Annales Societatis Geologorum Poloniae (2020), vol. 90: 247–260 doi: https://doi.org/10.14241/asgp.2020.15

TRACE FOSSILS FROM THE UPPER CRETACEOUS CAPACETE FORMATION, SANFRANCISCANA BASIN, CENTRAL BRAZIL

Daniel SEDORKO[1*], Luciano ALESSANDRETTI[1], Lucas Veríssimo WARREN[2], Mariano VERDE[3], Caio César RANGEL[1], Kimberly Silva RAMOS[4] & Renata Guimarães NETTO[4]

[1] Institute of Geography, Federal University of Uberlândia, LMG-746 Km 1, CEP 38500-000, Campus Monte Carmelo, MG, Brazil; e-mails: sedorko@ufu.br, luciano.geors@gmail.com, caiocrangel@ufu.br
[2] Department of Geology, Institute of Geosciences and Exact Sciences, São Paulo State University, Avenida 24-A, Bela Vista, 178, CEP 13506-900, Rio Claro, SP, Brazil; e-mail: lucas.warren@unesp.br
[3] Paleontology Department, Sciences Faculty, University of the Republic, Iguá 4225, 11400, Montevideo, Uruguay; e-mail: verde@fcien.edu.uy
[4] Geology Graduate Program, Unisinos University, São Leopoldo, RS, Brazil; e-mails: kimberlyr@edu.unisinos.br, nettorg@unisinos.br
**Corresponding author*

Sedorko, D., Alessandretti, L., Warren, L. V., Verde, M., Rangel, C. C., Ramos, K. S. & Netto, R. G., 2020. Trace fossils from the Upper Cretaceous Capacete Formation, Sanfranciscana Basin, Central Brazil. *Annales Societatis Geologorum Poloniae*, 90: 247–260.

Abstract: The Upper Cretaceous Capacete Formation, from the intracratonic Sanfranciscana Basin, central Brazil, consists of epiclastic sediments with a significant aeolian contribution. This unit has been traditionally interpreted as deposited by alluvial fans distally grading to braided rivers in an arid- to semiarid climate within the central part of southwestern Gondwana. Locally, some expositions with wide lateral extension show architectural elements indicative of deposition in meandering rivers, such as floodplain fines (FF) interbedded with crevasse splay (CR), lateral-accretion macroforms (LA), and channels (CH). Bioturbation within the meandering fluvial deposits is commonly associated with the floodplain element, mainly occurring in fine-grained sandstone and mudstone. The lateral-accretion elements and channel deposits are barren of trace fossils. Sandstone with climbing ripples (Sr) from the element CR show low bioturbation of meniscate trace fossils assigned to *Taenidium, Beaconites,* and *Scoyenia* ichnogenera. Simple vertical and horizontal burrows identified as *Skolithos* and *Palaeophycus* occur associated with *Taenidium* and *Camborygma* in sandstone facies (Sr, St and Sh), as well as rhizoliths, representing the *Scoyenia* ichnofacies. The predominance of trace fossils related to the FF and CR architectural elements attests to the colonization mostly by insects in episodic and vegetated flood plains of the meandering river system from the Capacete Formation. Thus, despite the primarily arid to semiarid conditions interpreted for the inner parts of the newly formed South American continent during the Upper Cretaceous, our new data support deposition under humid conditions in some intervals of the Capacete Formation from the Sanfranciscana Basin.

Key words: Meandering fluvial system, insects, continental trace fossils, *Scoyenia* ichnofacies.

Manuscript received 16 May 2020, accepted 18 September 2020

INTRODUCTION

The Upper Cretaceous Capacete Formation is an exclusively continental unit deposited by the reworking of the coeval volcanic rocks from the Santonian–Campanian Patos Formation (83.6 ± 1.4 Ma, Gibson *et al.*, 1995). This unit is classically interpreted as deposited in distal alluvial fans that grade to braided fluvial systems, with a substantial contribution of aeolian sediments (Campos and Dardenne, 1997a). The deposition under semiarid to arid conditions is grounded on the putative predominance of gravitationally-driven debris flows and aeolian processes, and the apparent absence of a paleontological record (fossils and ichnofossils, Campos and Dardenne, 1997a).

Thus, studies regarding trace fossils from the Sanfranciscana Basin are also rare and limited to a few records of vertebrate tracks (e.g., Carvalho and Kattah, 1998, Mescolotti *et al.*, 2019) and brief descriptions of invertebrate trace fossil (*Taenidium* in the Três Barras Formation of the underlying Areado Group, Mescolotti *et al.*, 2019). Considering the scarce palaeoichnological and sedimentological studies focusing on the Capacete Formation, this manuscript aims to: (1) record the first occurrence of invertebrate trace fossils in this unit; (2) apply the study of the trace fossil assemblage as an auxiliary tool for the environmental reconstitution of continental successions; and (3) contribute to the palaeoclimatic reconstitution of the inner part of the newly formed South American continent.

GEOLOGICAL SETTING

The central part of the South American Platform (Almeida, 1967) comprises Archean to Mesoproterozoic cratonic terranes surrounded by Neoproterozoic mobile belts, and both are covered by Palaeozoic and Mesozoic nonmarine deposits of intracontinental basins (Riccomini *et al.*, 2005). Following the continental breakup of Gondwana, the inner parts of the South American Platform underwent critical tectonic and magmatic events related to the opening of the South Atlantic Ocean and influence of the Trindade Mantle Plume below its continental crust (Gibson *et al.*, 1995; Thompson *et al.*, 1998). The extensive couplet tectonic uplift and magmatic activity promoted the creation of regional topographic highs that deeply influenced the sedimentation and climatic regimes of the surrounding areas (Campos and Dardenne, 1997b; Mescolotti *et al.*, 2019). From the Jurassic to Early Cretaceous, recurrent reactivations of regional structures along the Neoproterozoic Brasília Fold Belt, nearby the southwestern border of the São Francisco Craton, developed a positive tectonic feature named Alto Paranaíba High (Hasui *et al.*, 1975), which acted as a barrier separating the coeval and active Bauru and Sanfranciscana basins (Campos and Dardenne, 1997b; Riccomini *et al.*, 2005; Figs 1, 2). This topographic high was also affected by a regional magmatic event during the Late Cretaceous, being intruded by alkaline mafic- and ultramafic rocks from the Patos Formation (Mata da Corda Group, Gibson *et al.*, 1995). The emplacement of plutonic complexes and hypabyssal intrusions, followed by extrusion of lavas and tuffs related to effusive and pyroclastic magmatism (Campos and Dardenne, 1997a), influenced the configuration of the Alto Paranaíba High and the depositional architecture in the surrounding basins. In general, the Sanfranciscana Basin has its major axis oriented along N–S direction, occupying approximately 150.000 km^2 in central Brazil, corresponding to the subsiding area located to the northeast of the Alto Paranaíba High, and is divided in the Abaeté and Urucuia sub-basins (Figs 1A, 2).

Stratigraphy of the Sanfranciscana Basin

The Carboniferous to Cretaceous Sanfranciscana Basin (Fig. 1A, B) belongs to the Phanerozoic cover of the São Francisco Craton (Campos and Dardenne, 1997a). This basin comprises a mixed succession of terrigenous sedimentary rocks with minor alkaline volcanic rocks contribution encompassed within five lithostratigraphic units separated by regional-scale unconformities (Campos and Dardenne, 1997b; Fig. 2). The Late Carboniferous and Permian sedimentary succession includes the Floresta and Tabuleiro formations from the Santa Fé Group (Campos and Dardenne, 1997a). These units are unconformably covered by Lower Cretaceous continental successions from the Areado Group (see Fig. 1C; Campos and Dardenne, 1997a; Mescolotti *et al.*, 2019). Finally, the Areado Group is succeeded by Upper Cretaceous units, represented by the Urucuia and Mata da Corda groups (Campos and Dardenne, 1997a; Fig. 2).

The Mata da Corda Group (object of this study) was exclusively deposited in the southern Abaeté Sub-basin and comprises the coeval Patos and Capacete formations (Campos and Dardenne, 1997a). The Patos Formation is mainly composed of mafic to ultramafic alkaline lavas and pyroclastic rocks (Campos and Dardenne, 1997a; Sgarbi, 2000; Sgarbi and Gaspar, 2002; Karfunkel *et al.*, 2014). Radiometric K-Ar dating performed on phlogopite crystals from a lava flow overlying sandstone of the Areado Group provided an age of 83.6 ± 1.4 Ma (Gibson *et al.*, 1995). The Capacete Formation has a maximum thickness of 150 m (Sgarbi, 2000) and consists of epiclastic conglomerate and sandstone containing abundant volcanic lithoclasts recycled from the Patos Formation (Campos and Dardenne, 1997a). The Capacete Formation is interpreted as deposited by distal alluvial fans grading to braided rivers under arid to semiarid climate conditions, and locally, this unit presents a significant contribution of frosted quartz grains of aeolian origin (Campos and Dardenne, 1997a).

