

Neogene Eastern Amazon carbonate platform and the palaeoenvironmental interpretation

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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, palaeocarcinological and sedimentary facies, in order 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. Eighteen palynomorph species were identified in the tidal flat deposits including 1 alga, 3 fungi, 5 pteridophytes, and 9 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 1 Callinassoidae, 2 Calappidae, and 6 Portunidae, represented by *Euphyllax*, †*Necronectes*, *Portunus*, and *Scylla*, the ecology

of which is associated with beaches of marginal lagoons. The main factor of 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 palaeodischarges from incipient river systems along the Amazon coast.

Keywords Amazon · Carbonate · Pirabas · Palaeoenvironmental · Palynology · Crustacea

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

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currents driven by oceanic currents, a macrotidal regime (AzeBeardsley et al. 1995) and wave processes. In addition, 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 palaeovegetation of the Pirabas Formation is marked by the predominance of *Zonocostites ramonae* (Germeraad 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 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 palaeoenvironmental study.

Early contributions of White (1887) and Maury (1925), particularly on mollusk, bryozoan and coral research, and Petri (1954, 1957) about foraminifera, Beurlen (1958), Brito (1971, 1972, 1977) and Martins-Neto (2001) about crustaceans, Santos (1958, 1967) about echinoids, Santos and Travassos (1960) and Santos and Salgado (1971) about fishes, Paula-Couto (1967), Toledo (1989), and Toledo and Domning (1989) about sirenians, and Lalor and Távora (2006) about 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, palaeocarcinology and facies research for the interpretation of the palaeoenvironment.

Geological setting

The Bragantina platform (North Brazil, Pará) corresponds to emerged and submerged areas, which were stable during episodes of distentional tectonics following the break-up of Gondwana and the opening of the Equatorial Atlantic during Jurassic and Lower Cretaceous (Sztamari 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 trough

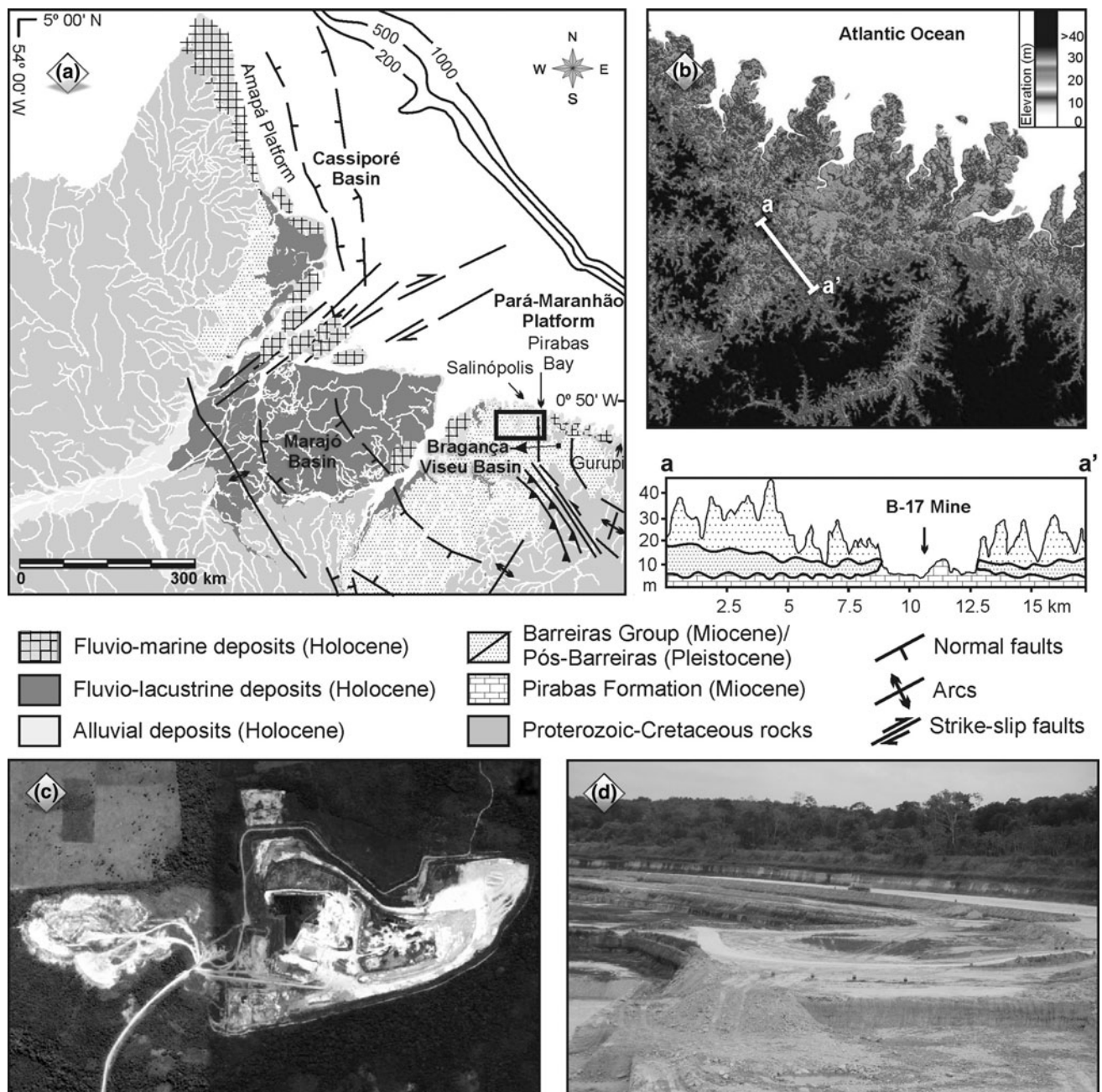


Fig. 1 Location map. **a** Regional geology. **b** Digital elevation model of the northern coast of the Pará state. **c** Aerial view (modified from Google earth) and **d** panoramic view of the B17 mine

