) shows that the formation rests unconformably on Upper Cretaceous to Paleocene deep-water formations, with a highly diachronous erosional surface (Figure 4) that was subaerial or paralic as suggested in the northernmost outcrops (Cerro Espiritu Santo), where bored limestone clasts are set in an altered matrix of Upper Cretaceous Sabana Grande Fm. (Di Marco et al., 1995; Jaccard & Münster, 2001; Jaccard et al., 2001). In the north transgression/progradation of the upper Barra Honda over the altered Upper Cretaceous surface starts with lenses of cross-laminated oolitic packstones and grainstones containing *Neodiscocyclina grimsdalei*, thick-shelled *Ranikothalia catenula antillea* and *R. c. tobleri*, as well as large melobesian rhodoids encrusted by *Polystrata alba*, forming bafflestones. These rather high energy, near-shore facies are overlain by calm-water, neritic wackestones rich in *Distichoplax biserialis*, and thin-shelled *Ranikothalia*, such as *R. catenula catenula* and *R. c. soldadensis* attesting for a late Paleocene age (Baumgartner-Mora & Baumgartner, 2016). Calvo and Bolz (1991) recognized a late Paleocene–early Eocene age of the Espiritu Santo limestones but did not relate them with the Barra Honda Fm.

In outcrops to the southeast (Pochote; Figure 3a), Jaccard et al. (2001) described a sequence with abundant reworked pelagic limestone clasts, certainly reworked from the Piedras Blancas Fm. according to the presence of the late Campanian–Maastrichtian *Globotruncana ventricosa*, included in an open-marine micritic matrix containing the upper Paleocene *Morozovella velascoensis* and *Pseudohastigerina* sp. Here the Barra Honda encroaches with a sharp, but apparently conformable contact over the sandy forearc turbidites of the Paleocene Curú Fm. Up-section, shallow-water clasts increase and a typical, massive Barra Honda facies with abundant squamariacean *Polystrata alba* follow towards the top. Here, the onset of Barra Honda takes place in an offshore marine, foreslope paleoenvironment without a major erosional hiatus at its base. In the lower part, Upper Cretaceous lithoclasts were reworked from the substrate cropping out up-slope, while intraformational poorly lithified shallow-water clasts dominate in the upper part of the section. Aguilar and Denyer (2001) reported coral patch reefs from the eastern outcrops of Barra Honda, near Puerto Nispero (Figure 3a). Chesnel et al. (2024) revisited the Puerto Nispero outcrops and described typical Barra Honda facies interbedded with a coral patch reef attributed by them to a Maastrichtian age, based on the presence of *Nerinea* and the coral genus *Marcelohelia* sp. These carbonates around Puerto Nispero, along the East bank of the lower Tempisque estuary (Figure 3a) were previously mapped as Barra Honda Fm. (Denyer et al., 2014b), and represent undoubtedly the lowest (and oldest) part of this formation, resting unconformably on hemipelagic lime- and claystone attributed to the Campanian-Maastrichtian Piedras Blancas Fm. (Denyer et al., 2014b).

Unfortunately, Chesnel et al. (2024) defined a new “Puerto Nispero Fm.”, which includes both the deformed hemipelagic “claystone” and the unconformably overlying shallow carbonates, defining rather a Maastrichtian “chronozone” than a formation in the sense of the International Code of Stratigraphy (Murphy & Salvador, 1999). However, the illustrated, poorly preserved, planktonic foraminifera of the “claystone” (*Rugoglobigerina rugosa* and *Globotruncanella* sp.) range from middle Campanian to Maastrichtian (Huber et al., 2016; Petrizzo et al., 2020), which fits the age range of the Piedras Blancas Fm.

Baumgartner-Mora and Baumgartner (2016) produced a refined model that shows an asymmetric carbonate shoal fringing an uplifted and tilted area of the forearc. Based on the available biostratigraphic data, these authors postulated a late Paleocene rapid south to north onlap of the Barra Honda shoal. The probably uppermost Cretaceous very shallow coral-bearing Barra Honda facies described by Chesnel et al. (2024) encroached on a local, probably subaerial paleo-high where the substrate was eroded down to the Campanian-Maastrichtian pelagic sediments of the Piedras Blancas Fm. The Puerto Nispero outcrops are located in the core of a roughly North–South-oriented anticline (Denyer et al., 2014b), which is flanked on both sides by higher Barra Honda facies. Although the stratigraphic continuity towards higher Barra Honda facies cannot be observed and fossils attesting for early Paleocene ages are lacking, a stratigraphic continuity can be assumed. Hence, uplift occurred first in the southwest followed by subsidence, while uplift moved to the northeast followed by subsidence during the late Paleocene when a shallow, restricted lagoon produced the chloralgal carbonate mud of the upper Barra Honda. Its high production resulted in sediment export towards deeper, offshore areas (e.g., Pochote), where the progradation of the shallow environments finally produced an oolitic rim.

In the Cerro Calera, facing the Nicoya town (Figure 3a), Barra Honda rests with a tectonic contact on both the underlying Curú Fm. and the lower Eocene Zapotal Member (Mb.) of the Descartes Fm. (Denyer et al., 2014a, 2014b). The latter was originally mapped as Upper Cretaceous Sabana Grande Fm. (Flores et al., 2003a), because it contains cherty facies (here considered as part of the Buenavista

Fm.) that resemble those of the Zapotal Mb. We have modified the geological map (Figure 3b) according to our observations in the Teresita quarry area, and a radiolarian sample described from this unit by Bandini et al. (2008) is reevaluated in this study as of early Ypresian (early Eocene) age.

3. Materials and methods

3.1. Field work and sampling

Two upper Paleocene–lower Eocene sections were measured and sampled in the Tajo Santa Teresita (here called "Teresita quarry"), located 4.5 km east of the town of Nicoya (Costa Rica; Figure 3b). The quarry section (code TTQ; 10°08'36.66"N /85°24'47.16"W) is about 109 m thick, whereas the road section (code TTR; 10°08'24.78"N/85°24'45.60"W) is about 3 m thick. The 0-meter mark in these stratigraphic logs has been placed at the boundary between the Barra Honda Fm. and the Buenavista Fm.

3.2. Micropaleontological analysis

Thin sections from 28 samples were examined with an optical microscope to characterize the facies and microfossils. Polished thin sections were scanned with an Olympus VS110 slide scanner. A motor-driven turntable can take several hundred overlapping images to produce an image of about 12'000 x 26'000 pixels with a 4x lens, resulting in a resolution of about 622 pixels/mm (pixel size 1.6 µm). This resolution is sufficient to allow detailed analysis of microfossils across an entire thin section.

For a coherent biochronologic interpretation of new and existing (Appendix A) data on planktonic foraminifera we use the zonation summarized in Olsson et al. (1999), Pearson et al. (2006), Wade et al. (2011), and Huber et al., (2016), and its calibration to absolute time by Speijer et al. (2020), in which the Paleocene–Eocene boundary is defined by the negative δ^{13}C-shift of the PETM (Aubry et al., 2007). For a re-evaluation of a radiolarian assemblage published in Bandini et al. (2008), we use the zonation of Jackett et al. (2008).

3.3. Optical cathodoluminescence

40 µm polished thin sections were used for cathodoluminescence optical analyses (CL). CL images were obtained using an OPEA electron gun adapted to the vacuum chamber of a CTTL, Technosyn 8200 MkII, mounted on an Olympus optical microscope with a mobile tube and an object stage fixed in height. The OPEA was operated at 15-20 kV and 0.4-0.5 mA with an unfocused cold cathode electron beam under an air atmosphere of 0.2 torr.

3.4. CA-ID-TIMS on zircon

Zircon was separated from the sediment in the laboratories of the University of Lausanne. Approximately 1 to 2 kg of the ash-rich layer TTR5 was crushed and then decarbonated for three days using 35% HCl. After several washings, the sample was treated with hydrogen peroxide (H_2O_2) for 5 days to disperse the clays. The dispersion of the clays was finalized by heating the hydrogen peroxide. The sample was then treated for three weeks with 40 % hydrofluoric acid (HF) to dissolve minerals such as quartz or feldspar.

U–Pb chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS) was used to date the zircon grains at the University of Geneva. Individual zircon crystals free of visible inclusions and cracks were hand-picked using a binocular microscope at a magnification of 20x to 40x. Individual zircons were washed in 3 ml Savillex beakers in an ultrasonic bath 4 times using 7N HNO_3.

The zircons were then transferred into individual 200 μL Savillex microcapsules, along with 1-2 drops of HF_{conc} and 1-2 drops of a mixed ^{202}Pb-^{205}Pb-^{233}U-^{235}U tracer solution (ET2535, Condon et al., 2015; McLean et al., 2015), and dissolved at 210 °C in a Parr bomb for 48 hours, to ensure complete dissolution. After dissolution, samples were dried down on a hotplate at 120 °C, converted to chloride form by addition of 6N HCl and placed back in the Parr bomb over-night. Finally, the sample is again dried and re-dissolved in 3N HCl, and then U and Pb were separated using a single column anion exchange chemistry. U and Pb were loaded on outgassed, zone-refined, single Re filaments with a silica-gel/phosphoric acid emitter solution (Gerstenberger & Haase, 1997).

Pb was measured in dynamic mode using a Daly detector, while U was measured as an oxide in static mode using Faraday detectors coupled to 1012 Ω resistor amplifiers. The electronic baselines and amplifier calibration was performed on a weekly basis, prior to standard and unknown sample analyses. Measured isotopic ratios were corrected for interferences of $^{238}U^{18}O^{16}O$ on $^{235}U^{16}O_2$ using a $^{18}O/^{16}O$ composition of 0.00205, based on repeated measurements of the U500 standard. Mass fractionation of Pb is calculated and corrected using a $^{202}Pb/^{205}Pb$ ratio of 0.99923913 ± 0.00026555 (1σ) (Condon et al., 2015). For all U analyses, U mass fractionation is corrected using a $^{233}U/^{235}U$ ratio of 0.995062 ± 0.000108 (2σ) and a $^{238}U/^{235}U$ ratio of 137.818 ± 0.045 (2σ) (Hiess et al., 2012; Condon et al., 2015). The common Pb in zircon is considered laboratory blank, and is corrected using the isotopic composition $^{206}Pb/^{204}Pb$ of 17.43 ± 0.71, a $^{207}Pb/^{204}Pb$ of 14.73 ± 0.38 and a $^{208}Pb/^{204}Pb$ of 35.58 ± 1.04. All U-Pb dates are corrected for initial ^{230}Th disequilibrium, assuming a Th/U ratio of the source magma of 3.5 ± 1. During the period of data acquisition, the ET 100 solution was repeatedly analyzed and yielded a weighted mean of 100.176 ± 0.006 Ma (MSWD = 2; n = 22), matching the consensus value of 100.173 ± 0.003 Ma (Schaltegger et al., 2021).