MATERIALS AND METHODS

The description and analysis of sedimentary facies, considering geometry, texture, composition, primary sedimentary structures, and trace fossil content, followed the protocol of Miall (1996). Trace fossils were prospected in all stratigraphic horizons, and their descriptions were based on the ichnotaxobases proposed by Bromley (1996). The quantification of the bioturbation followed the visual scale (no quantitative analysis was performed) as proposed by Reineck (1963). The most representative samples were collected, polished, and analyzed in the Laboratório de Paleontologia Estratigráfica (housed in the paleontological collection under codes M 0045 to M 0055) from the Institute of Geography, Uberlândia Federal University.

RESULTS AND DISCUSSION

Sedimentary facies and depositional settings

The sedimentary succession of the Capacete Formation was described in two distinct outcrops in the vicinities of the Coromandel town, western Minas Gerais State, Brazil (see Table 1 and Figs 1B, 3). Outcrop 1 has received significant attention in the last decades due to the presence of detrital diamonds in their basal conglomerate (Fernandes *et al.*, 2014; Karfunkel *et al.*, 2014; see Fig. 3). The Capacete Formation in the study area is generally described as presenting conglomerate, pyroclastic rocks, sandstone, and tuffs (Karfunkel *et al.*, 2014), facies that are absent in Outcrop 2, 6.5 km

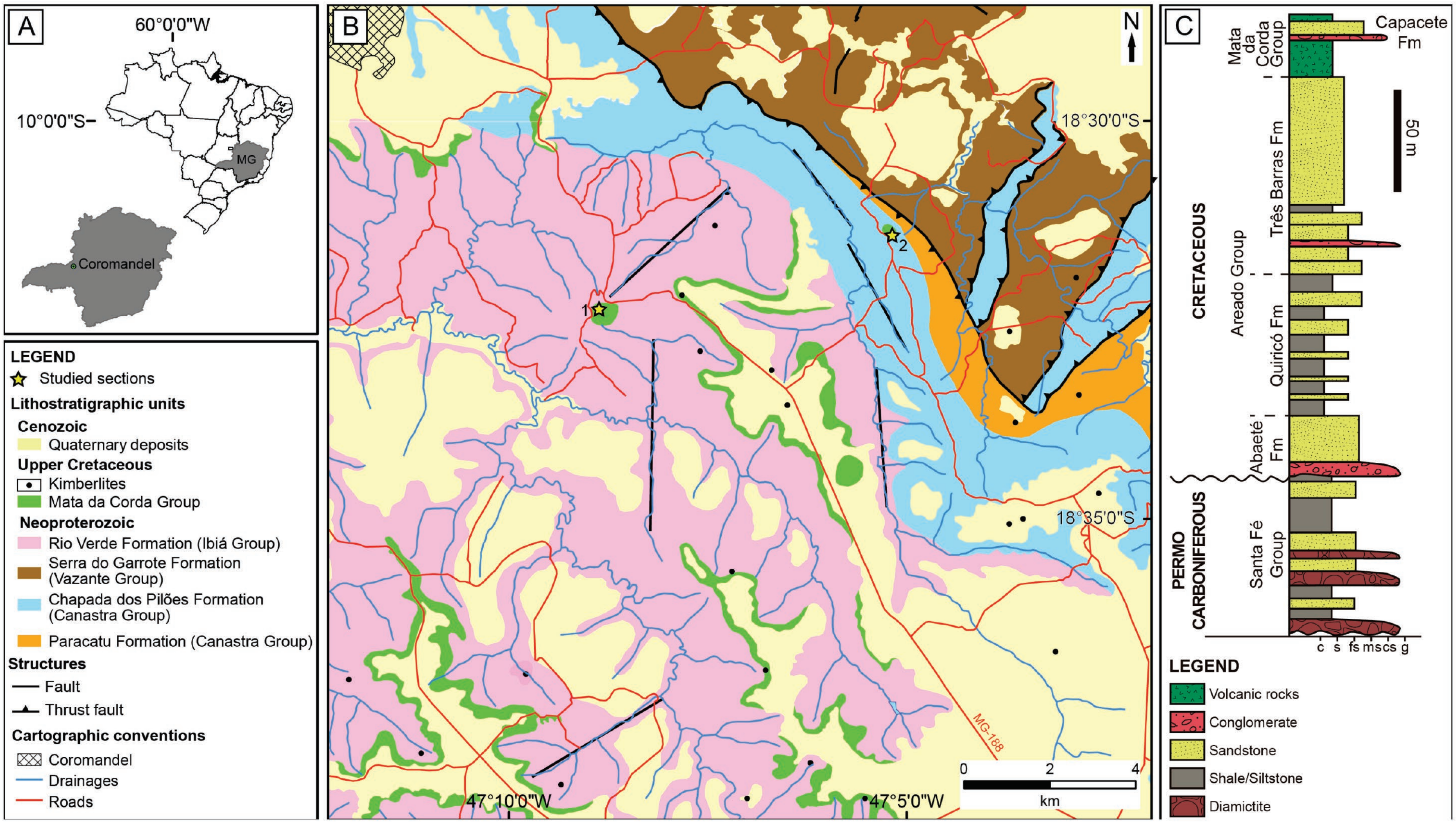

Fig. 1. Location and stratigraphic setting of study area. **A**. Map of Brazil with the location of the Minas Gerais State and Coromandel town. **B**. Simplified geological map of the Coromandel region. **C**. Stratigraphic column of the Sanfranciscana Basin; the Capacete Formation corresponds to the uppermost sandstones from the Mata da Corda Group, at the top of the lithostratigraphic profile (modified from Mescolotti *et al.*, 2019). Fm – Formation; MG – Minas Gerais State; C – clay; S – silt, fs – fine sand; ms – medium sand; cs – coarse sand; g – granule.