The assignment of an 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 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

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)		
	MIDDLE middle/upper Barreiras Fm.	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
	unconformity 2		
	EARLY 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
LATE OLIGOCENE	Pirabas Fm.		
	unconformity 1 (lateritic/bauxitic soil)		
CRETACEOUS	Itapecuru Group		

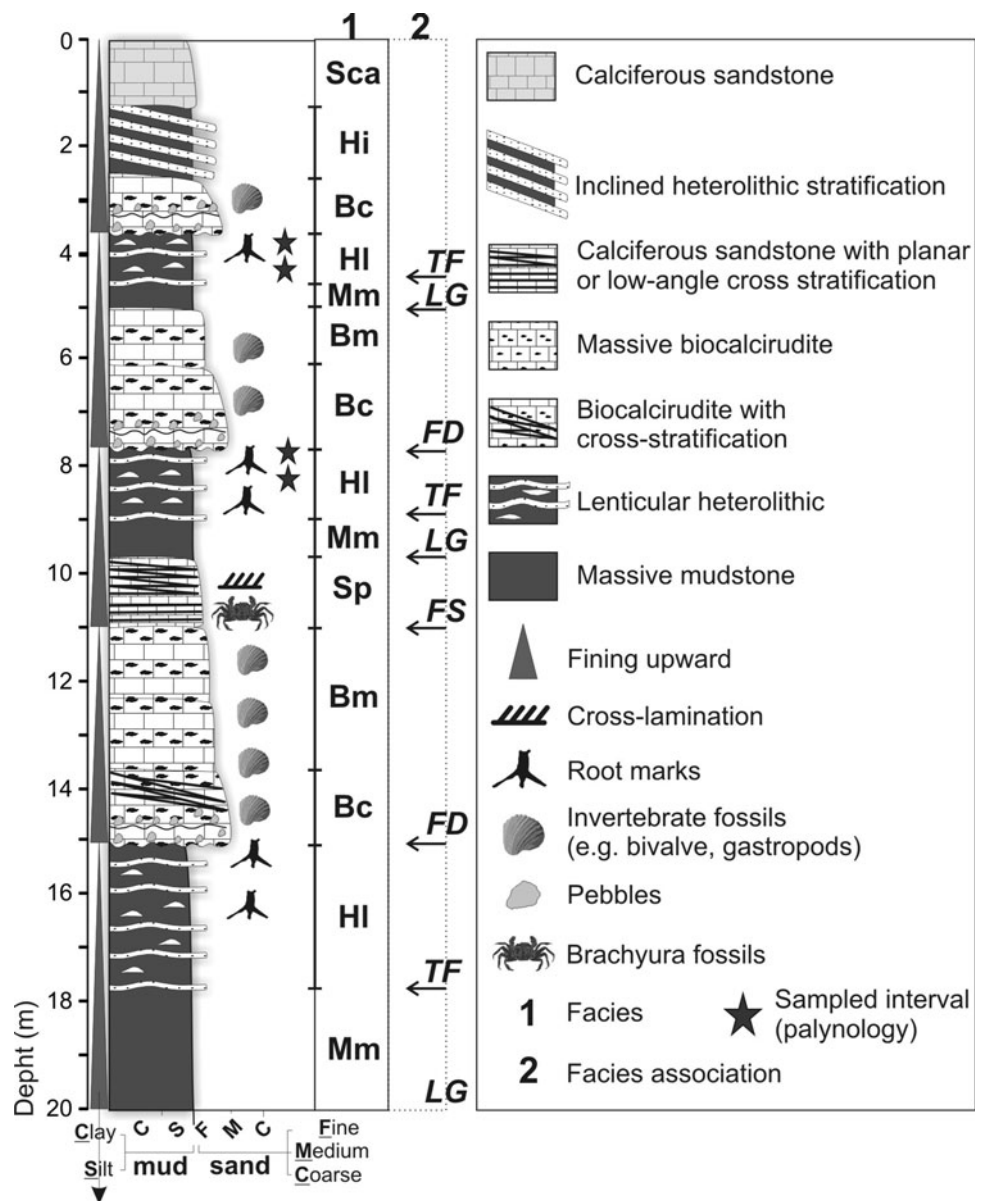
Walker (1992), and were codified according to Miall (1978).