All data were processed using the Tripoli, Redux U-Pb, YourLab and Isoplot software/excel packages (Ludwig, 1991; McLean et al., 2011; Schmitz & Schoene, 2007; Bowring et al., 2012). Weighted mean U-Pb age uncertainties are reported at the 2σ level in the format A ± X/Y/Z, where A is the weighted mean age, X is analytical uncertainty, Y is analytical and tracer uncertainty combined, and Z is analytical, tracer, and decay constant uncertainties combined (Schoene et al., 2006). Lower intercept ages are calculated for samples with assumed inherited components and discordance. The results are presented in Table S1 (Supporting Information S1).

3.5. X-Ray diffraction on bulk rocks

Bulk-rock mineralogy of 29 samples has been analyzed using an X-TRA Thermo-Arl SCINTAG 2000 diffractometer, following the procedures of Kübler (1983) and Adatte et al. (1996). The whole-rock mineralogy was determined by a semi-quantitative method, using XRD peak intensities of the main minerals in comparison with external standards (Klug & Alexander, 1974; Kübler, 1983; Adatte et al., 1996). The precision is 5 wt% for grain minerals and 5 to 10 wt% for phyllosilicates. The results are presented in Table S2 (Supporting Information S1).

3.6. Stable isotope compositions

Oxygen and carbon isotope analyses (48 samples) were made in the stable isotope laboratory of the University of Lausanne with a Gas-Bench II interfaced with a Thermo Fisher Scientific DeltaPlus XL isotope ratio mass spectrometer following a method described in Spötl & Vennemann (2003). The stable carbon and oxygen isotope ratios are expressed in delta notation as per mil (‰) relative to the Vienna Pee Dee Belemnite (VPDB) international reference standard. Multiple analyses of an in-house standard (Carrara marble, calibrated to international carbonate standards), were run parallel with the samples to correct raw isotopic values. The analytical precision of the method is better than ± 0.1 ‰ (1σ) for both C- and O-isotope compositions. The results are presented in Table S3 (Supporting Information S1).

4. Results

4.1. Log description

The lower part of the quarry section consists of 64 m of shallow-water limestones with some levels rich in cherts (at –53 m, –50 m and –0.2 m below the top of the Barra Honda Fm.; Figure 5). The upper part of the quarry section is characterized by marls and detrital deposits. The first 7 meters above the Barra Honda Fm. are characterized by a high proportion of marls and clays with some cherts, sandy beds, and rare centimetric ash layers (Buenavista Fm.). The uppermost part of the quarry section corresponds to turbiditic deposits with some marl intercalations (Zapotal Mb.). The shorter road section presents the same lithological association as the quarry section. The first meter of the road section is characterized by massive shallow-water limestones of the Barra Honda Fm. with the presence of cherts a few tens of centimeters below its top. The upper part of the road section is dominated by clayey deposits and cherts, with scarce centimetric ash layers (at 0.05 m, 0.5 m, and 1 m) and sandy beds, which is similar to the facies association deposited on top of the Barra Honda Fm. in the quarry section.

From a facies perspective, the massive shallow-water limestones of both sections are characterized by red algal packstones and wackestones. Most of these limestones contain *Polystrata alba*, *Melobesia*, larger benthic foraminifera, miliolids, planktonic foraminifera and some siliceous sponges. Pack- to wackestone microfacies and *Polystrata alba* (Pfender, 1936; Denizot, 1968) are very common in most of the upper Barra Honda rocks. This squamariacean red alga encrusted rhodoids and other firm substrates. It is typical of algal platforms of the Upper Cretaceous and Paleocene, although its range extends from the Barremian to the Eocene (Massieux & Denizot, 1964; Praturlon, 1966; Baumgartner-Mora & Baumgartner, 2016). The upper part of the quarry and road sections is characterized by alternating clayey and sandy deposits, with low carbonate proportions. Thin sections show wackestone to mudstone microfacies including mainly planktonic foraminifera (such as *Morozovella*), sponge spicules, radiolarians, and debris of red algae. These deposits are characteristic of an open sea environment receiving a significant detrital input.

4.2. Biostratigraphic ages

Sample TTQ650 is a pelagic limestone rich in planktonic foraminifera (Figure 6) from the Buenavista Fm., that was recovered 6.5 m above the top of the Barra Honda limestone (quarry section; Figure 5). It yielded *Acarinina* cf. *quetra* (top E3-E6 Zones), *Morozovella subbotinae* (P5-E5 Zones), *Morozovella gracilis* (P5-E5 Zones), *Planorotalites pseudoscitula* (P5-E7 Zones), *Morozovella aequa* (P4c-E5 Zones), *Morozovella* cf. *formosa*, *Morozovella* cf. *lensiformis*, and *Acarinina angulosa* (P5-E7 Zones). The concurrent range of these taxa is from top E3 to E5 Zones (early to middle Ypresian age).

In an earlier study (Bandini et al., 2008), we described a radiolarian fauna of sample 01-18-01-02 from the Teresita quarry area in the transition from the Buenavista Fm. to the Zapotal Mb. of the Descartes Fm. The sample was collected about 30 m east of the eastern rim (quarry limits in 2020) of the Teresita quarry at 10° 8'38.29"N, 85°24'49.06"E (Figure 3b). Bandini et al. (2008) concluded on a late Thanetian to Ypresian age of this sample. Here we slightly revise the taxonomy and the age ranges of the taxa encountered, based on the UA-zonation of Jackett et al. (2008). The sample contains *Lychnocanium carinatum* (UA 11-12), *Podocyrtis* (*Podocyrtis*) *papalis* (UA 11-22), *Phormocyrtis striata exquisite* (UA 3-20), *Stylotrochus nititus* (UA 5-22), *Circodiscus circularis* (UA 5-22), *Phormocyrtis turgida* (UA 11-22), *Calocyclas hispida* (UA 11-22), *Stylosphaera coronata coronata* (UA 1-22), and *Buryella tetradica* (UA 2-20). Of this association several species are not older than UAZ 11 (base of the Eocene) and *Lychnocanium carinatum* is restricted to UA 11-12 in Jackett et al. (2008). These two Unitary

Associations correlate with the planktonic foraminiferal zones (see Pearson et al., 2006) P5 top half (=E1-E2 Zones) and P6a-b (=E3-E4 Zones), indicating an early Ypresian age. This age overlaps with the age range of planktonic foraminifera from the new sample TTQ650, collectively suggesting that the Buenavista Fm. is restricted to the early to middle Ypresian in the Teresita quarry.

4.3. U–Pb zircon CA-ID-TIMS age

Ash-rich layer TTR5 was sampled 5 cm above the limit between massive limestones of the Barra Honda Fm. and overlying clayey beds of the Buenavista Fm. Five single-grain zircon analyses were undertaken on sample TTR5, all of which are concordant within analytical and decay constant uncertainties (Figure 7). Four out of five analyses cluster between 56 and 57 Ma, whereas one analysis yielded a distinctly older age (62.4 Ma) than that of all other analyses. The younger cluster of $^{206}Pb/^{238}U$ dates yield a weighted mean date of 56.30 Ma ± 0.11/0.12/0.13 Ma (2σ, n = 3, MSWD = 2.2), which approximates the depositional age of the ash-rich layer TTR5.

4.4. Bulk-rock mineralogy

The mineralogy of the quarry and road sections is mainly composed of calcite, quartz, and phyllosilicates, with minor amounts of plagioclase and alkali feldspar, and punctual presence of dolomite, ankerite, and goethite (Figure 5). The unquantified fraction represents generally less than 3 wt% and may correspond to poorly crystallized clays, Fe-oxides, Fe-hydroxides, zeolites and organic matter. For each section, two parts can be distinguished based on mineralogical contents.

The lower part of the quarry and road sections consists of 81 to 98 wt% calcite and very low proportions of quartz and phyllosilicates. This part coincides with massive limestones of the Barra Honda Fm. (–65 m to 0 m in the quarry section, –0.7 m to 0 m in the road section).

The upper part of the quarry and road sections consists of variable proportions of phyllosilicates (0–83 wt%), quartz (1 to 94 wt%), and calcite (0 to 63 wt%), which coincide with ash-rich beds, cherts, and clayey deposits (0 m to 44 m in the quarry section, 0 m to 2.3 m in the road section). This mineralogical variability reflects the lithological heterogeneity of the Buenavista Fm. and Zapotal Mb.: (i) cherts at 0.75 m/12 m in the quarry section and at 0.75 m/1.75 m in the road section present high amounts (> 70 wt%) of quartz; (ii) ash-rich beds at 0.05 m/0.5 m/1 m in the road section have high proportions (63 to 83 wt%) of phyllosilicates; (iii) marls throughout the quarry section and at one level of the road section show a mix of siliciclastic material (6 to 30 wt% phyllosilicates, 1 to 40 wt% quartz, 0 to 7.5 wt% alkali feldspar, and 0.5 to 9 wt% plagioclase) and calcite (35 to 63 wt%).

4.5. Stable isotope geochemistry

4.5.1. $\delta^{13}C_{carb}$

$\delta^{13}C_{carb}$ values have a range between –0.8 ‰ and 4.3‰ in the quarry section (Figure 5). In the lower part of the section (middle to upper Thanetian Barra Honda Fm.), most values are around 2.8 ‰ except for two positive shifts towards 4.3 ‰ at –50 m and 4.0 ‰ at –0.6 m. A shift of –3.3 ‰ occurs across the boundary between the Barra Honda Fm. and the Buenavista Fm. This is followed by a positive shift to 2.4 ‰ at 0.8 m and a second negative shift to –0.3 ‰ at 2 m, at the base of the lower Ypresian Buenavista Fm. $\delta^{13}C_{carb}$ values increase from –0.3 ‰ at 2 m (Buenavista Fm.) to 2.4 ‰ at 14 m (Zapotal Mb.), after which they steadily decrease towards 1.3 ‰ at 40 m.

