

Erratum to: Neogene eastern Amazon carbonate platform and the paleoenvironmental interpretation

Orangel Aguilera · José Tasso Felix Guimarães ·
Heloisa Moraes-Santos

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Abstract The Early Miocene Pirabas Formation represents extensive carbonate and siliciclastic belts deposited in marine coastal environments along the eastern Amazon coast. This formation was studied in its palynological, crustacean decapods and sedimentary facies, to develop a model of its depositional processes, faunal and floral assemblages and the sedimentary environments, as observed in the B17 mine (Capanema, Pará). The sedimentary records consist mostly of light gray to greenish gray mudstones with tidal bedding, calciferous sandstones, stratified biocalcirudites and levels with conglomerates deposited in a carbonate/siliciclastic transitional system with lagoon, tidal flat, flood-tide delta and foreshore environments. 18 palynomorph species were identified in the tidal flat deposits including one alga, five pteridophytes and nine angiosperms. Among the latter, mangrove pollen and spores of *Zonocostites ramonae*, *Zonocostites minor*

and *Deltoidospora adriennis* are reported. Nine species of crustacean decapods were recognized in the foreshore deposits, comprising one Callianassoidae, two Calappidae and six Portunidae, represented by *Euphyllax*, †*Necronectes*, *Portunus* and *Scylla*, the ecology of which is associated with beaches of marginal lagoons. The main factor in the formation of these carbonate environments is assumed to have been related to the lack of a large-scale drainage system such as the Amazon River basin in the transition Oligocene–Miocene, which may also have influenced carbonate production and resulted in a strong decrease of paleodischarges from incipient river systems along the Amazon coast.

Keywords Amazon · Carbonate · Pirabas · Paleoenvironment · Palynology · Crustacea

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O. Aguilera · H. Moraes-Santos
Museu Paraense Emilio Goeldi, Coordenação de Ciências da Terra e Ecologia, CCTE, Av. Perimetral, 1901, Terra Firme, Belém, PA 66077-830, Brazil
e-mail: orangel.aguilera@gmail.com

H. Moraes-Santos
e-mail: hmoraes@museu-goeldi.br

J. T. F. Guimarães (✉)
Instituto Tecnológico Vale-ITV, Rua Boa Ventura da Silva, n° 955, 3° andar, Umarizal, Belém, PA 66055-090, Brazil
e-mail: tasso.guimaraes@itv.org

Introduction

The tidal shelf of the eastern Amazon was characterized by an extensive and thick accumulation of early Miocene carbonate deposits related to the Pirabas Formation (Maury 1925), the latest carbonate deposit in northern Brazil. The Amazon fan was only incipient during late Oligocene–early Miocene and the influence of siliciclastic sediments supplied by the river flow to the Atlantic coast was low (Figueiredo et al. 2009), which has been attributed to the initial eastern Andean cordillera uplift (Shephard et al. 2010) during the Oligocene (Horton et al. 2010). Therefore, the substantial Andean uplift in the late Miocene resulted in the establishment of the Amazon drainage to the Atlantic coast (Hoorn et al. 1995). The low sediment input into the ocean during early Miocene favored carbonate formation and expansion of the photic zone, and the development of a

high-diversity shallow marine flora and fauna along the eastern Amazon coast.

The sedimentary deposition of the Pirabas Formation was influenced by water masses with high-energy flow of the Atlantic Ocean (Johns et al. 1998, 2002), with long-shore currents driven by oceanic currents, a macrotidal regime (Beardsley et al. 1995) and wave processes. Additionally, changes in the sources of siliciclastic sediments, the water temperature (Zachos et al. 2001), and the eustatic and relative sea-level oscillations (Haq et al. 1988; Carter 1998; Kominz et al. 2008) controlled the distribution of carbonate and siliciclastic belts deposited in the marine coastal environments (Rossetti 2006; Rossetti and Santos 2004).

The heterotrophic carbonate producers, such as mollusks, echinoids and bryozoans, were abundant and diverse in the Pirabas Formation (Rossetti and Góes 2004; Távora et al. 2010; Aguilera and Páes 2012). Oligotrophic corals are absent, except for isolated records of Agariciidae (Lalor and Távora 2006). The early Miocene Pirabas Formation is time equivalent to the period when the Caribbean reef-building corals had declined and the diversity became reduced by 50 % (Johnson et al. 2009). Similarly, Bourrouilh-Le Jan and Hottinger (1988) described a drastic early Miocene decline in coral reefs on a number of Pacific atolls. This absence of corals in the tropics with respect to carbonate producers may correspond to the worldwide bloom of coralline red-algal (rhodalgae) facies (Halfar and Mutti 2005).

Many plant remains were also identified along the coastal deposits of the Pirabas Formation (Toledo 1989; Arai 1997; Leite et al. 1997a, b; Fernandes 1984; Távora et al. 2010), suggesting deposition in a tidal flat and lagoon environments (Rossetti 2006; Rossetti and Santos 2004). Leite et al. (1997a, b) proposed that the paleovegetation of the Pirabas Formation is marked by the predominance of *Zonocostites ramonae* Gemeraad et al. 1968, a Miocene species that inhabited mangrove-type environments.

There are at least 27 outcrop localities recorded from the Pirabas Formation (Távora et al. 2010). However, the exposures are restricted in thickness to a few meters along the tidal zone. The only exception is the Capanema Mine B17, with around 40 m thick of exposed section. Here, we recorded an exceptional horizon with hundreds of crab carapaces, chelae and fragments of portunids (blue crabs), calappids (box crabs) and suitable palynological samples for a paleoenvironmental study.

Early contributions of White (1887) and Maury (1925), particularly on mollusk, bryozoan and coral research, and Petri (1954, 1957) on foraminifera, Beurlen (1958), Brito (1971, 1972, 1977) and Martins-Neto (2001) on crustaceans, Santos (1958, 1967) on echinoids, Santos and Travassos (1960) and Santos and Salgado (1971) on fishes,

Paula-Couto (1967), Toledo (1989), and Toledo and Domning (1989) about sirenians, and Lalor and Távora (2006) on corals, as well as many further references summarized in Rossetti and Góes (2004) and in Távora et al. (2010), provide additional descriptions, records and/or reviews of different fossils groups from the Pirabas Formation.

Considering the regional relevance of this fossiliferous carbonate deposit in relation to the Atlantic Ocean, the objective of this paper is the integrated study of palynology, crustacean decapods and facies research for the interpretation of the paleoenvironment.

Geological setting

The Bragantina platform (North Brazil, Pará) corresponds to emerged and submerged areas, which were stable during episodes of distention tectonics following the breakup of Gondwana and the opening of the Equatorial Atlantic during Jurassic and Lower Cretaceous (Sztatmari et al. 1987). Despite this tectonic stability, thick sedimentary units of Miocene age were deposited in this region. Therefore, Rossetti (2001) proposed that the reactivation of normal and strike-slip faults from Precambrian basement, combined with sea-level changes, was responsible for the genesis of these units in the deep tectonic troughs (e.g., Vigia-Castanhal and Marajó basins). The Neotectonic activity of the northeastern Pará is controlled by E–W transcurrent faults connected with NW–SE normal faults, while the structural and sedimentary evolution is related to the reactivation of the basement architecture (Costa et al. 1996). Structural entities such as the Pará platform and Bragança–Viseu basin are shown in Fig. 1a.

The Bragantina platform comprises around 2,000 m of Jurassic/Cretaceous deposits. The sedimentary cover of the Paleogene and Neogene (~1,500 m thick) is not tectonically influenced by the ancient depositional centers, which indicates higher stability in the adjacent coastal basins (Gorini and Bryan 1976). The Bragança–Viseu basin represents a Graben bordered by normal faults along a NW–SE structural profile. The sediments are composed of lithostratigraphic units of Cretaceous age, including the Bragança, Grajaú, Codó and Itapecuru formations, which are overlain by Neogene carbonate rocks of the early Miocene Pirabas Formation, which in turn is overlain by the siliciclastic Miocene Barreiras Group and the Pleistocene Pós-Barreiras Formation (Figs. 1b, 2).