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 samples were dried, weighed, triturated, submitted to hydrochloric and hydrofluoric acid for carbonate and silicate removal, sieving with a 10- μ m mesh, and mounting 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., 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 collections 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. Complimentary data were retrieved from published literature (e.g., Beurlen 1958; Brito 1971, 1972, 1993; Martins-Neto 2001, 2005, 2007; Vega et al. 2009; Schweitzer et al. 2006). The classification follows De Grave

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



sandstones, stratified biocalcirudites and levels with conglomerates. Invertebrates, pollen and spore records were added to facies characteristics in order 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 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), and is overlain by inclined sandstone and mudstone (facies Hi) and facies HI. These facies are related to a tidal regime with deposition of mud from suspension and sand from the ebb and

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 in 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 sandwaves 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

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 %), *Mauritiidites franciscoi* var. *franciscoi* (0–3 %) showed lower percentages, but it 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 as

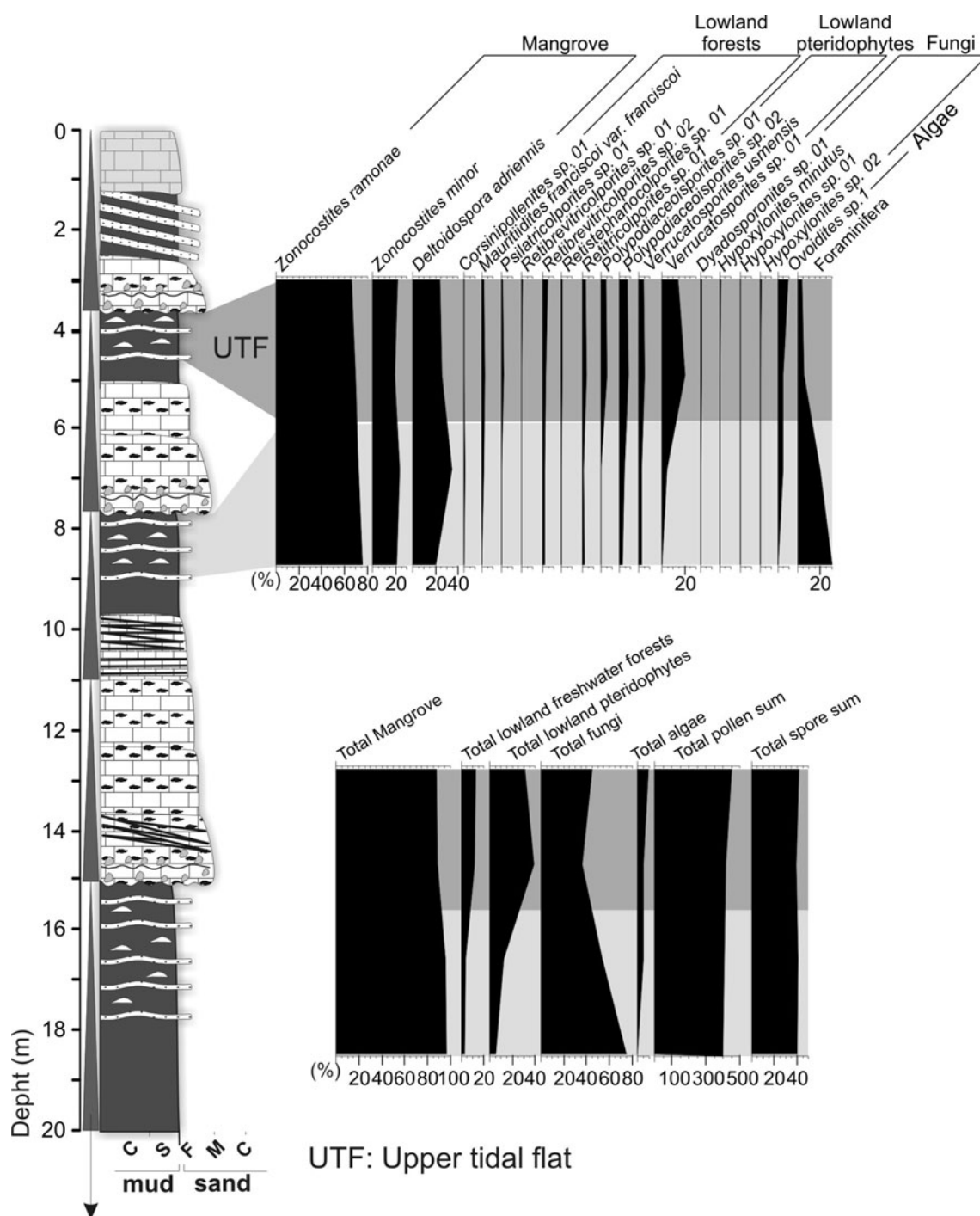


Fig. 4 Integrated stratigraphic section, pollen and spore record

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

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

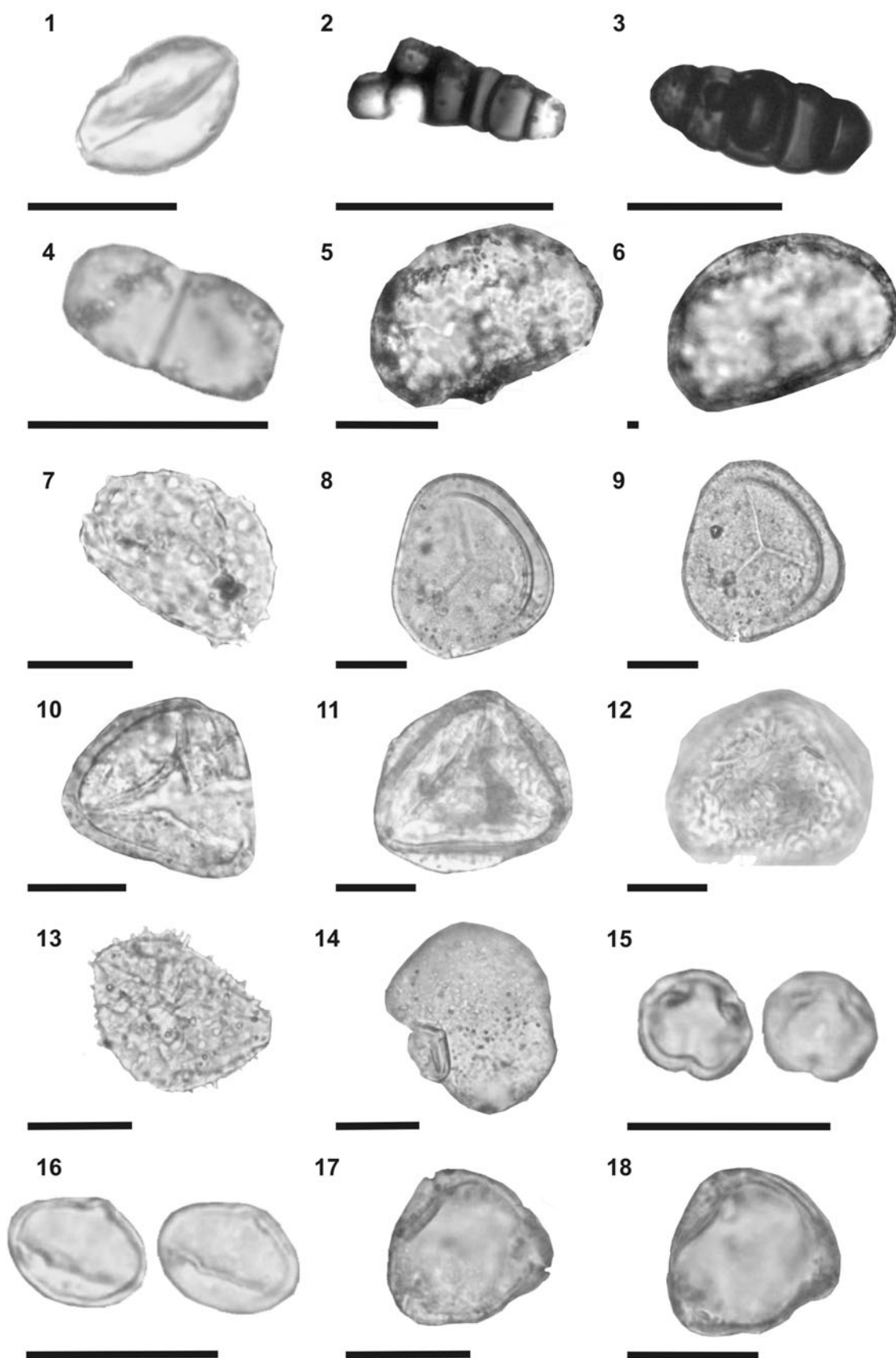
Fungi

Group Amerosporae

Hypoxylonites Elsik 1990

Hypoxylonites minutus Elsik 1990

(Fig. 5.2)



