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Evolution and palaeoenvironment of the Bauru Basin (Upper Cretaceous, Brazil)

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Abstract

The Bauru Basin was one of the great Cretaceous desert basins of the world, evolved in arid zone called Southern Hot Arid Belt. Its paleobiological record consists mainly of dinosaurs, crocodiles and turtles. The Bauru Basin is an extensive region of the South American continent that includes parts of the southeast and south of Brazil, covering an area of 370,000 km^2. It is an interior continental basin that developed as a result of subsidence of the central-southern part of the South-American Platform during the Late Cretaceous (Coniacian–Maastrichtian). This sag basin is filled by a sandy siliciclastic sequence with a preserved maximum thickness of 480 metres, deposited in semiarid to desert conditions. Its basement consists of volcanic rocks (mainly basalts) of the Lower Cretaceous (Hauterivian) Serra Geral basalt flows, of the Paraná-Etendeka Continental Flood Basalt Province. The sag basin was filled by an essentially siliciclastic psammitic sequence. In lithostratigraphic terms the sequence consists of the Caiuá and Bauru groups. The northern and northeastern edges of the basin provide a record of more proximal original deposits, such as associations of conglomeratic sand facies from alluvial fans, lakes, and intertwined distributary river systems. The progressive basin filling led to the burial of the basaltic substrate by extensive blanket sand sheets, associated with deposits of small dunes and small shallow lakes that retained mud (such as loess). Also in this intermediate context between the edges (more humid) and the interior (dry), wide sand sheet areas crossed by unconfined desert rivers (wadis) occurred. In the central axis of the elliptical basin a regional drainage system formed, flowing from northeast to southwest between the edges of the basin and the hot and dry inner periphery of the Caiuá desert (southwest). Life in the Bauru Basin flourished most in the areas with the greatest water availability, in which dinosaurs, crocodiles, turtles, fish, amphibians, molluscs, crustaceans, and charophyte algae lived. The fossil record mainly consists of transported bones and other skeletal fragments. In the northeastern and eastern marginal regions fossils are found in marginal alluvial fan deposits, broad plains of braided streams and ephemeral alkaline water lakes. In the basin interior the fossil record is related to deposits in sand sheets with braided streams, small dunes, and shallow lakes. In the great Caiuá inner desert a few smaller animals could survive (small reptiles and early mammals), sometimes leaving their footprints in dune foreset deposits. The aim of this article is to present and link the basin sedimentary evolution, palaeoecological features and palaeontological record.

Keywords: sag basin, paleoecology, dinosaur, vertebrate, taphonomy

1. Introduction

The Bauru Basin was one of the great Cretaceous desert basins of the world, evolved in arid zone called Southern Hot Arid Belt (Chumakov, 1995), between 0 ° and 30 ° South latitudes. The basin is also important due to its paleobiological record of the period, consisting mainly of dinosaurs, crocodiles and turtles. It is a sag basin that developed in the south-central part of the South American Platform as a result of subsidence during the Late Cretaceous, after the breakup of the Gondwana supercontinent and the opening of the South Atlantic Ocean. The basin is filled by an essentially sandy, 480 metres thick siliciclastic sequence (red beds). The sequence, which covers an area of 370,000 km^2, lies mainly upon the Serra Geral basalt flows, of the Paraná-Etendeka Continental Flood Basalt Province (Neocomian, Turner *et al*. 1994). The basalts and sandstones are separated by an erosional unconformity. The Upper Cretaceous Bauru Supersequence (Milani et al., 2007) occurs covering parts of the states of São Paulo, Paraná, Mato Grosso do Sul, Minas Gerais, and Goiás in Brazil, and also part of northeastern Paraguay (Fig. 1).

Fig. 1. Geological map of the Bauru Basin. Lithostratigraphy: **1**. Rio Paraná Fm., **2**. Goio Erê Fm., **3**. Santo Anastácio Fm., **4**. Undivided Caiuá Gr., **5**. Vale do Rio do Peixe Fm., **6**. Araçatuba Fm., **7**. São José do Rio Preto Fm., **8**. Presidente Prudente Fm., **9**. Uberaba Fm., **10**. Marília Fm. Alignments: Rio Piquirí (**Pi**), Rio Alonzo (**A**), São Jerônimo-Curiúva (**J**), Guapiara (**G**), Paranapanema (**Pp**), Ibitinga-Botucatu (**I**), Rio Moji Guaçú (**M**), São Carlos-Leme (**S**), Rio Paraná (**P**). After: Almeida (1980), Ferreira et al. (1981), Coimbra (1991), Riccomini (1997).

Desert conditions, as in the Atacama region (Chile), has existed in the South America since at least 90 Ma. (Houston and Hartley, 2003). The South America Platform has maintained its latitudinal position for the last 165 Ma. There are two remarkable Late Cretaceous eolian sandstones, accumulated in the South boundary of the Hadley circulation zone (Houston and Hartley, 2003): in the Bauru Basin, Brazil (Caiuá Group; Fernandes et al., 2007), and in the Salta Basin, Argentina (Lecho Formation; Marquillas et al., 2005). Although the continentality effect may have suffered some reduction with the opening of the Atlantic, the inner basin positions can be considered as main cause of aridity and interior desert conditions. The Hadley circulation expanded poleward during the Early and Late Cretaceous (Hasegawa et al., 2012), creating there subtropical arid conditions.

The Bauru Supersequence (BSS) was deposited in a semiarid climate in an asymmetric endorheic basin, of elliptical shape, which became desertic towards its interior. Sedimentation proceeded simultaneously with the progressive uplift of the borders, which were defined by important positive tectonic structures that separated it from other neighbouring Cretaceous basins. At present, the basin has a butterfly shape, with the Paraná River as its main axis. Its present boundary is erosive, related to the regional structures and the Cenozoic evolution of the tectonic platform.

Almeida (1964, in Almeida 1980) called the depression that received the Late Cretaceous sedimentation the Upper Paraná Basin, and treated it as part of the Paraná Basin. Fernandes and Coimbra (1996) first proposed the name 'Bauru Basin' for the accumulation area of the BSS. They separated the Upper Cretaceous sequence of the Paraná Basin, and considered this sequence to have been accumulated in the new 'Bauru' basin after the breakup of Gondwana (Milani et al., 2007). Contemporaneous small basins tectonically embedded in the Rondonópolis Anteclise, such as the Cambembe, Poxoréu and Itiquira basins, are present to the northwest of the Bauru Basin (Coimbra, 1991).