The early Miocene Pirabas Formation (Maury 1925) consists of carbonate rocks of an offshore shelf environment (grainstone and consolidated packstone, stratified wackestone packstone and laminated mudstone). However, coastal facies (shoreface/foreshore), marginal lagoons,

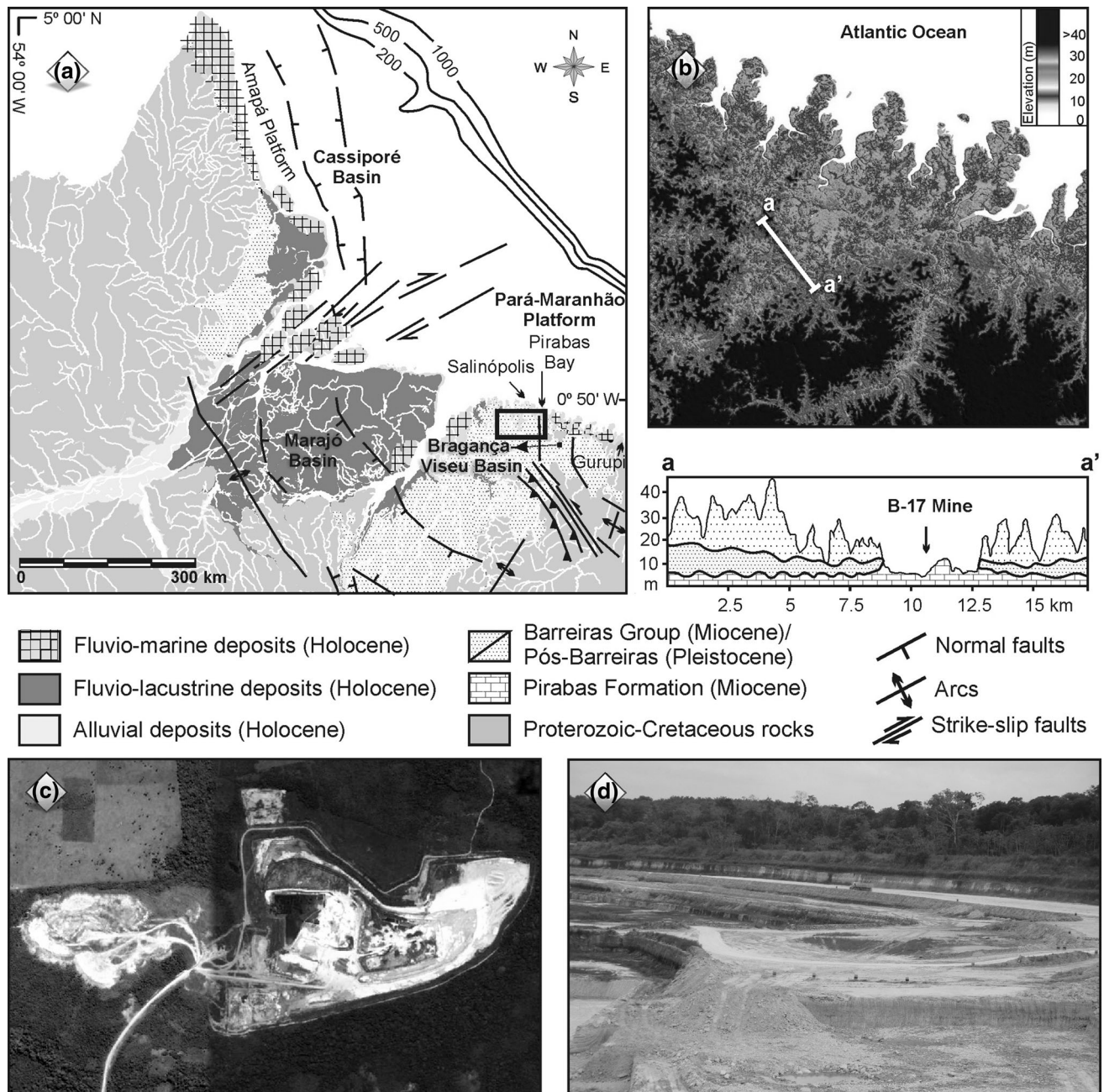


Fig. 1 Location map. **a** Regional geology. **b** Digital elevation model of the northern coast of the Pará state. **c** Aerial view (modified from Google earth) and **d** panoramic view of the B17 mine

(gray to olive mudstone and conglomeratic sandstone) and tidal flats (massive dark mudstone) have also been recorded (Góes et al. 1990; Rossetti 2001; Rossetti and Góes 2004). More details of these heterogeneous lithostratigraphic sequences and the associated fossil faunas were presented and discussed by Aguilera and Páes (2012).

The assignment of early Miocene for the Pirabas Formation follows Petri (1957), Fernandes (1984), Ferreira et al. (1978), Fernandes and Távora (1990) and Távora and Fernandes (1999). The heterogeneous variation of the faunal

composition recorded in the different outcrops (Aguilera and Páes 2012) suggests that different members should be recognized, and accurate geochronological research may reveal different ages within the Pirabas sequence.

Materials and methods

Several field trips (August and December 2011 and April 2012) to the B17 mine of the CIBRASA S/A near

Fig. 2 Stratigraphic chart for the Bragantina Platform, Brazil (modified from Rossetti 2001)

AGE	LITHOSTRATIGRAPHIC UNIT	DESCRIPTION	AVERAGE THICKNESS (m)
PLIO- PLEISTOCENE	Pós-Barreiras	Yellowish, well-sorted, fine-grained massive sandstone.	5
MIOCENE	unconformity 3 (lateritic soil)		
	LATE		
	MIDDLE	Mudstone with plane-parallel, lenticular, wavy and flaser beddings; massive and cross-stratified sandstone with reactivation surfaces and mud drapes forming thick/thin couplets attributed to tidal cycles. Variegated colors.	5-10
	EARLY		
LATE OLIGOCENE	unconformity 2		
	lower Barreiras Fm.	Terrigenous limestone, carbonaceous black mudstone and calcareous yellowish sandstone interfingering with mudstone and sandstone with variegated colors and showing plane-parallel, lenticular, wavy and flaser beddings, as well as cross stratification, reactivation surface and mud drapes forming thick/thin couplets attributed to tidal cycles	15-20
	Pirabas Fm.		
CRETACEOUS	unconformity 1 (lateritic/bauxitic soil)		
	Itapecuru Group		

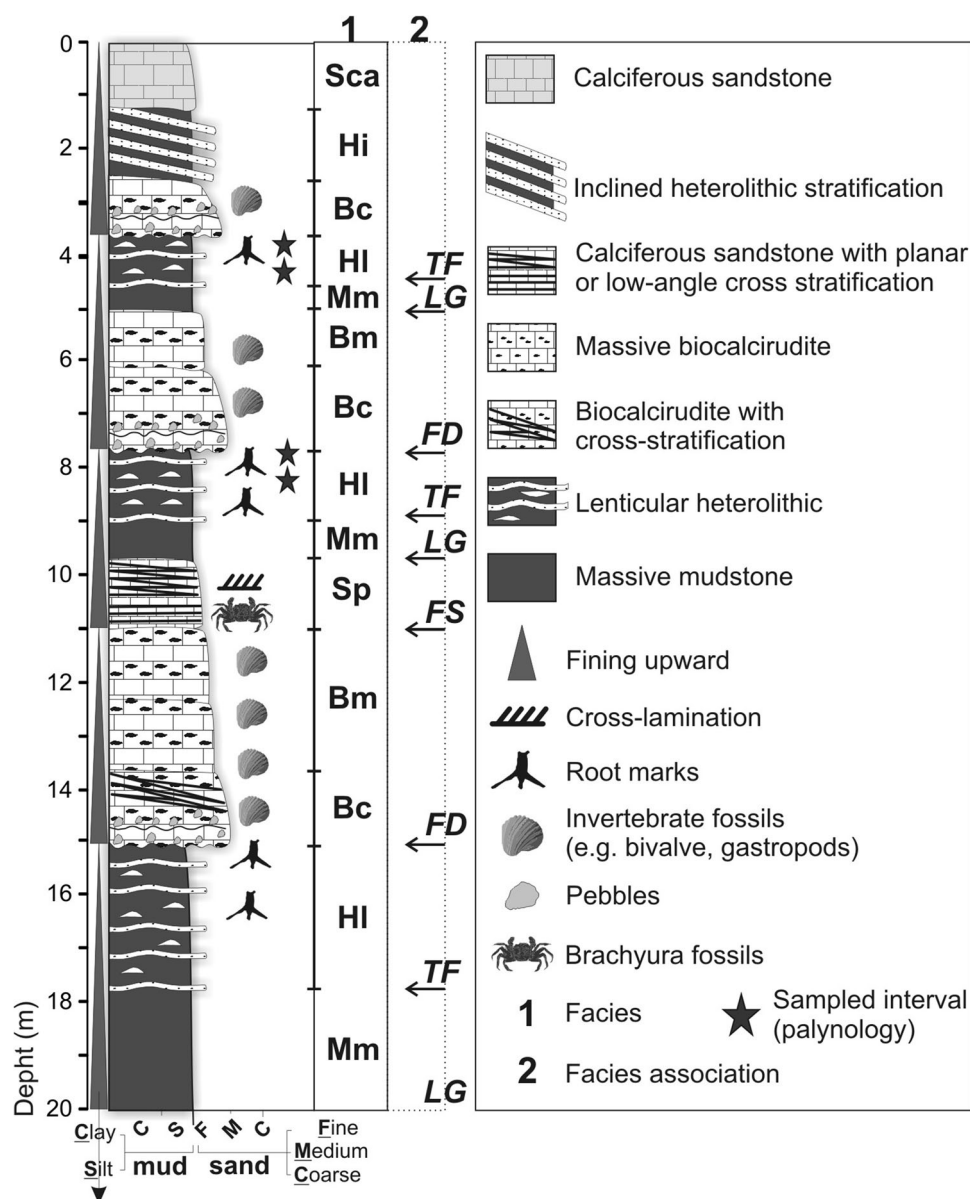
Capanema, Pará (Fig. 1c, d; 01°10'S, 47°13'W) permitted the construction of a biostratigraphic section and facies interpretation, based on direct field measurements and analysis. Facies analysis included descriptions of color, lithology, texture and structures based on methods presented by Walker (1992), and were codified according to Miall (1978).

