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Palynological and sedimentary analysis of the Igarapé Ipiranga and Querru 1 outcrops of the Itapecuru Formation (Lower Cretaceous, Parnaíba Basin), Brazil

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ABSTRACT

The siliciclastic sediments of the Itapecuru Formation occur in a large area of the Parnaíba Basin and its deposits crop out along the Itapecuru River, in Maranhão State, northern Brazil. The palynological analysis of the Igarapé Ipiranga and Querru 1 outcrops strata yields a rich and diversified data. The presence of index-palynofloras in assemblages allows the identification of the *Complicatisaccus cearensis* Zone, of Late Aptian-Early Albian age. Terrestrial palynomorphs are abundant in the assemblages, being represented by bryophytes and pteridophytes, especially perisporate trilete spores (*Crybelosporites* and *Perotrilites*), and gymnosperms and angiosperms (*Afropollis* and *Elaterosporites*). The composition of palynological assemblages suggests the presence of moist soils for both outcrops. Acritarchs were recovered in the Querru 1 outcrop, which suggest a marine setting supporting a tidal flat environment indicated by facies associations. Furthermore, reworked Paleozoic palynomorphs were observed in the Querru 1 outcrop. The microflora from Igarapé Ipiranga outcrop suggests terrestrial environment corroborating with floodplain environment indicated by facies association.

1. Introduction

The thick Aptian-Albian deposits of the Itapecuru Formation, which consists of siliciclastic sediments deposited in dominantly continental palaeoenvironments, are exposed throughout a large geographic area in the Parnaíba Basin and surrounding basins (Caputo, 1984; Góes and Feijó, 1994; Pedrão et al., 1996; Vaz et al., 2007). This unit is best represented in the subsurface, where it reaches thicknesses of up to 2000 m in the São Luís Basin and 700 m in the Parnaíba Basin (Lima and Leite, 1978; Caputo, 1984; Lima et al., 1994; Zalán, 2007). The Itapecuru Formation contains important palynomorphs, which contribute to Early Cretaceous biostratigraphical studies, palaeoenvironment characterization and paleoclimatic interpretation.

A large number of macrofossil and microfossil taxa from the Itapecuru Formation has been documented (Carvalho, 1994; Carvalho et al., 2003; Santos and Carvalho, 2004). Among these microfossils, there are palynomorphs, which are organic remains recovered in palynological preparations, such as spores (bryophytes and pteridophytes), pollen grains (gymnosperms and angiosperms), dinoflagellates, scolecodonts, acritarchs, colonies of chlorophytic algae and prasinophycean phycomata.

The assignment of palynomorphs to terrestrial, freshwater and marine groups, and the variations in abundance of the taxa within these assemblages, alongside sedimentologic data from the Itapecuru Formation, have allowed the development of palaeoenvironmental interpretations (Müller, 1966; Gonçalves and Carvalho, 1996; Rossetti et al., 2001; Pedrão et al., 2002; Vaz et al., 2007; Ferreira, 2015).

The palynomorphs recovered from the Itapecuru Formation allowed the identification of index-fossil bioevents used at biostratigraphic studies (Pedrão, 1995; Pedrão et al., 1996, 2002; Pedrão and Corrêa-Martins, 1999; Ferreira et al., 2008, 2011; Ferreira, 2015).

The purpose of this study is to characterize biozones based on

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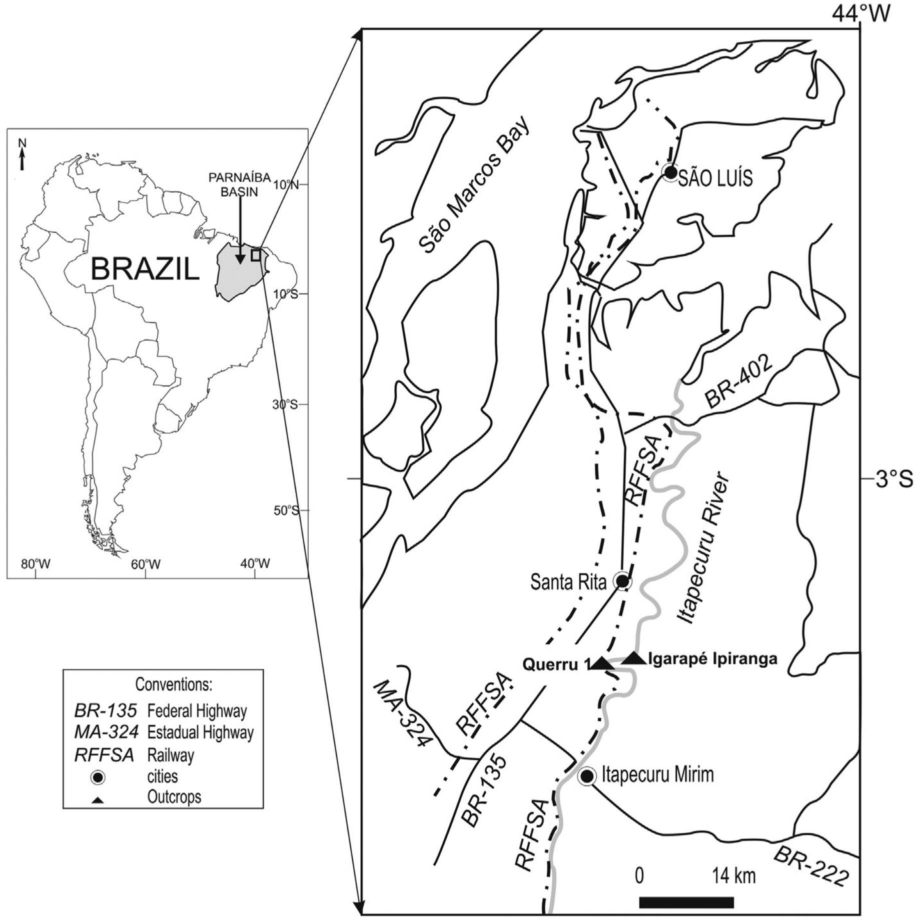

Fig. 1. Location map of the Itapecuru Formation outcrops.

the palynomorphs recovered, to assign relative age dates, and to carry out the paleoecological analysis of the deposits exposed along the banks of the Itapecuru River, in the municipalities of Itapecuru Mirim and Santa Rita, Maranhão State, northern Brazil.

2. Geologic setting

The Parnaíba Basin is located between latitudes 2° and 10° South and longitudes 42° and 48° West (Fig. 1). The basin measures approximately 600,000 km^2 and extends parts of the states of Piauí, Maranhão, Tocantins, Pará and Ceará (Góes et al., 1989; Góes and Feijó, 1994). The Cretaceous section of this basin is also called the Grajaú Basin by Rossetti et al. (2001).

The Parnaíba Basin contains rocks from the Paleozoic, Mesozoic and Cenozoic ages. The Cretaceous section is represented by the Codó, Grajaú and Itapecuru formations, with the last lithostratigraphic unit being the focus of this study (Fig. 2). This unit conformably overlies the Codó and Grajaú formations and is partially covered by Quaternary sediments (Caputo, 1984). The record of the palynomorph species *Sergipea variverrucata* in the Codó Formation allowed the identification of a corresponding homonymous zone that dates these deposits to the Late Aptian (Lima, 1982; Pedrão, 1995; Antonioli, 2001; Maizatto et al., 2011).

The Itapecuru Formation was divided into three members

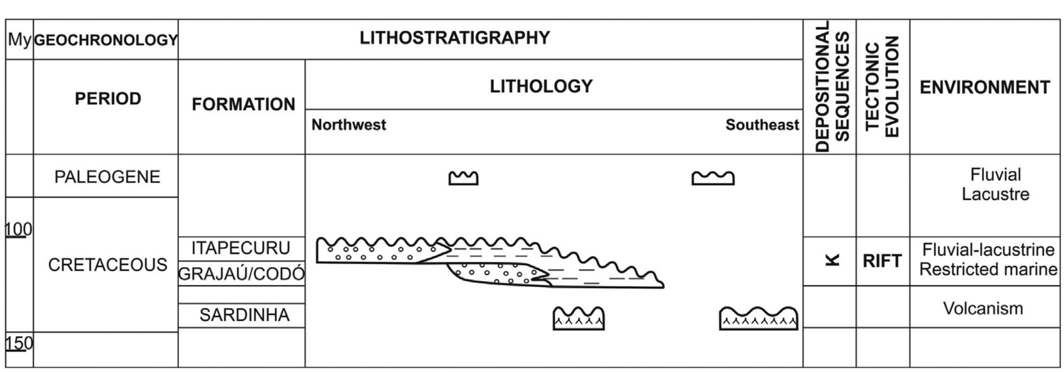

Fig. 2. Stratigraphic framework of the Parnaíba Basin (modified from Góes and Feijó, 1994).