◀**Fig. 5** Palynological specimens. 1, *Ovoidites Dyadosporites* sp. 01; 2, *Hypoxylonites minutus* Elsik 1990; 3, *Hypoxylonites* sp. 01; 4, *Verrucatosporites usmensis* (Van der Hammen 1956a) Germeraad et al. (1968). Proximal view, 5, *Verrucatosporites usmensis* (Van der Hammen 1956a) Germeraad et al. (1968). Distal view, 6, *Verrucatosporites* sp. 01; 7, *Deltoidospora adriennis* (Potonié and Gelletich 1933) Frederiksen et al. (1983). Distal view, 8, *Deltoidospora adriennis* (Potonié and Gelletich 1933) Frederiksen et al. (1983). Proximal view, 9, *Polypodiaceosporites* sp. 01; 10, *Polypodiaceosporites* sp. 02. Distal view, 11, *Polypodiaceosporites* sp. 02. Proximal view, 12, *Mauritiidites franciscoi* var. *franciscoi* (Van der Hammen 1956a) Van Hoeken-klinkenberg (1964); 13, *Corsinipollenites* sp. 01; 14, *Psilatricolporites* sp. 01; 15, *Retitricolporites* sp. 01; 16, *Retibrevitricolporites* sp. 01. Proximal view, 17, *Retibrevitricolporites* sp. 01. Distal view. Scale bar 20 µm

Material examined. B17; EF: 23F/3.

Description. Monocellate, aseptate, elliptical contour; aperturate, aperture does not reach the poles; rounded poles with one narrowly rounded end, psilate ornamentation.

Dimensions. Body size 18 × 12 µm.

Stratigraphic range. Eocene to Pleistocene (Elsik 1990).

Taxonomic affinity. *Hypoxylon*—Xylariaceae (Elsik 1990).

Comparisons. *Hypoxylonites elongatus* Salard-Chebouldaëff and Locquin 1980 has a spore wall that appears to have more than one layer. *Hypoxylonsporites miocenicus* Kumar 1990 has a longitudinal slit extending from one end to the other.

Hypoxylonites sp. 01

(Fig. 5.3)

Material examined. B17; EF: 24S/3.

Description. Monocellate, aseptate, elliptical contour; aperturate, aperture does not reach the poles, aperture 23-µm length; rounded poles with narrowly rounded ends, psilate ornamentation.