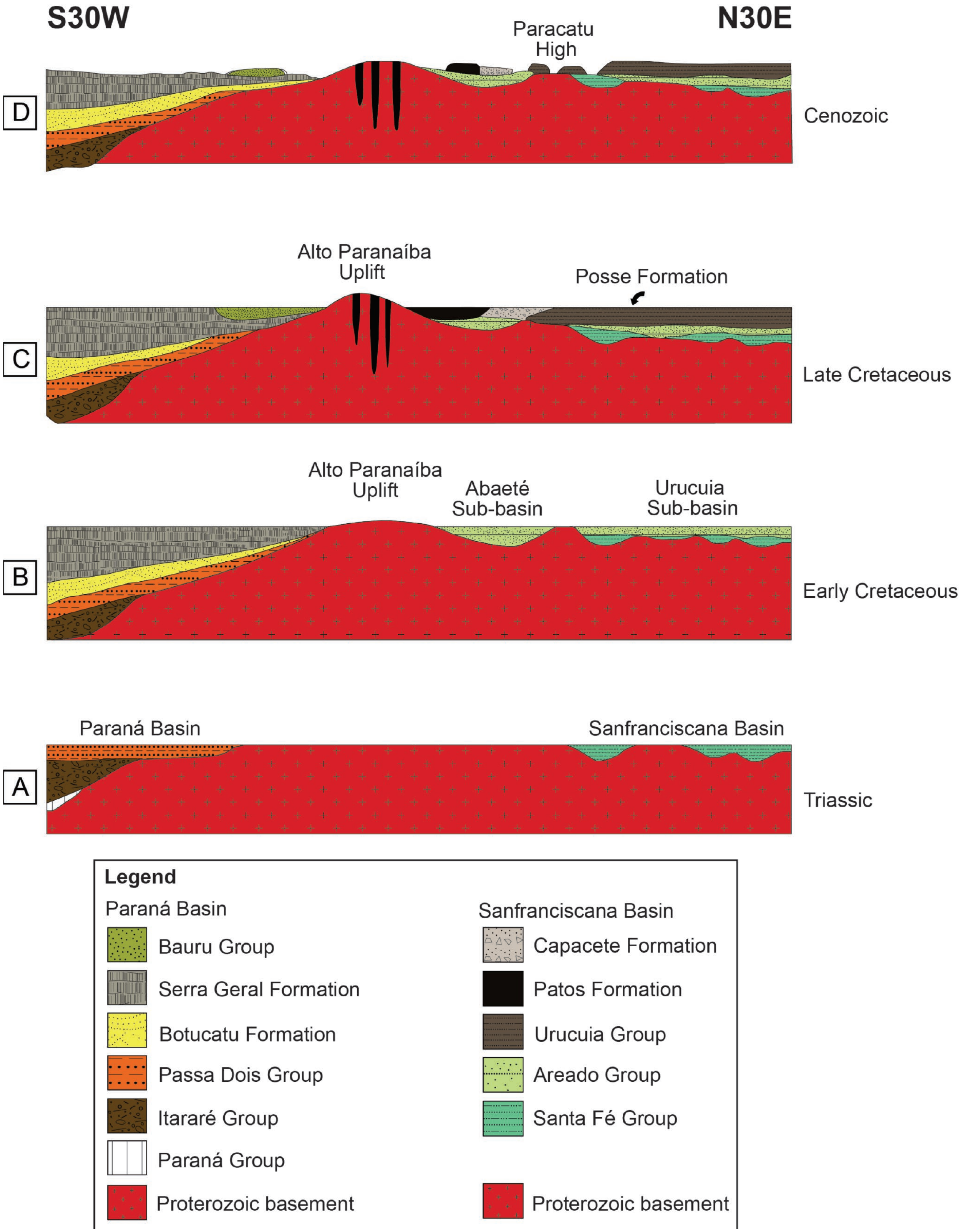

Fig. 2. Geologic evolution of the Alto Paranaíba region. **A.** Early Mesozoic – Intense erosive processes reworked the Santa Fé and Passa Dois groups. **B.** Deposition of the Areado Group and development of tafrogenic features in the Areado Sub-basin. Deposition of the Botucatu Formation and subsequent volcanism of the Serra Geral Formation in the Paraná Basin. Beginning of the uplift of the Alto Paranaíba High. **C.** Late Cretaceous – deposition of the Urucuia Group in the Sanfranciscana Basin and the Bauru Group in the homonymous basin. Alkaline magmatism in the uplifted area. **D.** Cenozoic – the onset of the present geomorphological surface and incision of plateau landforms. Modified from Hasuy and Haralily (1991) and Campos and Dardenne (1997a).

Table 1

Sedimentary facies and biogenic sedimentary structures from studied outcrops.

Code	Facies	Description	Biogenic sedimentary structures	Depositional processes	Fig.
Cg	Conglomeratic sandstones	Poorly sorted, structureless, clast-supported conglomeratic sandstone, with subangular to rounded grains. Coarse-grained sand is the predominant granulometry class	Absent	Migration of gravel bedforms deposited in fluvial channels	4A
Sp	Planar cross-bedded sandstone	Fine- to medium-grained sandstone with planar cross-stratification, locally with granules, disposed in lenticular beds	Absent	Migration of 2D sand dunes under unidirectional flows	4B
St	Trough cross-bedded sandstone	Lenticular beds of very fine- to fine-grained sandstone with trough cross-stratification. This facies locally occurs in the lower part of point bars	Rhizoliths and *Palaeophycus*	Migration of 3D sand dunes under unidirectional flows	4B, F–G
Sl	Low-angle stratified sandstone	Lenticular bedding of very fine- to fine-grained sandstone with low-angle cross-stratification, locally with granules or pebbles	Absent	Migration of low amplitude bedforms under upper flow regime in the upper part of fluvial bars	4C
Sh	Horizontal bedding sandstone	Lenticular bedding of very fine- to fine-grained sandstone with horizontal bedding	Rhizoliths, *Taenidium, Beaconites, Scoyenia, Skolithos, Camborygma*	Deposition under plane-bed (super-critical) flow	4C
Sr	Climbing ripple cross-laminated sandstone	Lenticular bedding of fine- to medium-grained sandstone with climbing ripple cross-lamination	*Taenidium, Beaconites, Palaeophycus*, *Scoyenia, Skolithos, Camborygma*	Migration of ripples under current activity	4D
Sm	Massive sandstones	Tabular beds of very fine-grained sandstone	Rhizoliths	Alternated traction and settling of mud in absence of flow	4E
S	Siltstone	Tabular bed, of massive to poorly laminated, red to brown siltstone	Absent	Settling of mud in calm water	4H
P	Palaeosol	Tabular beds of structureless, fine- to medium-grained sandstone, locally with manganese nodules and ghosts of structures	Rhizoliths	Pedogenesis	4F

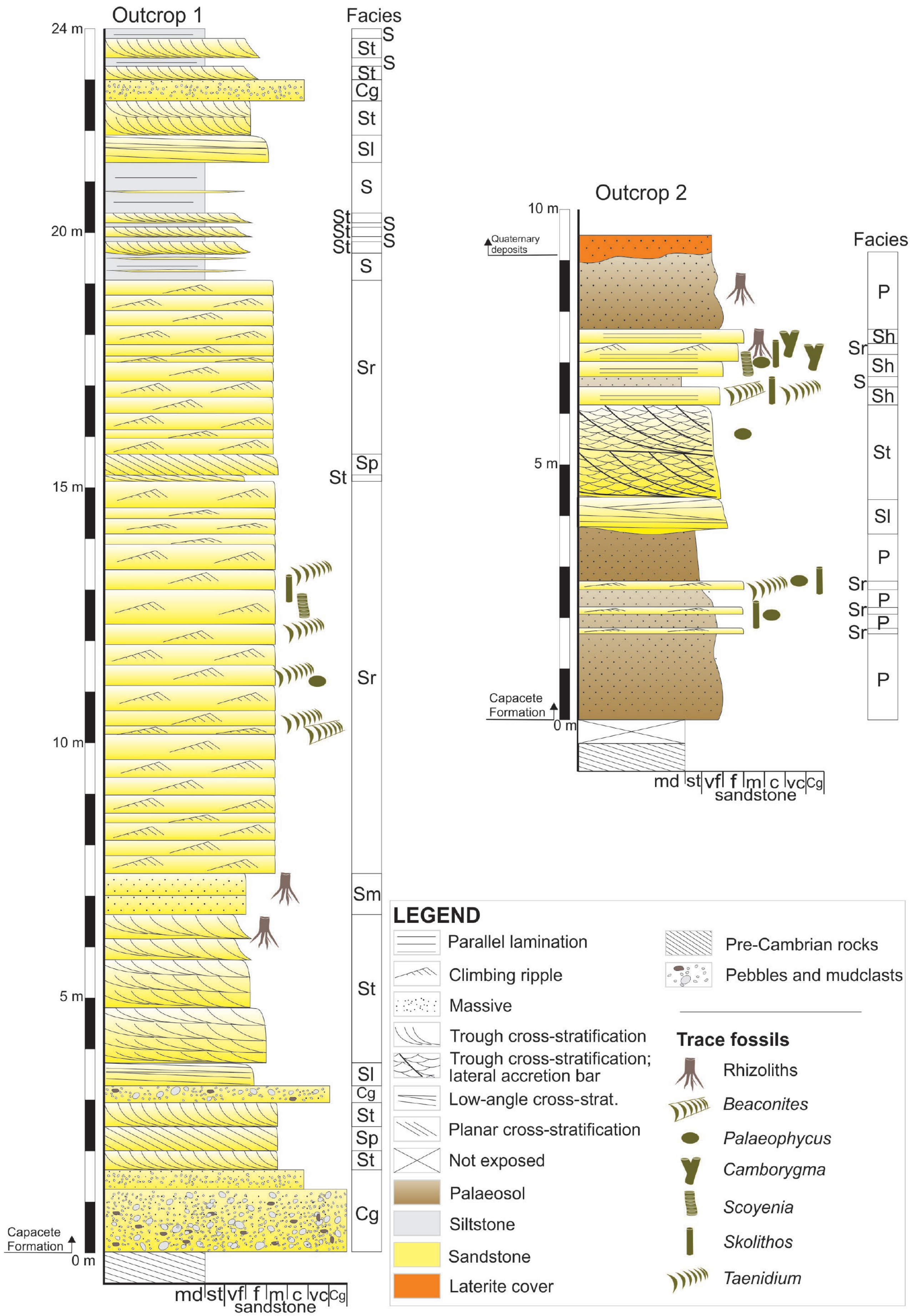

Fig. 3. Measured columnar sections with the stratigraphic position of the trace fossils. Md – mudstone; st – siltstone; f – fine; m – medium; c – coarse; vc – very coarse; Cg – conglomerate.

away from Outcrop 1 (Fig. 1B). Both outcrops present Neoproterozoic metamorphic rocks of the Brasília Fold Belt as their basal datum (Fig. 3); conglomeratic facies (Cg, Fig. 4A) are absent in Outcrop 2, where palaeosol horizons predominate (Fig. 4F). Despite the disparity in the sedimentary facies, both columnar sections are considered stratigraphically correlated.

Outcrop 1 is 24 m-thick and mostly composed of conglomeratic sandstone followed by fine-grained sandstone and culminating with mudstone deposits at the top (Fig. 3). At the base of Outcrop 1, it is possible to observe that the basal conglomerate with thinning upward pattern (Sg) grades to fine- and medium-grained planar or trough cross-bedded sandstone facies (St and Sp, Fig. 3). These basal facies are succeeded by a 15 m-thick succession mainly composed of very fine-grained sandstone with climbing ripples (Sr) and presenting some rare trace fossils and rhizoliths. At the top of the succession, siltstone (S) is interbedded with fine-grained sandstone facies (Sl and St).