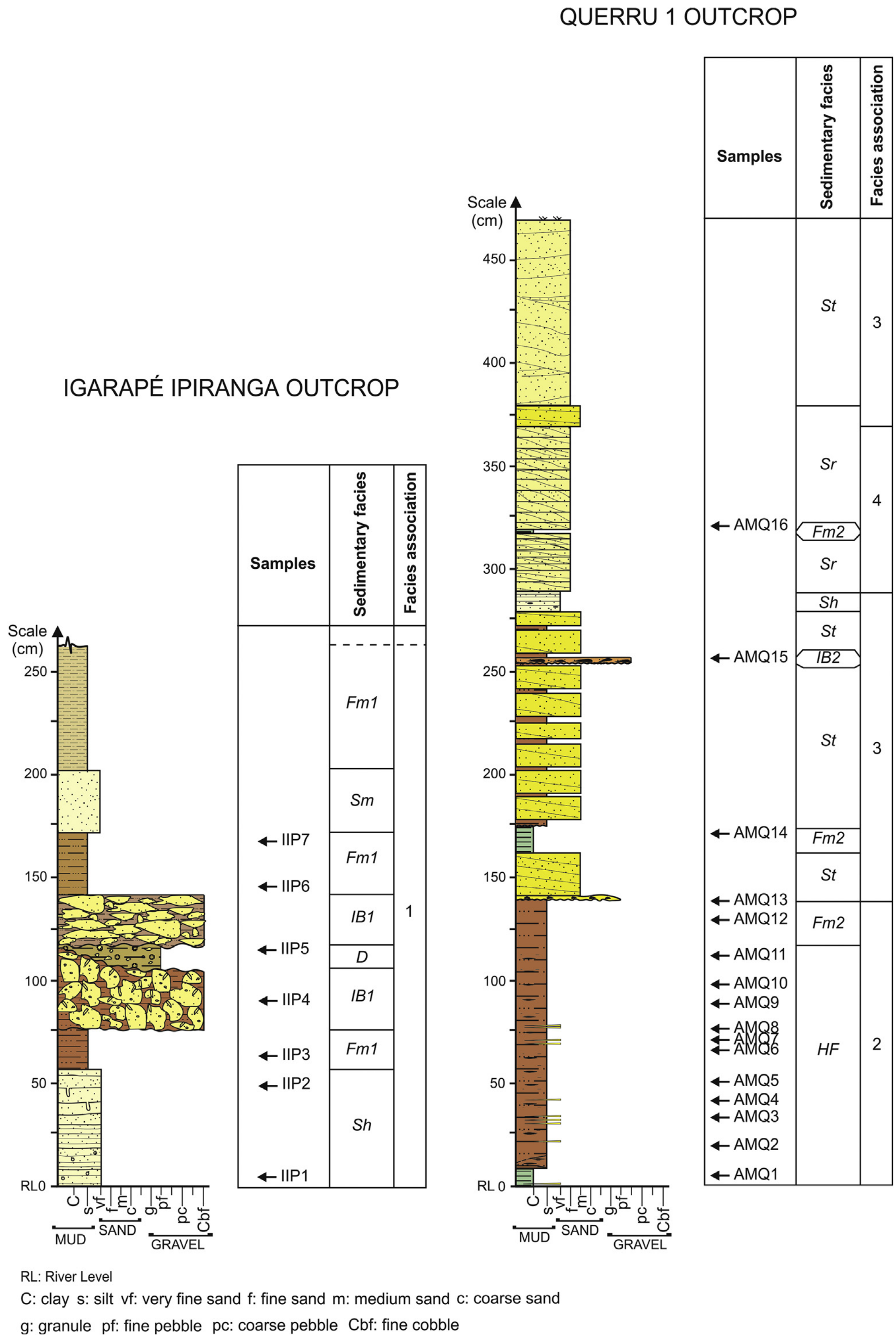

Fig. 3. Columnar sections of the Igarapé Ipiranga and Querru 1 outcrops, Itapecuru Formation. For legends of sedimentary facies, see Fig. 4.

(lower, middle and upper) based on seismic sections and well profiles. These members are considered to reflect the main stages of rifting during the Gondwana fragmentation. The lower member of the Itapecuru Formation is comprised of sandstones that grade into siltstones. The middle member is composed of sandstones, conglomerates and siltstones. The upper member is predominantly composed of sandstones and siltstones (Aranha et al., 1990; Pedrão et al., 2002).

The Itapecuru Formation was deposited in fluvial, fluvial-estuarine and marine environments (Caputo, 1984; Lima et al., 1994; Gonçalves and Carvalho, 1996; Rossetti et al., 2001; Pedrão et al., 2002; Ferreira et al., 2013; Ferreira, 2015). Tropical to subtropical weathers were suggested for this formation based on the presence of the typical elater-bearing palynomorphs of the Albian-Cenomanian Elaterates Province (Müller, 1966; Pedrão, 1995; Herngreen et al., 1996; Ferreira, 2015). These conditions are

Code	Diagnostic Facies	Description	Process of transportation interpreted
IB1	Intraformational breccia with sandstone clasts	Intraformational massive breccia with framework formed by irregular fragments of massive fine sandstone of up to 15 cm. The sandstone clasts may are deformed (elongated) and are 10YR7/4 in colour. The matrix is greenish gray (5GY4/1 or 6/1) sandy silt. Intense bioturbation may be present in both the framework and matrix.	Subaqueous gravitational flow affecting pelitic and sandy unconsolidated to semi-consolidated layers; post-depositional changes (bioturbation)
IB2	Intraformational breccia with claystone clasts	Massive Intraformational breccia with framework formed by claystone clasts and matrix of fine to medium sand; centimetric thicknesses, located at the base of sets of trough cross structures. The colour of the sandy matrix is 10YR8/2.	Accumulation of pelitic clasts at the base of sandy megaforms; erosion of pelitic substrate
D	Diamictite with bioclasts	Diamictite with mud matrix (5GY4/1) and fine sandstone pebbles (10YR7/4) and dispersed bioclasts (fish teeth and scales, coal), massive.	Subaqueous gravity flow.
Sh	Pebbly sandstone with plane-parallel stratification	Very fine, silty sandstone with fine clay pebbles and fine silicified sandstone pebbles and granules, rounded and highly spherical; plane-parallel lamination and stratification and bioturbation (*Skolithos*); 5GY6/1.	Superposition of sand sheets in upper flow regime.
Sm	Massive sandstone	Very fine micaceous sandstone, massive, 5Y7/2.	Driving hydrodynamic flow; post-depositional changes
St	Sandstone with interbedded mudstone and trough cross-stratification	Fine to medium sandstone, micaceous, with wavy bedding. Trough cross stratification in *sets* of decimetric thickness with grain size decreasing upward and clay intraclasts at the base of the deposit. Deformation of the cross structures may represent slipping of the frontal face of the dune. 5Y5/2 or 7/2 and 10YR7/4 or 8/2.	Driving unidirectional flow, migration of mid-size dunes with sinuous ridges.
Sr	Sandstone with cross-lamination	Very fine to medium sandstone, micaceous with cross laminations, sets of 4-5 cm, with mud *drapes*. 10YR7/4.	Unidirectional driving flow, migration of sandy wavelets and clay settling over the bedforms at times of hydrodynamic current stops.
Fm1	Massive sandy siltstone	Massive sandy siltstone, 5GY4/1 or 6/1, with strong mottling near the ground surface.	Settling of fine sediments and post-depositional changes.
Fm2	Massive to weakly laminated mudstone	Silty claystone, micaceous, massive to weakly laminated.	Settling of fine sediments and post-depositional changes.
HF	Pelite with heterolithic facies	Silty mudstone with linsen lamination and subordinate wavy lamination; 5Y6/1; intensely bioturbed (*Planolites*?)	Settling of fine sediments and migration of scarce isolated sandy wavelets.

Fig. 4. Relationship and summary description of the sedimentary facies identified in the Igarapé Ipiranga and Querru 1 outcrops. Sedimentary facies code partially adopted from Miall (1978, 1996).

supported by the palaeogeographycal setting of the basin in low latitudes during the Cretaceous (Scotese, 2001).

3. Materials and methods

The material for the palynological analysis consisted of 23 samples collected from the Igarapé Ipiranga outcrop (3°15′13.1″ S, 44°17′58.6″ W) and the Querru 1 outcrop (3°15′27.9″ S, 44°19′48.4″ W) (Fig. 3). These samples were collected between 8 and 13 December 2013, when the low level of the Itapecuru River allowed access to less weathered exposures of the Itapecuru Formation.

The criteria for grain-size classification of the samples from the stratigraphic columns were those of Blair and McPherson (1999). The roundness and circularity scales of Powers (1953) and Rittenhouse and Gordon (1943) were used to characterize the gravel clasts and sand grains, respectively. The Munsell Rock Color Chart (Geological Society of America (1991)) was used to record the colors of the rocks. The sedimentary facies were classified, in part, using the facies identification codes of Miall (1978, 1996).

The sediments underwent palynological processing for Cretaceous rocks recommended by Uesugui (1979) and Wood et al. (1996).

For the semi-quantitative analysis, 300 palynomorphs were counted according to Chang (1967). The author considers this number to correspond to a population and to involve an error of approximately 4%. The relative abundance of each taxon was