The first records of the occurrence of sandstones over the flood basalts, i.e., the BSS, are from the early twentieth century (Gonzaga de Campos, 1905; Hussak, 1906, apud Hasui, 1968; Florence, 1907). The first palaeontological discoveries were also recorded at this time (*e.g.,* Ilhering 1911). The first map of the BSS (Florence and Pacheco, 1929) showed the sequence divided into the Bauru and Caiuá units. Maack (1941) recognized the Caiuá Sandstone (Washburne, 1930) and charted a larg area of it in the northwest of Paraná State. In Minas Gerais State the Bauru unit was described and charted by Hasui (1967, 1969), Barbosa et al. (1970), Sad et al. (1971) and Ladeira et al. (1971), and the unit was mapped in Mato Grosso and Goiás states by Sousa Jr. (1984). The first attempts at stratigraphic subdivision of the BSS were performed in São Paulo (Setzer, 1943; Almeida and Barbosa, 1953; Mezzalira and Arruda, 1965). Several regional mapping studies in São Paulo and Paraná states (Suguio, 1973; Landim and Soares, 1976; Coimbra, 1976; Suguio et al., 1977; Brandt Neto et al., 1978; Stein et al., 1979) resulted in the stratigraphic subdivision that was used for about two decades, as proposed by Soares et al. (1980) and Almeida et al. (1980). Based on a regional review of the eastern part of the basin, Fernandes and Coimbra (2000) redefined the BSS stratigraphy, which consists of two chronocorrelative groups: the Caiuá Group (the Rio Paraná, Goio Erê and Santo Anastácio formations) and the Bauru Group (the Uberaba, Vale do Rio do Peixe, Araçatuba, São José do Rio Preto, Presidente Prudente and Marília formations, and the Taiúva Analcimites) (Fig. 2).

Fig. 2. Lithostratigraphy of the Bauru Basin.

The BSS was deposited in the Late Cretaceous, between the Coniacian and the Maastrichtian (Fig. 3). Its dating is constrained by: a) the Senonian age (88.5 to 65 Ma) attributed to vertebrate fossils by Huene (1939); b) the minimum(?) absolute ages of analcimites from the Taiúva region, São Paulo State (Coutinho et al., 1982); and c) the correlation between the deposition of the Caiuá and Bauru groups within the platform, and the enhanced sediment deposition in the Santos Formation (Moreira et al., 2007) of the

Santos Basin on the Brazilian continental margin. Palynological studies of material from the edge of the basin (and the basal part of the sequence?) from the Descalvado region (São Paulo State) indicated a Coniacian age (Lima et al., 1986), possibly early Santonian (Mitsuro Arai 1994, Petrobras, oral communication). Based on careful micropalaeontological study, Dias-Brito et al. (2001) suggested two intervals of deposition for part of the sequence, namely Turonian–Santonian and Maastrichtian.

Fig. 3. Chronology of the Bauru Supersequence.

2. Tectonic setting

In the Early Cretaceous the Earth's crust underwent colossal fracturing, followed by basaltic magmatism on a colossally large scale: the Paraná-Etendeka Continental Flood Basalt. The main volcanic period was between 137 and 127 Ma (Turner et al., 1994). This magmatic event was associated with the breakup of Gondwana and the beginning of the evolution of the South Atlantic Ocean. It marked the end of extensive sedimentation in large intracratonic areas such as the Paraná Basin. After the opening of the Atlantic Ocean, the South American Platform kept rising in the way that began in the Early Cretaceous, until the accumulation of nearly 2,000 metres of basaltic lavas caused the inversion of this crustal behaviour. This happened in evolution to a new isostatic adjustment of the platform portion where were accumulated the Serra Geral flows. During the Late Cretaceous a depression over the basaltic package received and accumulated siliciclastic material from the alteration and erosion of Palaeozoic and Precambrian rocks that were exposed at the edges. The material reached the interior after its erosion and transport over hundreds of kilometres. Fernandes and Coimbra (1996) separated the Upper Cretaceous sequence of the sedimentary record of the Paraná Basin, considering it to have been accumulated in a new basin, called the Bauru Basin.

Lithospheric flexure caused by basaltic overload was the main mechanism of subsidence during the evolution of the Bauru Basin (Figs. 4 and 5). At the same time, the present limits of the main basin are regional tectonic highs, in which many centres of Late Cretaceous alkaline magmatism are located. During BSS deposition there were two periods of higher intensity of intrusive alkaline events: 87–80 Ma and 70–60 Ma (Almeida and Melo, 1981). The record of these intrusive events includes intrusive bodies that punctuate the limits of the basin, which are more frequent at the northern edge. Within the basin only an occurrence of flood analcimite in the Taiúva region (São Paulo State) is present, which is intercalated with the Vale do Rio do Peixe Formation on the present eastern border (in the subsurface). In the basin interior tectonic activity was recorded as seismites in sedimentary aeolian units (Fernandes et al., 2007).

Fig. 4. Regional evolution of the Bauru Basin.

Fig. 5. Regional evolution of the Bauru Basin compared with that of the Santos Basin (after Macedo, 1989).

3. Stratigraphy, sedimentology and depositional systems

The BSS has a discordant basal contact (unconformity), especially with the basalts of the Serra Geral Formation. Its base is usually a thin breccia bed containing angular clasts of basalt in an immature sandy matrix. In lithostratigraphic terms, the BSS is composed of the Caiuá and Bauru chronocorrelative groups (Table 1), which show a gradual and interdigitated lateral transition. The first group comprises the Rio Paraná, Goio Erê and Santo Anastácio formations. The second group consists of the Uberaba, Vale do Rio do Peixe, Araçatuba, São José do Rio Preto, Presidente Prudente and Marília formations, and the Taiúva Analcimites (intercalated alkaline volcanic rocks). The Caiuá Group corresponds to an interior aeolian system tract of the Caiuá desert (Fernandes, 2006): deposits of complex large wind dunes with sinuous crests (*draas*) of the central region of the sand sea (the Rio Paraná Formation); peripheral deposits of aeolian dunes of moderate size, with sinuous crests and damp, wet and aqueous interdunes (the Goio Erê Formation); and deposits of sand sheets in wide and monotonous desert plains of the marginal sand sea (the Santo Anastácio Formation). The Bauru Group corresponds to deposits laid down in a semiarid climate, formed by marginal alluvial fans, sand sheets crossed by ephemeral river systems, and an endoreic paludial area. This material fed the sediments of the interior Caiuá desert (the Caiuá Group) (Figs. 6, 7, 8 and 9).

Fig. 6. Marginal alluvial fans, fluvial distributary system and minor lakes deposits, in columnar sections of Bauru Basin lithostratigraphic units. Type Sections of the Serra da Galga and Ponte Alta members/Marília Formation (BR 050 highway, km 153.2), and Uberaba Formation (FEPASA railroad crossing with Rod BR 050, km 128).

Fig. 7. Interior fluvial and paludial deposits, in columnar sections of Bauru Basin lithostratigraphic units. Type sections (holoestratotypes) of the São José do Rio Preto Formation (Crossing of the highways SP 425 and BR 053, entry São José do Rio Preto City), Presidente Prudente Formation (SP 425 highway, km 442.4, Presidente Prudente City, São Paulo State), and Araçatuba Formation (SP 300 highway, km 548.5).