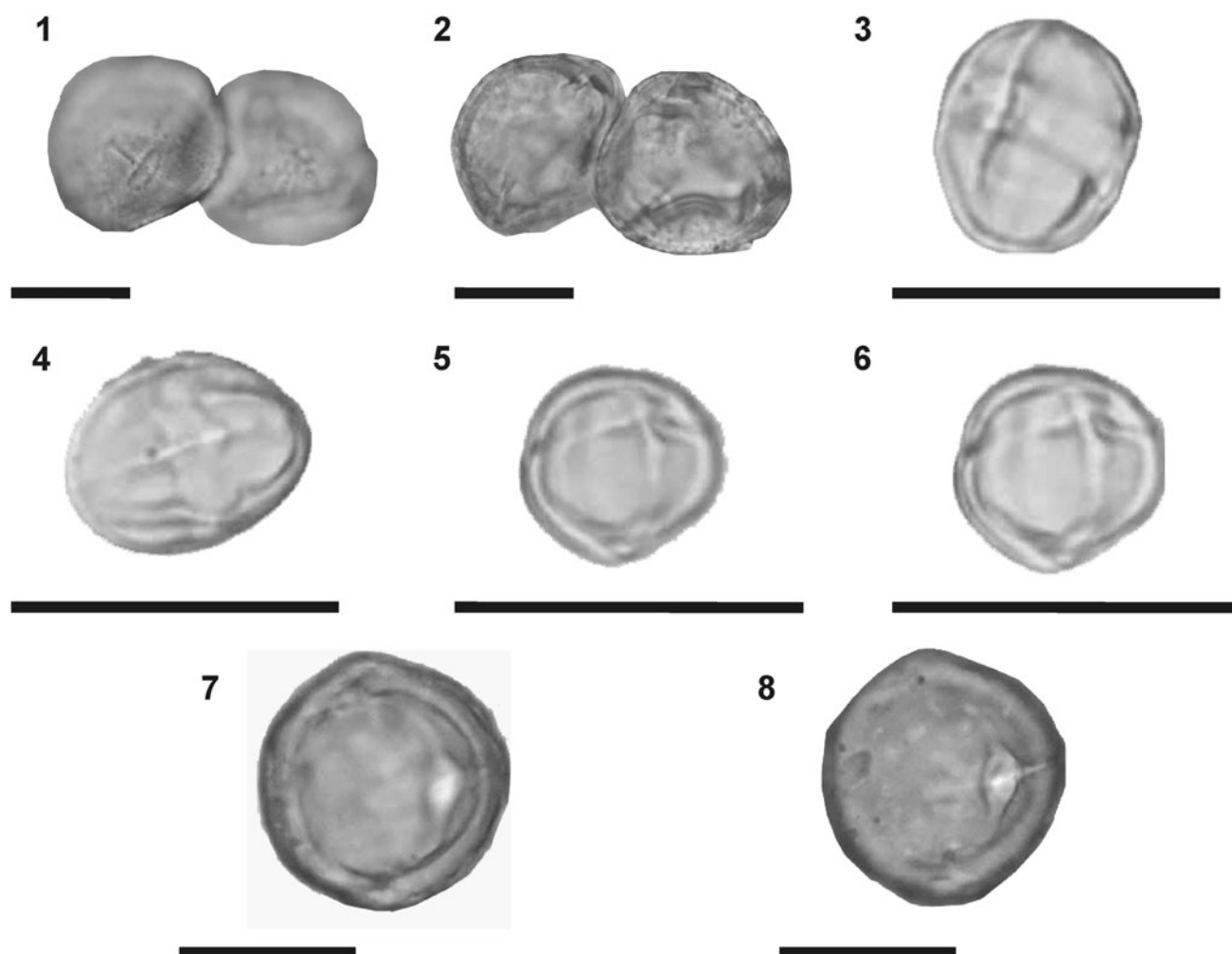


Fig. 6 Palynological specimens. 1 *Retibrevitricolporites* sp. 02. Proximal view, 2 *Retibrevitricolporites* sp. 02. Distal view, 3 *Zonocostites ramonae* Germeraad et al. (1968). Type 1, 4 *Zonocostites ramonae* Germeraad et al. (1968). Type 2, 5 *Zonocostites minor*

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. Scale bar 20 μm

commissure straight, exine 1.5- μm thick, psilate to micro-pitted 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. *Camarozonosporites* 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 perfectae* and psilate ornamentation over the entire spore grain. *Deltoidospora juncta* Singh (1964), is smaller (32–34 μm diameter).

Polypodiaceoisporites Potonie (1951) ex Potonié (1956)

Polypodiaceoisporites sp. 01

(Fig. 5.10)