Four bulk samples were collected from dark gray mudstones rich in organic matter of the section intervals between 9–8 and 5–4 m for palynological analysis (Fig. 3). Around 30 g per sample was dried, weighed, triturated, submitted to hydrochloric and hydrofluoric acid for carbonate and silicate removal, sieved with a 10 µm mesh and mounted on glass slides with Entellan medium following Uesugui (1979). Pollen and spore morphologies are based on Traverse (2008) and Hesse et al. (2008). The South American palynomorphs references are based on a rich existing literature (e.g., Van der Hammen 1956a, b; Van der Hammen and Wymstra 1964; Germeraad et al. 1968; Dueñas 1980; Lorente 1986; Muller et al. 1987; Hoorn 1993, 1994a, b; Jaramillo and Dilcher 2001; Silva-Caminha et al. 2010). Pollen and spores were described using the terminology of Punt et al. (2007) and the classification system of Iversen and Troels-Smith (1950). The pollen and spore taxonomic affinities and ecological interpretation follow Roubik and Moreno (1991),

Colinvaux et al. (1999) and Bush and Weng (2006). Samples were counted to a minimum of about 300 pollen grains. Pollen and spore data are presented in pollen diagrams as percentages of the total pollen amount. Taxa were grouped into mangrove, lowland freshwater forests, lowland pteridophytes, fungi, algae and foraminifera. The softwares Tilia and Tilia Graph were used for the calculation and plotting of palynological diagrams (Grimm 2004).

Fossil macro invertebrates, particularly crustacean decapods, were collected directly from the surface of the calciferous sandstone interval of 10–9 m during ongoing mining activities. The study of the fossil crustacean decapods was based on comparative analysis, with the collections from the Museu Paraense Emilio Goeldi, the Universidad Experimental Francisco de Miranda (see Aguilera et al. 2011) and those deposited at the Smithsonian Tropical Research Institute. Collections from the Pirabas Formation at the Museu de Geologia in the Universidade Federal do Pará, under the care of V. Távora, could not be accessed. Complementary data were retrieved from published literature (e.g., Beurlen 1958; Brito 1971, 1972, 1993; Martins-Neto 2001, 2005; Martins-Neto and Dias-Júnior 2007; Vega et al. 2009; Schweitzer et al. 2006). The classification follows De Grave et al. (2009) and Schweitzer et al. (2009).

Fig. 3 Stratigraphic section of the B17 mine. 1 Facies, *Mm* massive mudstone, *HI* lenticular heterolithic, *Bc* biocalcirudite with cross-stratification, *Bm* massive biocalcirudite, *Sp* sandstone with planar and/or low-angle cross-stratification, *Hi* inclined heterolithic, *Sca* calciferous sandstone. 2 Facies association, *LG* lagoon, *TF* tidal flat, *FD* flood-tide delta, *FS* foreshore



Results

Facies description from the Capanema Mine B17 section

The sedimentary record consists mostly of light gray to greenish gray mudstones with tidal bedding, calciferous sandstones, stratified biocalcirudites and levels with conglomerates. Invertebrates, pollen and spore records were added to facies' characteristics to define four facies associations grouped into fining and thinning upward cycles that represent a carbonate/siliciclastic transitional system, with lagoon (LG), tidal flat (TF), flood-tide delta (FD) and foreshore (FS) environments (Fig. 3; Table 1).

Lagoon (LG). This association is represented by massive mudstones without apparent structures. It is laterally continuous (facies Mm), about 2 m thick in the basal strata and decreases to 0.5 m along the sedimentation cycles (Fig. 3; Table 1). The LG association corresponds to a low-energy environment associated with the basin center and a deposition of mud from the suspension.

Tidal flat (TF). The TF association occurs at the top of each sedimentary cycle and represents mud with connected and discontinuous lenses of rippled sand (facies HI). Locally, root fragments and root marks can be observed. In the upper strata, the base of this facies is erosive, containing biocalcirudite with reworked bivalves and gastropods as well as scattered pebbles throughout the matrix (facies Bc),

Table 1 Facies description and sedimentary processes identified along the B17 profile

Facies	Description	Processes
Massive mudstone (Mm)	Light gray to dark mudstone without apparent structures	Deposition of clay and silt under low-energy flow from suspension
Lenticular heterolithic (Hl)	Lenses of greenish gray mudstone connected and/or isolated interbedded with pale olive calciferous sandstone. Roots and root marks can be observed on the top of the facies	Variation of bed load transport by tidal current with deposition of mud from suspension during very low-energy periods
Biocalcirudite with cross-stratification (Bc)	Limestone with fossil fragments and quartz pebbles with cross-stratification and large amounts of bivalves and gastropods with multi-oriented pattern of deposition	Deposition under moderate- to high-energy flow and decrease of energy through time. Reworking of fossils in sand waves with lateral and downstream migration under bidirectional (with predominance of flood flow) and combined flows. Fossil and pebbles are left behind, while sand is transported as bedload during the decrease of high-energy to moderate-energy flow
Massive biocalcirudite (Bm)	Fossiliferous limestone with well-preserved bivalves and gastropods with multi-oriented pattern of deposition	Sedimentation by high-energy flows, with progressive decrease through time
Sandstone with planar and/or low-angle cross-stratification (Sp)	Fine to very fine calciferous sandstone, well-sorted, with planar and/or low-angle cross-stratification	Deposition of sand under high-energy flow, with formation of slightly plane beds during swash and backwash
Inclined heterolithic (Hi)	Parallel and inclined beds of light gray mudstone and sandstone	Lateral accretion with deposition of sand and mud during low- to moderate-energy flows in a small-scale meandering channel
Calciferous sandstone (Sca)	Fine carbonate sandstone without apparent structures	Deposition of sand under low- to moderate-energy flow

and is overlain by inclined sandstone and mudstone (facies Hi) and facies Hl. These facies are related to a tidal regime with deposition of mud from suspension and sand from the ebb and flood tide, following the lateral migration of tidal channels with point-bar development (Fig. 3; Table 1). The pollen assemblage of the TF association (Figs. 4, 5, 6) is mainly represented by the mangrove species *Zonocostites ramonae* (67–76 %), *Zonocostites minor* (20–24 %) and *Deltoidospora adriennis* (20–35 %). In general, lowland freshwater forests of *Retitricolporites* sp. 1 (2–5 %), *Retibrevitricolporites* (2–5 %) and *Mauritiidites franciscoi* var. *franciscoi* (0–3 %) showed lower percentages, but also presented higher concentrations along the upper tidal flat cycle. Other spores of lowland pteridophytes occur with relatively high concentrations, such as *Verrucatosporites* sp. 01 (0–20 %), *Polypodiaceoisporites* sp. 02 (3–8 %) and *Verrucatosporites usmensis* (3–5 %). Foraminifera are very frequent in the lower TF cycle (13–30 %), decreasing in the upper TF cycle (4–10 %), while *Ovoidites*, a green algae commonly found in freshwater lakes and open-water marsh (Rich et al. 1982), shows an inverse pattern with an increase of concentration values until the upper TF cycle (0–3 to 5–10 %).

Flood-tide delta (FD). The FD association is characterized by biocalcirudites with cross-stratification (facies Bc), massive biocalcirudite (facies Bm) and conglomerates with pebbles, fragments of bivalves and gastropods in the basal levels that represent channel lag deposits (Fig. 3; Table 1).

This FD association overlies the TF association with an erosive unconformity, likely corresponding to channel dynamics during flood tides and intense rework of sediments from inner shelf/shoreface to lagoon and tidal flat environments under unidirectional and combined flows.

Foreshore (FS). This association is represented by calciferous sandstone with planar or low-angle cross-stratification (facies Sp). Cross-laminations may occur between the main bedding planes. A well-preserved assemblage of crustacean decapods was found in the FS association (Fig. 3; Table 1). This facies is indicative of sediment reworked under oscillatory flows during swash and backwash.