Fig. 8. Interior basin Aeolian deposits, in columnar sections of Bauru Basin lithostratigraphic units. Type sections (holoestratotypes) of the Rio Paraná Formation (Sluice of the Porto Primavera Hydroelectric, São Paulo State), Goio Erê Formation (BR 272 highway, km 58.7), Santo Anastácio Formation (after Suguio & Barcelos 1983, BR 58 highway, 2 km from the Santo Anastácio River, toward to Marabá Paulista, São Paulo State), and Echaporã Member/Marília Formation (BR 153 highway, km 275, Serra do Mirante, SE of Marília City). Contact between Araçatuba and Vale do Rio do Peixe formations, which records the burial of paludial deposits (lower) by aeolian sands (upper), SP 425highway, km 329.

Fig. 9. Unit transitions in the Bauru Supersequence in the Pereira Barreto Waterway Channel outcrop, São Paulo State.

Table 1: The Bauru Supersequence and descriptions of the corresponding lithostratigraphic units.

Lithostratigraphic units		Lithology and sedimentary structures	Depositional context	Notes
Caiuá Group	Rio Paraná Formation	Fine to very fine (rarely medium to coarse), reddish brown to purplish, well sorted, quartzarenite. Typically medium to large size cross-bedded, and, less frequently, intercalated with tabular beds of massive sandy mudstones. (Fig 10e).	Complex large wind dunes with sinuous crests (*draas*) of the central region of the sand sea.	Seismites have been described in the west of São Paulo State (Fernandes et al., 2007).
	Goio Erê Formation	Reddish brown to purplish gray, fine to very fine subarkosic sandstones, mineralogically mature and texturally submature. Association of cross-bedded strata and tabular massive beds, sometimes with plane-parallel lamination, adhesion ripples, climbing ripples and small wind-convoluted folds, all discontinuous and poorly defined.	Peripheral deposits of aeolian dunes with sinuous crests, of moderate size; and damp, wet and aqueous interdunes.	
	Santo Anastácio Formation	Decimetre-thick tabular strata of fine to very fine subarkosic sandstones, massive, poorly selected, with subordinate silt-clay fraction	Sand sheets in wide and monotonous marginal desert plains.	
Bauru Group	Marília Formation	**Serra da Galga Member:** immature coarse- to fine-grained sandstones, often conglomeratic, pale to reddish yellow, with minor interbedded conglomerates and mudstones. The sandstones have tabular and trough medium to small size cross-bedding,. The conglomerates are polymictic and texturally immature (quartz, quartzite, chalcedony, remobilized carbonate nodules, sandstones, mudstones, fragments of basalt and other igneous rocks, bone fragments, ventifacts). This member contains important occurrences of reptile bones (dinosaurs, crocodiles and turtles) and invertebrates. (Fig. 11a). **Ponte Alta Member:** immature sandy deposits strongly cemented by calcium carbonate, like massive sandy limestones, conglomeratic sandy matrix supported, and marls. The conglomerates are polymictic (quartz, quartzite, sandstone, marl, basalt and fragments of other rocks), sub-angular to sub-rounded, centimetre-size clasts (2–7 cm, up to 15 cm). The marls have a slightly greenish colour and mosaic texture (pseudobreccia), with displacive growth features. **Echaporã Member:** massive tabular strata generally 1 m thick, fine to medium sandstone, beige to pale pink, sometimes interbedded with massive sandy mudstones. In general, the layers have a greater development of nodules and carbonate crusts (calcretes). Sometimes there are discrete concentration of clasts at the base. Fluvial or aeolian cross bedding is rarely displayed. The conglomeratic lithofacies is commonly composed of carbonate and muddy centimetre-sized intraclasts and siliceous extraclasts (quartz, quartzite and silicified	The Ponte Alta and Serra da Galga members show a complex association. Regionally, the passage between the two units is gradual, caused by varying the intensity of cementation, and sometimes abrupt. The differentiation is mainly post -sedimentary, caused by the formation of zones of groundwater calcretes (Ponte Alta Member). Thus, both correspond to deposits in median to distal alluvial fans (fluvial distributary system, in the Nichols and Fisher, 2007 sense), with associated river systems, sometimes with occasional interbedded deposits of small wind dunes. In this context, there are still sporadic deposits from dense flows. The Echaporã Member formed as deposits of sand sheets, in which pedogenic and groundwater calcretes developed.	The Marília Formation is composed of three members: Serra da Galga, Ponte Alta and Echaporã. The first two occur only in the Triângulo Mineiro (Minas Gerais State). The Echaporã Member supports fingerlike plateaus, more pronounced in the regions of Marília and Echaporã (São Paulo State), Campina Verde (Minas Gerais State), Quirinópolis and Itajá (Goiás State), and Cassilândia (Mato Grosso do Sul State). In São Paulo State the Echaporã Member includes an isolated occurrence of polymitic conglomerates named Lithofacies Rubião Junior, near Botucatu City. It corresponds to more proximal deposits genetically related to the Serra da Galga Member in Minas

		sandstone, some of them ventifacts). Interbedded with thin lenses of brown sandy mudstones centimetres to decimetres in thickness (up to 1 m), frequently with a concave base and a horizontal top. (Fig. 10a, b).		Gerais State.
	Uberaba Formation	Tabular and lenticular strata of very fine sandstones to silt mudstones, greenish gray to olive, with a remarkable amount of perovskite grains. Massive, cross-tabular/through cross-bedding or plane-parallel lamination. Minor interbedded claystones, conglomeratic sandstones and a sandy matrix conglomerates. (Fig. 10f).	Deposits in braided river systems and sheet floods.	
	Vale do Rio do Peixe Formation [1]	Association of tabular strata of fine to very fine sandstones, moderately to well sorted, pink to orange-pale brown in colour, with sandy siltstones and mudstones, pale brown to brown in colour, with massive or poorly defined plane-parallel stratification, desiccation cracks and tubular bioturbation. The sandstones have massive aspect or tabular and trough cross-bedding on a medium to small scale, associated with poorly plane-parallel lamination, wind climbing ripples, adhesion ripples and planes with partition lineation. (Fig. 10c, d).	Aeolian deposits in wide flat areas of sand sheets with small dunes fields with loess deposits formed in fleeting aqueous bodies.	In northern Paraná State immature conglomerates and conglomeratic sandstones rich in ventifacts (Mairá Lithofacies) occur. These are interpreted as deflation deposits reworked by desert floods (*wadis*).
	Araçatuba Formation [1]	Silt to very fine sand in tabular strata, greenish-gray in colour, with plane-parallel stratification, climbing ripples, moulds and radial-fibrous pseudomorph crystals of gypsum, mudcracks and root marks. Carbonate cements and crusts parallel to stratification are common. (Fig. 10g, h).	Paludial environment, shallow saline lakes with slightly choppy water, with periods of exposure.	On the edges of this unit expositon beds with sigmoidal boundaries and internal stratification, low inclination, and poorly defined contorted stratification occur, which were caused by subaqueous landslides.
	São José do Rio Preto Formation [1]	Fine very fine moderately sorted sandstones, often conglomeratic, pale brown to pale yellow, with trough and tabular cross-bedding. There are minor sandstone to siltstone intercalations with plane-parallel bedding, ripple marks and massive clay mudstones. The pebbles are carbonate nodules, fragments of mudstones and shales, siliceous pebbles, bone fragments and other bioclasts. Carbonate cementation is common. (Fig. 11b, g)	Deposits in the sandy bars and floodplains of braided channels, broad and shallow systems. Immature sandy deposits, often conglomeratic.	
	Presidente Prudente Formation [1]	Very fine to fine sandstone pale reddish brown to beige and dark brown sandy mudstones. The sandy lenses exhibit trough and sigmoid cross-bedding (cut-and-fill units). The tabular strata of sandstones and siltstones exhibit plane-parallel bedding, ripple marks, climbing ripples, intraformational breccias (mudstones, carbonate intraclasts, siliceous clasts and bone fragments). (Fig. 11c, d, e).	Fine sandy meandering fluvial system, with shallow channels of low sinuosity. The rocks represent the filling deposits of large channels alternating with floodplains and crevasse splay deposits. The latter may preserve less disarticulated skeletons and carcasses, such as turtle carapaces.	
	Taiúva Analcimites	Pale reddish to yellowish brown igneous rock, with an aphanitic texture	Extrusive alkaline rocks intercalated at the top	Occurs in the subsurface near

