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New sedimentary unit with subaqueous facies of Curitiba Sedimentary Basin, Southern Brazil

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Abstract
The Curitiba Sedimentary Basin (CSB) is a small and shallow sedimentary basin, which is part of the Continental Rift of Southeastern Brazil. New exposures allowed for the identification of a subaqueous facies association, named Guatupê Unit, within the Guabirotuba Formation. For the first time in the CSB, sedimentary facies clearly deposited within a subaqueous environment, probably a swamp, are described and consists of wavy heterolithic and massive mud with linsen. In addition, mudflow deposits entering the water body are also identified and documented by massive sand facies with organic matter and load structures at their base. The latter indicates that the underlying sediments were plastic and contemporary. These sedimentary features, associated with palynoflora and a fossil trunk tree, indicate that the climate was humid enough to maintain permanent water bodies, like swamps, and vegetation, including trees. Other facies of the Guatupê Unit document mudflows and channelized tractive fluxes, whose association indicates that they were probably deposited in an alluvial fan environment. The facies, facies association, depositional processes, environment, and Miocene age of the Guatupê deposit are quite different from the previous sedimentary units reported for CSB sedimentary infill and the original definition of the formations.

KEYWORDS: Guatupê; Guabirotuba Formation; Curitiba Basin; Cenozoic; South America.

INTRODUCTION

The Curitiba Sedimentary Basin (CSB) is a small and shallow sedimentary basin developed over the Curitiba Plateau (Salamuni 1998). Its average sedimentary thickness is about 40 m, and its maximum thickness is 80 m (Salamuni *et al.* 2003). Its original extension was estimated at around 3,000 km^2 (Salamuni 1998), and the remaining area after fluvial dissection is estimated at 1,150 km^2 (Riccomini *et al.* 2004, Fig. 1).

The first reference to CSB was at the end of the nineteenth century by Siemiradzki (1898). Several mentions were made until the 1960s (Oliveira 1927, Carvalho 1934, Oliveira and Leonardos 1943, Maack 1947, 1948, Almeida 1952, 1955, Coutinho 1955, Ab'Saber 1957a, 1957b), but specific works on the sedimentary infill of CSB were performed between the end of the 1950s and the beginning of 1960s (Bigarella 1956, Bigarella and Salamuni 1957, 1958, 1959, 1962, Bigarella *et al.* 1961). Since that, several works have been performed on tectonic (Almeida 1976, Melo *et al.* 1985, Salamuni 1998, Salamuni *et al.* 1999, 2003, 2004, Riccomini 1989, Riccomini *et al.* 1989, 2004, Zalán and Oliveira 2005), stratigraphy and sedimentology (Becker 1982, Coimbra *et al.* 1996, Sant'Anna 1999, Machado 2009, Lima 2010, Cunha 2011, Lima *et al.* 2013, Vieira and Fernandes 2020, Vieira 2022), paleontology (Liccardo and Weinschütz 2010, Rogério *et al.* 2012, Garcia *et al.* 2013, Dias *et al.* 2014, Sedor *et al.* 2014, 2017, 2022, 2023a, 2023b, 2023c, Cunha 2016), palynology (Arai *et al.* 2023), and geoconservation aspects (Fernandes *et al.* 2016).

In 2021, road works provided new ephemeral exposures of the CSB where facies with abundant organic matter, and plant debris, including a tree trunk, were observed for the first time. A rich Miocene palynoflora was also therein identified (Arai *et al.* 2023). The occurrence of new facies undoubtedly deposited in a water body, probably a pond and swamp not previously identified in the CSB, prompted us to study this new sedimentary unit of CSB, named Guatupê Unit of Guabirotuba Formation (GF), whose characterization and interpretation are objective of this paper.

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REGIONAL SETTING

The CSB is part of the Continental Rift of Southeastern Brazil (Melo *et al.* 1985, Riccomini *et al.* 1989, 2004). In contrast to the other basins of this rift system, consisting of grabens,