$\delta^{13}C_{carb}$ values vary between –3.9 ‰ and 2.2 ‰ in the road section. The $\delta^{13}C_{carb}$ values are homogeneous at around 1.8 ‰ in the uppermost Barra Honda Fm. A significant decrease to –3.9 ‰ coincides with the base of the Buenavista Fm. The very low carbonate contents (<2 wt%) of the Buenavista Fm. from 0.5 m to 2.3 m precludes the analysis of carbon isotopes.

4.5.2. $\delta^{18}O_{carb}$

$\delta^{18}O_{carb}$ values range from –7.2 to –1.3 ‰ in the quarry section and from –8.3 to –1.7 ‰ in the road section (Figure 5). In both sections, a negative shift occurs around the boundary between the Barra Honda Fm. and the Buenavista Fm., which is 2.5 ‰ in the quarry section and 6.6 ‰ in the road section. In the quarry section, the $\delta^{18}O_{carb}$ record shows an overall decreasing trend above the formational boundary; values decrease from –4.9 ‰ at 2 m to –7.2 ‰ at 40 m, except for two positive excursions towards –2.4 ‰ at 4 m and towards –4.3 ‰ at 25 m.

5. Discussion

5.1. Barra Honda–Buenavista boundary: a record of the PETM?

The sharp lithological boundary between the Barra Honda and Buenavista formations has been previously interpreted as the demise of the Barra Honda carbonate shoal (Baumgartner-Mora & Baumgartner, 2016). The latter authors argued that the rapid demise of the carbonate shoal occurred through a combination of factors, which are (i) a relative sea level rise due to tectonic subsidence and an eustatic component, (ii) and a paleoclimatic change around the Paleocene–Eocene boundary resulting in intensified weathering, river runoff and eutrophication of the forearc basin by detrital input and dissolved organic matter. To discuss how these factors combined to cause the demise of the Barra Honda carbonate shoal, we first use our new data from the Teresita quarry to determine whether the timing of termination of carbonate shoal sedimentation was coeval with the PETM.

A large negative excursion of 3 to 5 ‰ in $\delta^{13}C_{carb}$ values in both Teresita quarry sections coincides with a prominent decrease in average calcite contents, from 90 % calcite in massive limestones of the uppermost Barra Honda Fm. to about 40 % calcite in overlying clayey layers of the lowermost Buenavista Fm. (Figure 5). Despite being analyzed in clayey beds with similar carbonate contents (estimated $CaCO_3$ yield = 28 to 39 %) in the quarry section, $\delta^{13}C_{carb}$ values at the base of the Buenavista Fm. span a wide range (from –0.8 to 2.5 ‰), which makes it unlikely that the change in calcium carbonate contents and lithology across the Barra Honda–Buenavista boundary had a significant effect on $\delta^{13}C_{carb}$ values. Instead, the timing of the combined lithological-mineralogical-isotopic change at the Barra Honda–Buenavista boundary is consistent with the PETM, which is supported by new U–Pb zircon CA-ID-TIMS age data, as well as new and existing biostratigraphic data. The fact that our new zircon age (56.30 ± 0.13 Ma) of the lowermost Buenavista Fm. is 0.1 to 0.3 Ma older than the currently established Paleocene–Eocene boundary age (56 Ma) may result from averaging the age of only three zircon grains, among which one older grain (56.5 ± 0.3 Ma) is pooled together with two younger zircon grains (56.2 ± 0.1 Ma and 56.1 ± 0.3 Ma).

The synchronicity of the Barra Honda–Buenavista boundary with the PETM can be further examined by comparing our new $\delta^{13}C_{carb}$ curve of the quarry section to the most recent global $\delta^{13}C$ curve of Speijer et al. (2020). Although the nature and rate of sedimentation differ among the Barra Honda, Buenavista, and Descartes formations, the overall shape of our new $\delta^{13}C_{carb}$ curve of the quarry section approximates the global Thanetian–Ypresian $\delta^{13}C$ curve (Figure 8), with the following key similarities: (i) two positive carbon isotope excursions occur in the Thanetian; (ii) a negative carbon isotope excursion (>2.5 ‰) characterizes the base of the Ypresian and is related to the PETM; (iii) Ypresian $\delta^{13}C$ levels are about 1.5 ‰ lower after the PETM negative carbon isotope excursion when compared to pre-PETM levels in the Thanetian.

5.2. Step-wise demise of Barra Honda carbonate shoal

The onset of shallow-water carbonate sedimentation in the Barra Honda shoal was favored by the combination of moderate tectonic subsidence and volcanic quiescence (Figure 9a). Tectonic subsidence followed a short-lived episode of km-scale forearc uplift, possibly related to the subduction of bathymetric features (Andjić et al., 2018a; Figure 2b). Once they entered deeper parts of the subduction interface, the bathymetric features caused cessation of volcanic activity within the Barra Honda area. The proximal forearc basin floor was shortly exposed to subaerial environments before initial moderate subsidence to shallow waters that favored the accumulation of the Barra Honda carbonate shoal (Jaccard et al., 2001; Baumgartner-Mora & Baumgartner, 2016; Figure 2c). Volcanic quiescence resulted in the reduction of the input of proximal coarse-grained volcaniclastic sediments compared to the underlying deep-water forearc formations. Only distal ash particles carried from distant volcanic sources made their way to the upper Barra Honda shoal, as suggested by discrete contents of phyllosilicates in the massive limestones (Figure 5; Baumgartner-Mora & Baumgartner, 2016). The lifespan of about 5 Ma and the thickness (350 m) of the upper Barra Honda shoal implies an average subsidence rate of the forearc basin of 70 m/Ma during the late Paleocene (61 to 56 Ma). This subsidence rate is comparable to that of long-lived (>10 Ma) carbonate platforms on passive margins (36 to 150 m/Ma; Immenhauser, 2021). This, however, raises the question as to why the shallow-water carbonate sedimentation of the upper Barra Honda shoal stopped at the Paleocene–Eocene boundary? In the following sections, we envisage a sequence of events that eventually led to the demise of the upper Barra Honda carbonate shoal during the earliest Ypresian.

5.2.1. Step 1 (56 Ma): Environmental effects of the PETM

The PETM may have affected the Barra Honda carbonate shoal in at least two ways. Global ocean acidification due to increased CO_2 levels resulted in reduced rates of accumulation and preservation of carbonate sediments in shelf areas (Bralower et al., 2018). In addition, the rise of sea surface temperatures (about 5 °C; e.g., McInerney & Wing, 2011) during the PETM reached levels that were probably beyond the tolerance range of benthic foraminifera, calcareous algae, and coral patch reefs of the Barra Honda carbonate shoal (e.g., Scheibner & Speijer, 2008). Moreover, increased precipitation at the onset of the PETM may have caused an increased discharge of fluvial sedimentary organic matter to shelf areas, favoring the proliferation of non-calcifying organisms such as dinoflagellates and bacteria (Sluijs et al., 2006; Kopp et al., 2009; Handley et al., 2012; Aze et al., 2014; Carmichael et al., 2017). Input of nutrients led to higher surface-water productivity and anoxic to low oxygen levels in bottom shelf waters (Sluijs et al., 2006, 2008). There is currently no quantitative data available from the Tempisque Forearc Basin to constrain whether an absolute increase in abundance and size of detrital grains occurred during the earliest Eocene. At the outcrop scale, basinal sections of the western Nicoya Peninsula and northern Santa Elena Peninsula (Figure 1b) show that there was no increase in volcanic activity inboard the Nicoya Peninsula around the Paleocene–Eocene boundary: pelagic sedimentation of the Buenavista Fm. dominated that interval (Figure 4) and only airborne ash was brought into the forearc basin from outboard volcanoes (Figure 2d). Rather, the onset of coarse detrital sedimentation of the Zapotal Mb. took place 3 to 4 Ma after the demise of the Barra Honda carbonate shoal, in response to renewed volcanic activity inboard the Nicoya Peninsula (Figures 2e and 9b). Nevertheless, the relative increase of the phyllosilicates/calcite ratio (from 1/18 to 1/2) and feldspars/calcite ratio (from 1/200 to 1/20) in the Teresita quarry is larger than the decrease by 50 % of carbonate proportions across the Barra Honda–Buenavista boundary (Figure 5), which may indicate that mud-sized clastic input and turbidity increased on the shelf during the earliest Ypresian, possibly in response to enhanced river discharge. The resulting reduced light intensity in surface waters would have led to a much shallower photic zone, contributing to the demise of the benthic communities relying on oligotrophic waters. This hypothesis remains to be tested in basinal sections of the Buenavista Fm. (e.g., Santa Elena area) by establishing whether a change in mineralogical contents coincided with the PETM.

Moreover, the presence of cherts in the Buenavista Fm. supports the view of increased opal production and burial to balance elevated weathering flux of silica (e.g., Penman et al., 2019). The latter possibly resulted from enhanced continental weathering and runoff in a warmer climate with increased seasonality of precipitation (McInerney & Wing, 2011). Excess silica that could not be incorporated in clay-rich layers of the Buenavista Fm. may have precipitated as opal-rich layers that later formed cherts (e.g., Muttoni & Kent, 2007). The proportion of nutrients brought by upwelling currents vs. terrestrial influx remains unconstrainted in this case, although climate–carbon cycle models with high-CO_2 levels predict that a weakening of the trade winds would lead to reduced Ekman-induced upwelling and nutrient availability in the equatorial Pacific (Winguth et al., 2012; Wade et al., 2020). However, it remains possible that upwelled water, characterized by low $\delta^{13}C$ values and high nutrient content (e.g., Watanabe et al., 2017), influenced the isotopic compositions of the Buenavista Formation and the production of biogenic silica.