The facies association of Outcrop 1 allows the interpretation that the basal conglomeratic deposits were formed by the migration of gravel bedforms in fluvial channels developed directly over the basement palaeorelief. These deposits laterally grade to medium-to-fine-grained sandstone facies deposited as 2D and 3D dunes (Fig. 4B, C) that migrate in the marginal area of these channels. The planar stratified sandstones (facies Sh) are interpreted as deposited by upper regime flow at the top of fluvial bars (Miall *et al.*, 2014). Above this association, the presence of a thick succession of Sr facies disposed in amalgamated tabular beds (Fig. 4D), demonstrate a decrease in the velocity of fluvial discharge. The great lateral continuity of this succession also indicates deposition by unconfined flows in adjacent flood plains, or in distal position, concerning the mouth of fluvial channels (Nichols and Fischer, 2007). Thus, this avulsive and unchannelized system probably reflects sedimentation in more distal conditions in a distributary/distributive fluvial system prograding in extensive low areas (Nichols and Fischer, 2007). The presence of small-scale channelized deposits and fine-grained deposits in the upper part of the succession, indicate the common incidence of settling in this terminal system, and reinforce the interpretation of deposition in muddy fluvial plains, occasionally sectioned by small distributive/distributary channels.

Outcrop 2 presents wide lateral extension (~300 meters) and is mainly constituted by thick beds of muddy/sandy palaeosols (facies P, see Figs 3, 4E). The most prominent elements are floodplain fines (FF), presenting a high degree of pedogenesis (facies P), crevasse channels (CS) associated with FF element, lateral accretion macroforms (LA, point bars) and channels with erosive base (Fig. 7). These deposits are interbedded with fine-grained planar and trough cross-bedded sandstone facies disposed in inclined beds (facies St and Sp, Fig. 4F). Above this, tabular beds of very fine-grained sandstone with climbing ripples (Sr) are commonly present. The columnar section culminates with a thick package of palaeosol (Fig. 3).

The facies association and architectural elements of Outcrop 2 are suggestive of deposition by meandering rivers (Fig. 7). The development of palaeosols associated with the element FF (see Outcrop 2 in Fig. 3), suggests extended periods of sediment influx starvation, favouring edaphization processes.

Trace fossil assemblage and palaeoenvironments

The deposits of Outcrop 1 show lower ichnodiversity than Outcrop 2 (Fig. 3). The most common ichnogenera are *Skolithos*, *Palaeophycus,* and *Taenidium,* recurring in fine-grained sandstone with climbing ripples (Sr) and heterolithic (H) facies (see Table 1 and Fig. 3). *Beaconites* and *Scoyenia* are less frequent and restricted to the intermediate part of Outcrop 1. In general, trace fossils are sparse and restricted to few intervals (BS 1-2). Locally, bioturbation can be moderate to high (BS 4–5) in Sr facies, generating a mottled aspect in the rock.

The most recurrent trace fossils are burrows characterized by meniscate structures, both horizontally- and vertically oriented to the bedding plane, lacking walls, and with a diameter varying from 8 to 11 mm. These structures are identified as *Taenidium* (Figs 5F, 6B) and likewise predominate the Sr facies. Lined meniscate burrows assigned to *Beaconites* also occur in few intervals (Fig. 6A).

Other recurrent trace fossil morphology is characterized by straight to slightly sinuous, non-branched, unlined excavations, vertically- or horizontally-oriented to the bedding plane, and filled by similar sediment of the host rock. These trace fossils have diameters varying from 7 to 19 mm and are identified as *Skolithos* when vertically oriented or *Palaeophycus* when disposed horizontally to bedding plane (Fig. 5A, B). Rhizoliths (Fig. 4F) are rare but occur locally in high-density clusters, characterized by branched structures decreasing in diameter after any branching. The rhizoliths present variable orientation, predominantly horizontal, and are filled by sandy sediments similar to the host rock or by sand cemented by calcite as rhizoconcretions (Fig. 5G). A carbonaceous lining commonly occurs (root casts, Fig. 4J).

Inclined- to vertically-oriented, irregularly walled excavations with scratch marks (or fine bioglyph), with slightly variable diameter and filled with conspicuously meniscated sediment are identified as *Scoyenia* and have a subordinated occurrence (Fig. 5C–F). The burrow filling is generally similar to the host rock, but locally might show different colours (Fig. 5D). *Scoyenia* occurs exclusively in low-bioturbated beds (BS 1–2).

Y-shaped, vertically-oriented structures with unlined, irregular borders locally showing scratch marks, passively filled and with a chamber close to the ramified portion, occur in Sr and Sh facies (BS 2). These structures appear as paired apertures in the bedding plane with 10 to 23 mm in diameter (Fig. 6C) and reach 10 cm in depth (Fig. 6D). This ichnofossil is here identified as *Camborygma.*

Fluvial bars (LA) are mostly barren of trace fossils, whereas in the floodplain elements FF and LA (facies Sr, Sp, and P, see Outcrop 2 in Fig. 3), they tend to occur in scarce (BS 1-2) to dense (BS 4-5) abundance. This evidence supports the clear preference of tracemakers by periodically exposed settings related to muddy facies, palaeosols, and fine-grained sandstone sporadically deposited in the flooded areas adjacent to the main river channel.