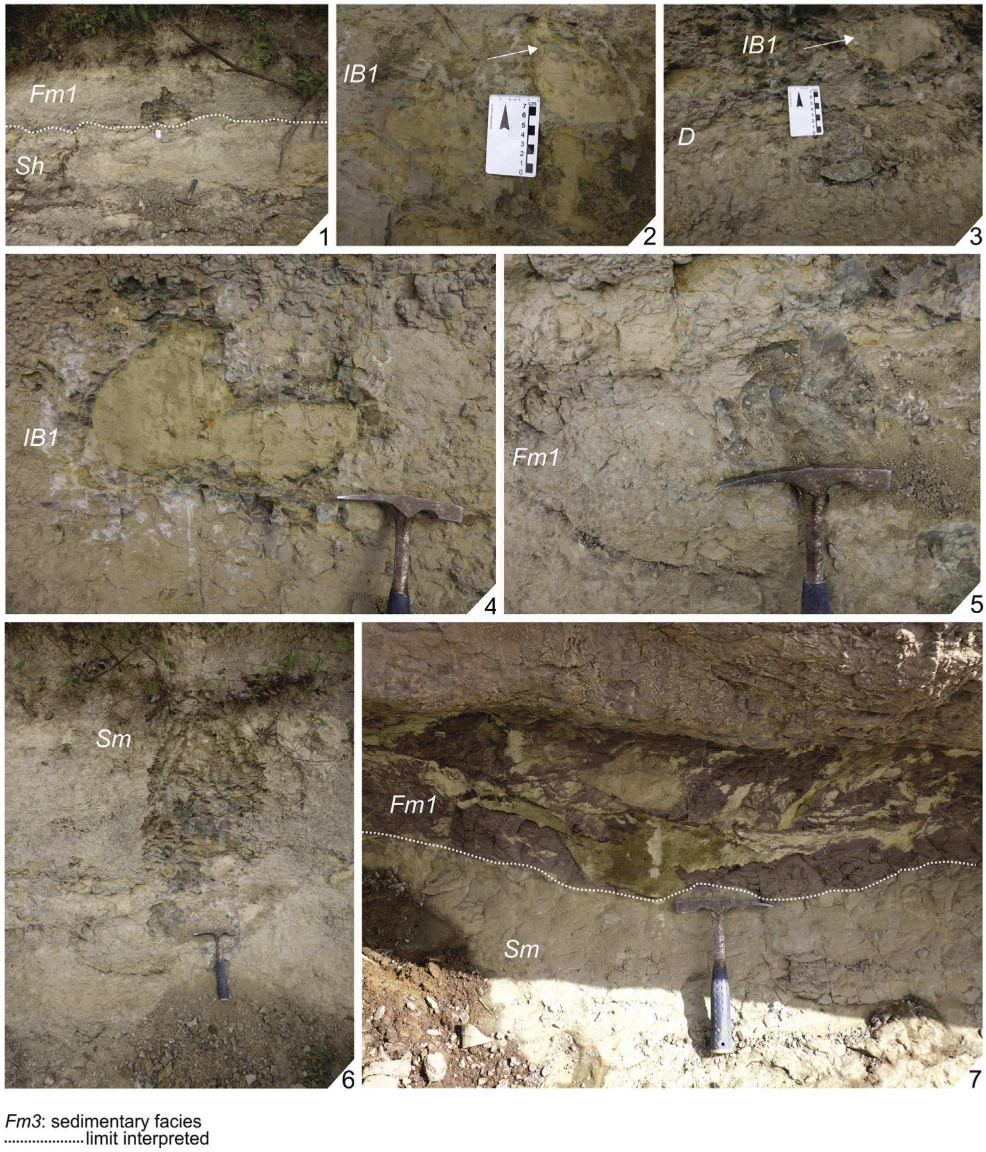

Fig. 5. Sedimentary facies identified in the Igarapé Ipiranga outcrop, Itapecuru Formation. 1. Facies *Sh*, fine sandstone with plane-parallel lamination. Facies *Fm1*, massive sandy siltstone of mottled aspect. 2. Facies *IB1*, massive intraformational breccia with framework formed by pebbles to cobbles of intensely bioturbed fine sandstone indicated by the white arrow. 3. Facies *D*, diamictite supported by sandy silt matrix, containing fine pebbles of sandstones and bioclasts. 4. Facies *IB1*, intraformational breccias with framework formed by clasts of fine non-bioturbed sandstone. 5. Facies *Fm1*, massive siltstone, grey. 6. Facies *Sm*, very fine massive sandstone, yellowish grey. 7. Facies *Fm1*, massive clayey siltstone with mottled aspect.

assigned to one of three verbal classes: present (1–3 specimens), common (4–30 specimens) and abundant (more than 30 specimens). The percentages are shown in the stratigraphic distribution charts of both outcrops.

4. Results and discussion

4.1. Sedimentary study

Ten sedimentary facies were identified in the Igarapé Ipiranga and Querru 1 outcrops (Figs. 4–6).

The sedimentary facies association 1 observed in the Igarapé Ipiranga profile (Fig. 3) includes very fine to fine sandstones with plane-parallel stratification (*Sh* facies), massive sandstones (*Sm* facies) and interbedded mudstone layers (*Fm1* facies) of decimetric thickness. Intraformational breccias (*IB1* facies) and diamictites (*D* facies) were also observed. These facies represent a river floodplain depositional environment, most likely one of a meandering river, with a predominantly pelitic sedimentation and strong bioturbation. The fine sandstone facies (*Sh* and *Sm*) are attributed to crevasse splays, and the intraformational breccias and diamictites were likely deposited by subaqueous gravitational flows. The sources of the diamictites and intraformational breccias most likely consisted of unconsolidated or semi-consolidated mud and sand layers eroded from the marginal levees of the meander channels in the proximal zones of the breach fans.

The Querru 1 outcrop (Fig. 3) has three distinct sedimentary facies associations. Facies association 2 consists of a 1.50 m-thick heterolithic deposit (*HF* facies). Facies association 3 consists primarily of sandstones with wavy bedding and trough cross-stratification (*St* facies), interbedded mudstones and thin layers of intraformational breccias (*IB2* facies). Facies association 4 is composed mainly of fine cross-laminated sandstones (*Sr* facies) and mud drapes. Based on these three facies associations, it is inferred

Fig. 6. Sedimentary facies identified in the Querru 1 outcrop, Itapecuru Formation. 1. Facies *HF*, mudstone with linsen and subordinately wavy lamination, intensely bioturbed. Facies *Fm2*, massive silty mudstone, light olive-grey. 2. Facies *St*, medium sandstone with small-scale trough cross stratification. 3. Facies *St*, medium sandstone with trough cross stratification. 4. General aspect of the outcrop.

that the Querru 1 outcrop represents a tidal flats depositional environment (Martinius et al., 2001; Zacharias and Assine, 2005).

4.2. Palynological study

Twenty-three samples were collected from the Igarapé Ipiranga and Querru 1 outcrops of the Itapecuru Formation and analyzed semi-quantitatively (Figs. 7 and 8). Of the 23 samples collected, 20 contained well-preserved palynological assemblages that included a total of 116 palynomorph taxa (Figs. 9–11; Appendix A). Three samples did not contain palynomorphs, but yield a considerable phytoclasts. The assemblages consist of gymnosperm (68 taxa) and angiosperm pollen (19 taxa) grains, and bryophyte (2 taxa) and pteridophyte spores (12 taxa). Palynomorphs of unknown botanical affinity (6 taxa), Chlorococcalean algae spores (2 taxa) and colonies (1 taxon) were also identified. Furthermore, acritarchs and phycomata of prasinophycean algae are recovered only in the Querru 1 outcrop.

4.2.1. Igarapé Ipiranga outcrop

Only samples IIP6 (142 cm) and IIP7 (164 cm), collected from the silt fraction of the *Fm1* facies, showed richer palynological assemblages. Fig. 7 shows the stratigraphic distribution of palynomorphs. Terrestrial palynomorphs were identified like perisporate trilete spores belonging to *Crybelosporites* sp. ?, *Crybelosporites pannuceus* and *C. truncatus*, which have affinity with the Marsileaceae and Selaginellaceae (Dettmann, 1994; Lupia et al., 2000), were identified in the palynological assemblages. Specimens of *Afropollis jardinus*, *Elaterosporites protensus* and *Elaterosporites* spp. (small size) are common in the assemblages.

In the assemblages are commom pollen grains assigned to *Araucariacites*, *Equisetosporites*, *Gnetaceaepollenites*, *Singhia* and *Steevesipollenites* genera and they exhibit morphological variation. Monocolpate (*Liliacidites* cf. *L. variegatus*), dicolpate (*Psiladicolpites laevis*), tetracolpate (*Tetracolpites reticulatus*) and periporate (*Cretacaeiporites polygonalis*) pollen grains were also identified in the assemblages.

4.2.2. Querru 1 outcrop

Palynomorphs of the Querru 1 outcrop samples were mainly recovered from the clay and silt fractions of *HF*, *Fm2* and *IB2* facies. The stratigraphic distribution of palynomorphs is exhibited in Fig. 8. The assemblages are dominated by terrestrial palynomorphs which are composed by perisporate trilete spores belonging to the genera *Perotrilites* and *Crybelosporites*, and by specimens of *Afropollis* and *Elaterosporites*. Inaperturate, reticulate tricolpate and polyplicate pollen grains display great morphological variation, but are not abundant.

Marine palynomorphs are represented by acritarchs of subgroups Acanthomorphitae, Polygonomorphitae and Herkomorphitae, according to the systematic classification proposed by Downie et al. (1963). Acritarchs have uncertain biological affinities (Evitt, 1963; Martin, 1993) or have been interpreted as unicellular protozoan (Strother, 1996) or microphytoplankton cysts (Le Hérissé et al.,

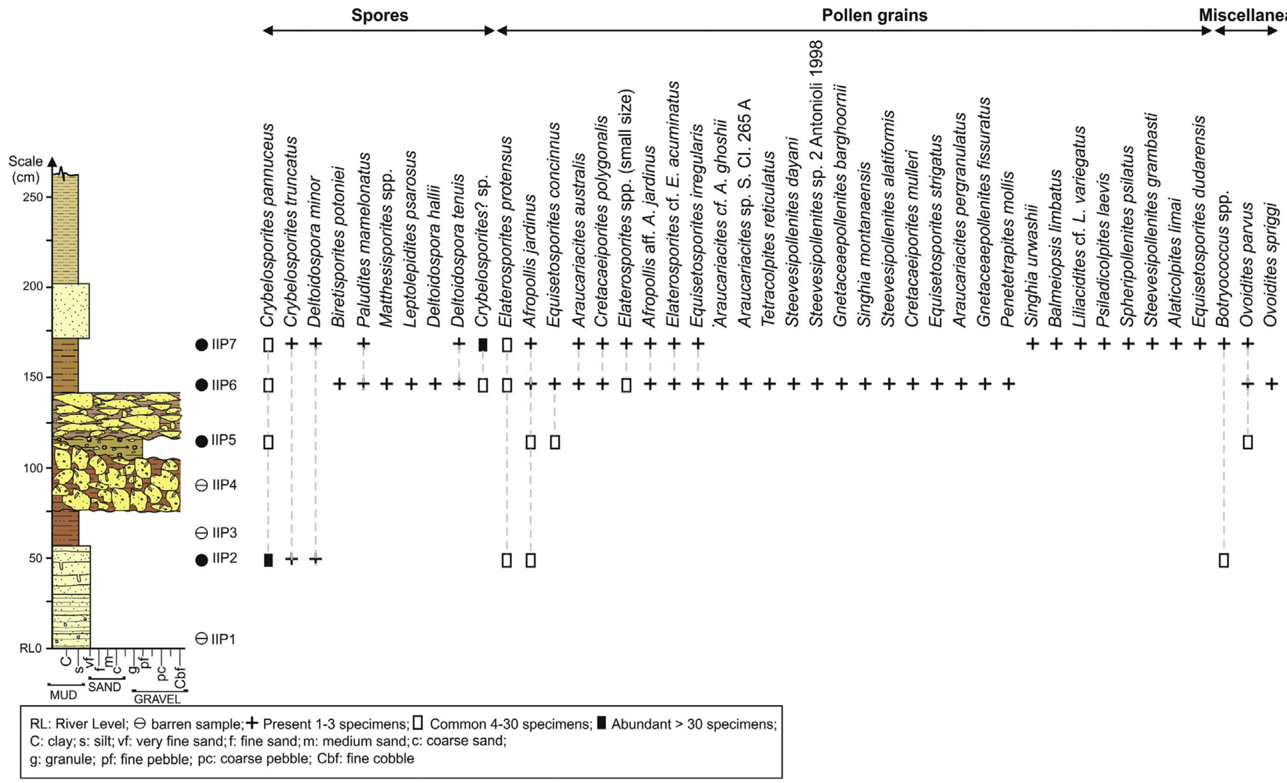

Fig. 7. Stratigraphic distribution of the main palynomorphs of the Igarapé Ipiranga outcrop.