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

Description. Tr

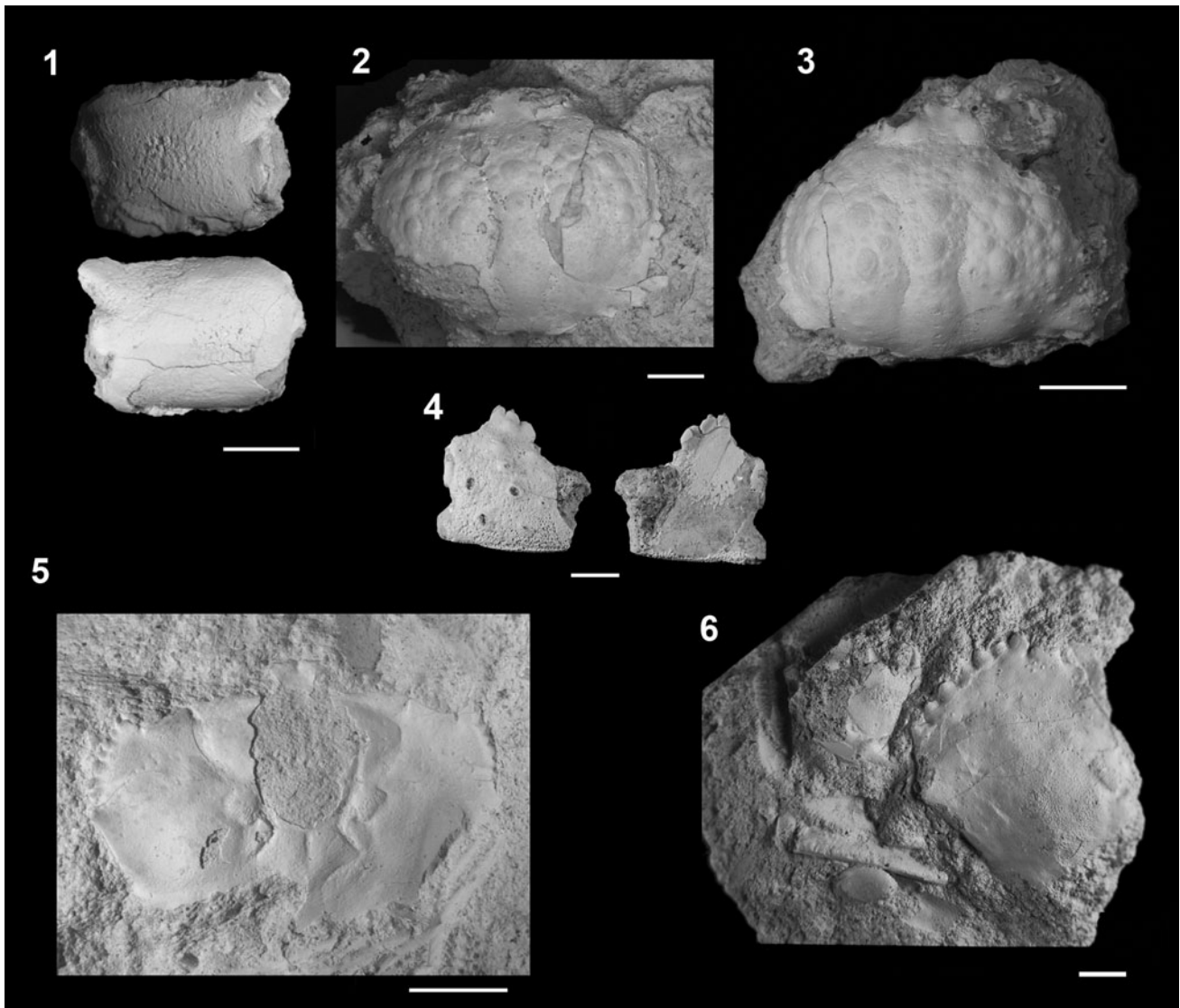


Fig. 7 Crustacean Decapods. 1 *Neocallichirus* sp. MPEG-2340-I, propodi, outer and inner view; 2, 3 *Calappila circularis*, MPEG-2337-I, MPEG-2338-I, carapaces, dorsal view; 4 *Calappila* sp. MPEG-2339-I, chela, outer and inner view; 5 *Euphylax septendentatus*,

MPEG-2333-I, carapace, dorsal view; 6 *Necronectes* sp., MPEG-2331-I, carapace, dorsal view. 1–5 Scale bar 5 mm; 6 Scale bar 10 mm