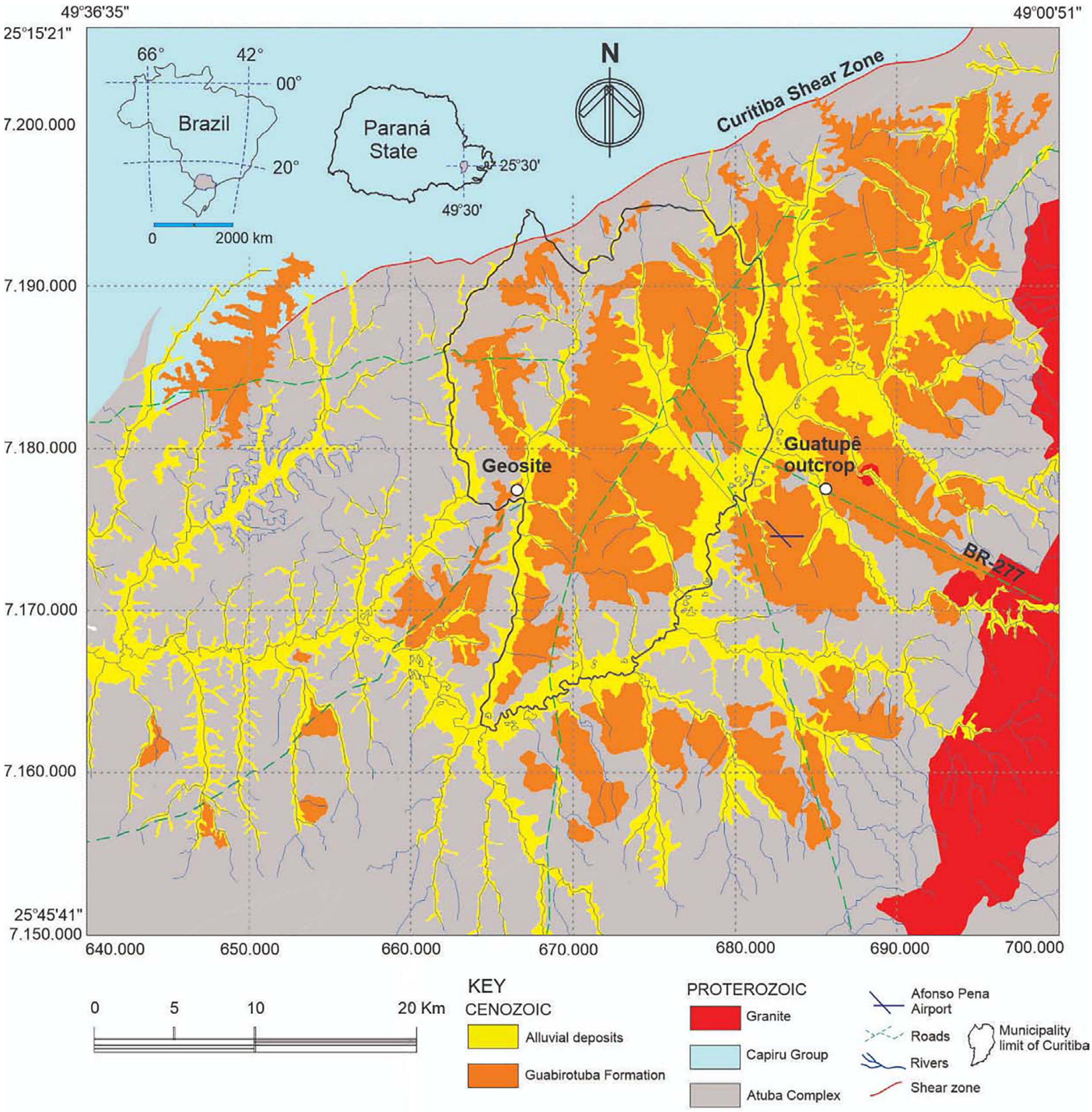

Figure 1. Area covered by CSB sedimentary deposits (after Salamuni *et al.* 2004). Note the large alluvial plains and the underfit modern meandering river channels.

the CBS is not clearly related to any structural feature at the regional scale (Zalán and Oliveira 2005), although Salamuni *et al.* (2003) proposed that nucleation and initial filling of the basin could have been provided by an aborted semi-graben.

The CSB sediments lie over the Proterozoic basement of the Atuba Complex (Siga Jr. *et al.* 1995), which consists of granites, gneisses, and migmatites intruded by Mesozoic diabase dikes related to the opening of the South Atlantic Ocean (Coutinho 2008). At present time, the preserved margin of the CSB is erosional (Fig. 1). A large paleo-fluvial network later dissected the CSB sedimentary cover and generated large alluvial plains (Fig. 1). The modern fluvial network, which corresponds to the Iguaçu River, shows underfit meandering river channels (Fig. 1).

In the CSB region, the climate is mesothermic and very humid without a dry season (Klein 1975). The mean annual temperature is between 15 and 20°C, and the mean annual rainfall spans 1,500–2,500 mm (Klein 1975). Predominant soils are Latosol and Cambisol (Fasolo *et al.* 2002). The CSB area was originally covered by meadows and *Araucaria* forest (Klein 1975), although nowadays most of the area is urbanized by the Curitiba Metropolitan Region.

Sedimentary deposits and stratigraphy

Bigarella and Salamuni (1962) identified two sedimentary "sequences" within the CSB, one corresponding to the GF and the other one to the modern fluvial deposits (Fig. 1). Later, three lithostratigraphic units were proposed: the Tinguis and Boqueirão Formations (Fms) by Becker (1982) and the Piraquara Formation (Fm) by Coimbra *et al.* (1996). The definition of these units is controversial because of the lack of data and different interpretations. The Tinguis and Boqueirão Fms are reported in an unpublished thesis, and the Piraquara Fm was just described in a congress abstract. In her Ph.D. thesis, Becker (1982) proposed the Tinguis Fm, which consists of feldspar-rich sand and fine-grained sediments overlying the GF. The Tinguis Fm layers were previously considered part of the GF (Bigarella and Salamuni 1962). A 1.2–1.5-m-thick bed of pink gravelly sand with incipient stratification composes the type-section in Tinguis Street, Curitiba (Becker 1982). Becker (1982) also used the denomination Boqueirão Formation to identify floodplain sand deposits attributed to the Late Pleistocene.

Coimbra *et al*. (1996) proposed the Piraquara Fm for reddish and whitish sands and clays with plane-parallel horizontal lamination and fining-upward trend, alternated with sigmoidal cross-stratified sand. These sediments occur with 3–5 m of thickness at the tops of the hills in the CSB area, laying above the GF with a transitional lower boundary. The Piraquara Fm is attributed to a meandering fluvial system, where clay was deposited in floodplains and sand in crevasse splay, respectively (Coimbra *et al*. 1996). The authors pointed out that the Piraquara Fm sediments are not correlative of the Guabirotuba Fm, because the latter pertains to a braided fluvial system, and neither to the Tinguis Fm, which is interpreted as the weathered part of Guabirotuba Fm (Coimbra *et al*. 1996).

According to Bigarella and Salamuni (1962), GF is the main stratigraphic unit of the CSB, with a thickness of around 60–80 m, and is mainly composed of claystone, feldspar-rich sand, and local conglomerates. The sediments are coarse-grained along the basin margin and finer in the central part. Because of the occurrence of abundant calcretes, the depositional environment was interpreted as alluvial fans and playa-lakes deposited under a semi-arid climate. Due to the lack of fossils, GF was tentatively considered Plio-Pleistocene (Bigarella *et al*. 1961).

Because the former type section of GF has been hidden by urbanization, a new one has been proposed at the fossiliferous site named CSB Geosite (Fig. 1; Vieira and Fernandes 2020), where the depositional environment is interpreted as "shallow channel deposits and floodplains of braided rivers in distributary fluvial systems" (Vieira and Fernandes 2020).