2009).

Duvernaysphaera angelae Deunff 1964 and *Umbellasphaeridium saharicum* Jardiné et al., 1972 are among the acritarch taxa identified (Figs. 11.10 and 11.17). Both are widespread in the Devonian strata of Brazilian Paleozoic basins and are interpreted herein as reworked palynomorphs. *D. angelae* occurs in Middle to Late Devonian deposits in the Algerian Sahara (Jardiné et al., 1974), and in late Early to Late Devonian deposits of the Parnaiba Basin and other South American basins (Brito, 1976; Wicander and Wood, 1981; Melo, 2000). *U. saharicum* has been reported in Late Devonian sequences of the Algerian Sahara (Jardiné et al., 1974) and of nearly all Paleozoic basins of Brazil (Quadros, 1980, 1985; Oliveira, 1997; Cruz, 2011). A fragmentary specimen doubtfully of the assigned to the genus *Exochoderma* (Fig. 11.18) could have been reworked from the Devonian. Furthermore, others specimens related to mainly of Acanthomorphitae subgroup (Fig. 11.3–11.5, 11.11, 11.13, 11.14, 11.16) are founded, which have long-ranging and are not restricted to Paleozoic sections (Martínez et al., 2008). Their occurrences at the Querru 1 outcrop are considered in situ supporting the indication of marine environment provided by 2, 3 and 4 facies associations.

The Querru 1 palynological assemblages also contain *Maranhites mosesii*, *Maranhites* spp., *Tasmanites* spp., and *Cymatiosphaera*? sp. (Figs. 11.8, 11.9, 11.15), all of which are considered as phycomata of prasinophycean algae (Guy-Ohlson, 1996). *Maranhites* specimens are Devonian reworked palynomorphs based on a taxonomic and stratigraphic reappraisal by Le Hérissé (2011). The genus *Maranhites* is common in the Middle and Upper Devonian of South America, particularly in Brazil and Bolivia (Brito, 1978; Le Hérissé, 2009). According to Le Hérissé (2011), the known stratigraphic range of *M. mosesii* extends from Frasnian through the late Famennian. In turn, occurrences of *M. mosesii* in Mississippian rocks (Brito, 1971, 1978; Burjack and Oliveira, 1989) are now regarded as reworked (Le Hérissé, (2011)). Lastly, algal phycomata of the genus *Tasmanites* are common in Brazilian Paleozoic basins (Müller, 1966; Quadros, 2002), and their occurrences in the Itapecuru Formation are interpreted as possibly reworked, even though the genus is also known from post-Paleozoic strata elsewhere in the world (Fensome et al., 1990; Barrón et al., 2015). The same applies to *Cymatiosphaera*, a long-ranging (Paleozoic–Neogene) prasinophyte genus common in Brazilian Paleozoic basins, and uncertainly identified in the Querru 1 material.

4.3. Biostratigraphy

The palynostratigraphic framework proposed by Regali et al. (1974) was used for the relative dating of the terrestrial sedimentary sequences of the Lower Cretaceous of Brazil. This framework was modified during the biostratigraphic studies by Beurlen and Regali (1987) in the Pará-Maranhão Basin, where the *Complicatisaccus cearensis* Zone was defined and included. Later, in the palynological studies in the Ceará Basin, Regali (1989) identified the *C. cearensis* Zone (Fig. 12), adopted in this work. The biozone was divided into four parts (Basal, Lower, Middle and Upper). The last occurrence of *S. variverrucata* and the first occurrence of *Elateropollenites jardinei* and *C. polygonalis* define the base and top of the Basal part, respectively. The base of the Lower part is defined by the first occurrences of *E. jardinei* and *C. polygonalis*, and its top indicated by the last occurrence of *Elateropollenites praecursor*. The base of the Middle part is characterized by the last occurrence of *E. praecursor*, and the top by the last occurrence of *Elateropollenites dissimilis*. Finally, the base of the Upper part is marked by the last occurrence of *E. dissimilis*, and the top is defined by an unconformity and records the last occurrences of *Quadricolpites reticulatus*, *Psiladicolpites comptus*, *P. laevis*, *P. papillatus*, *Penetetrapites mollis*, *Paludites mamelonatus*, *Gnetaceaepollenites concisus* and *Trisectoris*

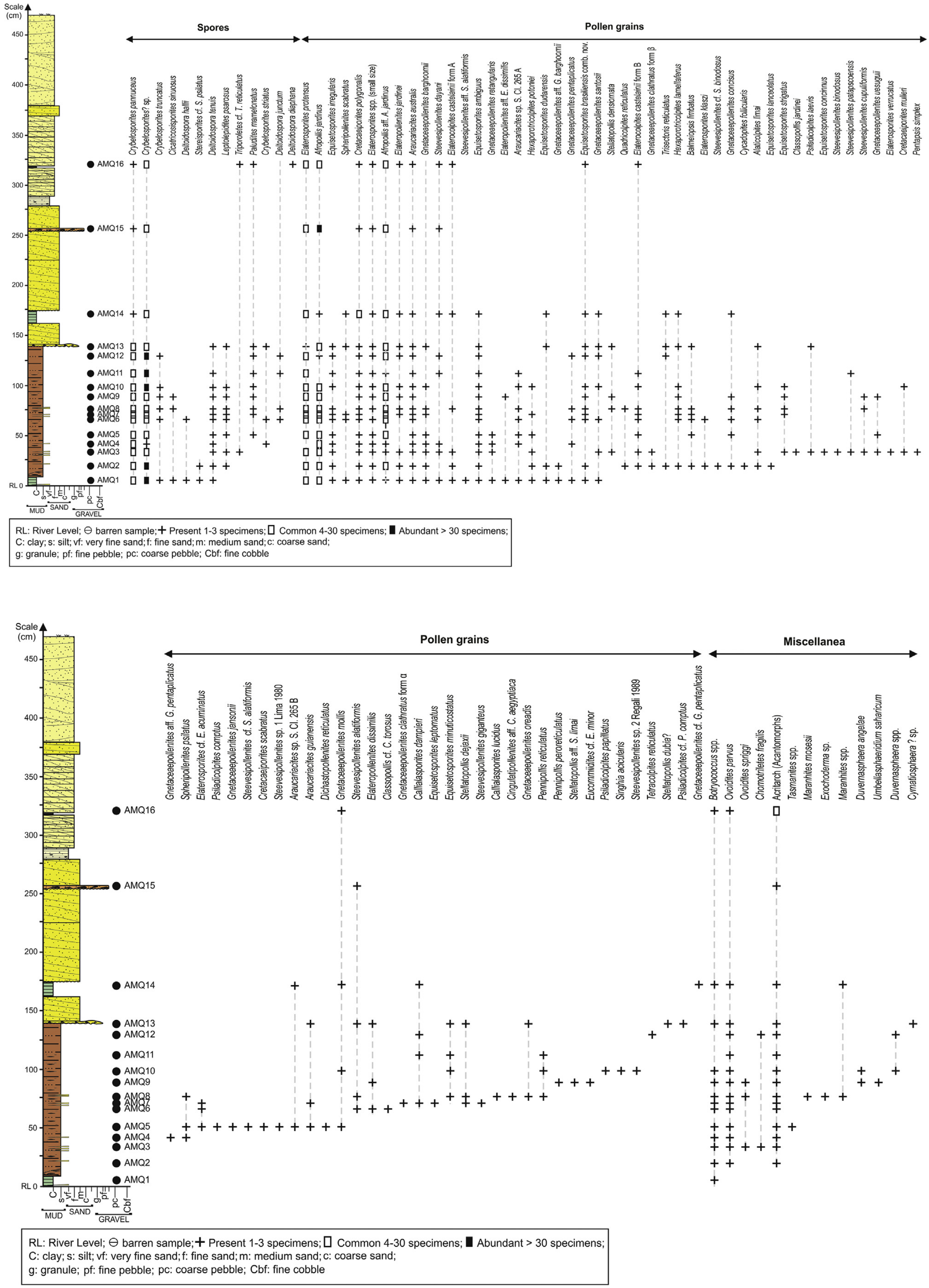

Fig. 8. Stratigraphic distribution of the main palynomorphs of the Querru 1 outcrop.