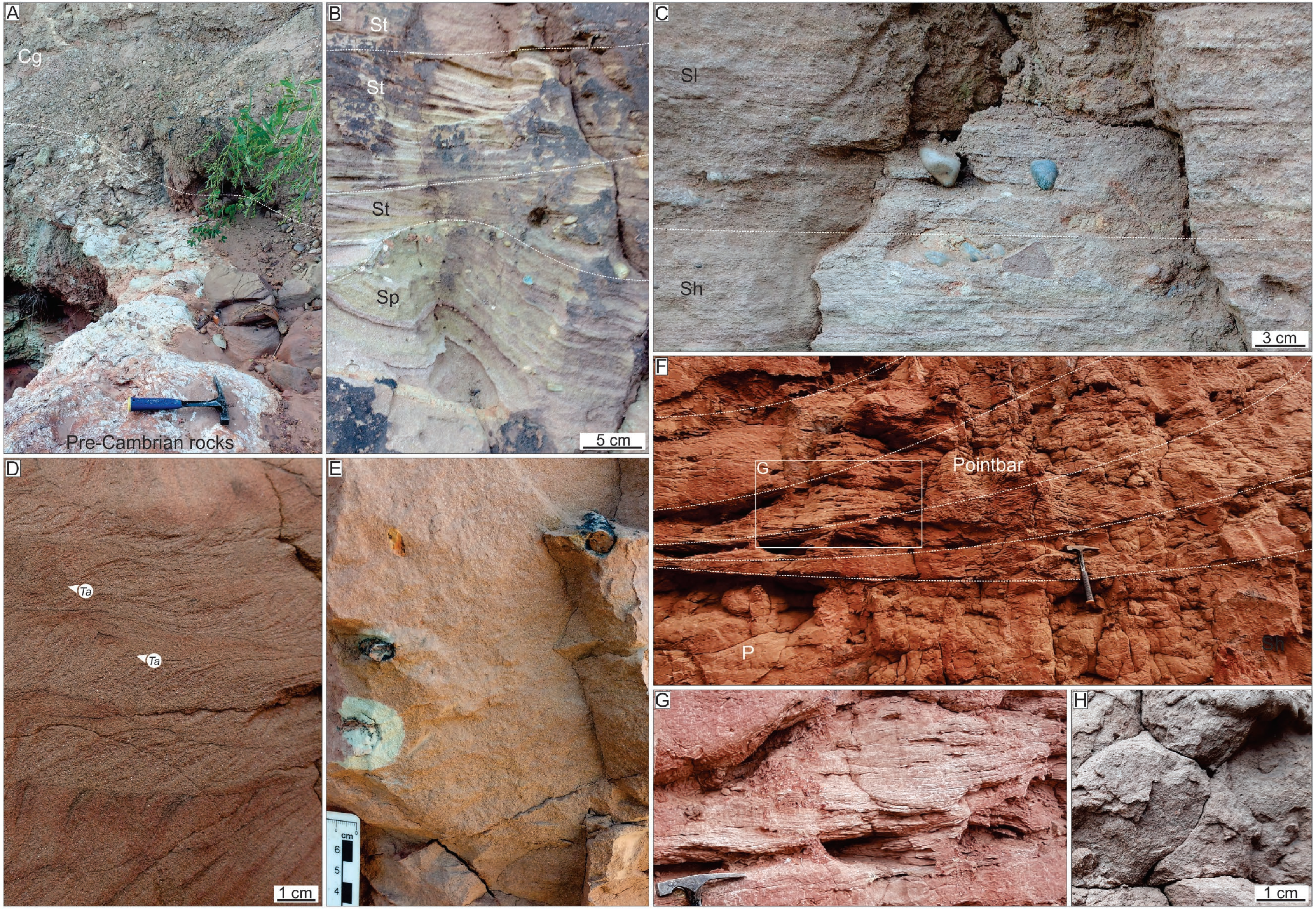

Fig. 4. Sedimentary facies from the Capacete Formation in the studied area. **A.** Unconformity between phyllites and schists from the Rio Verde Formation, Ibiá Group of the Neoproterozoic Brasília Fold Belt, and basal conglomerate (Cg) of Mata da Corda Group at Outcrop 1. **B.** Set of planar (Sp) and trough (St) cross-stratified sandstone, locally with granules and pebbles. **C**. Horizontal (Sh) and low-angle (Sl) cross-bedding, locally with pebbles. **D.** Fine-grained sandstone with climbing ripples (Sr); note the presence of sparse *Taenidium* in the upper part of the figure (*Ta*). **E**. Massive sandstone (Sm) with rhizoliths and palaeoroots. **F**. Fine- to medium- trough cross-stratified sandstone from lateral accretion bars (point bars); note the presence of a palaeosol (P) horizon at the bottom of the photograph. **G**. Detail of trough cross-stratification perpendicular to the accretionary surfaces of point bars. **H.** Detail of siltstone beds. The hammer as scale in A, F, and G is 28.5 cm in length.

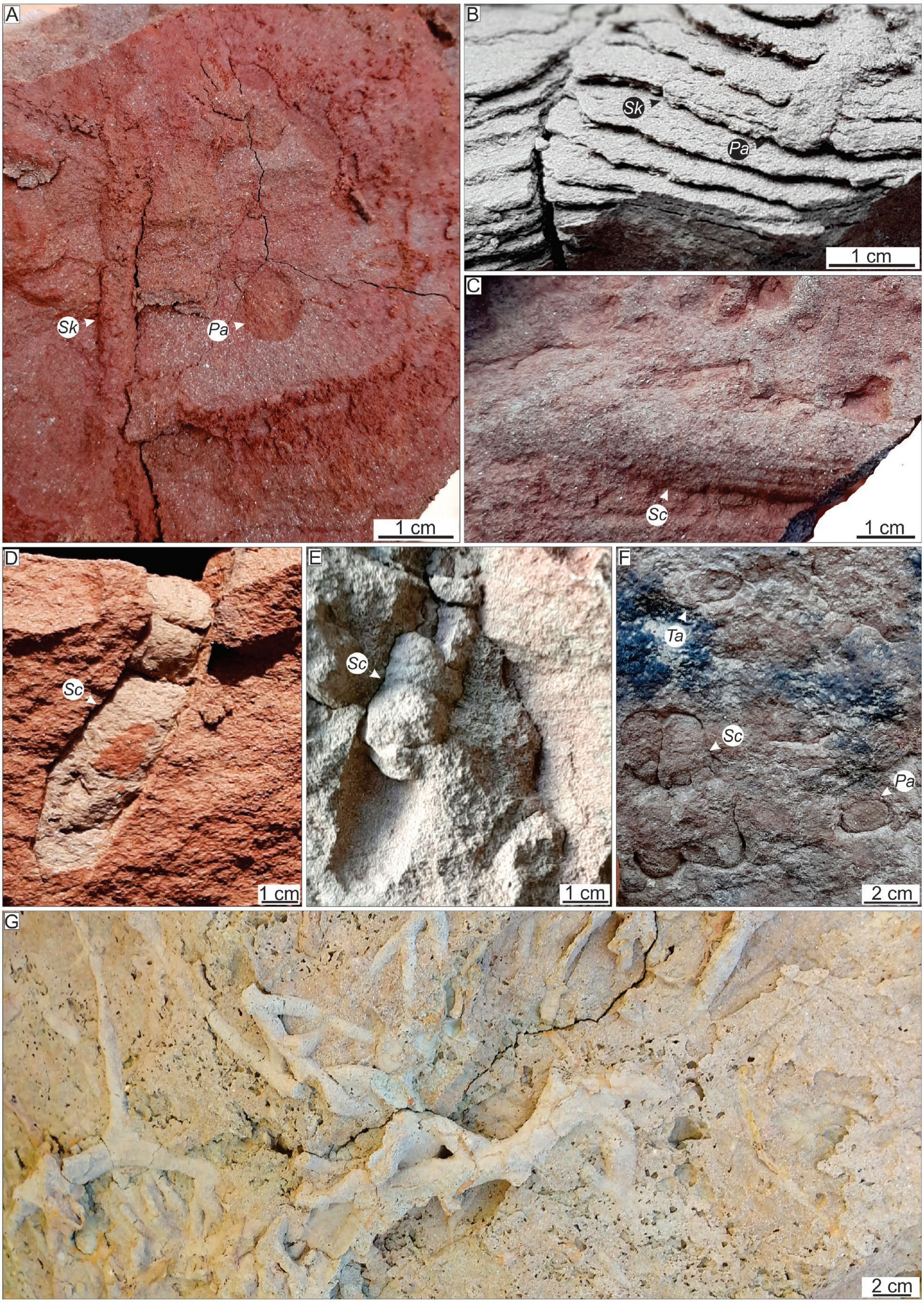

Fig. 5. Trace fossils from the Capacete Formation at Coromandel region. **A, B.** *Skolithos* (*Sk*) and *Palaeophycus* (*Pa*) in rippled sandstone. **C.** *Scoyenia* bearing longitudinal striae (*Sc*). **D, E.** *Scoyenia* (*Sc*) in Sr facies filled by distinct (D) or similar sediment (E) to the host rock. **F.** Ichnoassociation of *Scoyenia* (*Sc*), *Palaeophycus* (Pa), and *Taenidium* (*Ta*), recurrent in the facies Sr. **G.** Rhizoliths horizontally oriented in relation to the bedding plane.