5.2.2. Step 2 (56–55 Ma): Onset of accelerated tectonic subsidence and eustatic sea level rise

Extreme environmental conditions linked to the PETM were short-lived (about 0.2 Ma; Murphy et al., 2010; Zeebe & Lourens, 2019), after which the production of carbonates resumed in both deep-water and shallow-water settings globally (e.g., Zachos et al., 2005; Scheibner & Speijer, 2008). We speculate that the short duration of the hyperthermal event would have made it possible for the Barra Honda carbonate shoal to recover during the early Ypresian and to resume shallow-water carbonate sedimentation, as suggested by the deposition of early to middle Eocene shallow-water carbonates in the most proximal parts of the forearc basin (Laguna El Jicote; Jaccard et al., 2001; Figures 3a and 4). The fact that this did not occur may be primarily attributable to accelerated forearc subsidence that must have taken place by 55 Ma, not allowing renewed formation and deposition of carbonates in shallow shelf environments (Figure 9b). The fate of uplifted highs in forearc areas affected by subduction of bathymetric features is clear: once the impinging bathymetric feature has been subducted, uplifted forearc areas return to their pre-collisional morphology within 3 Ma at rates similar to those of the uplift episode (e.g., Corrigan et al., 1990; Cloos, 1993; Meffre & Crawford, 2001; Andjić et al., 2018a; Figure 2). In the case of the Tempisque Forearc Basin, the pre-collisional depth of the forearc basin floor (= Paleocene Curú Fm.) is estimated to be about 3000 m based on benthic foraminifera (Struss et al., 2008). Assuming that the proximal forearc basin returned to a water depth of 3000 m within 3 Ma after the PETM, a subsidence rate of 1000 m/Ma would have brought the Barra Honda to a depth of 1000 m by 55 Ma, largely exceeding the rate of sediment supply of any carbonate shoal. In contrast, moderate subsidence (70 m/Ma) combined with an early Ypresian 3rd-order eustatic sea level rise (30 m by 55 Ma; Speijer et al., 2020; Figure 8) may not explain the absence of post-PETM recovery of the Barra Honda shoal, because a relative sea level rise of similar magnitude already occurred from 60 to 58 Ma without preventing deposition of shallow-water carbonates.

6. Conclusions

Our work shows a sharp transition from massive shallow-water limestones of the upper Barra Honda Fm. to marl-chert alternations of the Buenavista Fm. in the Tempisque Forearc Basin at the Paleocene–Eocene boundary (56 Ma). The lithological and mineralogical change at the Barra Honda–Buenavista boundary is accompanied by a negative shift in carbon isotope ($\delta^{13}C_{carb}$) values of 3 to 5 ‰ and an increased detrital input. We postulate that the combination of two events caused the demise of the Barra Honda carbonate shoal during the earliest Eocene. First, the PETM led to a significant disturbance of the local oceanographic conditions of the forearc area: during the earliest Ypresian, seawater warming, acidification, eutrophication, and increased river runoff as well as likely upwelling may have led to a shift to siliceous sedimentation in the Buenavista Formation. These environmental changes were highly detrimental to the shallow benthic communities that had formed the upper Barra Honda carbonate shoal during the Thanetian. Secondly, accelerated subsidence of the Tempisque Forearc Basin closely followed the short-lived PETM event. Shallow shelf areas that were initially favorable to the establishment of the Barra Honda carbonate shoal gave way to deep-water basinal environments by 55 Ma, which did not allow a recovery of the Barra Honda carbonate shoal. After the PETM, the warm climate of the early Eocene was not a limiting factor to the growth of carbonate shoals in Costa Rica and Nicaragua (e.g., Baumgartner-Mora & Baumgartner, 2016; Andjić et al., 2018b). Locally, shallow-water carbonate sedimentation occurred on tectonic highs that provided a shelter from river discharges carrying volcaniclastic sediments from active volcanoes.

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Open research

New data generated in this study are available in the Supporting Information S1, and can also be found in https://zenodo.org/communities/geodiversity/ (detailed link to be provided).

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Captions

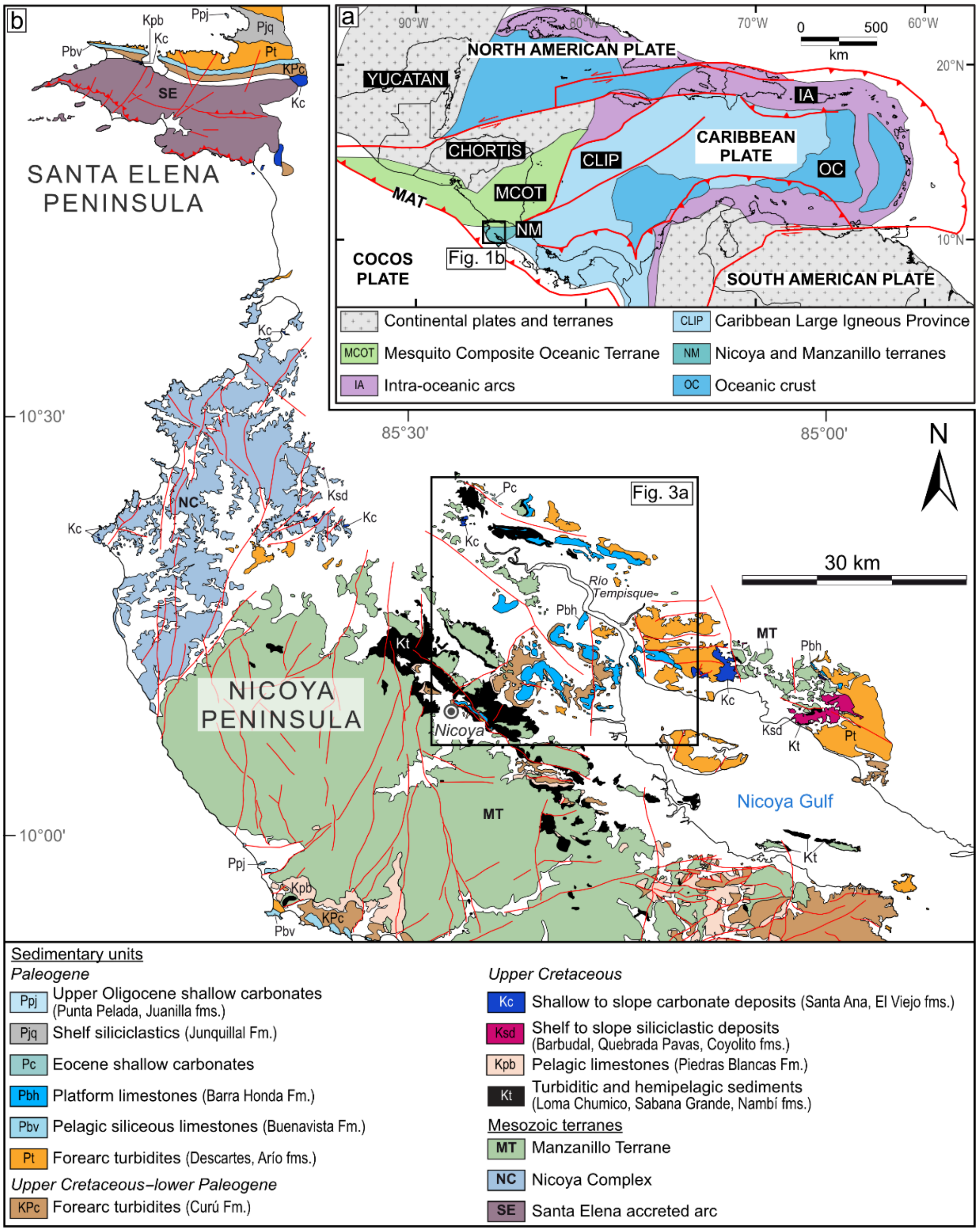

Figure 1. (a) Plate tectonic map illustrating the main units of the Caribbean Plate (modified after Baumgartner et al., 2008; Andjić et al., 2019b; Sanchez et al., 2019; Escalona et al., 2021; Romito & Mann, 2021). MAT = Middle America Trench. (b) Geological map of northwestern Costa Rica, centered on the Nicoya Peninsula (modified after Baumgartner et al., 1984; Mora & Baumgartner, 1985; Flores et al., 2003a, 2003b; Flores, 2006; Denyer & Alvarado, 2007; Bandini et al., 2008; Flores, 2009; Weber, 2013; Denyer et al., 2014b; Escuder-Viruete et al., 2015; Andjić et al., 2016, 2018a, 2019a).