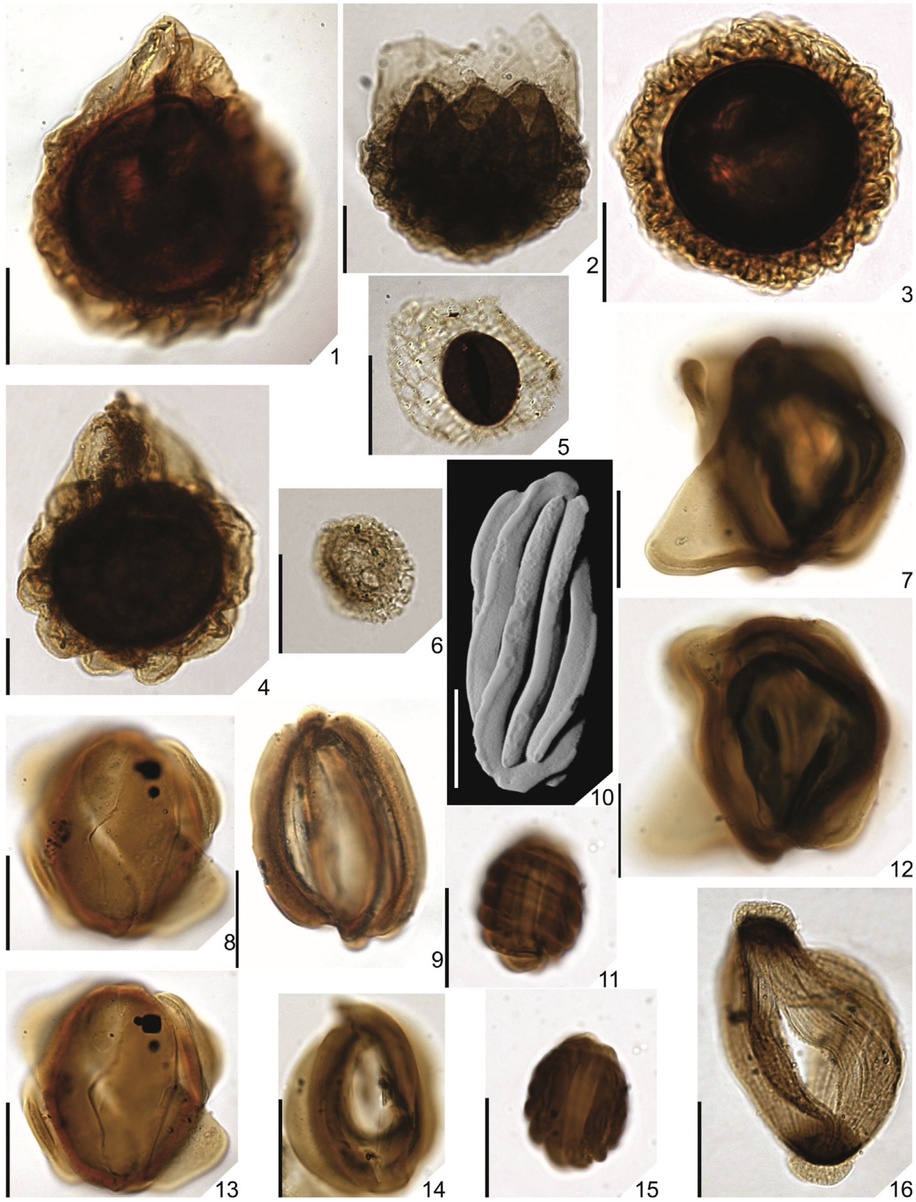

Fig. 9. Taxon name followed by grain position, outcrop, sample depth and *England Finder* coordinates. Scale: 20 μm. 1. *Crybelosporites pannuceus* (Brenner 1963) Srivastava 1975. Side view focusing on the cone formed by the perispore over the trilete mark. Querru 1, Depth 2 cm, V41-2. 2. *Crybelosporites truncatus* Lima 1979. Side view showing convolute perispore and open laesurae. Querru 1, Depth 2 cm, slide 1–2, Q40-2. 3. *Crybelosporites* sp.? Middle focus showing the densely convoluted perispore. Querru 1, Depth 31 cm, R42-4. 4. *Paludites mamelonatus* Lima 1979. Side view showing perispore ornamentation. Querru 1, Depth. 96.5 cm, H42-4. 5. *Afropollis jardinus* Doyle et al. 1982. High focus showing the internal body (endexine). Querru 1, Depth 2 cm, N48-3. 6. *Afropollis jardinus* Doyle et al. 1982. High focus showing irregular reticulum and small sized. Querru 1, Depth. 96.5 cm, K60-1. 7, 12. *Equisetosporites irregularis* (Herngreen 1973) Lima 1980. Side view. 7. Low focus showing exine. 12. High focus showing the irregular outline of the plica. Querru 1, Depth. 48.5 cm, F52-3. 8, 13. *Equisetosporites brasiliensis* (Herngreen 1973) nov. comb. Differential Interference Contrast (DIC) images in side view. 8. High focus showing plicae. 13. Medium focus showing the irregular outline of plicae in the equatorial portion of the grain. Querru 1, Depth 15 cm, K54-1. 9. *Gnetaceaepollenites pentaplicatus* Regali 1989. Oblique view, high focus showing plicae. Querru 1, Depth 63.5 cm, T50-3. 10. *Gnetaceaepollenites clathratus* form β Stover 1964. Side view, LSM image. Querru 1, Depth. 15 cm, B41. 11, 15. *Gnetaceaepollenites clathratus* form α Stover 1964. Side view. 11. High focus showing convergent plicae (CVR). 15. Low focus showing circular plica (CR). Querru 1, Depth 69.5 cm, L37-3. 14. *Gnetaceaepollenites concisus* Regali 1989. Side view, high focus showing plicae. Querru 1, Depth 63.5 cm, W56-1. 16. *Steevesipollenites dayani* Brenner 1968. Side view, high focus showing finely reticulated polar cap and plicae. Querru 1, Depth 127 cm, D49.

reticulatus. Later, Regali and Santos (1999) characterized the *C. cearensis* Zone in the Sergipe-Alagoas Basin and defined five subzones (Fig. 12). These subzones were correlated and calibrated with the *Globigerinelloides barri-Hedbergella* (*H.*) *gorbachikae* (AP-1), *Globigerinelloides* ex. *Gr. maridalensis-Hedbergella* (*H.*) *similis* (AP-2), *Globigerinelloides cushmani–Ticinella bejaouaensis* (AL-1) and *Ticinella bejaouaensis* (AL-2) planktonic foraminifera zones proposed by Koutsoukos and Bengston (1993). Thus, the *C. cearensis* Zone was dated as from the Upper Aptian-Lower Albian section. In this work, the palynostratigraphic framework of Regali (1989) is adopted and the chronostratigraphic interpretation is based on Regali and Santos (1999).

4.3.1. Igarapé Ipiranga outcrop

Species with biostratigraphic value in the Igarapé Ipiranga outcrop include *P. mollis*, *P. laevis and Equisetosporites irregularis.* These palynomorphs indicate the Upper part of the *C. cearensis* Zone (Fig. 13). The following species were also observed: *A. jardinus,*