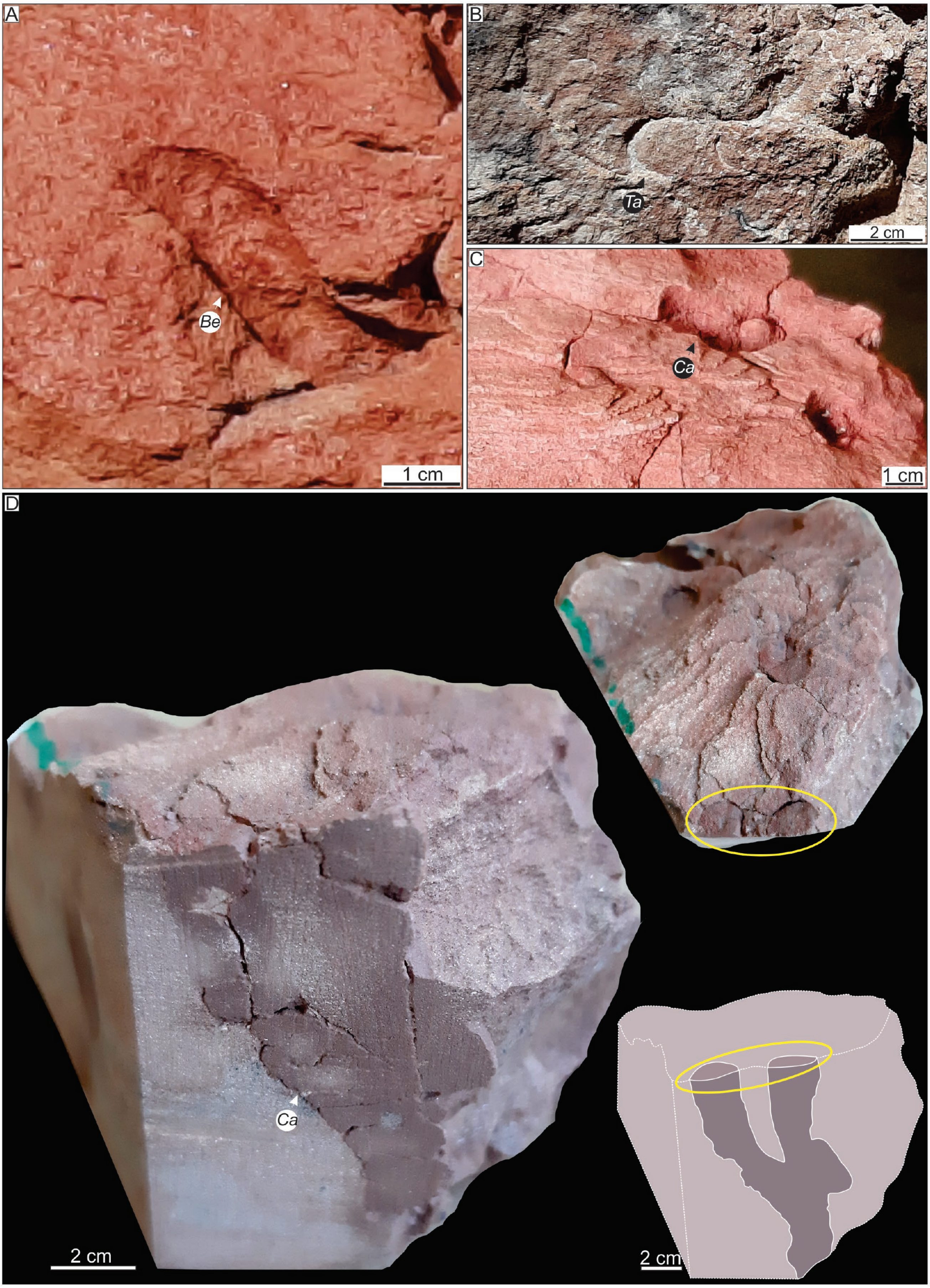

Fig. 6. Trace fossils from the Capacete Formation at Coromandel region. **A.** *Beaconites* (*Be*) in horizontally stratified sandstone (Sh). **B.** *Taenidium* (*Ta*) present in the Sr facies. **C.** *Camborygma* (*Ca*) in horizontal view. **D.** Polished sample of *Camborygma* (*Ca*) evidencing a chamber close to the ramification – see the paired apertures on bedding plane (yellow circle).

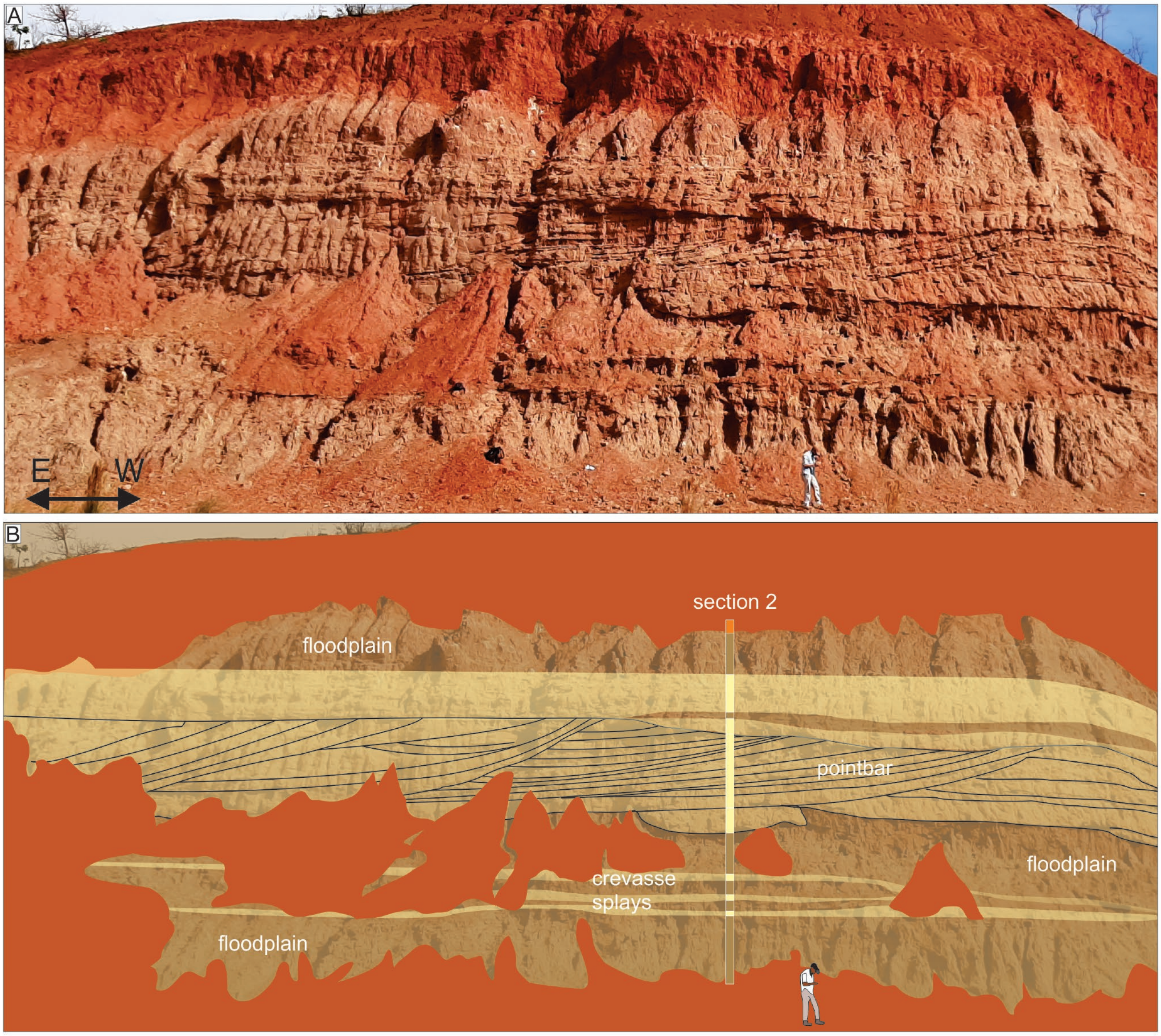

Fig. 7. Overview of Outcrop 2. **A.** Facies association and architecture of distal meandering river deposits from the base of the Capacete Formation. Note the erosive contact in the lower part of the channel element and the slightly dip of the point bars to the thalweg channel. **B.** Interpretive sketch of the panoramic view.

In the studied outcrops, meniscate trace fossils are common features and mostly represented by *Taenidium,* with subordinated occurrence of *Scoyenia* and *Beaconites*. This dominance is typical of periodically exposed palaeoenvironments, indicating a transition between aquatic and terrestrial depositional systems (Frey and Pemberton, 1984). While *Taenidium* and *Beaconites* are commonly produced in a soft substrate, scratch marks in *Scoyenia* can be considered a proxy of drier or firmground substrates, reflecting desiccation by subaerial exposure (Savrda *et al.*, 2000; Buatois and Mángano, 2002).

Sparse *Palaeophycus* and *Skolithos* occur in facies formed by relatively higher energetic flows (Sr, Sh, and St) if compared to the fine-grained facies (P and S), indicating episodic colonization of abandoned channel and crevasse splay deposits, mostly by arthropods (Ratcliffe and Fagerstrom, 1980; D'Alessandro and Bromley, 1987; Mazzucconi and Bachmann, 1995; Buatois and Mángano, 2004; Krapovickas *et al.*, 2009). Finally, *Camborygma* is a common component of *Scoyenia* ichnofacies since the Triassic, but it is also characteristic of the *Camborygma* ichnofacies (Hasiotis and Dubiel, 1993). In the studied area, this ichnogenus is restricted to Sr and Sh facies, being interpreted as crayfish domicile structures developed in the upper part of abandoned fluvial bars and crevasse splay deposits (e.g., Hasiotis and Mitchell, 1993). The depth of *Camborygma* can be an indicator of local fluctuations in the water table level because its chambers remain underwater while they are colonized (Hasiotis, 2007). The relatively low depth of these structures (up to 10 cm) suggests that the colonization occurred during a period of high groundwater level. The absence of erosive features and the shape of galleries preserving ramification corroborates this interpretation. The water level of the phreatic is an important factor for distribution of biogenic sedimentary structures in subaerial settings, controlling the archetypical continental ichnofacies (Buatois and Mángano, 2004, 2007; Netto and Grangeiro, 2009).

Several lines of evidence support the classification of this ichnoassemblage as belonging to the *Scoyenia* ichnofacies with prolonged water influence, as: (1) the recurrence of *Taenidium, Skolithos*, and *Palaeophycus,* with less frequent occurrences of *Beaconites, Scoyenia,* and *Camborygma*; (2) general low diversity; (3) recurrence of burrows bearing meniscate backfill associated with horizontal feeding structures and cylindrical vertical burrows; (4) predominance of traces in floodplain settings (Fig. 7), and (5) association with root traces (Frey *et al.*, 1984; Buatois and Mángano, 1995, 2011).