METHODS

At the Guatupê outcrop (25°30'09"S, 49°08'56"W; Fig. 1), we described six profiles named C1.SE, C1.NE, C2.SE, C2.NE, C3.SE, and C3.NE (Fig. 2). Facies description and interpretation were performed according to Walker and James (1992) with facies codes adapted from Miall (1978, 1996). The erosional surfaces were classified according to Miall (1996). Granulometric and X-ray diffraction (XRD) analyses were performed at the Minerals and Rocks Laboratory (LAMIR) of the Universidade Federal do Paraná (UFPR). The granulometric analysis was performed by wet laser diffraction with a Microtac S3500 particle size analyzer, and the XRD determination was performed according to Moore and Reynolds Jr. (1989). Palynological results are discussed elsewhere (Arai *et al*. 2023).

RESULTS

Sedimentary units

At the Guatupê outcrop, three sedimentary units were recognized, respectively, named Unit A, B, and C. Units A and B are superimposed and bounded by third-order erosional surfaces, and Unit C occurs isolated. Unit A has been named Guatupê Unit of GF.

Eight sedimentary facies bounded by second-order surfaces are recognized in the Guatupê Unit, two in Unit B, and one in Unit C (Table 1). The sedimentary succession lies above a strongly weathered basement composed of Lower Proterozoic Atuba migmatites complex and Early Cretaceous diabase dikes. All the unstable minerals have been transformed into clay minerals, and the basement surface is erosional and irregular.

Unit A (Guatupê Unit)

Surfaces and boundaries

Unit A, here named Guatupê Unit, shows erosional surfaces spanning three different orders. The first one corresponds to the internal lamination of sedimentary beds, the second one corresponds to the boundary of the sedimentary beds, and the third one corresponds to the unit boundary. The Guatupê Unit uncomfortably lies above the bedrock with an irregular erosional surface. The upper boundary is also erosional and characterized by the occurrence of a dark gray paleosoil. The maximum thickness observed is ca. 8 m (Fig. 3).

Sedimentary facies

In the Guatupê Unit, eight sedimentary facies were identified, respectively, named (Table 1): through cross-stratified sand (St), massive sand (Sm), massive sandy mud with organic matter and plant debris (Fm(o)), clast-supported gravel (Gh), wavy heterolithic (Hw), massive mud (Fm), massive mud with sand linsen (Fm(l)), and laminated clay (Fl). At the top, the Guatupê Unit shows pedogenetic features ascribed to a dark gray paleosoil (Ps) (Fig. 3).

Trough cross-stratified sand

Trough cross-stratified sand facies (St) is characterized by 0.3–1.0-m-thick lensoidal beds (Fig. 4). The basal contact is erosional (second-order surface). Sediment texture consists of poorly sorted gravelly sand with immature mineralogical petrography, frequently arranged in a fining-upward trend. This facies is interpreted as lunate or linguoid (3-D) subaqueous dunes.

Massive sand

The massive sand facies (Sm) is characterized by 0.3–1.5-m-thick lensoidal beds with erosional lower boundary (Fig. 3). The beds can be overlapped or alternated with cross-stratified sand beds. Sediment texture consists of poorly sorted gravelly sand with immature composition and variable content of mud. The clasts can reach boulder size. The beds