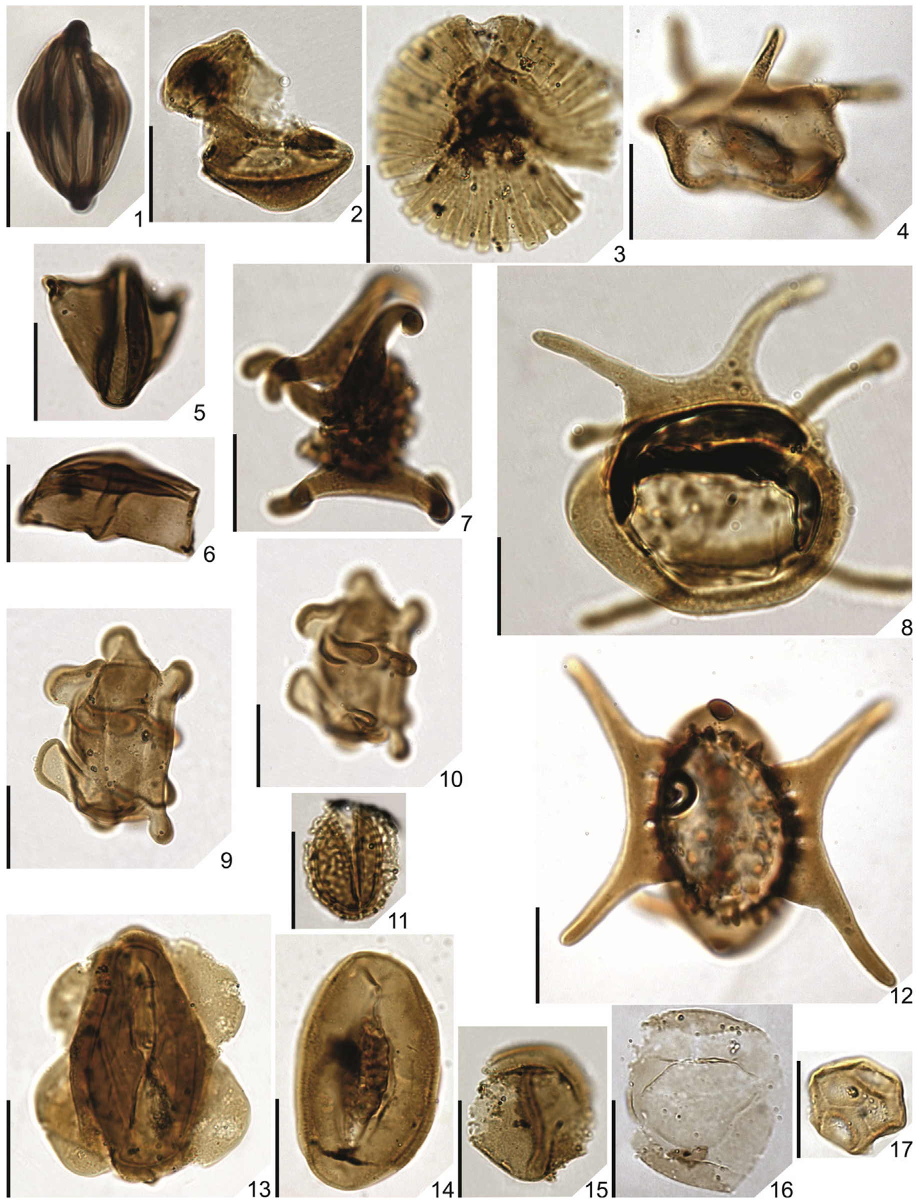

Fig. 10. Taxon name followed by grain position, outcrop, sample depth and *England Finder* coordinates. Scale: 20 μm. 1. *Steevesipollenites alatiformis* Regali et al. 1974. Side view, high focus showing spaced channels. Igarapé Ipiranga, Depth 142 cm, H46-1. 2. *Pentapsis simplex* Regali, Pedrão and Barrilari 2000. Side view, medium focus showing polar pentamerous plates. Querru 1, Depth 31 cm, K51-4. 3. *Trisectoris reticulatus* (Regali et al., 1974) Heimhofer and Hochuli 2010. Polar view, medium focus showing the three likely colpi at 120° angles. Querru 1, Depth 136.5 cm, P51-2. 4. *E. klaszi* (Jardiné and Magloire 1965) Jardiné 1967. Side view, high focus showing the grain surface. Querru 1, Depth 63.5 cm, G52. 5. *Elateropollenites jardinei* Herngreen 1973. High focus on wide folds. Querru 1, Depth 96.5 cm, F51-1. 6. *Elateropollenites dissimilis* Regali 1989. Medium focus showing underdeveloped folds. Querru 1, Depth 86.5 cm, K49. 7. *Elaterosporites* spp. (small sizes). Distal view, medium focus on the support with elater pairs. Querru 1, Depth 15 cm, K34. 8. *Elaterosporites verrucatus* (Jardiné and Magloire 1965) Jardiné 1967. Proximal view, high focus showing elater support without perforations and the annular band. Querru 1, Depth 31 cm, J55-1. 9, 10, *Elaterocolpites castelainii* form B Jardiné 1967. Medium and low focus showing the concave ends of the elaters. Querru 1, Depth 69.5 cm, P53-3. 11. *Pennipollis reticulatus* (Brenner 1963) Friis, Pedersen and Crane 2000. Side view médium focus showing the endexine, colpus and reticulum. Querru 1, Depth 75 cm, N60-3. 12. *Elaterosporites protensus* (Stover 1963) Jardiné 1967. Proximal view, medium focus showing the ornamentation and perforations at the base elater support. Igarapé Ipiranga, Depth 142 cm, W38-4. 13. *Alaticolpites limai* Regali et al. 1974. Side view, medium focus showing the exine and elaters. Querru 1, Depth 96.5 cm, P37-4. 14. *Psiladicolpites comptus* Regali 1989. Side view, medium focus showing the colpi. Querru 1, Depth 48.5 cm, C40. 15. *Psiladicolpites papillatus* Regali 1989. Side view, high focus showing the colpi and papillae. Querru 1, Depth 96.5 cm, P40-2. 16. *Psiladicolpites laevis* Regali 1989. Side view, medium focus showing the colpi. Igarapé Ipiranga, Depth 164 cm, H44. 17. *Cretacaeiporites polygonalis* (Jardiné and Magloire 1965) Herngreen 1973. DIC image, polar view, high focus showing the pores. Querru 1, Depth 2 cm, S58-4.

Afropollis aff. A. jardinus, *Alaticolpites limai*, *C. polygonalis*, *C. truncatus*, *Elaterosporites protensus*, *P. mamelonatus*, and *Steevesipollenites dayani*.

4.3.2. Querru 1 outcrop

The following species with chronostratigraphic value were identified in the Querru 1 outcrop: *E. dissimilis* and *Pentapsis simplex* (*P. valdiviae* sensu Regali, 1989). These palynomorphs characterize the Middle part of the *C. cearensis* Zone (Fig. 13). This section contains the following species: *A. jardinus, Afropollis aff. A. jardinus, C. polygonalis, C. truncatus*, *Elaterocolpites castelainii* form A, *Elaterocolpites castelainii* form B, *E. jardinei*, *Elaterosporites klaszi*, *E. protensus*, *E. verrucatus*, *Equisetosporites brasiliensis* nov. comb., *E. irregularis*, *Gnetaceaepollenites clathratus* form α, *G. clathratus* form

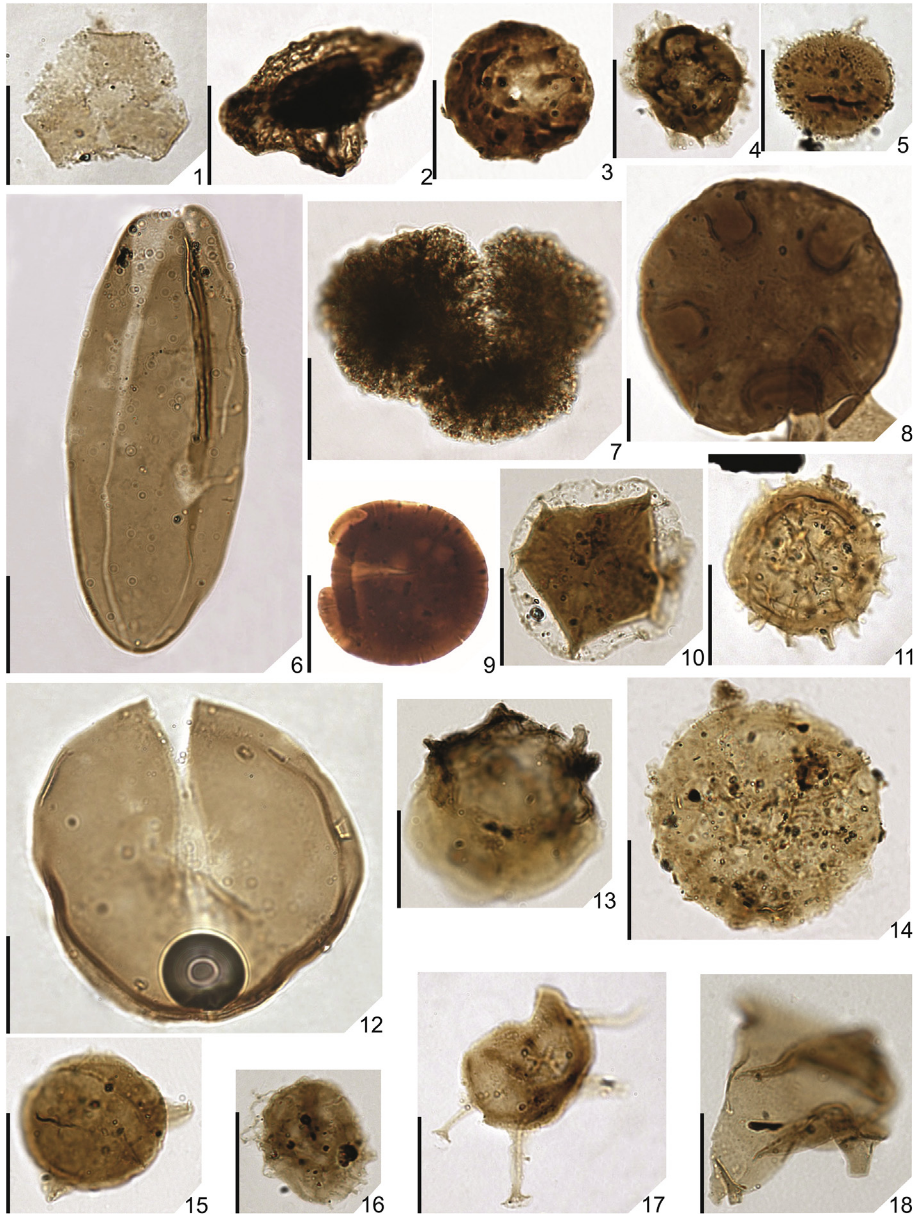

Fig. 11. Taxon name followed by grain position, outcrop, sample depth and *England Finder* coordinates. Scale: 20 μm. 1. *Penetetrapites mollis* Hedlund and Norris 1968. Polar view, medium focus showing the lenticular and polar openings. Igarapé Ipiranga, Depth 142 cm, B48. 2. *Quadricolpites reticulatus* Wingate 1980 *emend*. Ward 1986. Polar view, low focus showing the reticulum. Querru 1, Depth 15 cm, E40-2. 3. Acritarch from the subgroup Acanthomorphitae. High focus showing the processes. Querru 1, Depth 15 cm, O48. 4. Acritarch from the subgroup Pteromorphitae. High focus showing the cristae on the vesicle surface. Querru 1, Depth 48.5 cm, P60-4. 5. Acritarch from the subgroup Acanthomorphitae. High focus showing the processes. Querru 1, Depth 169 cm, D56-4. 6. *Ovoidites parvus* (Cookson and Dettmann 1959) Nakoman 1966. Side view, low focus showing the equatorial slit. Querru 1, Depth 110 cm, L47-2. 7. *Botryococcus* spp. Side view, high focus showing the equatorial arrangement of the cell colony. Querru 1, Depth 48.5 cm, Q61-3. 8. *Maranhites mosesii* (Sommer 1956) Brito 1967. High focus showing the five isolated peripheral structures. Querru 1, Depth 75 cm, G46. 9. *Tasmanites* spp. High focus showing the narrow wall channels. Querru 1, Depth 48.5 cm, F42-3. 10. *Duvernaysphaera angelae* Deunff 1964. High focus showing the equatorial radial folds and equatorial membrane of the vesicle. Querru 1, Depth 96.5 cm, M41-4. 11. Acritarch of the subgroup Herkomorphitae. High focus showing the cristae on the vesicle surface. Querru 1, Depth 63.5 cm, L50-3. 12. *Ovoidites sprigii* (Cookson and Dettmann 1959) Zippi 1998. Side view, high focus showing side slit. Querru 1, Depth 86.5 cm, G70-3. 13. Acritarch of the subgroup Acanthomorphitae. High focus showing the processes. Querru 1, Depth 75 cm, P49-4. 14. Acritarch of the subgroup Pteromorphitae. High focus showing the processes. Querru 1, Depth 69.5 cm, H53. 15. *Cymatiosphaera*? sp. High focus, showing the processes. Querru 1, Depth 136.5 cm, S41-1. 16. Acritarch of the subgroup Acanthomorphitae. High focus, showing the processes. Querru 1, Depth 96.5 cm, K48-4. 17. *Umbellasphaeridium saharicum* Jardiné et al. 1972. Low focus on processes. Querru 1, Depth 86.5 cm, U66. 18. *Exochoderma*? sp. High focus on processes. Querru 1, Depth 75 cm, G43-2.