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 (196

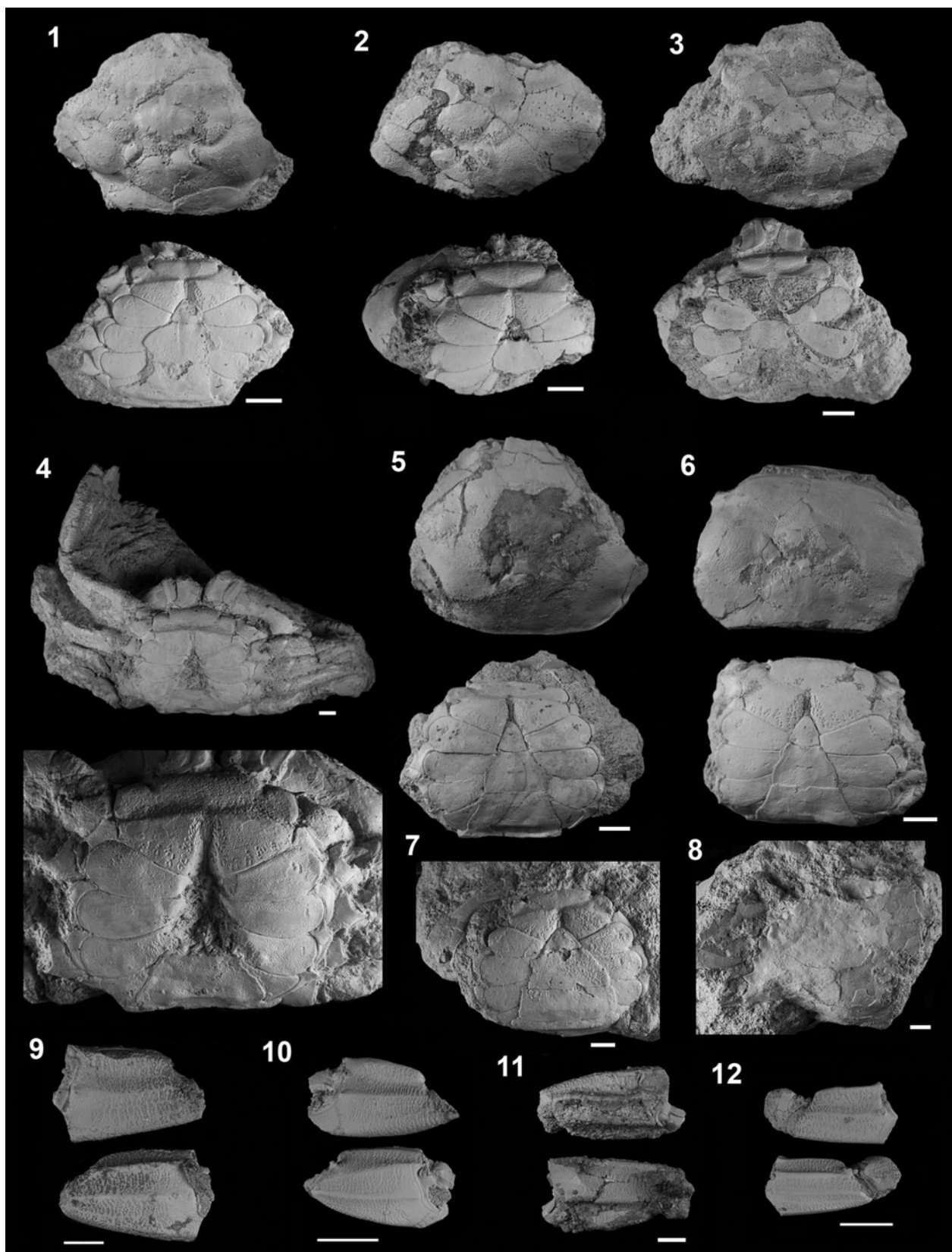


Fig. 8 Crustaceans Decapods. 1–5 *Portunus haitiensis*, MPEG-2323-I to MPEG-2327-I, carapace, dorsal and ventral view (except 4 only ventral view and enlarge details); 6, 7 *Portunus pirabensis*,

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

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. Palaeocene 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. 5.14)

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 towards 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 195

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 duquei* Dueñas (1980) has distinct collumelae.

Zonocostites minor Jaramillo and Dilcher (2001)
(Fig. 6.5, 6.6)

Material examined. B17; EF: 14W/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 (Germeraad et al. 1968; Muller et al. 1987).

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

Taxonomic affinity. Mangrove.

Comparisons. *Zonocostites ramonae* Germeraad 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)

Stephanocolporatae Iversen and Troels-Smith (1950)
Retistephanocolporites sp. 01
(Fig. 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 ornament

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)

(Fig. 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)

(Fig. 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 (18

†*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 palaeoenvironment 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 palaeoenvironment 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 palaeoenvironments 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 circum-tropical and equatorial regions during Miocene is a relict of a once broader distribution (Schweitzer et al

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 biotas of the area to be poorly connected with Caribbean biota proper. Based on the observed fossil record, the Neogene tropical western central Atlantic palaeobiogeographic 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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- Cookson, I. C., & Dettmann, M. E. (1959). On *Schizosporis*, a new form genus from Australian Cretaceous deposits. *Micropalaeontology*, 5(2), 213–216.
- Costa, J. B. S., Bemerguy, R. L., Hasui, Y., Borges, M. S., Ferreira, J. R. C. R. P., Bezerra, P. E. L., et al. (1996). Neotectônica da Região Amazônica: aspectos tectônicos, geomorfológicos e deposicionais. *Geonomos*, 4, 23–44.
- Dana, J. D. (1852). Macrourea. Conspectus Crustaceorum & Conspectus of the Crustacea of the Exploring Expedition under Capt. C. Wilkes, U.S.N. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 7, 175–177.
- De Grave, S., Pentcheff, N. D., Ah Yong, S. T., Chan, T.-Y., Crandall, K. A., Dworschak, P. C., et al. (2009). A classification of living and fossil genera of decapod Crustaceans. *Raffles Bulletin of Zoology*, 21, 1–109.
- de Haan, W. (1833–1850). Crustacea. In P. F. de Siebold (Ed.), *Fauna Japonica sive Descriptio Animalium, quae in Itinere per Japoniam, Jussu et Auspiciis Superiorum, qui Summum in India Batava Imperium Tenent, Suscepto, Annis 1823–1830 Collegit, Notis, Observationibus et Adumbrationibus Illustravit*. J. Muller et Co., Lugduni-Batavorum (¼ Leiden).
- Dettmann, M. E. (1963). Upper Mesozoic microforas from south-eastern Australia. *Proceedings of the Royal Society—Victoria*, 77, 1–148.
- Dueñas, H. (1980). Palynology of Oligocene–Miocene strata of borehole Q-E-22, Planeta Rica, northern Colombia. *Review of Palaeobotany and Palynology*, 10, 318–328.
- Elsik, W. C. (1990). Hypoxylonites and Spirotremesporites, form genera for Eocene to Pleistocene fungal spores bearing a single furrow. *Palaeontographica, Abteilung B*, 216, 137–169.
- Fernandes, J. M. G. (1984). Paleoeccologia da Formação Pirabas, Estado do Pará. *Anais do 33º Congresso Brasileiro de Geologia*, 1, 330–340.
- Fernandes, J. M. G., & Távora, V. A. (1990). Estudo dos Foraminíferos da Formação