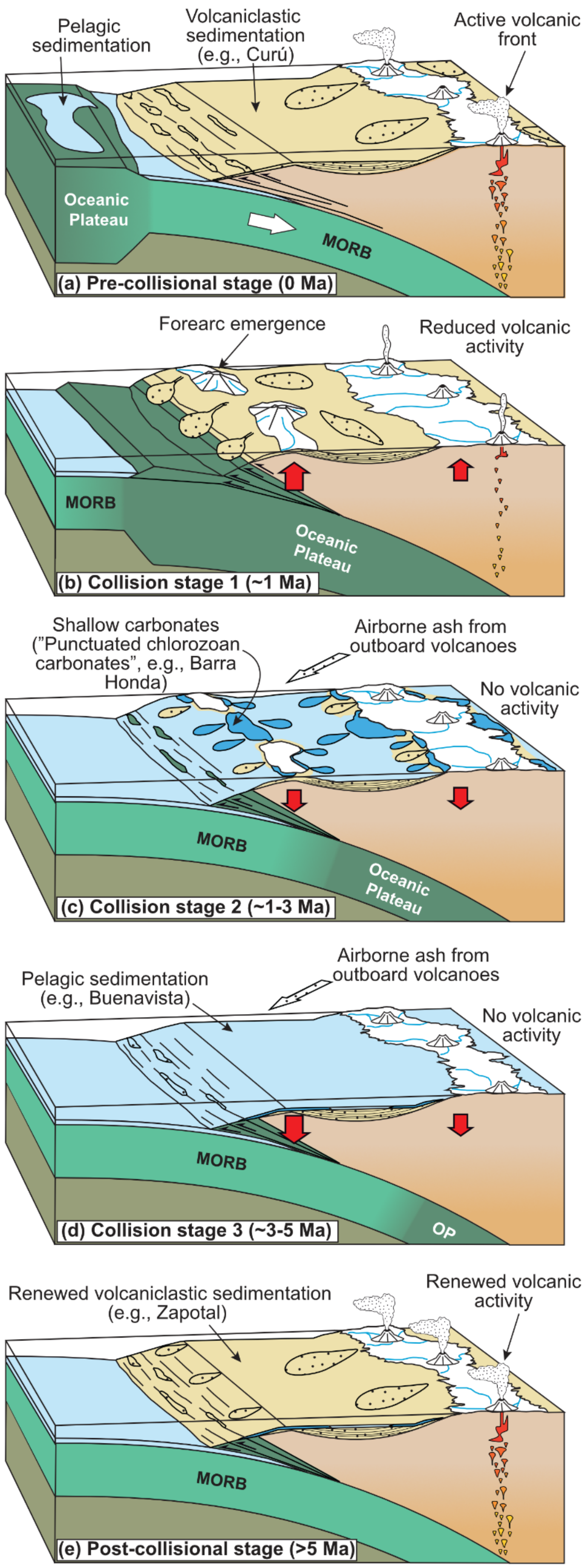

Figure 2. Formation and demise of carbonate shoals in response to rough crust subduction and arc extinction. The model is based on plateau collision events discussed in Baumgartner-Mora and Baumgartner (2016) and Andjić et al. (2016, 2018a, 2018b, 2019a). The drawing style is after Frisch et al. (2011). (a) Subduction of normal oceanic crust (labelled as MORB–Mid-oceanic ridge basalt) leads to arc volcanic activity. (b) Subduction of the bathymetric feature causes surface uplift in the forearc and progressive cessation of volcanic activity as the leading edge of the bathymetric feature reaches the window of major slab dehydration. Input of eroded detrital material and ongoing surface uplift hamper the formation and preservation of shallow-water carbonates. (c) Low forearc subsidence due to renewed subduction of normal oceanic crust at shallow depth. Ongoing subduction of the trailing edge of the bathymetric feature in the window of major slab dehydration sustains volcanic quiescence. The subsidence of the forearc and the reduced volcaniclastic input allow the short-lived development of shallow-water carbonate shoals (e.g., Barra Honda). (d) High forearc subsidence leads to the drowning of shallow-water carbonate factories and return to deep-water, pre-collisional levels. The trailing edge of the bathymetric feature sustains volcanic quiescence due its ongoing subduction in the window of major slab dehydration. (e) Subduction of normal oceanic crust in the window of major slab dehydration leads to renewed volcanic arc activity, which results in deep-water volcaniclastic sedimentation. Small-sized shallow-water carbonate factories may establish in areas sheltered from the detrital input derived from active volcanoes.

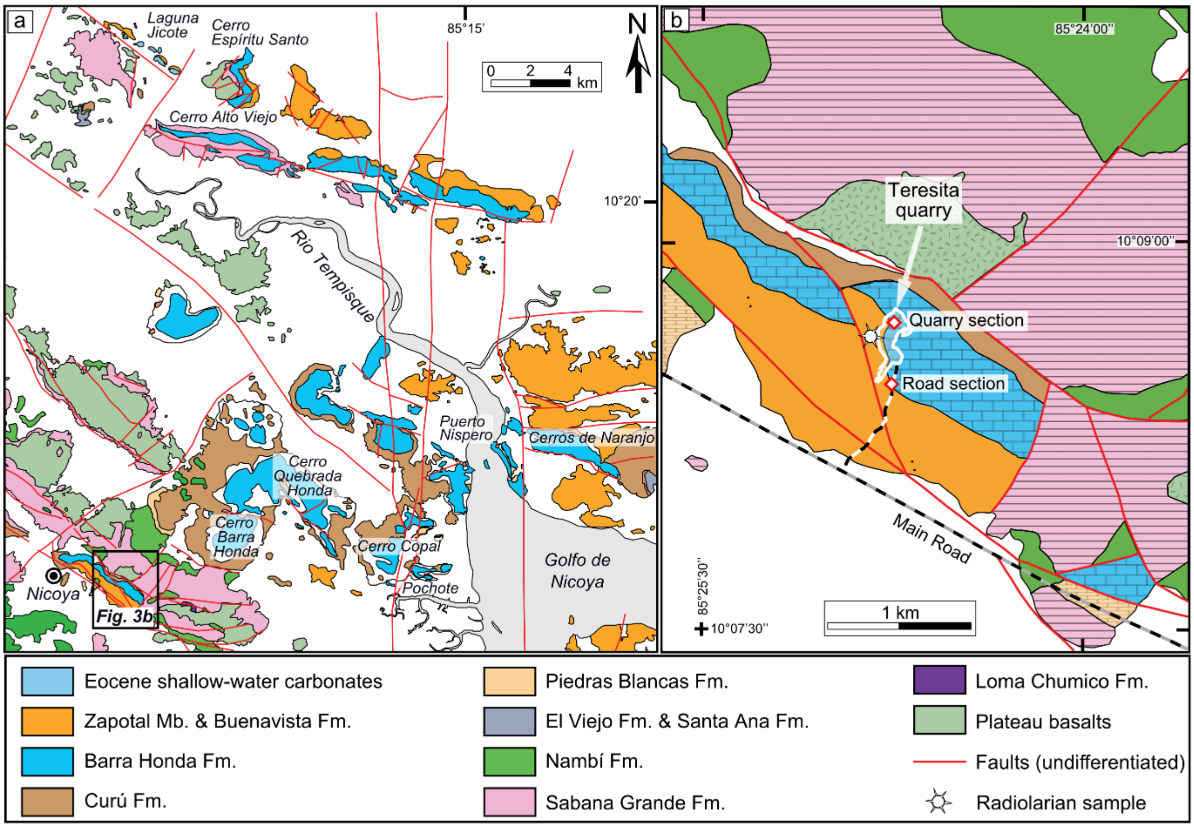

Figure 3. (a) Detailed geological map of the inner Tempisque Forearc Basin showing the outcrops of the Barra Honda Formation (in blue) and its stratigraphic substratum (modified after Flores et al., 2003a, 2003b; Denyer et al., 2014b; Baumgartner-Mora & Baumgartner, 2016). (b) Geological map of the Nicoya town area (modified after Denyer et al., 2014b). The studied road and quarry sections of the upper Barra Honda Formation are indicated.

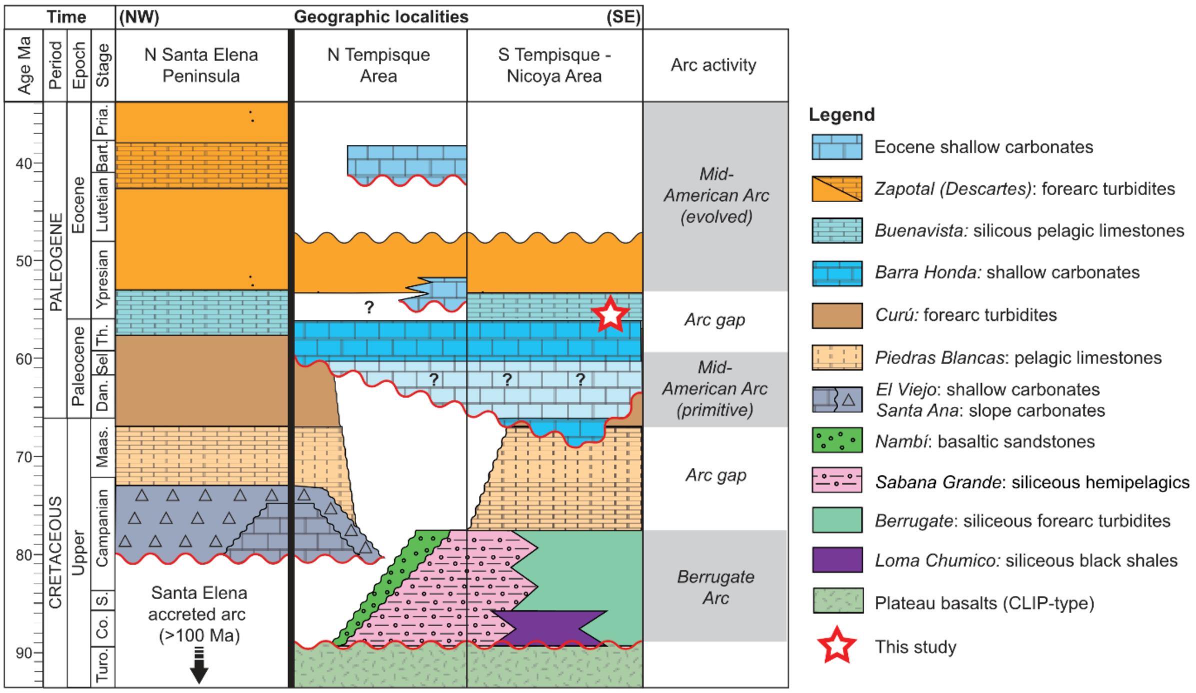

Figure 4. Chronostratigraphic logs of the Tempisque-Nicoya and northern Santa Elena areas (adapted from Baumgartner-Mora & Baumgartner, 2016; based on data from Baumgartner et al., 1984; Bandini et al., 2008; Denyer et al., 2014a, 2014b; Andjić et al., 2016, 2018a, 2019a). Formation names are indicated in italics. Major unconformities are marked with red wavy lines. White areas are stratigraphic gaps due to erosion or non-deposition. Light blue fields with question marks represent temporal uncertainties of stratigraphic gaps. Two successive arc systems are recorded by the forearc sedimentation: the Berrugate Arc, restricted to the Manzanillo Terrane precedes the docking of the Santa Elena and Nicoya Terranes, while the Mid-American Arc produced forearc sediments in the overlap sequences of the three terranes (see Figure 1b for a terrane map). A temporary arc gap is documented by the Barra Honda carbonate shoal and the distal, overlying pelagic Buenavista Fm.