	(non-outcropping)	and features indicating an extrusive volcanic character.	of the Vale do Rio do Peixe Formation, maximum thickness of 15 m.	to Jaboticabal, São Paulo State (Coutinho et al., 1982).

[1] Corresponds to a part of the former Adamantina Formation (Soares et al., 1980).

Fig. 10. a. Narrow plateaus supported by carbonate cemented sandstones (calcretes) of the Echaporã Member/Marília Formation, vicinity of Marília City (São Paulo State). **b.** Echaporã Member/Marília Formation: sand sheet deposits of sandstone strata of massive aspect, with carbonate cement (calcretes). Serra do Mirante, SW from Marília (São Paulo State), km 275 of the BR 153 highway; maximum height of the outcrop: 12 meters. **c.** Aeolian deposits of small dunes and sand sheets, with minor interbedded silty mudstones (loess retained in ponds associated with ephemeral wadis). Vale do Rio do Peixe Formation, Santo Inácio region (Paraná State). Local km 80.6 of the PR 317 highway, fossiliferous site. **d.** Aeolian sand sheet deposits of massive and cross-bedded strata, interbedded with massive silty mudstone tabular strata (loess). Vale do Rio do Peixe Formation, Mirante do Paranapanema region (São Paulo State), km 41.8 of the SP 272 highway. **e.** General aspect of the Rio Paraná Formation: large cross-bedding with minor massive strata of sand sea deposits. Right wall of the sluice of the Porto Primavera Hydroelectric Plant, Pontal do Paranapanema region (São Paulo State). **f.** Outcrop of the Uberaba Formation: sandy silt bars interlaced river system deposits. Cut the railroad FEPASA, situated SE of the city of Uberaba (Minas Gerais State). **g.** Araçatuba Formation: fine sandstones and siltstones in tabular layers with plane-parallel stratification. Highway cut of the SP 300 highway, near from Araçatuba City (São Paulo State) Scale: 1 metre. **h.** Gypsum molds, Araçatuba Formation, from the region of Guararapes City (São Paulo State).

Fig. 11. a. Sandstones and conglomeratic sandstones with tabular cross-bedding, of sandstones and conglomeratic sandstones of alluvial fan and fluvial distributary system deposits. Serra da Galga Member/Marília Formation (NW of Uberaba City, Minas Gerais State), km 153 of the BR 050 highway, fossilifeous site. **b.** São José do Rio Preto Formation: sandstones with trough cross-bedding, of sandy bars and floodplains of shallow braided fluvial systems. SP 425 and BR 153 highways crossing, near to São José do Rio Preto City (São Paulo State). **c.** President Prudente Formation: channel filling and crevasse splay deposits, of sandy meandering fluvial system, vicinity of the Presidente Prudente City, km 442.4 of the SP 425 highway. Scale: 1 metre. **d.** Climbing ripple cross-lamination of aqueous streams of lower energy regime, from the Presidente Prudente Formation, km 585 of the SP 294 highway. **e.** Concentration of turtle carapaces in deposits of crevasse splays, with carbonate cementation, in a cut of a deactivated railroad. In fractures and voids of the bone structure, from this occurrence, was identified the mineral gorceixite. Presidente Prudente Formation, Pirapozinho City region (São Paulo Stae), near to km 463 of the SP 425). **f.** Part of a dinosaur bone showing displacive growth of carbonate cement, from the Echaporã Member/Marília Formation, vicinity of Marilia City, São Paulo State (Mr. William Nava collection, Marília City). **g.** Concentric structure of phosphatic materials, meso and microvoids (L). Thin section, São José do Rio Preto Formation, bone collected in the vicinity of Tanabi City (São Paulo State), on the km 476.5 of the SP 320 highway). Uncrossed polarizers. **h.** Internal structure of indeterminate dinosaur bone showing Haversian (mesovugs) and Volkmann (V)channels. Secondary electrons SEM image of bone from the Echaporã Member/Marilia Formation, near Marília City (São Paulo State).

3.1. Carbonate cementation and stratigraphic remarks

The Bauru Basin deposits are characterized by abundant occurrence of red bed sandstones and calcretes that suggest dominance of arid climate. Palygorskite and/or sepiolite coating (Marília Formation) and possible pseudomorphs of gypsum (Araçatuba Formation), indicate conditions of insufficient rainfall to leaching of soluble salts, where Aridisols form. Are shallow calcareous (calcic, petrocálcic or Bk) horizons, generally less than 1m deep, forming broad nodular or continuous strata.

The most significant calcrete occurrences of the Bauru Basin belong to the Marília Formation. Petrologic analysis shows the predominance of alfa microfabrics, like floating grains, strongly micritic matrix recristalization, some dolomitization and localized silicification. The presence of sepiolite or palygorskite coatings confirmed the regional semi-arid to arid conditions of the Bauru Basin. The calcretes features indicate that both pedogenic and groundwater processes acted. They were divided in two types, Ponte Alta and Echaporã (Fernandes, 2010), mainly based on calcrete facies associations and microfabric characteristics. The high frequence of the alfa microfabric indicates the predominance of non biogenic processes in the calcretes development. Phreatic processes were the most intense, probably of the last and/or the most important event. That cementation modified initial pedogenic features. The dendritic configuration of the long and narrow plateaux, sustained by calcified sandstones of the Marília Formation indicates processes of landscape elaboration through the relief inversion. (Fig. 12).

Fig. 12. Narrow plateaus sustained by calcified sandstones of the Marília Formation (calcretes), due to differential erosion of uncemented sandstones of the Vale do Rio do Peixe Formation, caused processes of landscape elaboration of relief inversion.

The carbonate cementation of the Marília Formation appears to have been decisive in the lithostratigraphic subdivision and must have influenced the stratigraphic and evolutionary models of the Bauru Basin. Calcrete analysis and facies associations of the Marília Formation suggest that the Echaporã Member and the Vale do Rio do Peixe Formation, as well as the Ponte Alta and the Serra da Galga members, are deposits containing similar facies associations that were subsequently differentiated by phreatic carbonate cementation (groundwater calcretes).