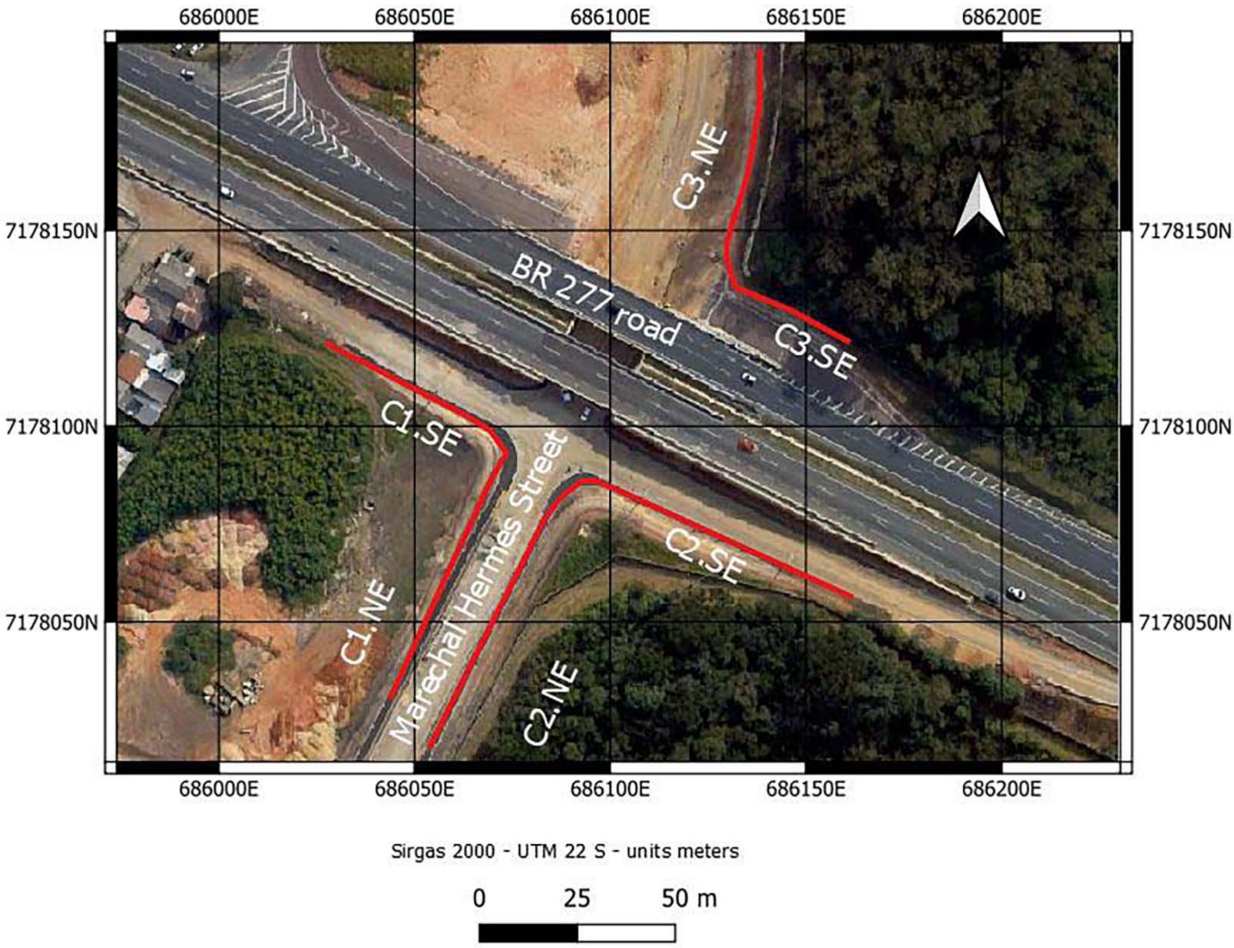

Figure 2. Guatupê outcrop profile localization.

Table 1. Sedimentary units and facies recognized at the Guatupê outcrop.

Unit	Facies	
	Name	**Code**
A*	Trough cross-stratified sand	St
	Massive sand	Sm
	Massive sandy mud with organic matter and plant debris	Fm(o)
	Clast-supported gravel	Gh
	Wavy heterolithic	Hw
	Massive mud	Fm
	Massive mud with sand linsen	Fm(l)
	Laminated clay	Fl
B	Massive sand	Sm
	Massive mud	Fm
C	Trough cross-stratified sand	St

*Guatupê Unit.

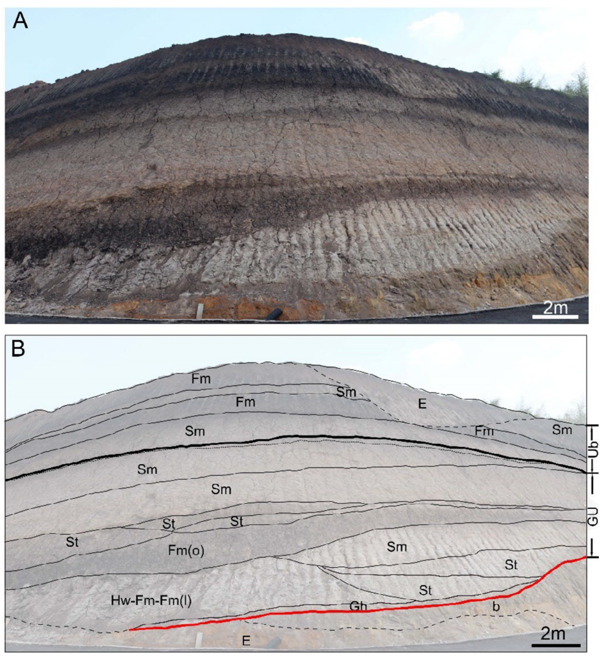

Figure 3. (A) Overview and (B) facies interpretation of Guatupê Unit (GU) and Unit B (Ub) at C1.SE/NE profile (see Fig. 2 for location). Massive mud (Fm); massive sand (Sm); trough cross-stratified sand (St); massive sandy mud with organic matter and plant debris (Fm(o)); wavy heterolithic (Hw); massive mud with sand linsen (Fm(l)); clast-supported gravel (Gh); bedrock (b); and hidden (E). Unit boundaries: nonconformity (red line), third-order erosional surface (black bold line). Second-order erosional surfaces correspond to facies limits (black lines) and hidden limits (dashed lines).

frequently show a fining-upward trend. This facies also contains deformed muddy-sand clasts (Fig. 5). The clay fraction is composed of smectite (montmorillonite), kaolinite, and probably chlorite and vermiculite (Tables 2 and 3, Sample 4.1). This facies is attributed to be produced by mudflow and debris flow.

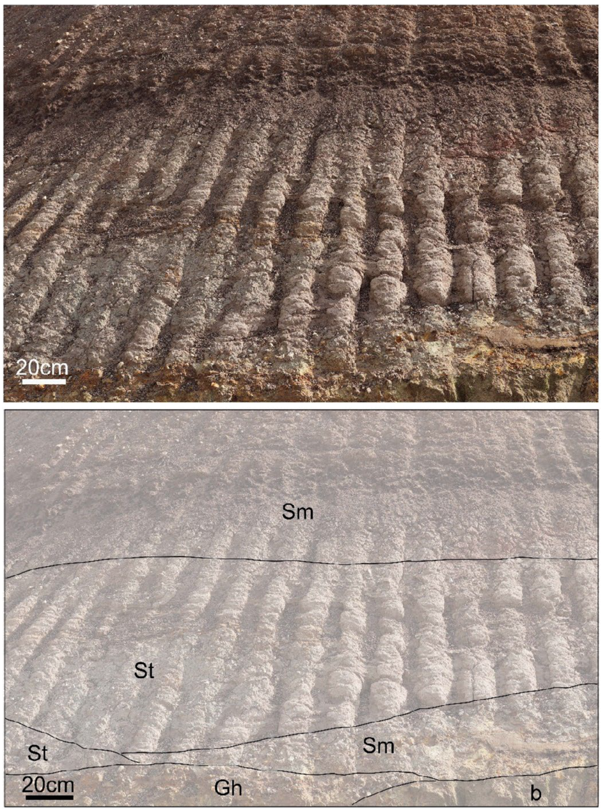

Figure 4. Trough cross-stratified sand (St), massive sand (Sm), clast-supported gravel (Gh), and bedrock (b).