Systematic palynology

Algae

Turma Cystites Potonié and Kremp 1954

Ovoidites Potonié ex Krutzsch 1959

Ovoidites sp. 1

(Fig. 5.1)

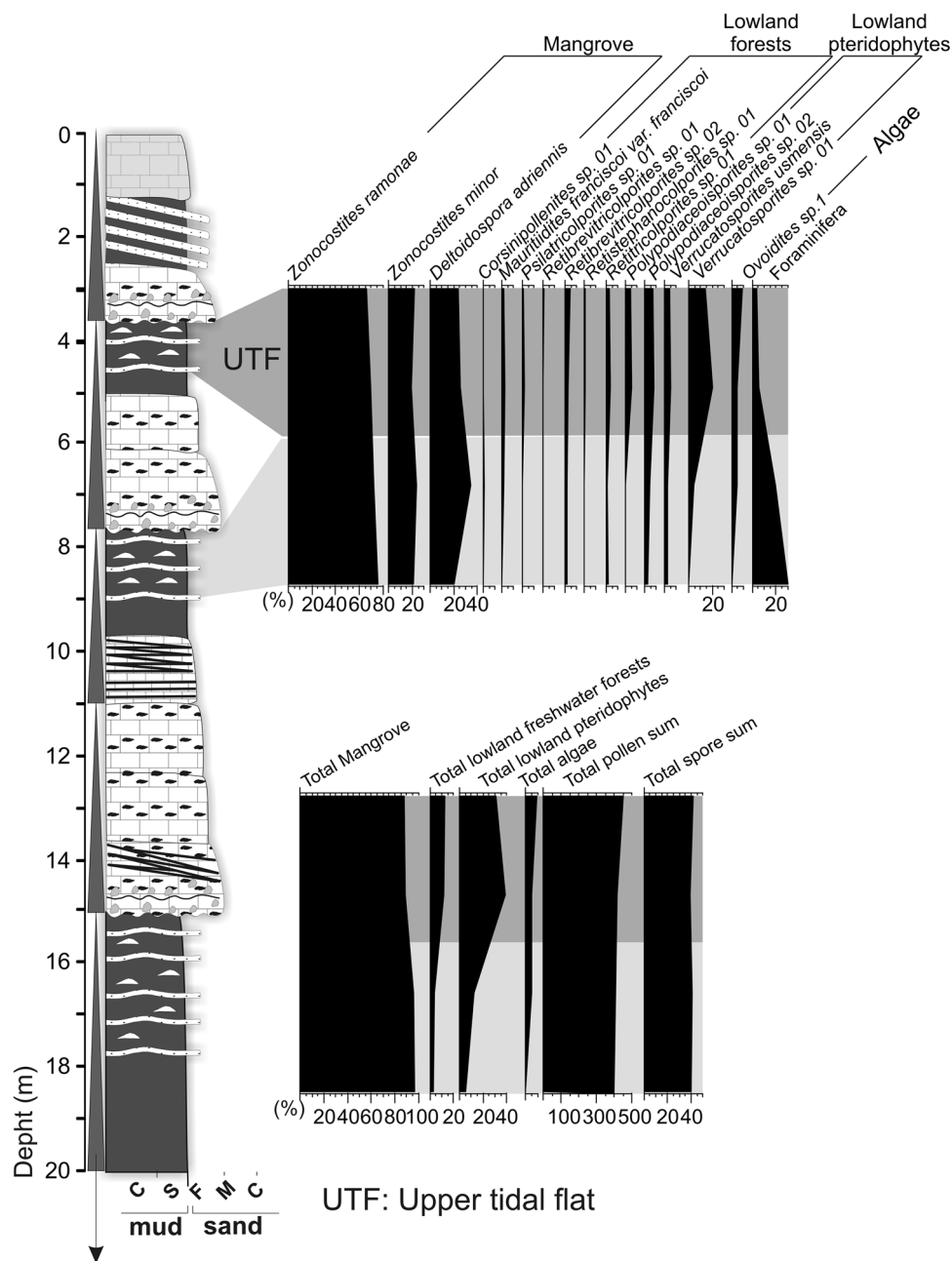
Material examined. B17; EF: 25S/4.

Description. Elliptical, psilate ornamentation.

Dimensions. Equatorial length 25.1 µm, equatorial width 16.5 µm.

Stratigraphic range. Cretaceous to Recent (Cookson and Dettman 1958).

Fig. 4 Integrated stratigraphic section, pollen and spore record



Taxonomic affinity. *Ovoidites* and *Schizosporis* represent spores of Zygnemataceae related to the current genus *Spirogyra* (Van Geel and Van der Hammen 1978).

Comparisons. *Ovoidites parvus* (Cookson and Dettman 1959) Nakoman 1966 is bigger (71–105 μm diameter) than the specimens obtained from the Pirabas Formation.

Pteridophytes

Monoletes Ibrahim 1933

Verrucatosporites Thompson and Pflug 1953

Verrucatosporites usmensis (Van der Hammen 1956a) Germeraad et al. 1968

(Figs. 5.2, 5.3)

Material examined. B17; EF: 21R/3.

Description. Monolete, bilateral symmetry, elliptical; verrucate ornamentation, verrucae 1.5 μm in height and base 1.8 μm wide, exine 1 μm thick.

Dimensions. Equatorial diameter 52.7 μm , polar diameter 31.1 μm .

Stratigraphic range. Upper Eocene–Lower Oligocene to Recent (Lorente 1986; Germerrad et al. 1968). Lower Eocene to Pliocene (Salard-Cheboldaef 1990), and Upper Eocene to Upper Miocene (Regali et al. 1974).

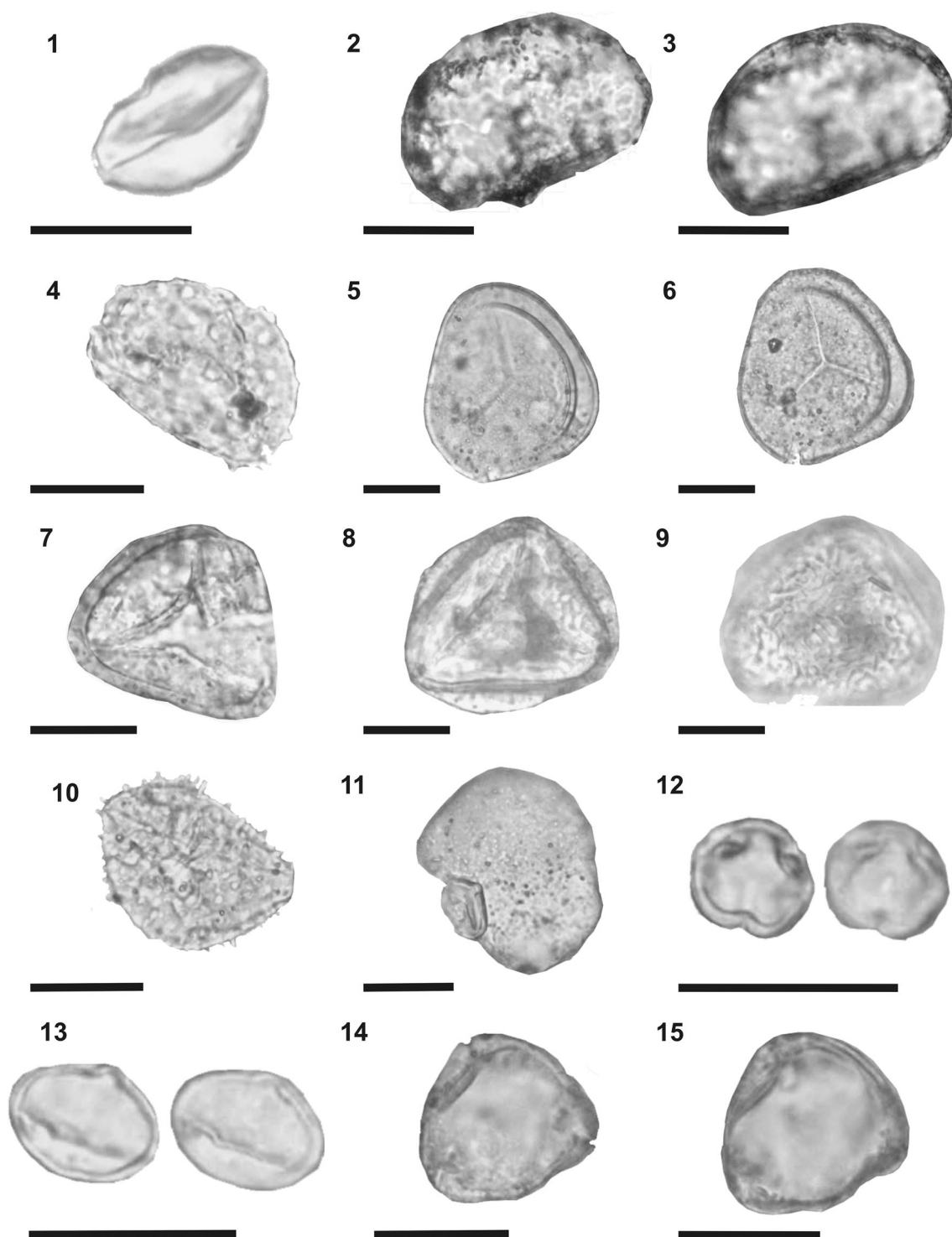
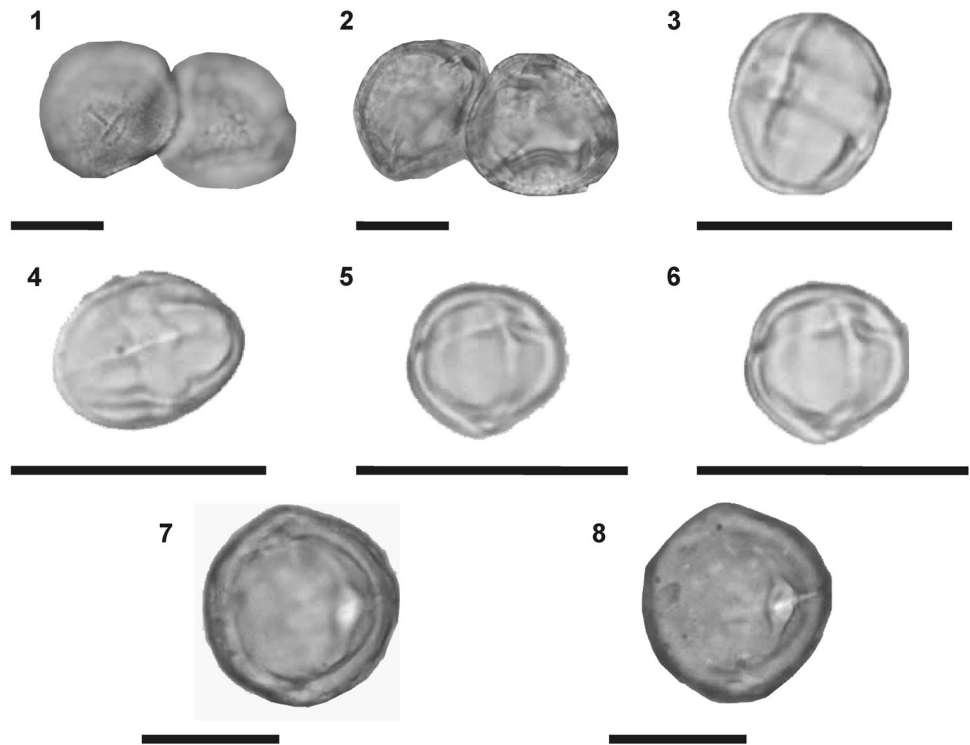