Thus, the tabular strata of massive sandstones with calcretes intercalated with subordinate sandy mudstones of the Echaporã Member have been modified by diagenetic processes, and are of the same facies association as the Vale do Rio do Peixe Formation. This lithostratigraphic unit is composed of tabular sandstone strata of massive aspect, sometimes with cross-bedding, intercalated with subordinate sandy mudstone layers. The two lithostratigraphic units correspond to deposits in sand sheets and small dune fields with shallow temporary ponds that retained loess-type deposits, and in desert floods.

The massive sandstones with interbedded paraconglomeratic facies of the Ponte Alta Member have similar facies associations to those of the Serra da Galga Member, and are differentiated only by the degree of cementation. The two members correspond to distal alluvial fan deposits with distributary fluvial channels and ephemeral ponds, deposited closest to the edges of the basin. Cementation also influenced the separation of stratigraphic units, as boundaries have often been traced using geomorphological criteria. The greater resistance to erosion of the cemented intervals generated long and narrow hills with a dendriform appearance on the map, which have been used as criteria for the identification and mapping of the Marília Formation.

4. Basin evolution

Infilling of the Bauru Basin occurred simultaneously with continuous slow isostatic subsidence of the basement, which is also indicated by the absence of significant local tectonic movements or brittle tectonic structures, and by the fact that the largest thicknesses of sediment coincide with the areas of greatest accumulation of basaltic lavas. During subsidence, the main structural patterns of the substrate were maintained as a result of tectonic inheritance. In addition to the uplift behaviour of the basin margins, the evolution of the basin was influenced by the action of internal highs, such as those associated with the Paranapanema (Fúlfaro, 1974) and Tietê (Coimbra et al., 1977) alignments. The reactivation of marginal structures and reflections of the Andean orogeny promoted subsequent modifications in the Late Cretaceous and Palaeocene, with a dominantly directional character (Riccomini, 1997; Zalán, 2004). In the Maastrichtian a tectonic input started, as evidenced by the increasing supply of sediments mainly associated with the Paranapanema and Ibitinga-Botucatu lineaments and by alkaline volcanism along the Rio Moji-Guaçu Lineament. That volcano-sedimentary episode remains compatible with syn-depositional extension tectonics. Post-sedimentary deformation is marked by two superimposed tectonic regimes of transcurrence, the later probably neotectonic (Riccomini, 1997), as indicated, for example, by the Rio Paraná Alignment (Fig. 1).

The basaltic substratum has apparently not undergone substantial tectonic changes altering its regional morphology since the beginning of the sedimentation. The basal units of the sequence filled lower areas, reducing and eliminating the original, possibly very significant, gaps. The current topography of the substrate shows a good fit with the distribution of lithofacies associations, especially the earlier ones. The area of the Araçatuba Formation, for example, coincides with a depressed area of basement. The western boundary of this formation is rectilinear and consistent with an elongated shoulder, the Jales-Andradina Sill, which would have acted as the western edge of the paludal environment in which the formation accumulated. In addition, the Rio Paraná Formation occupies a large northeasterly band coincident with a main channel controlled by the relief of the basalt substrate.

Sedimentation in the Bauru Basin occurred in semiarid conditions at the basin margins, and in desert conditions inside the basin. In the northern and northeastern regions of the basin records of originally proximal deposits are preserved, such as sandstones and conglomeratic sandstones of alluvial fan and fluvial distributary system deposits (Nichols and Fisher, 2007 sense). The advance of sedimentation to the interior led to the progressive burial of the basaltic substrate by extensive blanketing sand sheets, with small dunes and mudstone deposits (loess retained in temporary ponds). In this context, the minor fluvial deposits correspond to unconfined runoff from desert flows (*wadis*). The trough along the central axis of the elliptical basin constrained the regional drainage system from northeast to southwest, between the edges of the Bauru Basin and the periphery of the interior hot and dry Caiuá Desert (Fig. 13).

Fig. 13. Palaeoenvironments of the Bauru Basin. Sedimentation in semiarid conditions at the margins and in desert conditions inside the basin, that accumulated alluvial fan and fluvial distributary system deposits, extensive sand sheets with small dunes and desert flows (*wadis*), and draas in the interior hot and dry sand sea (Caiuá Desert).

Intensification of tectonic activity at the north-northeastern and eastern margins, and probably also at the northwestern margin, caused significant changes in the palaeogeography, promoting the progradation of alluvial fans. At the same time, climatic changes increased the humidity in the marginal zones. These changes mark the beginning of the sedimentary phase during which important fluvial systems running from northeast to southwest were established between the marginal zone and the inland Caiuá Desert.

Infilling of the Bauru Basin occurred in two main phases (Fig. 14). The first phase took place mainly in desert conditions (desert system tract), and the second phase involved more water, although the climate was semiarid (fluvial-aeolian systems tract). The first phase corresponds to the progressive burial of the basaltic substrate by an extensive and homogenous sandy blanket, formed mainly of sand sheet deposits, with moderate-sized dunes and interbedded loess deposits. At this stage, the small amount of fluvial activity was restricted to desert runoff flows (*wadis*). In lithostratigraphic terms, the desert system tract comprises the Vale do Rio do Peixe, Santo Anastácio, Goio Erê and Rio Paraná formations. In the initial phase of infilling, the original relief of the substrate created endorheic conditions in the inner zone of the basin, where an extensive marshy area in a semiarid climate (the Araçatuba Marshland) became established. The deposition of the braided river system of the Uberaba Formation, which is restricted to the northeastern edge, occurred during this phase.

Fig. 14. Palaeogeographical evolution of the Bauru Basin: **1.** initial desert phase (sandsheet and paludial deposits); **2.** borders uplift and alkaline magmatism; **3.** Aeolian-fluvial phase, mainly in semiarid climate and inner desert conditions, but involving more water availability (sandsheet, braided rivers and dune deposits); **4.** current phase. **AF**: Araçatuba Formation (inner paludial deposits), **UF**: Uberaba Formation (braided fluvial deposits).

The reactivation of tectonic structures on the eastern, north-northeastern and northwestern margins caused major changes in the geographic context of the basin, resulting in the advance of alluvial fans into the basin. At the same time, gradual climate change, perhaps caused by changes in relief, brought more moisture to the marginal areas. These changes marked the beginning of the second phase of sedimentation, in which important river systems were developed. These river systems ran from northeast to southwest, between the edges and the basin interior. In lithostratigraphic terms, the fluvial-aeolian systems tract is composed of the Marília, São José do Rio Preto, and Presidente Prudente formations.

The climate remained hot and dry during both phases of sedimentation, with desert conditions inside the basin. In the main phase of uplift of the edges various alkaline rock bodies were emplaced in marginal highs, extrusive magmatism occurred near the eastern edge (Taiúva Analcimites), and localized silicification took place in the south of the basin. The new frame, highlighted in the passage to new environmental and depositional setting, corresponded to important tectonic highs: the Rondonópolis Anteclise (Coimbra, 1991) in the northwest, the Alto Paranaíba Uplift (Hasui and Haralyi, 1991) in the northeast, and Serra do Mar (Almeida, 1976) in the east (Fig. 1).