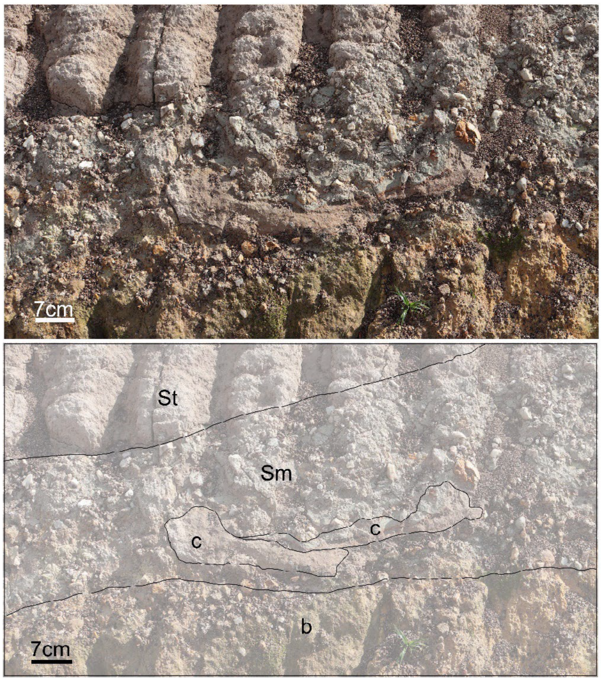

Figure 5. Deformed mud clast (c) within the massive sand facies (Sm). Trough cross-stratified sand facies (St) and bedrock (b) are also shown.

Massive sandy mud with organic matter and plant debris

The massive sandy mud with organic matter and plant debris facies (Fm(o)) is characterized by 0.3–0.5-m-thick irregular beds with erosional basal contact (Fig. 3). The texture consists of poorly sorted, organic-rich gravelly sand with immature petrography and plant debris, including tree trunks. Overall, the amount of gravel, sand, and fines is variable: excluding the gravel content, the sand can reach 36% and the fines 81% (Tables 2 and 3, Samples 1.1 and 2.1). Load structures are observed when this facies occurs above the Hw and Fm(l) facies. This facies is attributed to be produced by mudflow and debris flow.

Clast-supported gravel

The clast-supported gravel facies (Gh) is characterized by 0.1–0.2-m-thick tabular or irregular beds with erosional base. The texture is constituted by polymictic gravel, with dominant migmatite clasts that are strongly weathered and the clasts could present chemical bands (Fig. 6). One weathered clast granulometric analysis gave 9% of sand and 91% of fines (Table 2, Sample 7.1). This facies is interpreted as basal gravel produced by high-energy tractive flux.

Wavy heterolithic

The wavy heterolithic facies (Hw) is characterized by massive mud wavy drapes alternated with fine-grained, very well sorted quartzose sand wavy laminae (Fig. 7, Table 2, Samples 5.1, 6.1, and 8.1). The laminae thickness is 1–5 cm. Contorted laminae and deformation structures are frequent (Fig. 7). This facies changes laterally and vertically to Fm(l). Hw facies was generated by intermittent tractive fluxes. The sand planar laminae indicate high-regime planar bedforms, and the sand wavy laminae are ascribed to low-regime ripple bedforms. The clay laminae are drapes generated by the decantation process during calm-water periods.

Massive mud

Massive mud (Fm) is characterized by 0.1–0.3-m-thick tabular to irregular beds with a transitional lower boundary to massive mud with linsen (Fm(l) facies) (Fig. 7). The beds can change laterally to massive sand (Sm). Sediment texture consists of mud with a variable content of fine-grained sand. This facies is interpreted as produced by the decantation process alternating to weak tractive fluxes.

Massive mud with sand linsen

The massive mud with sand linsen facies (Fm(l)) is characterized by massive mud drapes alternated with planar and rippled sand laminae (Fig. 7). The mud laminae are 5–15 cm thick, and the sand laminae are 0.5–2 cm thick. This facies changes laterally and vertically to Hw (Fig. 7). This facies was produced by similar processes to Hw facies and has been differentiated because of a higher fine/sand ratio.

Laminated clay

The laminated clay facies (Fl) is characterized by finely laminated clay (Fig. 8 and Table 2, Sample A8). The basal contact could not be observed, being accessible only the upper 0.4 m of the facies. This facies was produced by the decantation process in a water body.

Table 2. Grain size classes and Folk and Ward statistical parameters of the Guatupê outcrop facies.

SI	Unit	Facies	Grain size classes (%)								
			G	Gr	VCS	CS	MS	FS	VFS	S	F
4.1	A	Sm(1)	0.82	3.77	6.98	5.52	14.06	16.98	4.01	52.20	47.70
1.1	A	Fm(o)	1.56	1.46	3.61	5.24	6.10	9.30	8.73	35.99	64.01
2.1	A	Fm(o)	–	0.37	0.79	1.55	1.61	7.72	6.58	18.62	81.38
A7	A	Fm(o)	0.19	1.42	4.26	6.58	6.25	7.65	10.34	36.68	63.32
7.1	A	Gh(2)	–	0.35	0.07	0.13	0.33	2.45	5.77	9.10	90.90
5.1	A	Hw	–	0.01	0.02	0.07	3.81	34.72	20.22	58.86	41.14
8.1	A	Hw	0.77	0.61	0.50	0.41	0.50	2.63	9.99	15.42	84.58
6.1	A	Hw(3)	–	–	0.07	0.49	10.11	53.22	14.59	78.48	21.52
A8	A	Fl	–	–	–	–	–	0.08	0.17	0.25	99.75
A9	B	A(p)	0.09	0.72	2.88	3.83	4.83	6.31	6.75	25.40	74.60
A10	B	A(a)	0.27	1.13	3.83	3.26	4.60	8.57	8.25	29.91	70.09
A11a	B	Sm(o)	0.24	0.64	2.69	4.14	4.55	6.01	6.01	24.27	75.73
A11b	B	S(m)	3.26	3.56	4.46	5.05	4.27	6.58	6.89	34.08	65.92
01	C	St	–	0.39	1.25	3.56	10.39	9.64	8.04	33.28	66.72
02	C	St	–	0.48	1.64	5.32	10.69	20.44	8.97	52.29	47.71
9.1	C	St	–	0.05	0.38	3.02	11.37	21.05	9.90	45.78	54.22

SI: sample identification; G: gravel; Gr: granule; VCS: very coarse sand; CS: coarse sand; MS: medium sand; FS: fine sand; VFS: very fine sand; S: total sand; F: total fines; [1]from contorted muddy-sand clast at Sm facies; [2]weathered clast from Gh facies; [3]sand lamina from Hw facies.