- Kumar, P. (1990). Fungal Remains from the Miocene Quilon Beds of Kerala State, South India. *Review of Palaeobotany and Palynology*, 62, 13–28.
- Lalor, A. M., & Távora, V. (2006). Novos elementos da coralinafauna da formação Pirabas (Mioceno inferior), estado do Pará. *Geociências*, 25(2), 187–195.
- Latreille, P. A. (1802–1803). *Histoire naturelle, générale et particulière, des crustacés et des insectes*, vol. 3. F. DuFart, Paris.
- Legoux, O. (1978). Quelques espèces e pollen caractéristiques du Neogene du Nigeria. *Bulletin Centre Recherche. Exploration-Production Elf-Aquitaine*, 2(2), 265–317.
- Leite, F. P. R., Oliveira, M. E. B., Arai, M., & Truckenbrodt, W. (1997a). Palinostratigrafia da Formação Pirabas e Grupo Barreiras, Mioceno do nordeste do estado do Pará, Brasil. *Revista da Universidade de Guarulhos*, 2, 141–147.
- Leite, F. P. R., Oliveira, M. E. B., Oliveira, P. E., Silvestre-Capelato, M. S., Arai, M., & Truckenbrodt, W. (1997b). Palinofloras miocenas da Formação Pirabas e Grupo Barreiras, na Região Bragantina, Estado do Pará, Brasil. *Revista da Universidade de Guarulhos*, 2, 128–140.
- Lorente, M. A. (1986). *Palynology and palynofacies of the upper Tertiary in Venezuela. (Dissertationes Botanicae, vol 99)* (p. 222). Berlin-Stuttgart: Lubrecht & Cramer Ltd.
- Manning, R. B., & Felder, D. L. (1991). Revision of the American Callianassidae (Crustacea: Decapoda: Thalassinidea). *Proceedings of the Biological Society of Washington*, 104(4), 764–792.
- Martins-Neto, R. G. (2001). Review of some Crustacea (Isopoda and Decapoda) from Brazilian deposits (Paleozoic, Mesozoic and Cenozoic) with descriptions of new taxa. *Acta Geologica Leopoldensia*, 24(52/53), 237–254.
- Martins-Neto, R. G. (2005). Estágio atual da paleoartropodologia brasileira: hexápodes, miriápodes, crustáceos (isopoda, decapoda, Eucrustacea e Copepoda) e Quelicerados. *Arquivos*

- Salard-Chebouldaëff, M. (1990). Intertropical African palynostratigraphy from Cretaceous to Late quaternary times. *Journal of African Earth Sciences*, 11, 1–24.
- Salard-Chebouldaëff, M., & Locquin, M. V. (1980). Champignons présents au Tertiaire le long du littoral de l'Afrique équatoriale. *105e Congrès National des Sociétés savantes, Caen, 1980, Sciences, fascicule, 1*, 183–195.
- Santos, M. E. C. M. (1958). Equinóides miocênicos da Formação Pirabas. *Boletim da Divisão de Geologia e Mineralogia*, 179, 1–24.
- Santos, M. E. C. M. (1967). Equinóides miocênicos da Formação Pirabas. *Atas do 1o Simpósio sobre a Biota Amazônica, 1*, 407–410.
- Santos, A. S., Carvalho, M. A., Santos, T. M., & Freitas, A. G. (2005). Caracterização da flora de montanha Quaternária com base em estudos palinológicos da Bacia da foz do Amazonas, Brasil. *Arquivos do Museu Nacional*, 63, 425–436.
- Santos, D. B., Garcia, M. J., Saad, A. R., & Bistrichi, C. A. (2010). Palinostratigrafia da Formação Itaquaquecetuba, Bacia de São Paulo, Brasil. *Revista Brasileira de Paleontologia*, 13(3), 205–220.
- Santos, R. S., & Salgado, M. S. (1971). Contribuição à paleontologia do Estado do Pará. Novos restos de peixes da Formação Pirabas. *Boletim do Museu Paraense Emílio Goeldi*, 16, 1–13.
- Santos, R. S., & Travassos, S. (1960). Contribuição à paleontologia do Estado do Pará. Peixes fósseis da Formação Pirabas. *Divisão de Geologia e Mineralogia, Departamento Nacional da Produção Mineral*, 16, 1–35.
- Schweitzer, C. E., Feldmann, R. M., Garassino, A., Karasawa, H., & Schweigert, G. (2009). Systematic list of fossil Decapod Crustacean species. *Brill, Leiden, Crustaceana Monographs*, 10, 1–221.
- Schweitzer, C. E., Iturralde-Vinent, M., Hetler, J. L., & Velez-Juarbe, J. (2006). Oligocene and Miocene decapods (Thalassinidea and Brachyura) from the Caribbean. *Annals of Carnegie Museum</*