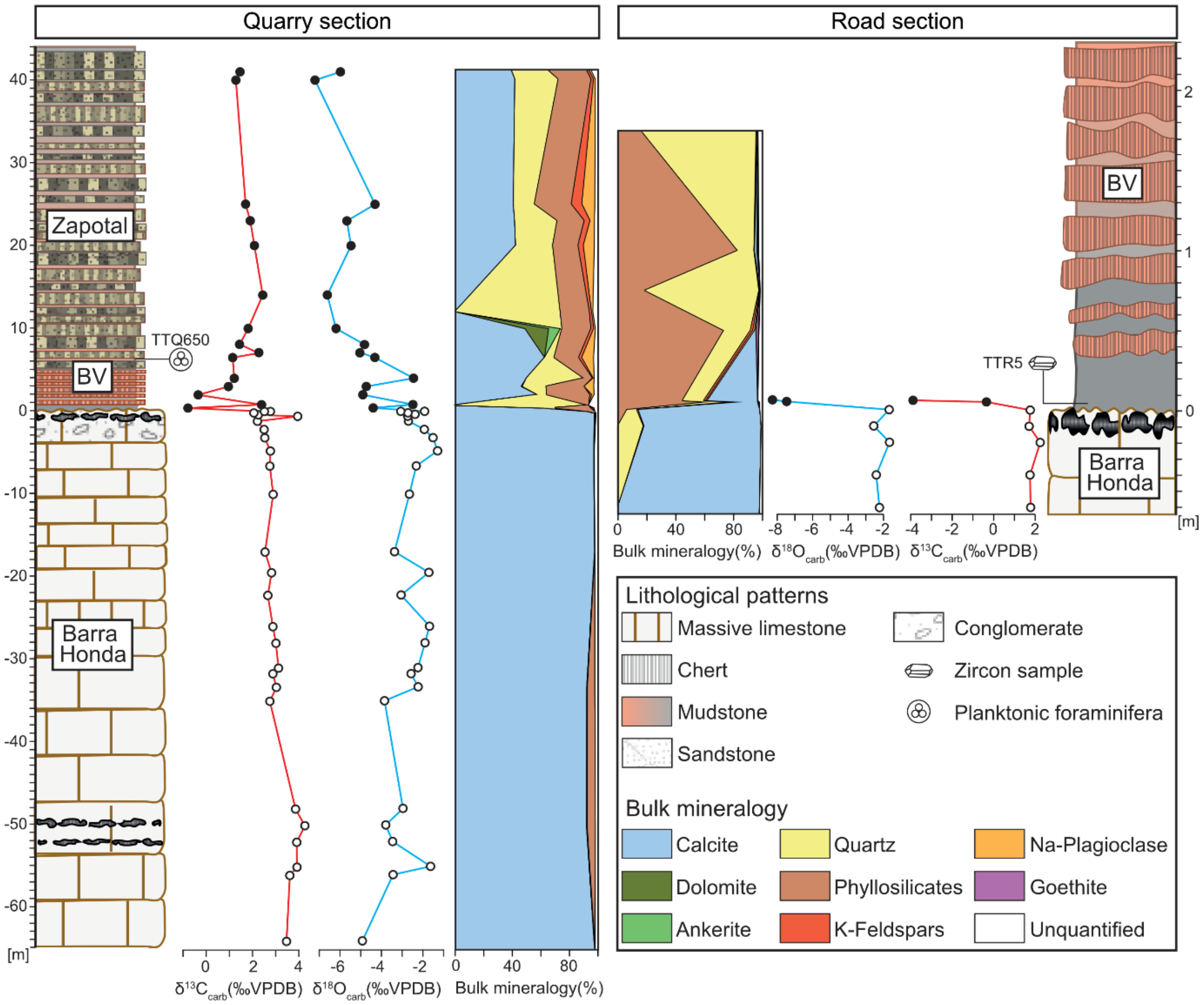

Figure 5. Lithological logs, stable isotope compositions, and bulk rock mineralogy of the quarry and road sections of the upper Barra Honda Formation in the Teresita quarry. BV = Buenavista Formation.

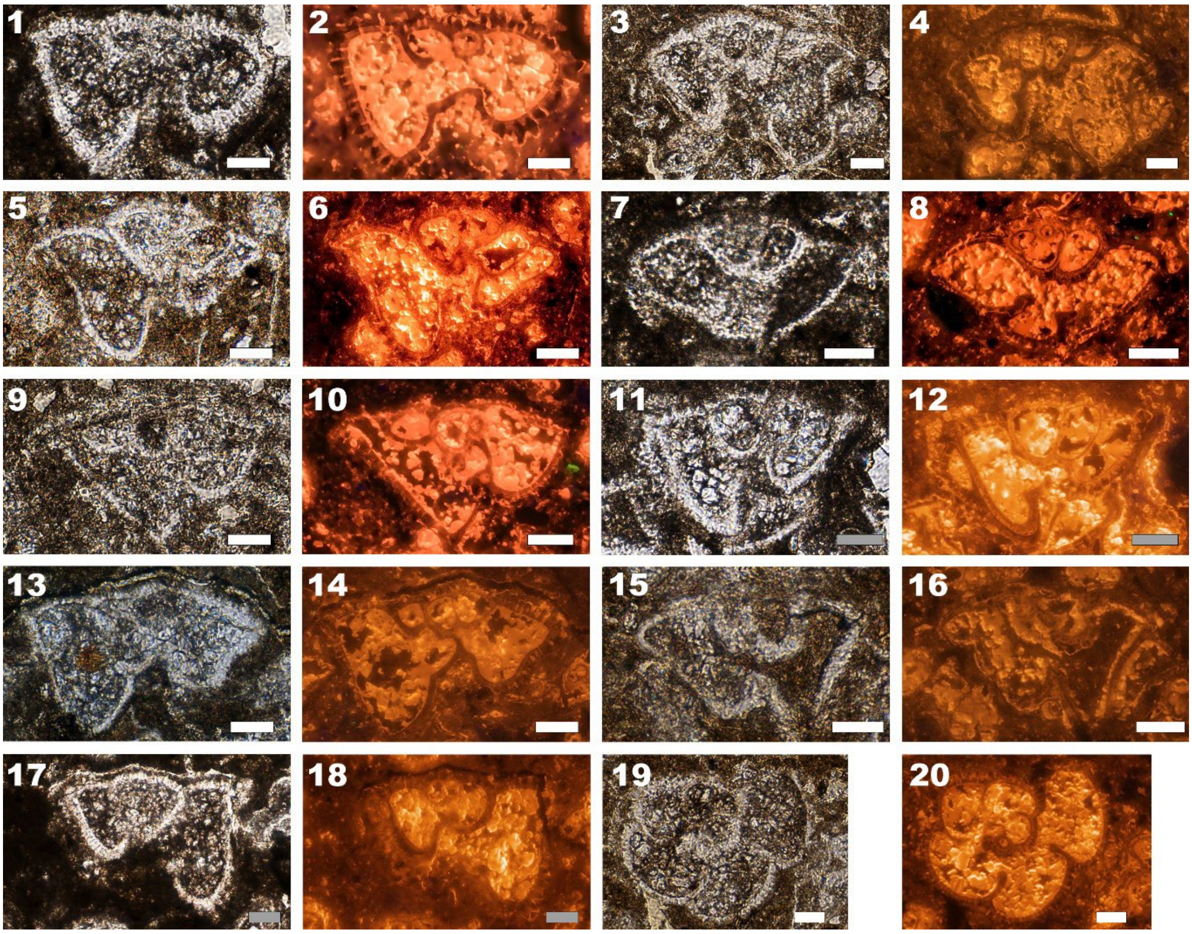

Figure 6. Planktonic foraminifera from the Buenavista Formation (sample TTQ650; quarry section). White scale bars are 50 µm and gray scale bars are 200 µm (11, 12, 17, 18). 1, 2, *Acarinina* cf. *quetra* (top E3-E6). 3, 4, *Morozovella* cf. *formosa*. 5, 6, *Morozovella gracilis* (P5-E5). 7, 8, *Planorotalites pseudoscitula* (P5-E7). 9–12, *Morozovella subbotinae* (P5-E5). 13–16, *Morozovella aequa* (P4c-E5). 17, 18, *Morozovella* cf. *lensiformis*. 19, 20, *Acarinina angulosa* (P5-E7). The concurrent range of these taxa is from top E3 to E5 Zones (early to middle Ypresian age).

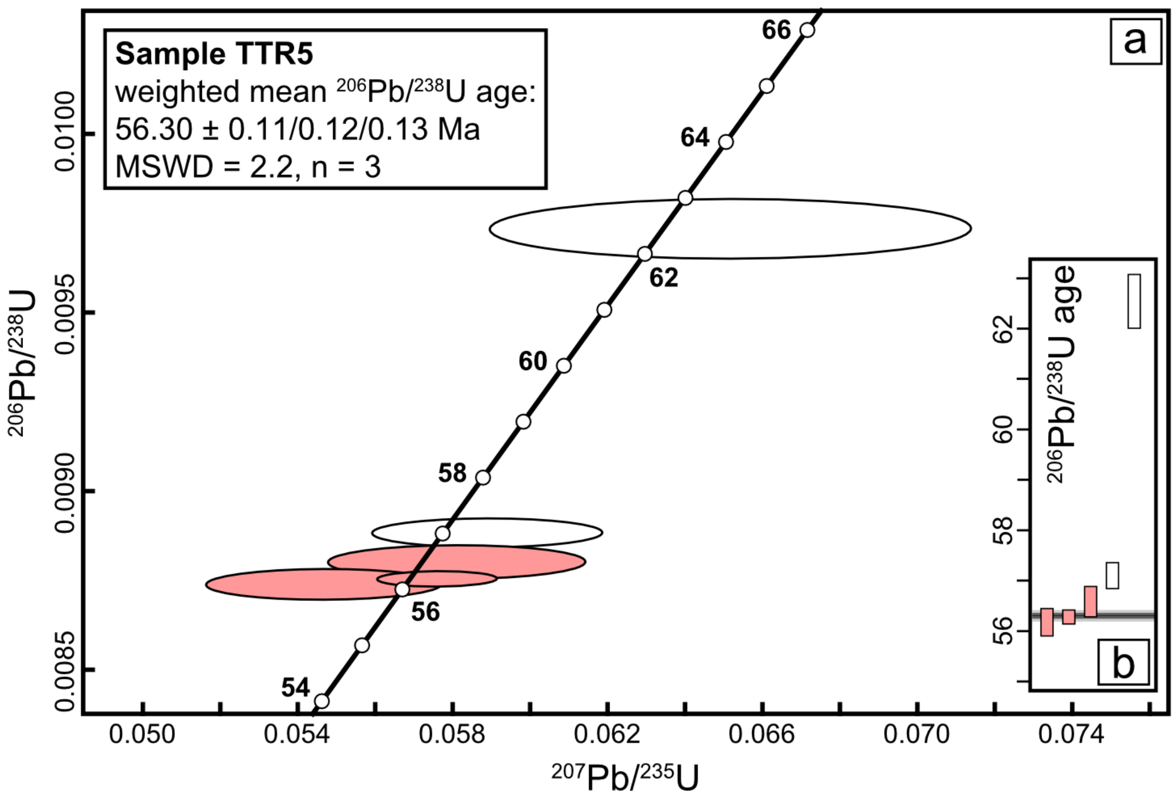

Figure 7. CA-ID-TIMS U–Pb dates for sample TTR5 (lowermost Buenavista Formation; road section). (a) The concordia curve is drawn as a continuous black line. Bold numbers are concordant dates (Ma). Error ellipses are drawn at the 2σ confidence level. Reddish and white error ellipses represent data points included in and excluded from the weighted mean $^{206}Pb/^{238}U$ date calculation, respectively. (b) Ranked single-grain $^{206}Pb/^{238}U$ dates. Box heights representing date uncertainties are drawn at the 2σ confidence level. The horizontal grey band represents the uncertainty of the weighted mean $^{206}Pb/^{238}U$ date calculation (95 % confidence).