Table 3. Mineral composition of the Guatupê outcrop facies by XRD analysis.

SI	Unit	Facies	Total powder	Treatment
4.1	A	Sm(1)	Quartz, Microcline, Albite	Smectite (Montmorillonite), Kaolinite, Chlorite (probable), Vermiculite (probable)
2.1	A	Fm(o)	Quartz, Magnetite, Microcline	Kaolinite, Smectite, Mica (Illite)
A7	A	Fm(o)	Quartz; Microcline	Smectite (Montmorillonite); Kaolinite
7.1	A	Gh(2)	Quartz, Illite, Anatase	Kaolinite; Mica (Illite)
5.1	A	Hw	Quartz, Microcline, Augite (probable)	Smectite (Montmorillonite), Kaolinite
8.1	A	Hw	Quartz, Microcline, Augite (probable)	Smectite (Montmorillonite); Kaolinite; Illite (probable)
A8	A	Fl	Quartz, Anatase	Kaolinite; Mica (Illite); Dodecahedral Vermiculite
A9	B	A(p)	Quartz, Anatase, Gibbsite	Kaolinite; Dodecahedral Vermiculite
A10	B	A(a)	Quartz, Anatase, Gibbsite	Kaolinite; Dodecahedral Vermiculite
A11a	B	Sm(o)	Quartz, Anatase, Gibbsite, Microcline	Kaolinite; Vermiculite
A11b	B	S(m)	Quartz, Anatase, Microcline, Albite	Kaolinite; Dodecahedral Vermiculite, Mica (Illite)
01	C	St	Quartz; Microcline	Smectite (Montmorillonite); Chlorite
02	C	St	Quartz; Microcline; Augite (probable)	Smectite (Montmorillonite); Chlorite; Mica (Illite)
9.1	C	St	Quartz, Microcline, Plagioclase	Smectite (Montmorillonite); Kaolinite (probable); Illite (probable)

SI: sample identification; [1]from contorted muddy-sand clast at Sm facies; [2]weathered clast from Gh facies.

Facies Association

Facies Association of wavy heterolithic, massive mud, and massive mud with sand linsen

The facies association of wavy heterolithic, massive mud, and massive mud with sand linsen (FAL) lies over a clast-supported gravel Gh and below the dark gray massive sandy mud with organic matter and plant debris facies (Fm(o)) (Fig. 7). The laminae of this facies association show micro-faults and deformed laminae and can dip 10–15° (Fig. 7). The lower and upper contacts are abrupt and irregular, and the lower one presents load structures, which indicates that sediment was plastic at the time of their depositions. Therefore, there was no significant time lap between the depositions of the sediments of the different facies of this facies association. The FAL is interpreted as the bottom sediment of a water body, probably a swamp, where intermittent tractive fluxes occur.

Facies Association of massive sand and cross-stratified sand

The facies association of massive sand and cross-stratified sand (FAC) constitutes most of the Guatupê Unit.

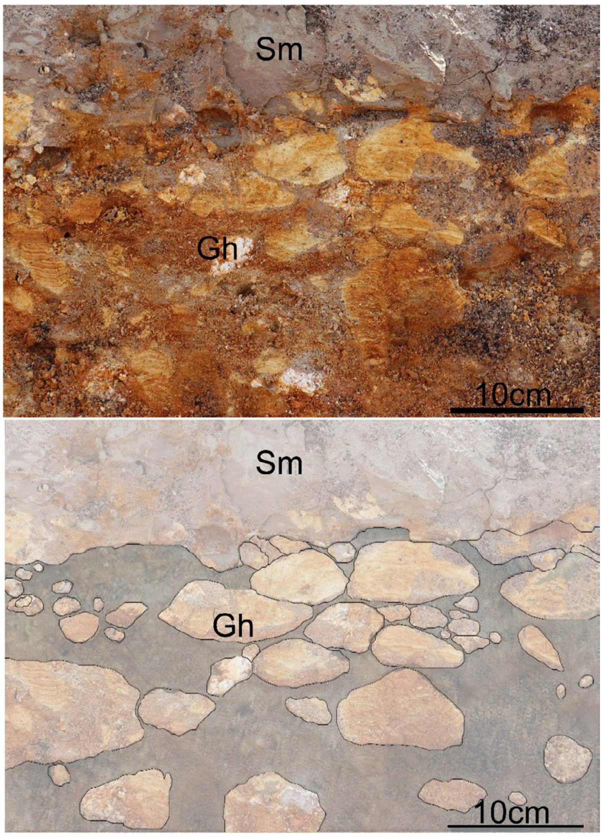

Figure 6. Highly weathered clast-supported gravel facies (Gh) with chemical bands, overtopped by a massive sand facies (Sm). The shadow areas correspond to sectors where the gravels cannot be distinguished in the picture because they are weathering or hidden by recent sand falling from the higher parts of the outcrops and not to the syngenetic matrix.