Fig. 5 Palynological specimens. 1, *Ovoidites* sp. 01; 2, *Verrucatosporites usmensis* (Van der Hammen 1956a) Germeraad et al. (1968). Proximal view, 3, *Verrucatosporites usmensis* (Van der Hammen 1956a) Germeraad et al. (1968). Distal view, 4, *Verrucatosporites* sp. 01; 5, *Deltoidospora adriennis* (Potonié and Gelletich 1933) Frederiksen et al. (1983). Distal view, 6, *Deltoidospora adriennis* (Potonié and Gelletich 1933) Frederiksen et al. (1983). Proximal view, 7,

Polypodiaceoisporites sp. 01; 8, *Polypodiaceoisporites* sp. 02. Distal view, 9, *Polypodiaceoisporites* sp. 02. Proximal view, 10, *Mauritidites franciscoi* var. *franciscoi* (Van der Hammen 1956a) Van Hoeken-klinkenberg (1964); 11, *Corsinipollenites* sp. 01; 12, *Psilatricolporites* sp. 01; 13, *Retitricolporites* sp. 01; 14, *Retibrevitricolporites* sp. 01. Proximal view, 15, *Retibrevitricolporites* sp. 01. Distal view

Fig. 6 Palynological specimens. 1, *Retibrevitricolporites* sp. 02. Proximal view; 2, *Retibrevitricolporites* sp. 02. Distal view; 3, *Zonocostites ramonae* Gemeraad et al., 1968. Type 1; 4, *Zonocostites ramonae* Gemeraad et al., 1968. Type 2; 5, *Zonocostites minor* Jaramillo and Dilcher, 2001. Distal view; 6, *Zonocostites minor* Jaramillo and Dilcher, 2001. Proximal view; 7, *Retistephanocolporites* sp. 01. Distal view; 8, *Retistephanocolporites* sp. 01. Proximal view



Taxonomic affinity. The species resembles *Stenochlaena palustris* of Blechnaceae (Gemeraad et al. 1968). *Polypodium*—Polypodiaceae (Lorente 1986).

Comparisons. *Laevigatosporites ovatus* Wilson and Webster 1946 has thinner exine (e.g., Santos et al. 2005).

Verrucatosporites sp. 01
(Fig. 5.4)

Material examined. B17; EF: 34W.

Description. Monolete, bilateral symmetry, elliptical; verrucate ornamentation, verrucae 1.5 μm in height and base 2.1 μm wide, exine 0.8 μm thick.

Dimensions. Equatorial diameter 39.4 μm , polar diameter 27.6 μm .

Taxonomic affinity. *Polypodium*—Polypodiaceae.

Comparisons. *Polypodiisporites speciosus* Sah 1967 and *Verrucatosporites speciosus* Harris, 1965 have wider verrucae (4–7 μm) and thicker intexine (1.5–2 μm).

Triletes Reinsch emend. Dettmann, 1963

Deltoidospora Miner 1935

Deltoidospora adriennis (Potonié and Gelletich 1933) Frederiksen 1983

(Figs. 5.5, 5.6)

Material examined. B17; EF: 11R.

Description. Trilete, anisopolar, radially symmetric, triangular–obtuse–convex, curvature absent, margo absent,

commissure straight, exine 1.5 μm thick, psilate to micropitted ornamentation.

Dimensions. Equatorial length 50.6 μm , equatorial width 46.5 μm .

Stratigraphic range. Upper Eocene (Santos et al. 2010), Lower Oligocene to Recent (Lorente 1986).

Taxonomic affinity. *Acrostichum auerum* L. (Hoorn 1993).

Comparisons. *Camazonosporites* sp. 1 Jaramillo and Dilcher 2001 has a rugulate distal face and is smaller in size (27–30 μm). *Matonisporites mulleri* Playford 1982 has curvatura perfecta and psilate ornamentation over the entire spore grain. *Deltoidospora juncta* (Kara Murza 1956) Singh 1964 is smaller (32–34 μm diameter).

Polypodiaceoisporites Potonié 1951 ex Potonié 1956

Polypodiaceoisporites sp. 01

(Fig. 5.7)

Material examined. B17; EF: 17T/2.

Description. Trilete, radially symmetric, triangular–obtuse–convex, curvatura perfecta; radii long, reaching the equator without extending into cingulum; cingulum psilate, 2.9 μm thick; reticulate ornamentation, lumina 1 μm wide and muri 0.9 μm wide.

Dimensions. Equatorial length 41.5 μm , equatorial width 38.5 μm .

Taxonomic affinity. Polypodiaceae.

Comparisons. *Polypodiaceoisporites fossulatus* Jaramillo and Dilcher (2001) has the equatorial outline, which is triangular–obtuse–straight and fossulate ornamentation. *Polypodiaceoisporites pseudopsilatus* Lorente 1986 is foveolate on the distal face and psilate on the proximal face.

Polypodiaceoisporites sp. 02
(Figs. 5.8, 5.9)

Material examined. B17; 44Q.

Description. Trilete, radially symmetric, triangular–obtuse, curvatura absent; radii long, reaching the equator without extending into cingulum, labrum 2.5–3 μm wide; cingulum reticulate, interradian thickening, cingulum 3.8 μm thick, radial thinning, cingulum <0.5 μm thick; rugulate ornamentation, muri 1–2 μm wide, lumina 1–2 μm wide.

Dimensions. Equatorial length 52 μm .

Taxonomic affinity. Polypodiaceae.

Comparisons. *Polypodiaceoisporites pseudopsilatus* Lorente 1986 has a cingulum of 2–3 μm thickness, a thinner labrum (2 μm wide) and a psilate cingulum. *Psilatriletes lobatus* Hoorn 1994b has a psilate ornamentation and a wider cingulum at the interradian region.

Angiosperms

Monocolpatae Iversen and Troels-Smith 1950

Mauritiidites Van Hoeken-Klinkenberg 1964

Mauritiidites franciscoi var. *franciscoi* (Van der Hammen 1956a) Van Hoeken-Klinkenberg 1964
(Fig. 5.10)

Material examined. B17; 27N/2.

Description. Monad, anisopolar, elliptical, monocolpate, monosulcate, sulcus simple intectate, exine 1–2 μm thick; echinate ornamentation, spines 2–4 μm height and 1–2 μm wide, conical.

Dimensions. Equatorial length 41.5 μm , equatorial width 34.5 μm .

Stratigraphic range. Paleocene to Pleistocene (Muller et al. 1987).

Taxonomic affinity. *Mauritia*—Arecaceae (Hoorn 1993).

Comparisons. *Mauritiidites franciscoi* var. *minutes* Van der Hammen and Garcia 1966 is smaller and also has shorter spines (0.5–1 μm height).

Triporatae Iversen and Troels-Smith 1950

Corsinipollenites Nakoman 1965

Corsinipollenites sp. 01
(Fig. 5.11)

Material examined. B17; EF: 17G.

Description. Monad, radially symmetric, anisopolar, elliptical; triporate, ecto and endospore coinciding, pore circular, 4.6 μm diameter; costate, costae 2 μm wide, annulus 4–5 μm wide; scabrate ornamentation, exine 1.5 μm thick and it thickens to 2.5–3 toward the pores.

Dimensions. Equatorial length 44 μm , equatorial width 38 μm .

Taxonomic affinity. Onagraceae—*Ludwigia*.

Comparisons. *Corsinipollenites scabratus* Silva-Caminha et al. 2010 has a distinct Y mark in one of the poles. *Corsinipollenites psilatus* Jaramillo and Dilcher 2001 is psilate. *Corsinipollenites oculusnoctis* (Thiegart 1940) Nakoman 1965 has also a Y mark and a thinner annulus (2–3 μm).