β, *G. concisus*, *G. pentaplicatus*, *P. mamelonatus*, *Pennipollis reticulatus*, *P. comptus*, *P. laevis*, *P. papillatus*, *Q. reticulatus*, *S. dayani* and *Trisectoris reticulatus*.

A divergence from the stratigraphic range of *E. protensus* and *E. verrucatus* presented by Regali (1989) was noted. According to Regali (1989, p. 240), the occurrence level of these two species is the base of the *E. jardinei* Zone and was used to differentiate the *C. cearensis* Zone from the *E. jardinei* Zone. However, in the palynological assemblage of the Querru 1 outcrop, *E. protensus* and *E. verrucatus* are associated with *Q. reticulatus*, *Pentapsis simplex*, *E. dissimilis*, *Pennipollis reticulatus*, *P. comptus*, *P. laevis* and *P. papillatus*, which have their last occurrences within the *C. cearensis* Zone. As a result of this record, the stratigraphic ranges of *E. protensus* and *E. verrucatus* may be extended.

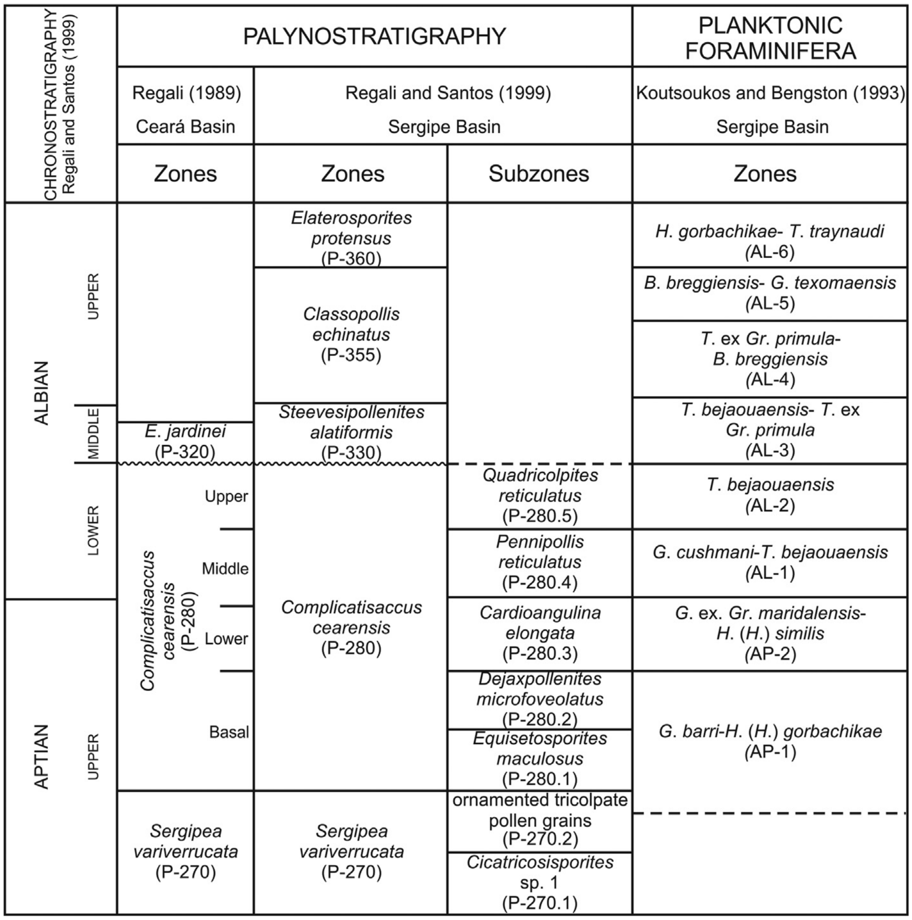

Fig. 12. Correlation of the palynological and planktonic foraminifera zones of the Ceará and Sergipe basins according to Regali and Santos (1999).

Among the palynomorph-index species identified, some have also been reported in the Cretaceous sections of Africa. In Morocco, specimens of *Q. reticulatus* were found in Albian deposits of the Tarfaya Basin (Bettar and Méon, 2001), and *T. reticulatus* (=*Cornetipollis herngreenii*) was found in the Middle-Upper Albian sediments of the Agadir-Essaouira Basin (Bettar and Méon, 2006). The species *Pennipollis reticulatus* was recorded in the Aptian (Doyle, 1992) and Aptian-Albian sections of Egypt and Morocco (Schrank, 1982; Schrank and Ibrahim, 1995; Ibrahim, 1996; Ibrahim et al., 2001; Ibrahim, 2002; Bettar and Méon, 2006). Taxa of *Elaterosporites* were encountered in Cretaceous deposits of Nigeria (Lawal, 1982; Abubakar et al., 2006), Egypt (Schrank and Ibrahim, 1995) and Ghana (Atta-Peters, 2013). In South America, *Elaterosporites* were documented in Albian-Cenomanian rocks in Colombia (Herngreen and Jimenez, 1990). This genus was also identified in the Albian section of ODP Leg 207 in Demerara, Equatorial Atlantic (Krauspenhar et al., 2014).

5. Palaeoenvironmental considerations

Terrestrial palynomorphs represented by ferns, gymnosperms and angiosperms dominate palynological assemblages of the Igarapé Ipiranga and Querru 1 outcrops, comprising more than 90% of the total assemblages. The Querru 1 assemblages showed a greater richness and diversity of trilete spores and pollen grains than the Igarapé Ipiranga ones.

In the Querru 1 palynological assemblages, high percentages of pollen grains (28–85%) and triletes spores (14–70%) are observed. Taxa of *Afropollis* are abundant and indicate humid tropical weather (Doyle et al., 1982). The genus is represented by *A. jardinus* (up to 32%), *Afropollis* aff. *A. jardinus* (up to 17%) and *Afropollis* spp. (up to 24%). The polyplicate pollen grains show great morphological variation, with *Gnetaceaepollenites* (up to 11%) being more abundant. Taxa of *Elaterosporites*, represented mainly by *E. protensus*, reach up to 7%. Perisporate types are found among the trilete spores and assigned to the genus *Perotrilites* (up to 45%) and to *C. pannuceus* (up to 11%), all of them attributed to Marsileaceae and Selaginellaceae. Rare marine palynomorphs represented by acritarchs are present (up to 6%). The intervals with high percentages of perisporate trilete spores (*Perotrilites* and *Crybelosporites*) and *Afropollis* suggest an environment with extremely moist soil and abundant water availability (marshy). Some specimens of acritarch (Acanthomorphitae, Polygonomorphitae and Herkomorphitae subgroups) were interpreted as evidence of marine influence during deposition. This interpretation corroborates the sedimentary analysis that proposed a tidal flat depositional environment for the Querru 1 outcrop (Figs. 3 and 4). The reworked palynomorphs recovered only from the Querru 1 outcrop suggest that the exposure of the Paleozoic section served as the source area of sediments.

The palynological assemblages of the Igarapé Ipiranga outcrop are dominated by perisporate trilete spores (61–72%), followed by pollen grains (up to 38%). The first group contains abundant specimens of *Crybelosporites* sp. ? (23–40%) and *C. pannuceus* (12–26%). Taxa of *Elaterosporites* (up to 16%) are found among the pollen grains, with *E. protensus* being the most abundant. Taxa of *Equisetosporites* (up to 13%) and *Afropollis* (up to 13%) are also common

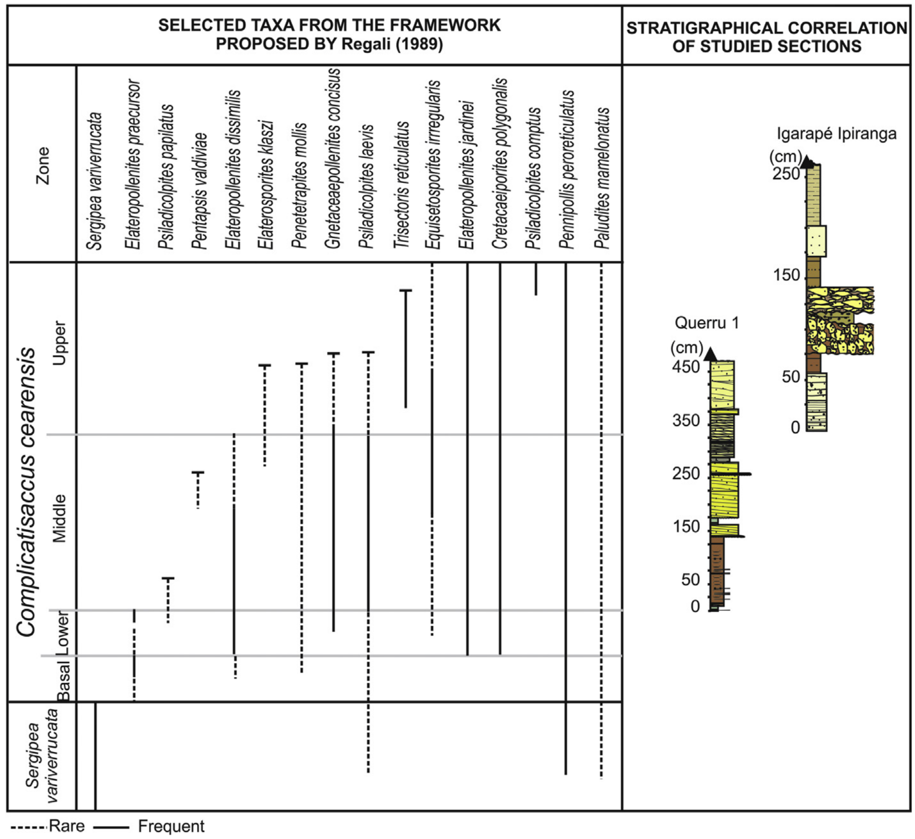

Fig. 13. Stratigraphical distribution of selected taxa from of the palynological framework proposed by Regali (1989).

in the assemblages, with *E. concinnus* and *A. jardinus* being the more representative species of these genera, respectively. The palynomorph assemblages of Igarapé Ipiranga indicate a humid tropical weather. This information corroborates the sedimentary analysis that points out the presence of floodplain deposits (Figs. 3–4).