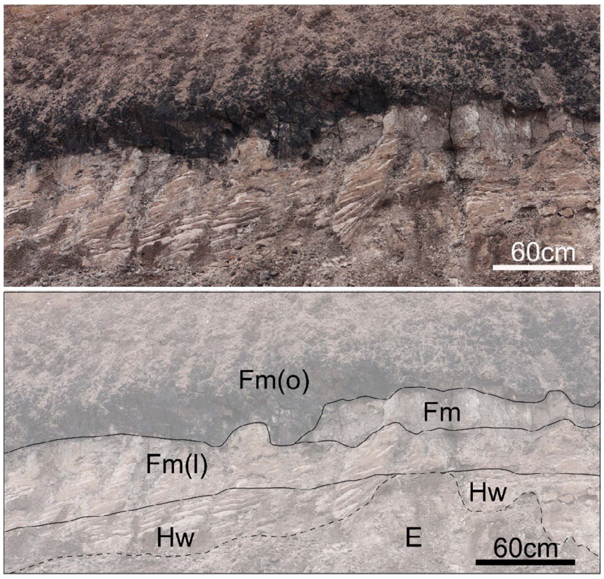

Figure 7. Wavy heterolithic (Hw), massive mud with sand linsen (Fm(l)), and massive mud (Fm) facies, corresponding to the facies association (FAL), overlaid by massive sandy mud with organic matter and plant debris (Fm(o)). Note the load structures at the base of Fm(o) and the deformation structures within the wavy heterolithic (Hw) and massive mud with sand linsen facies (Fm(l)) facies. (E) Covered.

The observed maximum thickness is around 7 m. The massive sand facies was generated by mudflows and debris flows. Locally the massive sand with organic matter and plant debris was deposited over the FAL, producing load structures (Fig. 7).

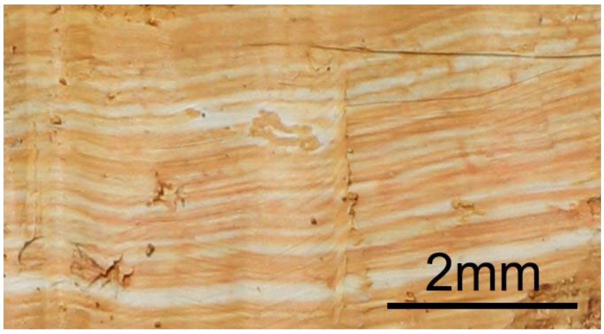

Figure 8. Laminated clay facies (Fl).

This relationship is interpreted as mudflows and debris flows entering a swamp and depositing over the water body floor sediments. In some places, the sediments of the FAC were directly deposited over the bedrock. The cross-stratified sand of this facies association was generated by tractive fluxes in unconfined or shallow channels. At the top, FAC presents a paleosoil horizon.

Unit B

Reddish and gray tabular and lensoidal massive sand beds (Sm) and dark gray tabular massive mud (Fm), interpreted as paleosoil horizons, form the Guatupê-B unit (Fig. 3). The observed maximum thickness is 2 m. Because of the reduced thickness, no facies association was interpreted.

Unit C

Unit C occurs at the profile C3.NE (Fig. 2), at a topographic level higher than the Guatupê Unit and Unit B. The contact between Unit C and the others was not observed because it is covered by a road; locally, Unit C directly lies on the bedrock. Unit C is composed of a set of trough cross-stratified sand lensoidal beds (Fig. 9). The facies shows a reddish color because of weathering (Fig. 9). The bed thickness is 0.2–0.6 m, and the base is erosional. The beds frequently show a fining-upward trend. The St facies is constituted by poorly sorted and petrographically immature gravelly sand. The unstable minerals, such as feldspar, are weathered and transformed into clay minerals. The sand content ranges from 33 to 52% and the fines from 48 to 67% (Table 2, Samples 01, 02, and 9.1). This facies is interpreted as lunate or linguoid subaqueous dunes generated by the tractive flux in shallow channels, likely in a braided fluvial system. The average paleo-current directions are from east to west.

DISCUSSION

Depositional processes and environments

The facies and facies association indicate that the three sedimentary units recognized at the Guatupê outcrop were deposited under different environmental conditions and probably at different times.

The Guatupê Unit (Unit A) has the largest exposure (Fig. 3). It bears spores, pollen grains, phytoliths, plant debris,

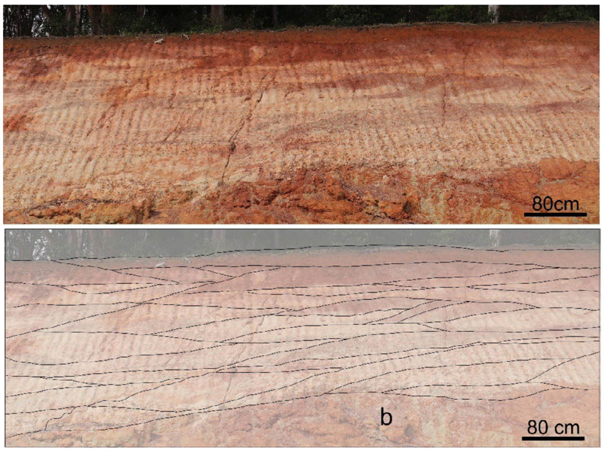

Figure 9. Lensoidal beds with trough cross-stratified sand facies (St) in Unit C, lying over the bedrock (b), at profile C3.NE (see Fig. 2 for location).

and a tree trunk (Arai *et al.* 2023). The unit lies above the bedrock, starting with a basal clast-supported gravel (Gh) generated by a high-energy tractive flux. Above Gh, the FAL facies association occurs, which was deposited within a water body, probably a pond (Figs. 3 and 7). Intermittent weak currents entered the pond, transporting and sorting the sand grains and generating the sand lamina, of the Hw facies. During quiet periods, the fine-grained particles were settling down and generating the massive mud and the mud laminae (drapes) of Hw and Fm(l) facies. Above the FAL facies association, a dark-gray massive muddy sand with organic matter and plant debris (Fm(o)) occurs. Its basal contact is abrupt with load structures, which indicates that underlying sediments were plastic during sedimentation and that the facies are contemporary. The FAL facies association also shows deformed laminae, which suggests that the massive muddy sand was transported by mudflow and deposited in a shallow water body, probably a swamp, where anoxic conditions prevailed. The FAL facies association is tilted (10–15°) and presents deformational structures, such as micro-faults and deformed laminae, which are interpreted as generated by gravitational movements (Fig. 7). The middle and upper parts of the Guatupê Unit are mainly composed of lensoidal beds of cross-stratified sand (St), which indicate deposition in shallow fluvial channels by tractive fluxes. This facies laterally switches to massive sand (Sm) and massive sandy mud (Fm(o)) facies generated by mudflows and debris flow deposits. This facies association is the characteristic of alluvial fan deposits. After the deposition, of the Guatupê Unit sediments, a soil developed at the top (Fig. 3).