Tricolporatae Iversen and Troels-Smith 1950

Psilatricolporites (Van der Hammen 1956a) Van der Hammen and Wymstra 1964

Psilatricolporites sp. 01
(Fig. 5.12)

Material examined. B17; EF: 35Q/4.

Description. Monad, radially symmetric, isopolar, elliptical, tricolporate, distinct colpi and pores; costate, costae 1 μm thick, exine 1.4 μm thick.

Dimensions. Equatorial length 11.3 μm , equatorial width 10.4 μm .

Taxonomic affinity. Caesalpinoideae.

Comparisons. *Psilatricolporites costatus* Dueñas 1980 has a distinct columella and a larger equatorial length (18–24 μm).

Retitricolporites Van der Hammen and Wymstra 1964.

Retitricolporites sp. 01
(Fig. 5.13)

Material examined. B17; EF: 22Q.

Description. Monad, radially symmetric, isopolar, elliptical, tricolporate, distinct colpi, ectocolpi costate, reticulate ornamentation, lumina 0.4 μm , muri 0.3 μm wide, exine 1 μm thick.

Dimensions. Polar length 15.3 μm , polar width 11.5 μm .

Taxonomic affinity. Papilionoideae.

Comparisons. *Striatricolporites poloreticulatus* Silva-Caminha et al. 2010 has a striate to reticulate ornamentation and a larger size (23 to 28 μm).

Retibrevitricolporites Legoux 1978

Retibrevitricolporites sp. 01

(Figs. 5.14, 5.15)

Material examined. B17; EF: 21T/1.

Description. Monad, radially symmetric, isopolar, triangular-obtuse-convex, tricolporate, colpi short, exine thickens toward the colpi and pore margins, costate, costae 2 µm thick; nexine 1.2 µm thick, sexine 1 µm, reticulate ornamentation, lumina 0.8 µm wide, muri 0.7 µm wide.

Dimensions. Equatorial length 27.2 µm, equatorial width 25 µm.

Taxonomic affinity. Papilionoideae.

Comparisons. *Syncolporites poricostatus* Van Hoeken-Klinkenberg 1966 is parasyncolporate and has a smaller equatorial length and width (16 and 12 µm, respectively). *Retibrevitricolporites triangulatus* Van Hoeken-Klinkenberg 1966 has a larger lumina and muri (1.5 µm wide).

Retibrevitricolporites sp. 02

(Figs. 6.1, 6.2)

Material examined. B17; 28G.

Description. Monad, radially symmetric, isopolar, elliptical, tricolporate, colpi short, distinct colpi and pores; ectocolpi costate, costae 3 µm thick, distinct; nexine 1.3 µm thick, sexine 1.6 µm thick, elliptical pore with 7×3 µm; collumellate, collumelae 0.9 µm; reticulate ornamentation, lumina 0.8 µm wide, muri 0.7 µm wide.

Dimensions. Equatorial length 36 µm, equatorial width 31 µm.

Taxonomic affinity. Caesalpinioideae.

Comparisons. *Retibrevitricolporites yavarensis* (Hoorn 1993) Silva-Caminha et al. 2010 has a smaller equatorial length and width (20 µm), lumina and muri (0.5 µm wide).

Zonocostites Gemeraad et al. 1968

Zonocostites ramonae Gemeraad et al. 1968

(Figs. 6.3, 6.4)

Material examined. B17; EF: 14Y/1.

Description. Monad, radially symmetric, isopolar, elliptical in equatorial view, tricolporate, distinct pores and colpi, zonorate, costate, costae 1.5 µm thick, pore 1.8 µm diameter, reticulate ornamentation, muri 0.8 µm wide, lumina 1 µm wide, exine 1.8 µm thick.

Stratigraphic range. Lower–Upper Eocene to Recent (Gemeraad et al. 1968; Muller et al. 1987).

Dimensions. Polar length 28 µm, polar width 25 µm.

Taxonomic affinity. *Rhizophora mangle* L.

Comparisons. *Zonocostites minor* (Jaramillo and Dilcher 2001) has smaller dimensions and is micropitted. *Zonocostites duei* Dueñas 1980 has distinct collumelae.

Zonocostites minor Jaramillo and Dilcher 2001

(Figs. 6.5, 6.6)

Material examined. B17; EF: 14 W/1.

Description. Monad, radially symmetric, isopolar, elliptical in equatorial view, tricolporate, distinct pores and colpi, pore diameter 0.5–0.6 µm, zonorate, costate, costae 0.5–0.7 µm thick, exine 0.8–1 µm thick, slightly reticulate to micropitted ornamentation.

Stratigraphic range. Lower–Upper Eocene to Recent (Gemeraad et al. 1968; Muller et al. 1987).

Dimensions. Equatorial diameter 12–14 µm, polar diameter 11–12 µm.

Taxonomic affinity. Mangrove.

Comparisons. *Zonocostites ramonae* Gemeraad et al. 1968 has similar features but is of larger size (26–19 µm) and has a reticulate ornamentation.

Retistephanocolporites Van der Hammen and Wymstra 1964

Stephanocolporate Iversen and Troels-Smith 1950

Retistephanocolporites sp. 01

(Figs. 6.7, 6.8)

Material examined. B17; EF: 27K.

Description. Monad, radially symmetric, isopolar, circular, stephanocolporate (6 colpi and pores), distinct pores and colpi, colpi short, costate, costae 1.4 µm thick, pore 3.2 µm diameter; exine 4 µm thick; slightly reticulate ornamentation.

Dimensions. Total diameter 28 µm.

Taxonomic affinity. *Diacidia*—Malpighiaceae.

Systematic paleontology

Crustacea

Decapoda Latreille 1802

Callianassoidae Dana 1852

Neocallichirus Sakai 1988

Neocallichirus sp.

(Fig. 7.1)

Material examined. MPEG-2340-I (4/4). Propodi.

Occurrence. The specimens were collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

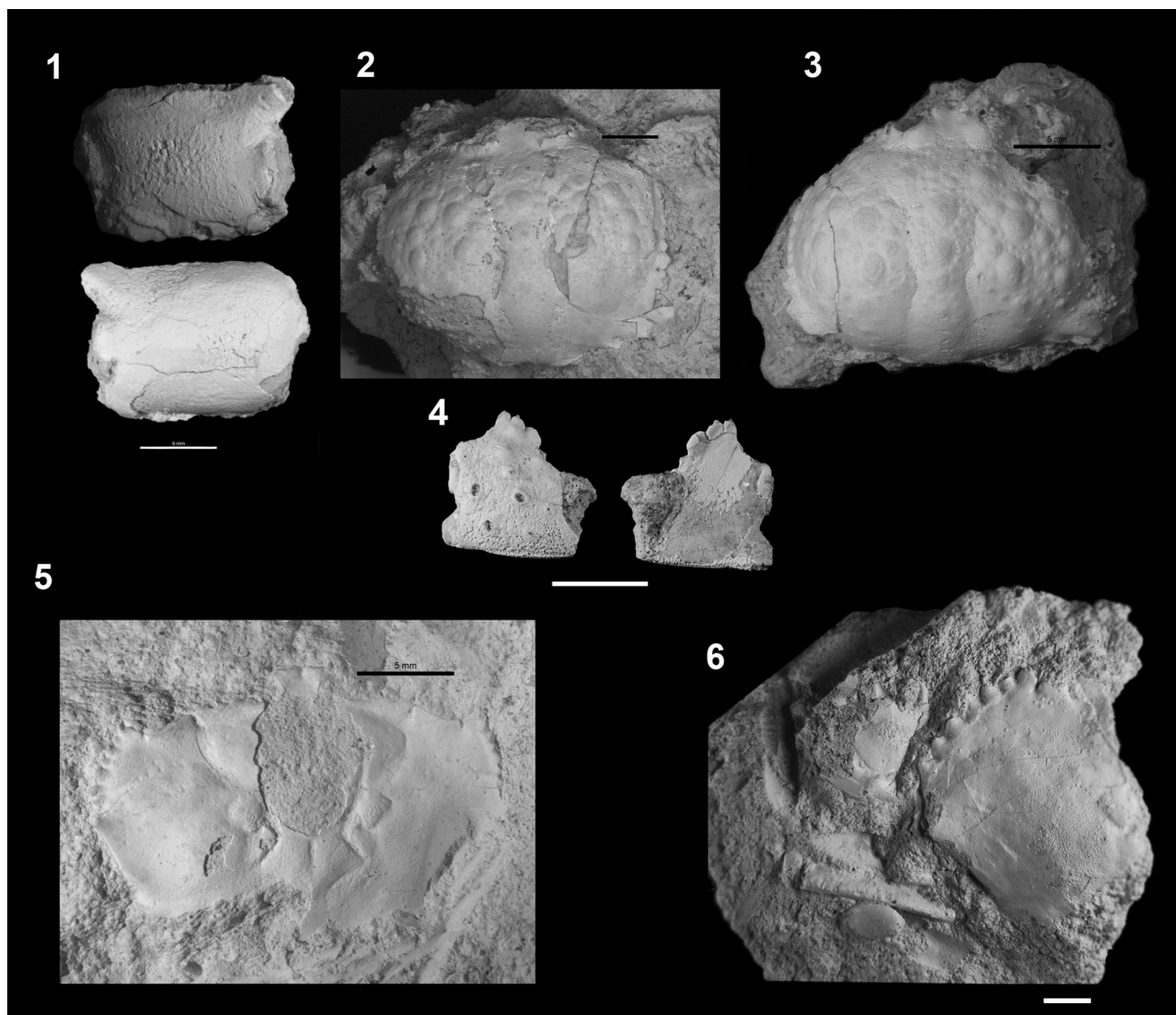


Fig. 7 Crustacean Decapods. 1 *Neocallichirus* sp. MPEG-2340-I, propodi, outer and inner view; 2,3 *Calappila circularis*, MPEG-2337-I, MPEG-2338-I, carapaces, dorsal view; 4 *Calappila* sp. MPEG-

2339-I, chela, outer and inner view; 5 *Euphylax septendentatus*, MPEG-2333-I, carapace, dorsal view; 6 *Necronectes* sp., MPEG-2331-I, carapace, dorsal view

Description. Manus rectangular, slightly highest proximally, both margins slightly serrated, bulbous, swelling; fixed finger stronger and broken, proximal section gently curved dorsally, movable finger unpreserved.