Among the effects of the tectonic movement that occurred after the initial phase, perhaps the most important was the Uberaba Formation post-depositional inlay in the northeastern part of the basin. The Uberaba depression was formed during this event (Hasui and Haralyi, 1991). From indications of the direction of sediment transport, the changes in relief resulted in the creation of a geographical barrier in the Itumbiara suture zone. The Serra da Galga Member, which overlies the Uberaba Formation, shows a northwestern palaeocurrent direction, while that of the Uberaba Formation was to the southwest.

The river flows that originated in the alluvial fans and fluvial distributary system of the northeastern margin (the Serra da Galga Member), reached the basin interior via a sandy braided system (the São José do Rio Preto Formation). Further into the basin the landscape became increasingly flat and the transported sediments became increasingly thinner. Due to the shallow gradient of the basin, the river system therefore tended to meander in its distal portions, but was still sandy (the Presidente Prudente Formation). More stable, better defined, shallow channels meandered in extensive floodplains with lagoons, especially after overflow events. At the basin scale the sandstones and conglomeratic sandstones of the Serra da Galga Member (and the Ponte Alta Member) were the source areas for the São José do Rio Preto and Presidente Prudente formations. Dryness increased towards the interior, caused by a progressive increase in evaporation and water scarcity in the environment, until the disappearance of the river system in the Caiuá desert sandy plains. The formation of river systems took place in unconsolidated sandy deposits, without an erosion phase at the basin scale. In general, the fluvial deposits are separated from the previous wind deposits by diastems. It should be noted that subsequent erosion has removed much of the top of the Upper Cretaceous sequence in the current valleys. The upper portion of the sedimentary record has been preserved only in regional hills. The Botswana Basin can be considered to be a possible analogue of the current depositional and palaeoenvironmental context of the Bauru Basin (*e.g*. Thomas and Shaw, 2002; Nash and McLaren, 2003; Haddon and McCarthy, 2005; Kampunzu et al., 2007; Thomas and Burrough, 2012).

The establishment of paludal conditions in the Araçatuba region, a peculiar sub-area formed in the initial stage, was caused by the original lower topographic position of the substrate in that region. The western boundary of the outcrop area of the Araçatuba Formation is curiously straight, corresponding to a high point in the basaltic substrate. The initial formation of wetland within the basin was probably caused by the damming of the water table up to that basement feature. Eventually the continuing contribution from aeolian sediments, which initially supplied dunes and sand sheets marginal to the pond, was exhausted and the original depression was overwhelmed.

The wind origin exhibits remarkable constancy in the direction of transport, indicating high stability of the regional pattern of atmospheric circulation during the deposition of the Upper Cretaceous sequence. The conditions established after the opening of the South Atlantic remained during the two stages of basin infilling and show a good resemblance to those of the present day. The stability of the palaeocurrents also suggests that there were no significant obstacles in relief that could have hindered the wind flows.

During the Late Cretaceous and the early Palaeogene the direction of movement of the Bauru Basin substrate reversed. The elevation and exposure of the BSS began the erosion cycle in which the South American Surface (King, 1956) or the Japi Surface (Almeida, 1964) developed. The current limits of the sequence are erosive, due to regional uplift of the edges during the Cenozoic.

The major drainage system formed during the second evolutionary phase of the Bauru Basin shows remarkable similarity to the current regional drainage network, represented by the Parnaíba and Paraná rivers. It is likely that the position of these rivers corresponds to the displacement that originated in the Upper Cretaceous in response to the rise of the eastern and northeastern edges. Regional (neo?)tectonic modifications, which deformed the sequence, promoted a partial reorganization of the drainage network, highlighting the WNW direction. The major tributaries of the Paraná River, for example, reflect such changes.

5. Paleobiological record

The Bauru Basin preserves a diversity of fossils and trace fossils that, together with the palaeoenvironmental evidence, allow us to elucidate some aspects of past life. Evidence of the presence of these animals and plants in their life environments are their remains, such as bones, dermal plates, teeth, shells, claws, spicules, and spines. The remains may be composed of calcium phosphate (apatite), cellulose, calcium carbonate, silica, or chitin, as well as imprints preserved in sediment (body fossils). These fossils usually occur in groups of vertebrates, invertebrates, plants and microfossils.

Other evidence that may elucidate the physiology and behaviour of these Mesozoic organisms are the vertebrate and invertebrate ichnofossils or trace fossils found in the Bauru Basin. Eggs, shells and fossilized nests, coprolites, gastroliths, footprints, tubes, trails, tracks, and burrows all demonstrates the diversity of these ichnofossils that occur in different palaeoenvironments.

In most cases, the fossils and ichnofossils listed above occur within the Bauru Basin, in the siliciclastic sediments of fluvial (the Marília, Uberaba and Vale do Rio do Peixe formations), lacustrine (the Vale do Rio do Peixe Araçatuba formations) and marsh (the Vale do Rio do Peixe Formation) palaeoenvironments. The degree of preservation of these materials may be related to the unique aspects of fossil diagenesis or post-diagenetic/weathering factors, which are both determinants of the rarity and/or abundance of these occurrences.

Fossils and ichnofossils preserved in the Bauru Basin occur in siliciclastic sediments of the BSS. In general, the fossil records related to the Caiuá Group (Rio Paraná, Goio Êre, Santo Anastácio formations) are scarcer than those concerning the Bauru Group (Uberaba, Marília, São José do Rio Preto, Vale do Rio do Peixe, Presidente Prudente formations).

5.1. Fossil record of the Bauru Basin

Despite the major importance of the fossiliferous/ichnofossiliferous group, only some records will be mentioned by formations and/or paleoenvironments related to the Bauru Basin (Table 2), especially due to a great number of fossil records. Some records used to be related with “Bauru Sandstone” (*e.g.* Mezzalira, 1974) and Paraná Basin (*e.g.* Petri, 2001); nevertheless nowadays these records are related to BSS sedimentary units.

Table 2. Examples of Bauru Basin fossils and ichnofossils records. Taphonomic aspects, type occurrences and paleoenvironmental setting.

The Rio Paraná Formation comprises large dune deposits of inner desert. Its fossiliferous records are trace fossils of vertebrates, especially footprints of coelurosaurs (Leonardi, 1977, 1989; Fernandes et al. 2009). Deposits of small dunes and wet interdunes, of Goio Êre Formation contain particularly only ichnofossils of preserved vertebrates (Leonardi, 1994, 1977, 1989).

Tabular structures are observed in laminated sandstones from Santo Anastácio Formation occurring associated with cement and carbonate nodules wich are interpreted as possible rizolites (Fernandes, 1992). Footprints of Theropoda indet. also observed in this unit (Leonardi, 1994).