Unit B overlies the Guatupê Unit and corresponds to pulses of mudflow events alternating with periods of no deposition when soils developed (Fig. 3).

Lensoidal beds 0.3–1.0-m-thick with trough cross-stratified sand facies (St) constitute Unit C, which corresponds to lunate or linguoid subaqueous dunes, probably deposited in shallow channels of a braided fluvial system (Fig. 9). This unit is altimetrically higher than Guatupê Unit and Unit B, but because their contact is hidden, their relative stratigraphy cannot be established.

The high content of fine-grained sediments in the St Facies

The high content of fine-grained sediment in the St Facies of Guatupê Unit and Unit C is incompatible with the original deposition in subaqueous dunes by tractive fluxes. By considering the overall immature petrography we observed, our interpretation is that the fine particles, mainly clay, were produced *in situ* by post-depositional weathering of unstable minerals, such as feldspar. Evidence of this is the presence of 90% of fine-grained particles and clay minerals, mainly kaolinite, in the weathered migmatite clasts of the basal gravel facies (Gh) of the Guatupê Unit (Sample 7.1, Tables 2 and 3, and Fig. 5).

Chronology and paleoclimate

Sedimentary deposits of the CSB are mostly non-fossiliferous, and the GF was tentatively ascribed to different Cenozoic series (e.g., Bigarella and Salamuni 1962). According to Garcia *et al.* (2013), the palynological assemblage identified in few outcrops of GF would suggest a Late Miocene-Pliocene age. Vertebrate fossils found at the CSB Geosite (Fig. 1) indicate a middle Eocene fauna (Sedor *et al.*, 2022, 2023a, 2023b, 2023c). The abundant palynological assemblage retrieved within the Guatupê Unit indicates the Miocene age (Arai *et al.* 2023).

Paleoclimate during the Guabirotuba Fm was considered semi-arid because of the abundant occurrence of calcretes (Bigarella and Salamuni 1962), which also occurred at the CSB Geosite (Vieira and Fernandes 2020). In contrast, no calcareous concretions were observed in the Guatupê deposit suggesting deposition under different paleoclimate or paleoenvironmental settings. The occurrence of water bodies and anoxic conditions indicate a humid climate. Therefore, it is possible that CSB was infilled during different episodes and different climates during the Cenozoic Era.

The Guatupê Unit and the CSB stratigraphy

The sedimentary description and facies interpretation presented in this study highlight for the first time the occurrence of water body depositional environment within the CSB. As reported at the beginning, the previous studies mostly documented facies related to high-energy rivers of a distributary system. In the case of the Guatupê outcrop, the occurrence of ponds and swamps is supported by the abundance of low-energy, organic-rich sediments, and water-logged soils. This remarkably different depositional environmental identity, defined by the third-order erosional boundary, justifies in our opinion the definition of a new sedimentary unit within the Guabirotuba Fm, named Guatupê Unit. Due to the unique occurrence and the unmappable size at 1:25,000 scale, the Guatupê unit is not currently formalized as a lithostratigraphic unit and must be considered informal.

Correlation between different stratigraphic units of CSB is hampered by the lack of lateral continuity and superposition, as pointed out by Becker (1982). In addition, the fossiliferous deposit at the CSB Geosite, with a well-defined middle Eocene age, is thin, isolated, and located at the basin margin. Two other problems complicate the stratigraphic framework of the CSB: the first one is that it is not possible to reassess some sites where the units were defined because they have been destroyed or hidden by urbanization (e.g., GF according to Bigarella and Salamuni (1962), and Tinguis Formation according to Becker 1982). The second one is that sites where the Piraquara Formation was defined (Coimbra *et al.* 1996) were not localized in the study (congress abstract).

CONCLUSION

For the first time in the CSB, we described facies which clearly deposited within a subaqueous environment, probably a pond, where intermittent tractive fluxes occurred. In the Guatupê Unit, the subaqueous facies consists of wavy heterolithic (Hw) and massive mud with linsen (Fm(l)) of the Facies Association FAL. In addition, mudflow deposits entering the water body were also identified, which are documented by the massive sand facies with organic matter (Sm(o)), overlying the facies association FAL with load structure at their base. This points out that the underlying sediments were plastic and that the facies are contemporary. These sedimentary characteristics associated with palynoflora (Arai *et al.* 2023) and a fossil trunk tree indicate that the climate was humid enough to maintain permanent water bodies, like ponds, and vegetation, including trees. The other facies of the Guatupê Unit indicates mudflows (Sm and Fm(o)) and channelized tractive fluxes (St and Gh), which association (FAC) indicates that they were probably deposited in an alluvial fan environment. Therefore, we proposed here the name Guatupê Unit of GF for Unit A of the Miocene age, based on palynology (Arai *et al.* 2023).

We stress that facies, facies association, and the inferred depositional processes and environment of Guatupê Unit are quite different from the previous ones reported for CSB sedimentary infill and original definition of the formations (e.g., Bigarella and Salamuni 1962 for GF; Becker 1982 for Tinguis and Boqueirão Formations; and Coimbra *et al.* 1996 for Piraquara Formation). The facies, facies association, depositional processes, environment, and age (Miocene) of the Guatupê Unit are also quite different from sedimentary deposits of CSB Geosite (middle Eocene).

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