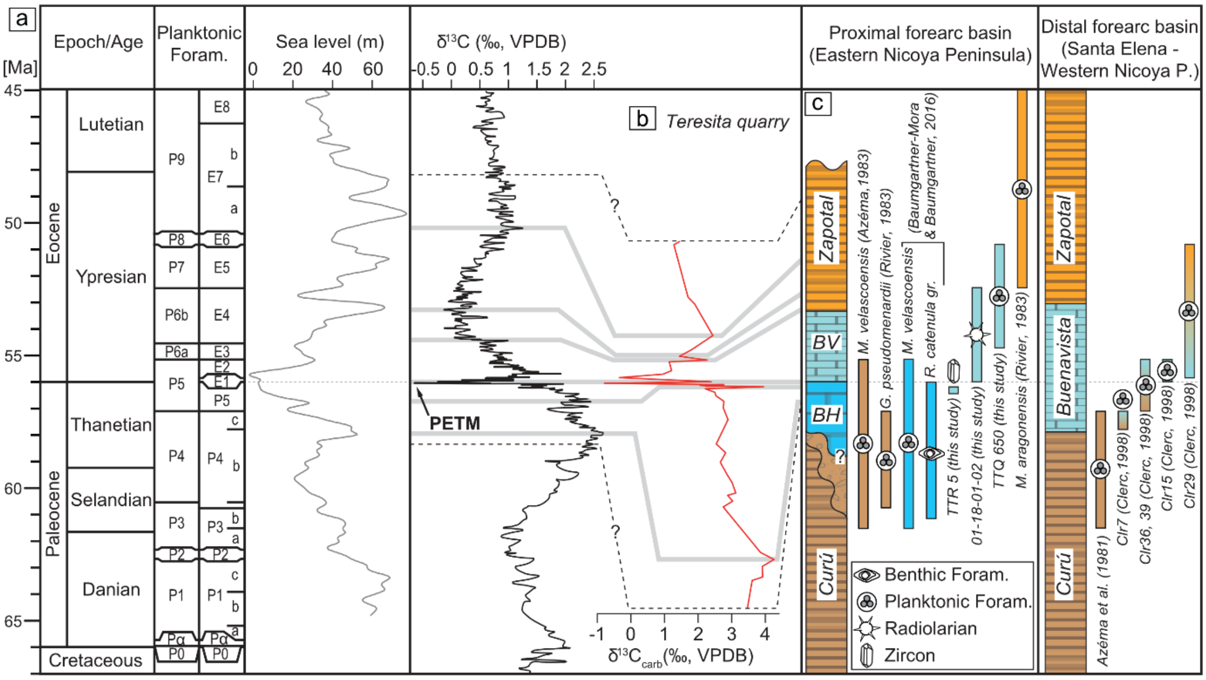

Figure 8. (a) Planktonic foraminifera biozonations (left column: Berggren et al., 1995; right column; Pearson et al., 2006) and global carbon isotope curve (see Speijer et al., 2020 and references herein) combined with the global mean sea level curve (Miller et al., 2020). Foram. = Foraminifera; PETM = Paleocene–Eocene Thermal Maximum. (b) $\delta^{13}C_{carb}$ curve from the quarry section of the Teresita quarry (this study). The grey lines tentatively correlate peaks of our new curve with those of the global carbon isotope curve. (c) Simplified chronostratigraphic logs of the Tempisque-Nicoya and northern Santa Elena areas combined with new and previous age constraints. The detailed explanation of previous biostratigraphic constraints is given in Appendix A. BH = upper Barra Honda Formation; BV = Buenavista Formation; P = Peninsula.

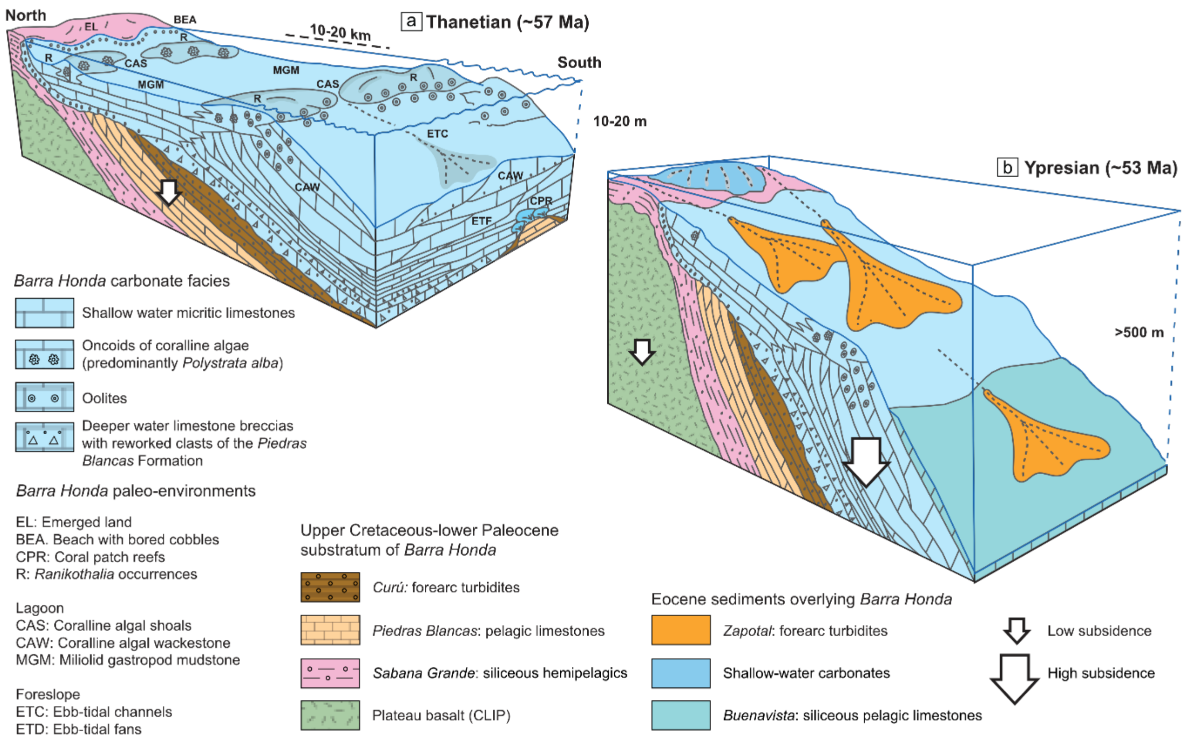

Figure 9. (a) Depositional model of the Barra Honda carbonate shoal during the Thanetian (modified after Baumgartner-Mora & Baumgartner, 2016). Towards the south, Barra Honda limestone breccias encroach on Curú forearc turbidites in an offshore environment and rework lithoclasts from the underlying erosional surface cutting into older formations (Sabana Grande, Piedras Blancas, and Curú). Upsection, massive intraclast breccias give way to platform sediments organized in ebb-tidal fans (ETF). Towards the north, Barra Honda lagoonal micritic facies (MGM) progressively onlap on higher-energy beach and foreshore sediments (BEA) on the eroded structural high during relative sea level rise (i.e., low subsidence). The higher stratigraphic levels of Barra Honda show patchy shoals of coralgal oncoid grain- and packstones (CAS) with *Ranikothalia* sp. (R) and locally oolites. Rare coral patch reefs (CPR) formed during the Maastrichtian in the lowermost stratigraphic levels of the Barra Honda Formation. (b) View of the forearc basin 3 Ma after the demise of the Barra Honda carbonate shoal. High forearc subsidence caused deepening of the basin floor to bathyal depths, preventing renewed shallow carbonate production in the Barra Honda carbonate shoal after the PETM (56 Ma). Shallow carbonate deposition may occur only on tectonic highs sheltered from detrital input.

Appendix A: Paleocene–lower Eocene biochronologic framework

The Paleogene, predominantly detrital formations of northern Costa Rica have been dated by means of occasional occurrences of planktonic and benthic foraminifera by several authors (Zoppis & Del Giudice, 1958; Dengo, 1962; Weyl, 1980; Azéma et al., 1981; Rivier, 1983; Baumgartner et al., 1984; Sprechmann, 1984). The existing fossil data of the Nicoya Peninsula was compiled by Denyer et al. (2014a, 2014b). Unfortunately, for most of this classical work, neither precise sample localities, nor illustrations of the reported fossils were provided, rendering precise biochronologic correlation difficult. More recently, published and unpublished, illustrated reports of microfossils in a more precise lithostratigraphic context have appeared, that are reviewed here for a biochronologic framework of the Paleocene–early Eocene time interval.