Calappidae Milne Edwards 1873

Calappila Milne Edwards 1873

Calappila circularis (Beurlen 1958) Martins-Neto 2001 (Figs. 7.2–7.3)

Material examined. MPEG-2337-I, MPEG-2338-I. Carapace.

Occurrence. The specimens were collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

Description. Carapace ovoid, widest at about midlength; anterolateral margin smooth, lacking prominent lateral spine, posterolateral margin with progressively well-developed spines developed on flares extension; surface coarsely nodose; nodes and grooves define carapace regions.

Calappila sp.
(Fig. 7.4)

Material examined. MPEG-2339-I. Left chela.

Occurrence. The specimen was collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

Description. Palm highest distally with almost three preserved spines and one broken in the dorsal border; external surface coarsely nodose; movable finger unpreserved.

Portunidae Rafinesque 1815

Euphylax Stimpson 1860

Euphylax septendentatus Beurlen 1958

(Fig. 7.5)

Material examined. MPEG-2333-I, MPEG-2334-I. Carapace.

Occurrence. The specimen was collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

Description. Carapace hexagonal, wider than long, length about two-thirds the maximum width, widest at about half the distance posteriorly; front T-shaped, often with sharp central spine; fronto-orbital width about 80 % maximum carapace width; orbit with granular rim, sometimes with two closed fissures positioned near the distal end, sometimes with concave reentrant near the outer-orbital angle to embrace eye; anterolateral margin usually with three to five spines including outer-orbital spine; transverse ridge extending from last anterolateral spine axially on dorsal carapace; transverse ridges often on protogastric and hepatic regions.

Necronectes Milne Edwards 1881

Necronectes sp.

(Fig. 7.6)

Material examined. MPEG-2331-I, MPEG-2332-I. Carapace.

Occurrence. The specimen was collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

Description. Carapace wider than long; axial regions generally well developed; dorsal surface covered with very fine granules; protogastric region defined by two circular swellings; mesogastric region broad posteriorly, narrowing anteriorly, well defined by grooves posteriorly and laterally, poorly defined anteriorly; cardiac region circular, elevated. Frontal margin with six spines including inner-orbital spine; spines small, blunt tipped. Anterolateral margin generally longer than posterolateral margin; eight spines on anterolateral margin including outer-orbital spine; spines increasing in size posteriorly except for eighth spine which is generally smaller than adjacent spine; spines triangular, with pointed tips; moving posteriorly spines become increasingly curved anteriorly. The ventral surface from the examined specimen is included in the matrix.

Portunus Weber 1795

Portunus haitiensis Rathbun 1924

(Figs. 8.1, 8.5)

Material examined. MPEG-2323-I to MPEG-2328-I, MPEG 2352-I, MPEG 2354-I. Carapace.

Occurrence. The specimens were collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

Description. Carapace much wider than long; carapace regions moderately developed; frontal and anterolateral spines are unpreserved in all specimens collected; abdomen enlarged, with somites 3–5 fused; the second abdominal is pentagonal.

Portunus pirabensis Martins-Neto 2001

(Figs. 8.6, 8.7)

Material examined. MPEG-2329-I, MPEG-2330-I, MPEG 2353-I. Carapace.

Occurrence. The specimens were collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

Description. Carapace much wider than long; carapace regions moderately developed; frontal and anterolateral spines are unpreserved in all specimens collected; abdomen enlarged, with somites 3–5 fused; the second abdominal is trapezoidal, with the posterior margin circa one and half times longer than the anterior margin.

Scylla Haan 1833

Scylla aff. *costata* (Rathbun 1924) Beurlen 1958

(Fig. 8.8)

Material examined. MPEG-2351-I. Carapace.

Occurrence. The specimen was collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

Description. Carapace about twice as wide as long, ovate, maximum width just over half the distance posteriorly; regions poorly defined, carapace smooth; front spines unpreserved in the examined specimen; anterolateral margins with nine spines including outer-orbital spines, last spine longest; gastric grooves strong. The ventral surface from the examined specimen is included in the matrix.

Portunidae, genera and species indeterminate
(Figs. 8.9, 8.12)

Material examined. MPEG-2341-I to MPEG-2350-I. Chela.

Occurrence. The specimens were collected from the Early Miocene Pirabas Formation, Capanema Mine B17 (1°10'S, 47°13'W).

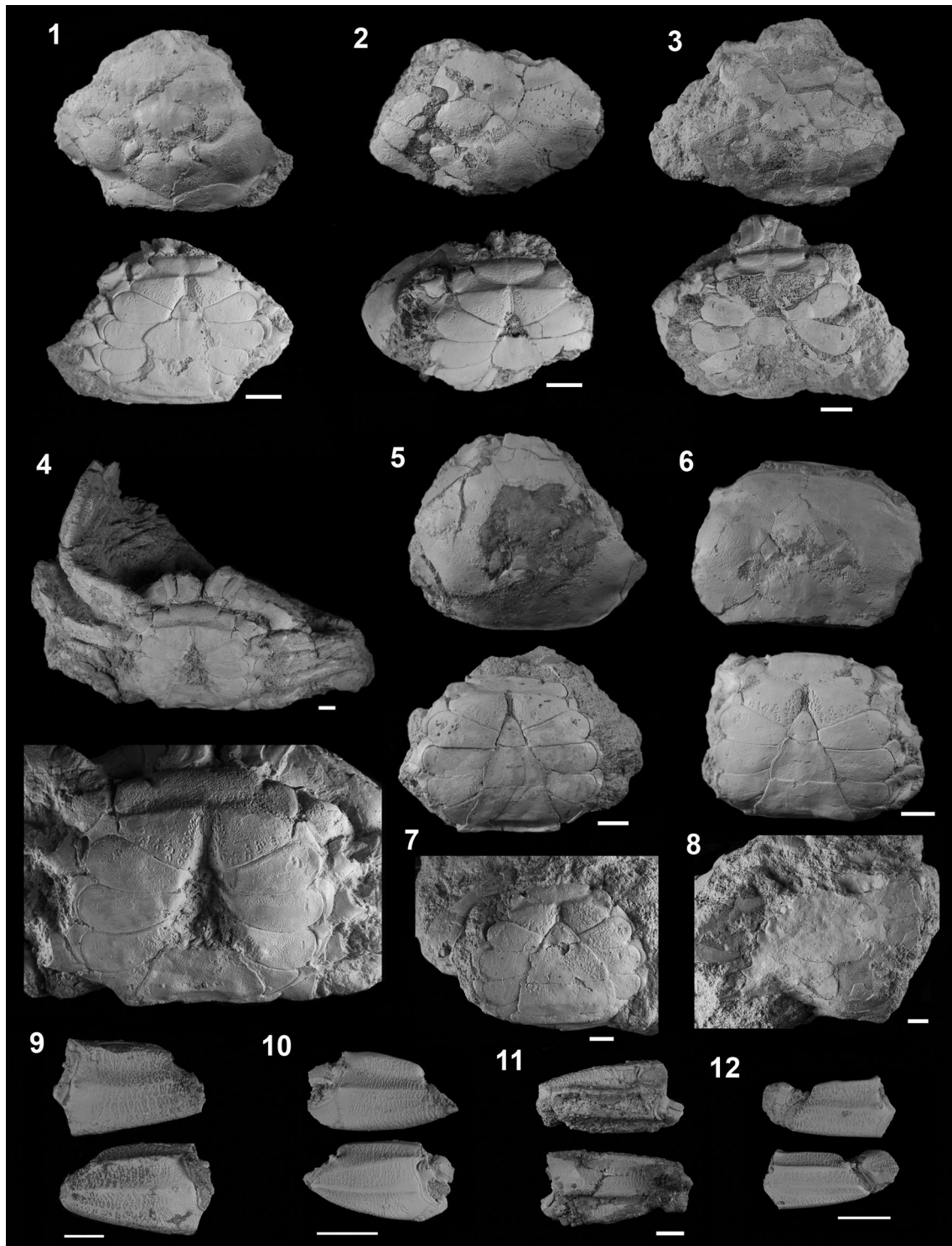


Fig. 8 Crustaceans Decapods. 1–5, *Portunus haitiensis*, MPEG-2323-I to MPEG-2327-I, carapace, dorsal and ventral view (except 4 only ventral view and enlarge details); 6, 7, *Portunus pirabensis*,

MPEG-2329-I, MPEG-2330-I, carapace, ventral view; 8, *Scylla* aff. *costata*, MPEG-2351-I, carapace, dorsal view; 9–12, Portunidae, chelas, outer and inner surface. Scale bar 10 mm

Description. Chelipeds massive, with very weak keels on outer surface palm, sometimes with two distal spines on upper margin; surface with anastomosed reticulations.