The *Scoyenia* ichnofacies is representative of deposition in subaqueous sediments that are periodically exposed to subaerial conditions, or subaerial sediments periodically flooded, commonly in river channel margins, overbanks, and sand bars (Frey and Pemberton, 1984, 1987). In the studied case, the presence of rhizoliths in association with different

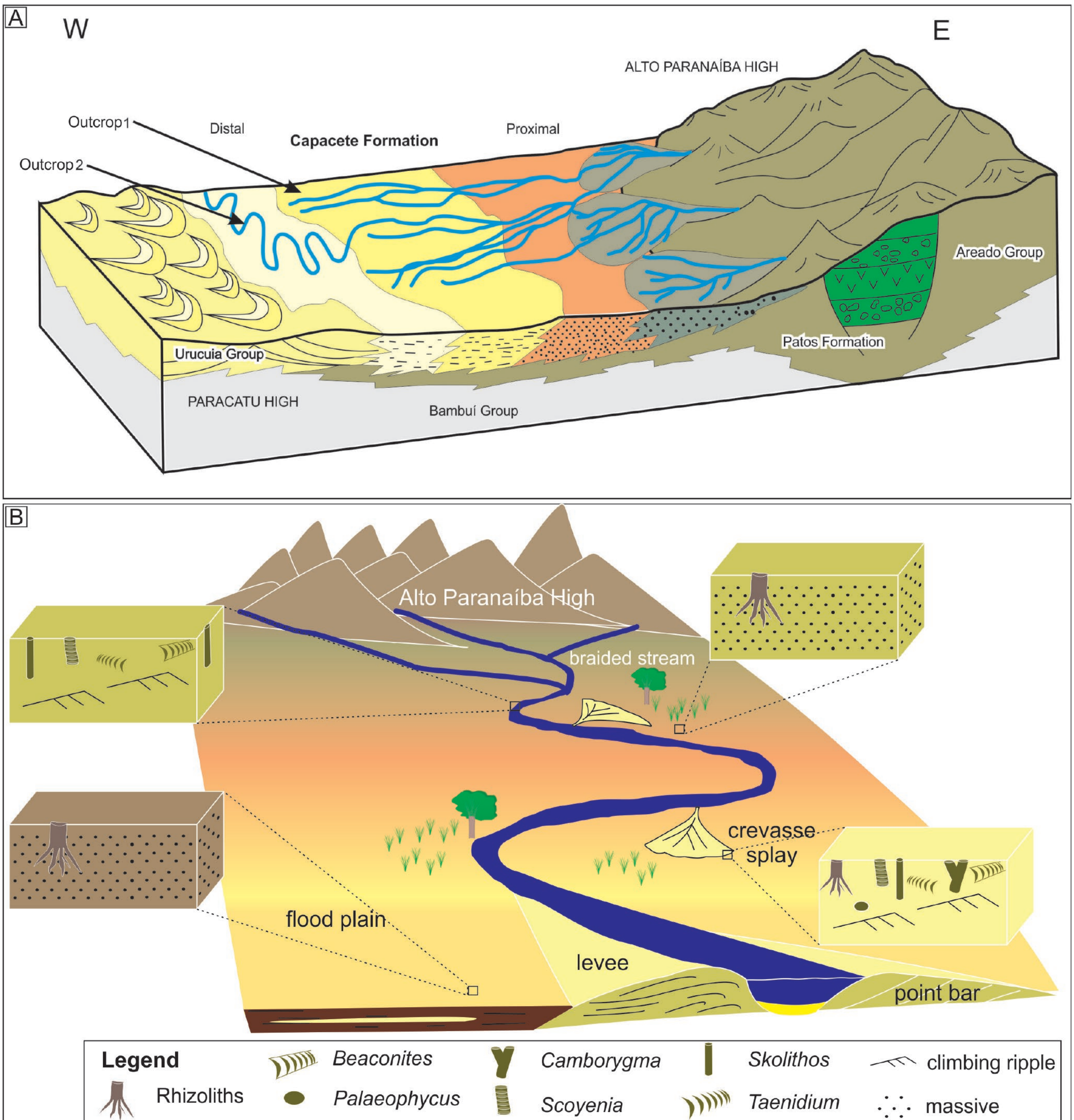

Fig. 8. Palaeoenvironmental reconstruction. **A.** Depositional model of the Capacete Formation during the Late Cretaceous. Adapted from Campos and Dardenne (1997a). **B.** Inferred distribution of trace fossils in Capacete Formation subenvironments.

types of trace fossils reinforces the hypothesis of sporadic colonization of the vegetated flood plains by invertebrate tracemakers (Fig. 8B). The dominance of meniscate burrows in floodplain settings have been widely documented (e.g., Bromley and Asgaard, 1979; Bracken and Picard, 1984; D'Alessandro *et al.*, 1987; Smith, 1993; Eberth *et al.*, 2000; Savrda *et al.*, 2000; Buatois *et al.*, 2007, 2020; Krapovickas *et al.*, 2009). The absence of physical structures indicative of periodic subaerial exposure (e.g., mudcracks or raindrop imprints) in the levels bearing trace fossils allows the interpretation of colonization under moist, possibly flooded zone. However, irregular walls and the filling sediment in *Camborygma* are indicative of firm substrates, evidencing the presence of two suites: a softground pre-desiccation suite characterized by backfilled structures (*Taenidium*, *Beaconites*) and a firmground post-desiccation suite characterized by *Camborygma*. The presence of this taphonomic filter evidences that trace fossils distribution was largely controlled by availability of humidity within substrate, and the restricted presence of trace fossils in overbank settings reveals high seasonality rains in an arid to semiarid setting (e.g., Buatois and Mángano, 2004).

Body fossils have a low potential for preservation in oxidized palaeosols of well-drained and dry settings (e.g., Retallack, 1998). The presence of the *Scoyenia* ichnofacies in some stratigraphic intervals of the Capacete Formation is, up to now, the only evidence of biologic activity during the Early Cretaceous for this arid to semiarid region. It changes the assumption of widespread harsh depositional conditions associated with gravity flows and explosive volcanic activity adjacent to the unit, at least in the described outcrops. Finally, the presence of typical architectural elements and facies associations related to deposition in meandering rivers and distributary/distributive channels evidences this fluvial style in the distal plains of the alluvial-fluvial braided system interpreted for the Capacete Formation (Fig. 8).

CONCLUSIONS

The sedimentological data and ichnological signatures indicate deposition by meandering rivers and distributary/distributive fluvial system in the Capacete Formation. Meniscate trace fossils (e.g., *Taenidium, Beaconites*, and *Scoyenia*), associated with *Skolithos, Palaeophycus*, and *Camborygma* attest the predominance of arthropod activity in those horizons. Rhizoliths are also recorded, indicating presence of vegetation in floodplain settings. The trace fossil suite suggests colonization of the substrate under predominantly aquatic conditions and the local presence of *Camborygma,* a crayfish burrow, is indicative of high water table level. Thus, despite the arid climate interpreted for the almost entire Upper Cretaceous units in the Sanfranciscana Basin, our new data support distal deposition under local humid (or at least, high moisture) conditions for the beds bearing trace fossils.

Acknowledgments

The authors are thankful to the organizing committee of the 3rd International Conference of Continental Ichnology in Halle, Germany for the successful event and the edition of this volume. D.S. thanks the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for the post-doc fellowship (process 159548/2018-7). L.V.W. and R.G.N. are research fellows of the CNPq. We thank Luis Buatois and Abdelouahed Lagnaoui for their suggestions during the peer-review process.

REFERENCES

Almeida, F. F. M., 1967. Origem e evolução da Plataforma Brasileira. *Boletim da Divisão de Geologia e Mineralogia*, 241: 1–36.

Bracken, B. & Picard, M. D., 1984. Trace fossils from Cretaceous/Tertiary North Horn formation in Central Utah. *Journal of Paleontology,* 58: 477–487.

Bromley, R. G., 1996. *Trace Fossils: Biology, Taphonomy and Applications*. Chapman and Hall, London, 361 pp.

Bromley, R. G. & Asgaard, U., 1979. Triassic freshwater ichnocoenoses from Carlsberg Fjord, East Greenland. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 28: 39–80.

Buatois, L. A. & Mángano, M. G., 1995. The paleoenvironmental and paleoecological significance of the *Mermia* ichnofacies: an archetypal subaqueous non marine trace fossil assemblage. *Ichnos,* 4: 151–161.

Buatois, L. A. & Mángano, M. G., 2002. Trace fossils from Carboniferous floodplain deposits in western Argentina: implications for ichnofacies models of continental environments. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 183: 71–86.

Buatois, L. A. & Mángano, M. G., 2004. Animal-substrate interactions in freshwater environments: applications of ichnology in facies and sequence stratigraphic analysis of fluviolacustrine successions. In: McIlroy, D. M. (ed.), *The Applications of Ichnology to Palaeoenvironmental and Stratigraphic Analysis. Geological Society of London Special Publications, London,* 228: 311–333.

Buatois, L. A. & Mángano, M. G., 2007. Invertebrate ichnology of continental freshwater environments. In: Miller, W., III (ed.), *Trace Fossils: Concepts, Problems, Perspectives*. Elsevier, Amsterdam, pp. 285–323.

Buatois, L. A. & Mángano, M. G., 2011. *Ichnology: Organism-Substrate Interactions in Space and Time.* Cambridge University Press, London, 366 pp.