Curú Formation: upper Maastrichtian to upper Paleocene forearc turbidites

The Curú Fm. (= Rivas Fm. in Nicaragua), originally defined as "Formación Arenisca-Lutita Barco Quebrado" by Baumgartner et al. (1984) conformably overlies the upper Campanian–lower Maastrichtian pelagic Piedras Blancas Fm. (Flores et al., 2003a; Figures 1b, 3, and 4). It marks the beginning of detrital forearc sedimentation in the Tempisque (northern Costa Rica) and southern Sandino (southern Nicaragua) basins with distal turbidites of mainly basaltic composition (Lundberg, 1982; Baumgartner et al., 1984; Astorga, 1987, 1988). Here, we re-evaluate the biochronologic age of the top of this formation in the Tempisque, Samara and Santa Elena areas.

While the lower part of the Curú Fm. is well-dated as late Maastrichtian by numerous mentions of globotruncanids, its top is poorly dated in the Nicoya Peninsula. In part, this is probably because it became partly or totally eroded (or never deposited?) beneath the unconformable base of the Barra Honda Fm. (Figure 4). On the other hand, the upper portion of the Curú Fm., the Cerco de Piedra Mb. (Sprechmann, 1982; Flores et al., 2003b) represents a coarsening and thickening megasequence (Baumgartner et al., 1984) that culminates in megaconglomerates containing Barra Honda-type boulders in its upper part. This facies is present in the area of Samara-Punta Indio and the Colorado de Abangares area (Denyer et al., 2014a), which is located southeast of the Barra Honda outcrops. The well-rounded conglomerates with up to m-sized boulders document subaerial erosion of basaltic to andesitic primitive island arc rocks (Patino et al., 2004), of tholeiitic basalts derived from the Manzanillo Terrane basement, and of overlying Upper Cretaceous formations, as well as possibly early parts of the Barra Honda Fm. Rivier (1983) dated this conglomerate as middle to late Paleocene based on its stratigraphic position and the occurrence of *Globanomalina pseudomenardii* (P4 Zone, middle Selandian–early Thanetian) near the top of the member. *Morozovella* gr. *velascoensis* is also reported by Azéma (pers. comm. 1983) in both the upper Curú Fm. and the overlying Buenavista Fm. of the Samara area.

In the Santa Elena area, the top of the Curú Fm. is transitional with the Buenavista Fm. and was examined by Azéma et al. (1981) and a more recent thesis by Clerc (1998). Azéma et al. (1981) dated the upper Curú Fm. in the area of Guajiniquil (Santa Elena area, Figure 1b) by the presence of *Morozovella velascoensis* (P3b-E2 Zones), *Subbotina triloculinoides* (P1b-P4 Zones), and *Globanomalina ehrenbergi* (P2-P4 Zones) resulting in a concurrent range of P3b-P4 Zones (middle Selandian–late Thanetian).

The sample Clr7 is located at the base of the section "Bahia Santa Elena" of Clerc (1998, approximately at 10°55'56"N, 85°48'57"W) in a dark colored thin-bedded limestone interbedded with arkosic turbidites and overlain by thin-bedded cherty limestone. It is here interpreted as the transition from the Curú Fm. to the Buenavista Fm. It contains *Acarinina mackannai* (P4a-P4c Zones), *Globanomalina imitata* (P1-P4c Zones), *Morozovella acuta* (P4b-E2 Zones), *Morozovella aequa* (P4c-E6 Zones), *Morozovella* *subbotinae* (P4c-E6 Zones), and *Morozovella velascoensis* (P3b-E2 Zones), which have a concurrent range of P4c (middle Thanetian).

Samples Clr36 and Clr39 are located in the middle and upper part of the "Bahia Blanca" section (Clerc 1998, approximately at 10°56'41"N, 85°52'33"W). This section was attributed to the Buenavista Fm. by Clerc (1998) but was mapped as upper Curú Fm. by Andjić et al. (2016) because of the fact that the section contains rather mafic detrital sediments and only rare hemipelagic intervals; in the most recent maps of the Santa Elena Peninsula, Denyer (2019) considered Buenavista-type siliceous carbonates as part of the lowermost Brito Fm. The samples contain: *Globanomalina chapmani* (P4-base E4 Zones), *Morozovella aequa* (P4c-E5 Zones), *Morozovella velascoensis* (P3b-E2), *Morozovella subbotinae* (P5-E5), *Morozovella acuta* (P4-E2 Zones), *Globanomalina luxorensis* (P5-E2 Zones) and *Subbotina* spp., which gives a concurrent range of P5-E2 Zones (late Thanetian–early Ypresian).

In summary, the transitional top of the Curú Fm. to the Buenavista Fm. can be dated in the northern Santa Elena area as late Thanetian–early Ypresian. In the Nicoya area, the Curú Fm. is either conformably overlain by the Descartes Fm. (see below), or partly eroded (or lacking), or represented by the Cerco de Piedra Conglomerate of possible middle Selandian to early Thanetian age. The presence of Barra Honda clasts in this conglomerate implies that the Barra Honda carbonate shoal started to develop at least since the early Thanetian and is therefore partly coeval with the upper Curú Fm. (see also Andjić et al., 2016).

Barra Honda Formation: Uppermost Cretaceous(?)–Thanetian carbonate shoal

The occurrence of *Ranikothalia* gr. *catenula* in the lowermost beds of the upper Barra Honda Fm. at Cerro Espiritu Santo (Figure 3a) is one of the rare biostratigraphic markers in the formation. Baumgartner-Mora and Baumgartner (2016) have largely discussed the age range of *Ranikothalia* gr. *catenula*, which still has uncertainties. The best calibration of its first appearance was proposed by Robinson and Wright (1993), who restricted *R. catenula* to the late Paleocene, based on independent dating of its first appearance by nannofossils (NP5-7 Zones, according to Jiang & Robinson, 1987), which corresponds to the middle Selandian–early Thanetian (middle P3b to upper part of P4b Zones; Speijer et al., 2020). This is probably the maximum age of upper Barra Honda in its northernmost sections. Danian-lower Selandian macro- and microfossils are rare in shallow carbonates and have not been found in any Barra Honda facies. The transition from lower "Puerto Nispero" to upper Barra Honda sections cannot be observed and could be a stratigraphic gap due to emersion during an eustatic sea-level low during the latest Cretaceous-Danian (Miller et al., 2005).

The top of Barra Honda Fm. can be dated by the occurrence of *Morozovella velascoensis* that occur in several outcrops in the upper part of the formation with open marine influence (Baumgartner-Mora & Baumgartner, 2016). This planktonic foraminifera goes extinct about 0.2 Ma to 1 Ma after the isotopically defined Paleocene–Eocene boundary (Pak & Miller, 1992; Kelly et al., 1998; Molina et al., 1999; Arenillas et al., 1999). Hence, the minimum age of the Barra Honda Fm. is likely to be latest Paleocene or earliest Eocene. It must be in part coeval with the basinal, lower part of the Buenavista Fm. outcropping in the Santa Elena Peninsula (Figures 1b and 4).

Buenavista Formation: upper Paleocene to lower Eocene pelagic cherty limestones and tuffaceous mudstones

Originally described by Baumgartner et al. (1984) in the Samara area and reported from the Santa Elena area, this formation was later ignored and included with the Zapotal Mb., the basal part of the Descartes Fm. It is coeval and most probably a lateral, more distal, equivalent of the lowest part of the Zapotal Mb. (*sensu* Denyer et al., 2014a). In contrast with the Zapotal Mb., this formation is largely pelagic to tuffaceous-hemipelagic and lacks coarse detrital turbidites. Abundant planktonic foraminifera and radiolarians allow precise dating of this short-lived stratigraphic interval.

In the type locality (Playa Buenavista, Samara area), the Buenavista Fm. was dated by Baumgartner et al. (1984) as late Paleocene–early Eocene, principally based on the recognition of *Morozovella* gr. *velascoensis.* In the Santa Elena area, the Buenavista Fm. was dated in several sections measured by Clerc (1998). Sample Clr15 is located in the middle of the "Bahia Santa Elena" section (Clerc, 1998; approximately at 10°56'4"N, 85°48'43"W) at the base of a faulted interval of thin-bedded siliceous limestones interbedded with abundant marls. It contains *Subbotina* sp., *Morozovella velascoensis* (P3b-E2 Zones), *Morozovella subbotinae* (P5-E5 Zones), *Morozovella aequa* (P4c-E6 Zones), *Morozovella acuta* (P4b-E2 Zones), *Globanomalina chapmani* (P3-base E4 Zones), *Acarinina pseudotopilensis* (E1-E7 Zones), and *Acarinina mckannai* (P4a-P4c Zones, possibly reworked), which gives a consistent concurrent range of E1-E2 Zones (late Thanetian–early Ypresian). This sample suggests that part of the Buenavista Fm. is at least late Thanetian in age. Sample Clr 24 is located at the top of the "Bahia Santa Elena" section (Clerc, 1998; approximately at 10°56'8"N, 85°48'38"W), which corresponds to the middle or upper part of the Buenavista Fm. It contains *Morozovella subbotinae* (P5-E5 Zones) and *Subbotina* sp. (P5-E5 Zones), which suggests a late Thanetian–middle Ypresian age. Sample Clr29 is located near the top of the "Isla Los Cabros" section (Clerc, 1998; approximately at 10°56'31"N, 85°48'58"W). It represents the transition between the Buenavista and the Descartes formations and contains *Pseudohastigerina* sp. (first appearance: E2 Zones), *Morozovella subbotinae* (P5-E5 Zones), which gives a range of E2-E5 Zones (early–middle Ypresian).

In summary, the Buenavista Fm. has an overall middle–late Thanetian to early Ypresian age. In the Santa Elena area the total age range of the formation is represented. In contrast, the lower Ypresian part of this formation overlies the Barra Honda Fm. in the Teresita quarry, as shown in section 5.2, where a new assemblage of planktonic foraminifera is described.

Zapotal Member (Descartes Formation): Eocene forearc turbidites

The Zapotal Mb. corresponds to a succession of siliceous and carbonate-bearing volcaniclastic turbidites of up to 2 km in thickness (Rivier, 1983; Astorga, 1987; Flores et al., 2003a). Rivier (1983) reported early to middle Eocene planktonic foraminifera from the Zapotal Mb.: *Morozovella gracilis* (P5-E5 Zones), *Morozovella formosa* (E4-E6 Zones), *Morozovella aragonensis* (E5-E9 Zones). In section 4.2., we re-evaluate a radiolarian assemblage reported by Bandini et al. (2008) from the Zapotal Mb.