The abundance of *Elaterosporites* and *Afropollis* indicate that the palynological assemblages from both outcrops are in the context of the Albian-Cenomanian Elaterates Province of Herngreen et al. (1996). However, the abundance of perisporate trilete spores related to the Marsileaceae and Selaginellaceae indicate that wet weather prevailed in the study area.

6. Conclusions

The sediments of the Querru 1 and Igarapé Ipiranga outcrops were deposited during the Early Cretaceous (Early Albian) according to characterization of the middle/upper *C. cearensis* Zone. The Querru 1 outcrop is older than the Igarapé Ipiranga outcrop due to the occurrence of the index fossils *E. dissimilis* and *Pentapsis simplex*. The abundance of perisporate trilete spores related to Marsileaceae and Selaginellaceae and *Afropollis* indicates humid tropical weather for both outcrops. The presence of acritarchs mainly in heterolithic and mud drapes deposits in Querru 1 outcrop indicates marine influence. The palynological data corroborate the interpretation of tidal flat depositional environment for Querru 1 outcrop indicate by succession of the three facies associations (2, 3 and 4). The palynological data support the succession sedimentary facies as floodplain deposits.

Acknowledgments

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Appendix A

List of palynomorphs

Spores
Bryophytes

Stereisporites cf. *S. psilatus* (Rouse 1949) Manum 1954

Triporoletes cf. *T. reticulatus* (Pocock 1962) Playford 1971

Pteridophytes

Biretisporites potoniei Delcourt and Sprumont 1955

Cicatricosisporites sinuosus Hunt 1985

Crybelosporites pannuceus (Brenner 1963) Srivastava 1975

Crybelosporites striatus (Cookson and Dettmann 1958) Dettmann 1963

Crybelosporites truncatus Lima 1979

Deltoidospora diaphana Wilson and Webster 1946

Deltoidospora hallii Miner 1935

Deltoidospora junctum (Kara-Murza 1956) Singh 1964

Deltoidospora minor (Couper 1953) Pocock 1970

Deltoidospora tenuis Lima 1978

Leptolepidites psarosus Norris 1969

Leptolepidites verrucatus Couper 1953

Unknown botanical affinity

Paludites mamelonatus Lima 1979

Pollen grains
Gymnosperms

Alaticolpites limai Regali et al. 1974

Araucariacites australis Cookson 1947

Araucariacites cf. *A. ghoshii* Srivastava *sensu* Volkheimer 1968

Araucariacites guianensis Van der Hammen and Burger 1966

Araucariacites pergranulatus Volkheimer 1968

Araucariacites sp. S. CI. 265 A Jardiné and Magloire 1965

Araucariacites sp. S. CI. 265 B Jardiné and Magloire 1965

Balmeiopsis limbatus (Balme 1957) Archangelsky 1977

Callialasporites dampieri (Balme 1957) Dev 1961

Callialasporites lucidus (Pocock 1962) Maheshwari 1974

Cingulatipollenites aff. *C. aegyptiaca* Saad and Ghazaly 1976

Classopollis jardinei Reyre, Kieser and Pujol 1970

Classopollis cf. *C. torosus* (Reissinger 1950) Couper 1958 *emend.* Burger 1965

Cycadopites follicularis Wilson and Webster 1946

Elaterocolpites castelainii forma A Jardiné 1967

Elaterocolpites castelainii forma B Jardiné 1967

Elateropollenites dissimilis Regali 1989

Elateropollenites aff. *E. dissimilis* Regali 1989

Elateropollenites jardinei Herngreen 1973

Elateropollenites aff. *E. jardinei* Herngreen 1973

Elaterosporites klaszi (Jardiné and Magloire 1965) Jardiné 1967

Elaterosporites protensus (Stover 1963) Jardiné 1967

Elaterosporites verrucatus (Jardiné and Magloire 1965) Jardiné 1967

Equisetosporites ambiguus (Hedlund 1966) Singh 1983

Equisetosporites brasiliensis (Herngreen 1973) nov. comb.

Equisetosporites cf. *E. brasiliensis* (Herngreen 1973) nov. comb.

Equisetosporites concinnus Singh 1964

Equisetosporites dudarensis (Deák 1964) Lima 1980

Equisetosporites irregularis (Herngreen 1973) Lima 1980

Equisetosporites lanceolatus Lima 1980

Equisetosporites leptomatus Lima 1980

Equisetosporites minuticostatus Lima 1980

Equisetosporites strigatus (Brenner 1968) Lima 1980

Eucommiidites cf. *E. minor* Groot and Penny 1960

Gnetaceaepollenites barghoornii (Pocock 1964) Lima 1980

Gnetaceaepollenites aff. *G. barghoornii* (Pocock 1964) Lima 1980

Gnetaceaepollenites clathratus form α Stover 1964

Gnetaceaepollenites clathratus form β Stover 1964

Gnetaceaepollenites concisus Regali 1989

Gnetaceaepollenites fissuratus (Paden-Phillips and Felix 1971) Lima 1980

Gnetaceaepollenites jansonii (Pocock 1964) Lima 1980

Gnetaceaepollenites mollis (Srivastava 1968) Lima 1980

Gnetaceaepollenites oreadis Srivastava 1968

Gnetaceaepollenites pentaplicatus Regali 1989

Gnetaceaepollenites aff. *G. pentaplicatus* Regali 1989

Gnetaceaepollenites cf. *G. pentaplicatus* Regali 1989

Gnetaceaepollenites retangularis Lima 1980

Gnetaceaepollenites santosii Lima 1980

Gnetaceaepollenites uesuguii Lima 1980

Pentapsis simplex Regali, Pedrão and Barrilari 2000

Singhia acicularis Lima 1980

Singhia montanaensis (Brenner 1968) Lima 1980

Singhia urwashii Srivastava 1968

Spheripollenites psilatus Couper 1957

Spheripollenites scabratus Couper 1958

Steevesipollenites alatiformis Regali, Uesugui and Santos 1974

Steevesipollenites cf. *S. alatiformis* Regali, Uesugui and Santos 1974

Steevesipollenites aff. *S. alatiformis* Regali, Uesugui and Santos 1974

Steevesipollenites binodosus Stover 1964

Steevesipollenites cf. *S. binodosus* Stover 1964

Steevesipollenites cupuliformis Azéma and Boltenhagen 1974

Steevesipollenites dayani Brenner 1968

Steevesipollenites giganteus Regali et al. 1974

Steevesipollenites grambasti Azéma and Boltenhagen 1974

Steevesipollenites patapscoensis (Brenner 1963) Lima 1980

Steevesipollenites sp. 1 Lima 1980

Steevesipollenites sp. 2 Antonioli 1998

Steevesipollenites sp. 2 Regali 1989

Angiosperms

Afropollis jardinus (Brenner 1968) Doyle, Jardiné and Doerenkamp 1982

Afropollis aff. *A. jardinus* (Brenner 1968) Doyle, Jardiné and Doerenkamp 1982

Cretacaeiporites mulleri Herngreen 1973

Cretacaeiporites polygonalis (Jardiné and Magloire 1965) Herngreen 1973

Cretacaeiporites scabratus Herngreen 1973

Dichastopollenites reticulatus May 1975

Hexaporotricolpites lamellaferus Jardiné, Doerenkamp and Legoux 1970

Hexaporotricolpites potoniei Boltenhagen 1969

Liliacidites cf. *L. variegatus* Couper 1953

Penetetrapites mollis Hedlund and Norris 1968

Pennipollis peroreticulatus (Brenner 1963) Friis, Pedersen and Crane 2000

Pennipollis reticulatus (Brenner 1963) Friis, Pedersen and Crane 2000

Quadricolpites reticulatus Wingate 1980 emend. Ward 1986

Stellatopollis dejaxii Ibrahim 2002

Stellatopollis densiornata (Lima 1976) Ward 1986

Stellatopollis dubia? (Lima 1976) Ward 1986

Stellatopollis aff. *S. limai* Ibrahim 2002

Tetracolpites reticulatus Srivastava 1966b

Trisectoris reticulatus (Regali, Uesugui and Santos 1974) Heimhofer and Hochuli 2010

Pollen grains with unknown botanical affinity

Psiladicolpites comptus Regali 1989

Psiladicolpites cf. *P. comptus* Regali 1989

Psiladicolpites laevis Regali 1989

Psiladicolpites papillatus Regali 1989

Chlorococcalean Algae

Botryococcus spp.

Ovoidites parvus (Cookson and Dettmann 1959) Nakoman 1966

Ovoidites spriggi (Cookson and Dettmann 1959) Zippi 1998

Prasinophyceans

Cymatiosphaera? sp.

Maranhites mosesii (Sommer 1956) Brito 1967
Tasmanites spp.

Zooclasts

Copepod egg - crustacean

Acritarchs

Duvernaysphaera angelae Deunff 1964

Exochoderma? sp.

Umbellasphaeridium saharicum Jardiné, Combaz, Magloire, Peniguel and Vachey 1972

"Incertae sedis" palynomorphs

Chomotriletes fragilis Pocock 1962

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