Few fossil records have been found in Uberaba Formation while comparing with other units of the basin. Such records are composed by indeterminate bone fragments, besides the vertebrae, external and appendicular remains of titanosaurid (Hasui, 1968; Goldberg, 1995). A megaraptoran specimen of dinosaur (Theropoda, Tetanurae) was specially described by Martinelli *et al.* (2013) in this formation. Ichnofossils, such as worm tubes and fossil eggs associated of order Ornithischia, suborder Ceratopsia (?) were also described in this unit (Campos and Bertini, 1985; Goldberg, 1995; Kellner *et al.,* 1998). Braided river system was described as being the paleoenvironmental of this unit.

The fossil records of Uberaba Formation are are scarcer than ohterr units of the basin. Such records are composed by indeterminate bone fragments, besides the vertebrae, external and appendicular remains of titanosaurid (Hasui, 1968; Goldberg, 1995). A megaraptoran, a dinosaur specimen (Theropoda, Tetanurae) was described by Martinelli *et al*. (2013) for this formation. Ichnofossils, such as worm tubes and fossil eggs associated of order Ornithischia, suborder Ceratopsia (?) were discovery in this unit (Campos and Bertini, 1985; Goldberg, 1995; Kellner *et al.,* 1998). Braided river system was described as being the paleoenvironmental of this unit.

The main fossiliferous deposits of Triângulo Mineiro zone, Minas Gerais State, belong to the strata of Serra da Galga Member of the Marília Formation, located in Peirópolis (Caieira site) and surrounding zones at the BR 050 Highway from the Uberaba County. It corresponds to distal fluvial braided deposits. Several bones and teeth of reptiles related to the sauropod (Titanosaur) and theropod (Abelisauridae and maniraptors) dinosaurs, as well as other remains of fishes, crocodiles, turtles (bones, teeth, osteoderms and scales) are preserved in the arenitic sediments of this formation. Besides, the occurrence of one lizard and a partially complete specimen of frog (Baez, 1985; Baez and Peri, 1989; Barbosa *et al*. 1970; Bertini and Carvalho, 1999; Campanha *et al*., 1994; Campos *et al*., 2005; Candeiro, 2002, 2005; Candeiro *et al*., 2004; Carvalho *et al*., 2004; Estes and Price, 1973; França and Langer, 2005; Kellner *et al.*, 2005; Kischlat *et al*., 1994; Machado *et al*., 2013; Novas *et al.*, 2005, 2008; Price, 1955). Also, in the Marília Formation, at São Paulo State, bones of sauropod (Aelosaurus) and theropod (Abelisauridae) dinosaurs (Ariel *et al*., 2014; Santucci, 2013) were discovered. Remains of gastropods and bivalves (invertebrates), conchostracans and ostracods (invertebrate microfossils) and sporocarps of ferns and carophytas algae (plant fragments) also were collected (Campanha *et al*., 1994; Petri, 1955; Senra and Silva e Silva, 1999, Suárez & Campos, 1995). Other specimens, like ichnofossils of invertebrates and vertebrates were found, such as worm tubes, and sauropod eggs/eggshells and coprolites (Price, 1951; Magalhães Ribeiro, 1999a, b; 2000; 2002a, b; 2003; 2013; Mezzalira and Arid, 1981; Ribeiro, 2003; Ribeiro and Ribeiro, 1999; Souto 2008). The specimens of invertebrate and vertebrate fauna and their ichnofossils (invertebrate/vertebrate), as well as remains of plants are represented by several taxa/parataxa, which were well preserved in the sedimentary environment of the Serra da Galga Member (Marilia Formation, Bauru Basin), in the Triângulo Mineiro zone (Candeiro and Brito, 2001; Ribeiro and Carvalho, 2007).

The Ponte Alta Member (Marília Formation) occurs only in the Triângulo Mineiro zone and corresponds to distal fluvial braided deposits. In its pelitic lithofacies were found girogonites of carophytas, ostracods, microgastropodes, internal molds of conchostracans, bone fragments and fish scales, and worm tubes (Campanha *et al*., 1994). Capilla (1997) also reported structures of algae and ostracods associated with lacustrine sediments (carbonates) of the Marilia Formation (Ponte Alta Member). In this unit was collected a sauropod dinosaur egg, partially complete (Magalhães Ribeiro, 1998, 2000; Ribeiro, 2003).

The quantity and diversity of fossils extracted from the Serra da Galga Member (*Fossiliferous Site of Peirópolis and Serra da Galga*) is much higher than those found in the Ponte Alta Member, a high carbonate cemented sandstone unit.

In the fluvial braided system, characterized by sediments of São José do Rio Preto Formation (Bauru Group), some fossils have been described like skeletal remains, shells and teeth of reptiles (Abelisauridae dinosaurs, crocodiles and turtles), as well as invertebrates and fishes, usually disarticulated and fragmented by transport. Also, the record of well preserved articulated remains of smaller reptiles like crocodiles, whose preservation was due, possibly, to the habit of life of these animals (Fernandes, 1998; Ariel *et al*, 2014).

Important fossil records are known in the Echaporã Member (Marília Formation), which is composed by deposits of eolian plains of sand sheets. Especially reptiles, such as dinosaurs and crocodilians and also fossil remains of fishes, molluscs, molds of roots and digs of small organisms. Teeth of Theropoda dinosaur from this member of Marília Formation were described by Santucci et al. (2013).

In the same paleoenvironmental setting, the Vale do Rio do Peixe Formation (Bauru Group) preserved part of a varied fauna that inhabited the basin, especially in the upper part of this unit. In general, are found complete or disarticulated bone fragments of reptiles, which were transported and buried by aeolian or flood deposits. Fittipaldi *et al*. (1989) reported the discovery of some bone fragments of tetrapod found in Pereira Barreto channel, São Paulo State. Remains of molluscs and arthropods also had the same type of eolian or flood transport and are found fragmented; however, sometimes presents a better state of preservation. Plant remains, such as oogonia of algae, root molds and small tubes of invertebrates were observed in several places this formation. This unit is also associated with lacustrine sediments and sometimes, with marshy deposits. Rare brachiopods and gastropods, some bivalves, remains of fishes (bones/scales) and of crocodiles (bones/teeth/osteoderms), of turtles (bones/shells) and bones of sauropod and teropod dinosaurs generally are preserved in the lacustrine stracta. Microfossils, ichnofossils of invertebrate/vertebrate (crocodyliphorm eggs/eggshells and coprolites) and fragments of plants were found in smaller amount (Fernandes, 1998; Magalhães Ribeiro *et al*., 2004; Souto, 2008).

Mezzalira (1974) reported the discovery of molds of conchostracans in the paludial deposits of the Araçatuba Formation (Bauru Group). Crocodyliphorm eggs and eggshells were also found in this formation (Ribeiro, Carvalho and Nava, 2006). Remains of fishes, brachiopds, insect/worm tubes and charophytas algae also were reported for this formation (Fernandes, 1998).