Buatois, L. A., Uba, C. E., Mángano, M. G., Hulka, C. & Heubeck, C., 2007. Deep bioturbation in continental environments: evidence from Miocene fluvial deposits of Bolivia. In: Bromley, R., Buatois, L. A., Mángano, M. G., Genise, J. & Melchor, R. (eds), *Sediment-Organism Interactions: A Multifaceted Ichnology. SEPM Special Publication*, 88: 123–136.

Buatois, L. A., Wetzel, A. & Mángano, M. G., 2020. Trace-fossil suites and composite ichnofabrics from meandering fluvial systems: The Oligocene Lower Freshwater Molasse of Switzerland. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 558, 109944 (in press).

Campos, J. E. G. & Dardenne, M. A., 1997a. Estratigrafia e sedimentação da Bacia Sanfranciscana: uma revisão. *Revista Brasileira de Geociências*, 27: 269–282.

Campos, J. E. G. & Dardenne, M. A., 1997b. Origem e evolução tectônica da Bacia Sanfranciscana. *Revista Brasileira de Geociências,* 27: 283–294.

Carvalho, I. S., Kattah, S. S., 1998. As pegadas fósseis do paleodeserto da Bacia Sanfranciscana (Jurássico Superior-Cretáceo Inferior, Minas Gerais). *Anais da Academia Brasileira de Ciências*, 70: 53–67. [In Portuguese.]

D'Alessandro, A. & Bromley, R. G., 1987. Meniscate trace fossils and the *Muensteria-Taenidium* problem. *Palaeontology*, 30: 743–763.

D'Alessandro, A., Ekdale, A. A. & Dane Picard, M., 1987. Trace fossils in fluvial deposits of the Duchesne River Formation (Eocene), Uinta Basin, Utah. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 61: 285–301.

Eberth, D. A., Berman, D. S., Sumida, S. S. & Hopf, H., 2000. Lower Permian terrestrial paleoenvironments and vertebrate paleoecology of the Tambach Basin (Thuringia, Central Germany): the Upland Holy Grail. *Palaios*, 15: 293–313.

Fernandes, A. F., Karfunkel, J., Hoover, D. B., Sgarbi, P. B. A., Sgarbi, G. N. C., Oliveira, G. D., Gomes, J. C. S. P. & Kambrock, K., 2014. The basal conglomerate of the Capacete Formation (Mata da Corda Group) and its relation to diamond distributions in Coromandel, Minas Gerais state, Brazil. *Brazilian Journal of Geology*, 44: 91–103

Frey, R. W. & Pemberton, S. G., 1984. Trace fossil facies models. In: Walker, R. G. (ed.), *Facies Models*, Geoscience Canada, Reprint Series 1: 189–207.

Frey, R. W. & Pemberton, S. G., 1987. The *Psilonichnus* ichnocoenose, and its relationship to adjacent marine and nonmarine ichnocoenoses along the Georgia coast. *Bulletin of Canadian Petroleum Geology*. 35: 333–357.

Frey, R. W., Pemberton, S. G. & Fagerstrom, J. A., 1984. Morphological, ethological, and environmental significance of the ichnogenera *Scoyenia* and *Ancorichnus*. *Journal of Paleontology,* 58: 511–528.

Gibson, S. A., Thompson, R. N., Leonardos, O. H., Dickin, A. P. & Mitchell, J. G., 1995. The Late Cretaceous impact of the Trindade mantle plume: evidence from large-volume, mafic, potassic magmatism in SE Brazil. *Journal of Petrology*, 36: 189–229.

Hasiotis, S. T., 2007. Continental ichnology: fundamental processes and controls on trace fossil distribution. In: Miller, W., III (ed.), *Trace Fossils: Concepts, Problems, Perspectives.* Elsevier, Amsterdam, pp. 268–284.

Hasiotis, S. T. & Dubiel, R. F., 1993. Continental trace fossils of the Upper Triassic Chinle Formation, Petrified Forest National Park, Arizona. The nonmarine Triassic. *Bulletin of the New Mexico Museum of Natural History and Science*, 3: 175–178.

Hasiotis, S. T. & Mitchell, C. E., 1993. A comparison of crayfish burrow morphologies: Triassic and Holocene fossil, paleo- and neo-ichnological evidence, and the identification of their burrowing signatures. *Ichnos: An International Journal of Plant & Animal,* 2: 291–314.

Hasui, Y., Sadowski, G. R., Suguio, K. & Fuck, R. A., 1975. The Phanerozoic tectonic evolution of the western Minas Gerais State. *Anais da Academia Brasileira de Ciências*, 47: 431–438.

Karfunkel, J., Hoover, D., Fernandes, A. F., Sgarbi, G. N. C., Kambrock, K. & Oliveira, G. D., 2014. Diamonds from the Coromandel Area, West Minas Gerais State, Brazil: an update and new data on surface sources and origin. *Brazilian Journal of Geology*, 44: 325–338.

Krapovickas, V., Ciccioli, P. L., Mángano, M. G., Marsicano, C. A. & Limarino, C. O., 2009. Paleobiology and paleoecology of an arid–semiarid Miocene South American ichnofauna in anastomosed fluvial deposits. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 284: 129–152.

Mazzucconi, S. A. & Bachmann, A. O., 1995. Geographic distribution of the Gerridae in Argentina (Insecta, Heteroptera). *Insecta Mundi,* 9: 363–370.

Mescolotti, P. C., Varejão, F. G., Warren, L. V., Ladeira, F. S. B., Giannini, P. C. F., Assine, M. L., 2019. The sedimentary record of wet and dry eolian systems in the Cretaceous of Southeast Brazil: stratigraphic and paleogeographic significance. *Brazilian Journal of Geology*, 49: 1–20.

Miall, A. D., 1996. *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis and Petroleum Geology*. Springer-Verlag Incorporation: Heidelberg, 582 pp.

Miall, A. D., 2014. *Fluvial Depositional Systems*. Springer International Publishing, Berlin, 323 pp.

Netto, R. G. & Grangeiro, M. E., 2009. Neoichnology of the seaward side of Peixe Lagoon in Mostardas, southernmost Brazil: the *Psilonichnus* ichnocoenosis revisited. *Revista Brasileira de Paleontologia*, 12: 211–224.

Nichols, G. J. & Fisher, J. A., 2007. Processes, facies and architecture of fluvial distributary system deposits. *Sedimentary Geology*, 195: 75–90.

Ratcliffe, B. C. & Fagerstrom, J. A., 1980. Invertebrate lebensspuren of Holocene floodplains: their morphology, origin and paleoecological significance. *Journal of Paleontology*, 54: 614–630.

Reineck, H. E., 1963. Sedimentgefüge im Bereich der südlichen Nordsee. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft,* 505: 1–138.

Retallack, G. J., 1998. Fossil soils and completeness of the rock and fossil records. In: Donovan, S. K. & Paul, C. R. (eds), *The Adequacy of the Fossil Record*. John Wiley, Hoboken, pp. 133–163.

Riccomini, C., Velázquez, V. F. & Gomes, C. B., 2005. Tectonic controls of the Mesozoic and Cenozoic alkaline magmatism in central-southeastern Brazilian Platform. In: Comin-Chiaramonti, P. & Gomes, C. B. (eds), *Mesozoic to Cenozoic Alkaline Magmatism in the Brazilian Platform.* Editora da Universidade de São Paulo, São Paulo, pp. 31–56.

Savrda, C. E., Blanton-Hooks, A. D., Collier, J. W., Drake, R. A., Graves, R. L., Hall, A. G., Nelson, A. I., Slone, J. C., Williams, D. D. & Wood, H. A., 2000. *Taenidium* and associated ichnofossils in fluvial deposits, Cretaceous Tuscaloosa Formation, Eastern Alabama, Southeastern USA. *Ichnos*, 7: 223–242.

Sgarbi, G. N. C., 2000. The Cretaceous Sanfranciscan Basin, eastern plateau of Brazil. *Revista Brasileira de Geociências*, 30: 450–452.

Sgarbi, P. B. D. & Gaspar, J. C., 2002. Geochemistry of Santo Antonio da Barra kamafugites, Goiás, Brazil. *Journal of South American Earth Sciences,* 14: 889–901.

Smith, R. M. H., 1993. Sedimentology and ichnology of floodplain paleosurfaces in the Beaufort Group (Late Permian), Karoo Sequence, South Africa. *Palaios*, 8: 339–357.

Thompson, R. N., Gibson, S. A., Mitchell, J. G., Dickin, A. P., Leonardos, O. H., Brod, J. A. & Greenwood, J. C., 1998. Migrating Cretaceous–Eocene magmatism in the Serra do Mar Alkaline Province, SE Brazil: Melts from the deflected trindade mantle plume? *Journal of Petrology*, 39: 1493–1526.