Type species of Crustacean Decapods from the Pirabas Formation, Pará state, Brazil.

†*Calappilia circularis* Beurlen 1958. MN-4619-I. Loc. Salinópolis e Ponta da Fazenda. (Schweitzer et al. 2009: 23 extinct species are included in this genus).

†*Sesarma paraensis* Beurlen 1958. DNPM? (Without catalog data). Loc. Colônia Pedro Teixeira (Schweitzer et al. 2009: 2 extinct species).

†*Parthenope trituberculata* Beurlen 1958. DNPM-4459. Loc. Colônia Pedro Teixeira (Schweitzer et al. 2009: 13 extinct species).

†*Callinectes paraensis* Beurlen 1958. MN-4585-I. Loc. Colônia Pedro Teixeira (Schweitzer et al. 2009: 8 extinct species).

†*Euphyllax septendentatus* Beurlen 1958. DNPM-4457. Loc. Rio do peixe Boi, Capanema (Schweitzer et al. 2009: 6 extinct species).

†*Hepatella amazonica* Beurlen 1958. DNPM-4458. Loc. Colônia Pedro Teixeira (Schweitzer et al. 2009: monospecific).

†*Cyclocancer tuberculata* Beurlen 1958. MN-4617-I. Loc. Colônia Pedro Teixeira e ilha de Fortaleza (Schweitzer et al. 2009: monospecific).

†*Typilobus unispinatus* Martins-Neto 2001. DNPM?. Without catalog data. Loc. Ponta da Fazenda (Schweitzer et al. 2009: 17 extinct species and 10 species are dubious).

†*Portunus pirabaensis* Martins-Neto 2001. MN-5402, MN5400, MN5401. Loc. Colônia Pedro Teixeira (Schweitzer et al. 2009: 48 extinct species).

†*Paratumidocarcinus marajoarus* Martins-Neto 2001. RGMN-T06. Loc. Colônia Pedro Teixeira. (Schweitzer et al. 2009: monospecific).

†*Panopeus capanemaensis* Martins-Neto 2001. MN-5012-I. Loc. Rio Japerica, Primavera (Schweitzer et al. 2009: 22 extinct species).

†*Uca inaciobrito* Martins-Neto 2001. MN-5014-I, MN-5015-I, UFRJ- IG-242, 264, 265. Loc. Furo de Baunilha Grande (Schweitzer et al. 2009: 10 extinct species).

Discussion

Faunal assemblage interpretation

Callianassidae are burrowers, constructing lengthy domicile galleries in nearshore or intertidal sediments (Manning and Felder 1991; Aguilera et al. 2010). *Neocallichirus*, common in the Mine B17, inhabited a paleoenvironment characterized by shallow waters, soft bottom and sandy

shorelines in intertidal or shallow subtidal rear-shore habitats. The most abundant bioturbation causes in the field are those generated by burrows of *Neocallichirus*.

†*Calappilia* (an extinct, speciose genus within the Calappidae) and its inferred paleoenvironment is based on comparison with the extant genera *Calappa* and interpreted as shallow water over coral reefs, shelly, sandy or muddy substrate (Bellwood 1998; Aguilera et al. 2010).

Portunidae are swimmers and back-burrow crabs. This ‘family’ forms a monophyletic group, and their first occurrence in the Eocene is followed by major Miocene radiation (Karasawa et al. 2008). The occurrence of portunids in the stratigraphic section of the Capanema Mine B17 includes *Euphyllax*, †*Necronectes*, *Portunus* and *Scylla*, whose ecology is in agreement with the facies interpretation treated here and other fossil portunid records in the tropical Americas (Aguilera et al. 2010). These genera are associated with shallow waters and neritic coastal paleoenvironments over sandy and soft bottom, beaches, estuaries, and in marginal lagoons with sea grass and mangrove protected area.

Euphyllax is known primarily from the Miocene, when the genus was apparently most speciose in the Caribbean and Central America (Nyborg et al. 2003; Schweitzer et al. 2006). Fossil species of *Necronectes* (an extinct genus within the Portuninae) are known from the Oligocene and Miocene along the east coast of North America, Central America, Caribbean islands, South America and from Tethyan Europe (Schweitzer et al. 2006). *Scylla* appeared during the late Oligocene or early Miocene and its occurrences in circumtropical and equatorial regions during Miocene is a relict of a once broader distribution (Schweitzer et al. 2006).

The status of several other specimens of Portunidae remains that of unidentified species, because they are based solely on fragmented carapaces or isolated chelipeds.

Paleoenvironmental interpretation

Aguilera and Páes (2012) distinguished the Capanema B17 Mine faunal assemblage from other four outcrops of the Pirabas Formation in the vicinity (Ilha de Fortaleza, Estação Agronômica, Aricuru, and Colônia Pedro Teixeira) based on the PCA analysis. Their observation is corroborated by the facies analysis previously developed by Petri (1957) as ecofacie Caneco (=Capanema) for “littoral coastal marine to transitional basin border, reaching 10 m deep”, a frequently cited facies name in literature (e.g., Távora et al. 2007). The sedimentary system in the Capanema Mine B17 section treated here is interpreted as a transitional tidal platform with infaunal and epifaunal invertebrate richness associated with a high calcareous

algal productivity (photic zone), as indicated by the presence of portunids (blue crabs) and Calappidae (box crabs) and their preference for shallow water littoral to tidal influence and marginal coastal lagoons under brackish paleoenvironment.

The lagoonal strata along the section studied show a thickness similar to deposits of the tidal flat with mangrove vegetation. The mangrove vegetation, with strong marine influence as indicated by high amounts of foraminifera, remained relatively stable in the tidal flats area over time during the evolution of this environment. However, the increase of species diversity from freshwater forests, low-land pteridophytes and freshwater algae, coupled with decrease in foraminifera diversity in the upper tidal flat deposit is interpreted as an indication of a slight increase of precipitation rates and freshwater inflow.

Divergent paleoenvironmental conclusions were brought forward by previous researchers as open continental shelf with shallow tropical water, moderate- to high-energy flow and a wave-dominated estuarine environment (Góes et al. 1990; Rossetti and Góes 2004) and extensive lagoon system (Távora et al. 2007). However, the successions suggest more heterogeneity of laterally coexisting environments in a coastal depositional system (Walker 1992) and attempts to honor all faunal, floral and sedimentological data observed. The majority of Oligocene–Miocene Caribbean decapods suggest that they preferred clastic bottom, with a variety of settings, including sea grass mud plains, calcareous detrital environments, siliciclastic ramps, deltas and quiet lagoons (Schweitzer et al. 2006).

Paleogeographic interpretation

During the early Miocene, extensive carbonate platforms were present along the continental margin in the eastern Amazon, northern Brazil, represented in the Pirabas Formation, characterized by diverse and abundant marine fauna, closely related to similar assemblages known from the Oligocene–Miocene carbonate deposit of the Caribbean.

When the Andes cordillera progressively uplifted from the late Oligocene through the late Miocene, the modern South American hydrographic basins were established, and the Amazon River began shifting its drainage and sediment input to the Atlantic coast (e.g., Hoorn et al. 2010). This resulted in a drastic reduction of carbonate deposition and establishment of clastic dominated environments influenced by the continuous water currents from the eastern Amazon and eastern Caribbean along the marine coastal environments where the Amazon–Orinoco deltas discharged freshwater flow and great quantities of siliclastics into the sea. The geological and oceanographic barrier, established since the late early Miocene until today, results

in marine biota of the area to be poorly connected with Caribbean biota proper. Based on the observed fossil record, the Neogene tropical western central Atlantic paleobiogeographic sub-province was erected (Aguilera et al. 2011; Aguilera and Páes 2012) and the Brazilian biogeographic province was established separately based on extant faunal distribution (e.g., Pérez-Ruzafa et al. 2012).

Conclusion

The integration of facies, pollen and spores, and crustacean decapod data led to the identification of a carbonate/siliciclastic transitional depositional sedimentary system with lagoon, tidal flat, flood-tidal delta and foreshore environments. The tidal flats were predominantly colonized by mangrove species such as *Zonocostites ramonae*, *Zonocostites minor* and *Deltoidospora adriennis*. Crustacean decapods of *Euphyllax*, †*Necronectes*, *Portunus* and *Scylla* genera were abundant in the foreshore environment, and are also indicative of the presence of shallow water and marginal lagoons with mangrove protected areas. The formation of these extensive carbonate environments is thought to be related to the lack of large continental drainage systems such as the Amazon River basin.

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