The deposits of meandering fluvial system of Presidente Prudente Formation (Bauru Group) contains fossils of gastropods, bivalves and conchostracans. Also bones, teeth and osteoderms of crocodyliphorms, several fossil remains of turtles, of sauropod and teropod dinosaurs (bones and teeth). Kellner *et al*. (1995) described remains of part of skull and mandible of a crocodilian *Sphagesaurus*. Besides, charophytas algae and molds of roots were discovered in those fluvial strata, as well as ostracodes of genus *Eucandonidae* and *Cypridae* (Fernandes, 1998; Suárez and Campos, 1995). This formation focuses a great amount of fossil records, along with the Marília (Serra of Galga Member) and São José do Rio Preto formations.

5.2 Taphonomic, paleoenvironmental and paleogeographic aspects

Life in the Bauru Basin was generally the most developed in the areas with the greatest water availability, such as the broad plains of braided streams with ephemeral alkaline water lagoons. Reptiles were present, mainly dinosaurs, crocodiles and turtles. Increasing aridity toward the interior of the basin resulted in a gradual reduction of the palaeobiological record in the inner, central basinal units, until its almost complete absence in the sand sea deposits of the central palaeodesert (Fernandes and Coimbra, 1996) (Fig. 15).

Fig. 15. Fossil occurrences and distribution of taxa during life in the Bauru Basin fossil. After Campos and Castro (1978), Mezzalira (1981).

The Bauru Basin fossils occur in several units, but the most important concentrations are in those of fluvial origin: Marília (Serra da Galga and Echaporã members), São José do Rio Preto and Presidente Prudente formations, composed of entire and transported materials. The sand sheets units of semiarid environments such as Vale do Rio do Peixe Formation and the Echaporã Member, were eventually achieved by torrential flows and transported as debris flows (Fernandes, 1998).

The known fossil occurrences are in the eastern part of the basin and were palaeogeographically controlled. They consist of remains of bone, mainly from reptiles (dinosaurs, crocodiles, turtles), as well as amphibians and fishes. Besides bones, molluscs, crustaceans, and charophyte oogones occur. The main occurrences are in lithofacies of fluvial origin, associated with the reworking and transport of material, which explains the rare preservation of articulated and/or complete skeletons. The fossils are associated with two main types of deposits: river overflow plains with ephemeral ponds and sandy bars of braided systems, in the basin interior; and the braided stream plains with lagoons and alluvial fan areas at the basin margins. In floodplains there is a mixture of reworked vertebrate bones, a few buried intact, and remains of invertebrates inhabiting shallow lakes. Hot desert conditions prevailed in the interior of the basin during both sedimentary phases.

The hard parts—bones, teeth and dermal plates of reptiles—show that fossilization occurred often with perfect preservation of bone structure and maintenance of the nature of the original phosphate, independent of the lithofacies. Bones are composed of low-birefringence fluorapatite, with concentric lamination, Haversian canals and fibrous material, similar to the bones of present-day vertebrates (Fig. 11g and h). No post-burial mechanical deformation was observed, thanks to the low degree of diagenesis to which the sediments were exposed, beyond the protection provided by early carbonate cementation. This cement is common and often permineralizes or partially replaces the organic structure. Sometimes the internal spaces are filled by detrital material.

There are no known records of Upper Cretaceous flora in the basin, except for traces of plant roots and a few occurrences of algae (charophyte oogonia). Higher plants, which would have fed large herbivorous dinosaurs, were not preserved due to the absence of paleoenvironment suitable for their preservation (semiarid climate).

Sediment transport by braided rivers and torrential rain floods was responsible for another common feature of most fossil occurrences, especially in the basin interior. The vast majority of the fossil record in these areas consists of fragmented and/or disarticulated bones concentrated in shallow channels bars or wadi facies. On the other hand, the fossil deposits in the Peirópolis region (Minas Gerais State), located near the edge of the basin, contain vertebrate bones in the best state of preservation and a higher diversity of species. Undoubtedly, the increased water availability favoured the development and maintenance of wildlife in marginal regions, as water bodies formed in lagoons and floodplains from coalescing alluvial fans. The fossils found there were less transported before burial. Different from those found in more inland areas, in deposits of sand sheets, desert rivers and ephemeral lakes (Echaporã Member). In these regions, the higher porosity of the sediments and the availability of carbonate-rich water caused the intense cementation of bones, which were commonly broken up by expansive (displacive) calcite growth (Fig. 11f).

The main reason for the better preservation of crocodilian fossils (skulls and articulated skeletal parts) was their tendency to take refuge in burrows to protect themselves during periods of adverse weather. Turtle fossils can also occur in a good state of preservation, sometimes in anomalous concentrations (Fig. 11e). Living turtles tend to get into groups in ponds during periods of water shortage, a behaviour known as aestivation. The rapid deposition of material transported during flash floods could have buried these animals alive. Thus, they were buried without transportation, explaining their good state of preservation.

In some cases, bones have been replaced by carbonate fluorapatite, aluminum phosphate and barium (gorceixite). In the last case, which as yet has hardly been studied, it is assumed that the enrichment of Ba, Sr and Ce is associated with the supergene processes of subtropical zones (Coutinho et al., 1996; Coimbra et al., 1997).

The tetrapod footprints in the Caiuá Group sandstones have increased the area of occurrence of this little-known fauna of the Cretaceous Brazilian desert environment, recorded in sandstones of ancient dune foresets. This occurrence indicates that even the most central regions of the Caiuá Desert were occasionally visited by predators or inhabited by animals adapted to aridity (Fernandes et al., 2009).

6. Conclusions

The Bauru Basin formed within the South American platform after the breakup of the Gondwana megacontinent, as a result of subsidence caused by isostatic adjustment resulting from the accumulation of the Serra Geral basalt flows (of the Paraná-Etendeka Continental Flood Basalt Province). The volcanic activity ceased in the Early Cretaceous, and the area that would become the Bauru Basin remained exposed, although subsiding, until the base level allowed the accumulation of sediment within the basin during the Late Cretaceous.

Sedimentation in the Bauru Basin occurred in semiarid conditions at the basin margins, and in desert conditions inside the basin. In the northern and northeastern regions of the basin records of originally proximal deposits are preserved, such as sandstones and conglomeratic sandstones of alluvial fan and fluvial distributary system deposits. The trough along the central axis of the elliptical basin constrained the regional drainage system from northeast to southwest, between the edges of the basin and the periphery of the inner hot and dry Caiuá Desert.

The fossil occurrences are in the eastern part of the Bauru Basin. They consist of remains of bone, mainly from reptiles (dinosaurs, crocodiles, turtles), as well as amphibians and fish. Besides bones, are found molluscs, crustaceans, and oogones of charophyte algae. The main occurrences are in lithofacies of fluvial origin, associated with the remobilization and transport of material, which explains the rare preservation of articulated and/or complete skeletons. The fossils are associated with two main types of deposits: river overflow plains with ephemeral ponds and sandy bars of braided systems; and the braided stream plains with lagoons and alluvial fan areas on the basin margins. In floodplains there is a mixture of reworked vertebrate bones, a few intact buried, and remains of invertebrates inhabiting shallow lakes.

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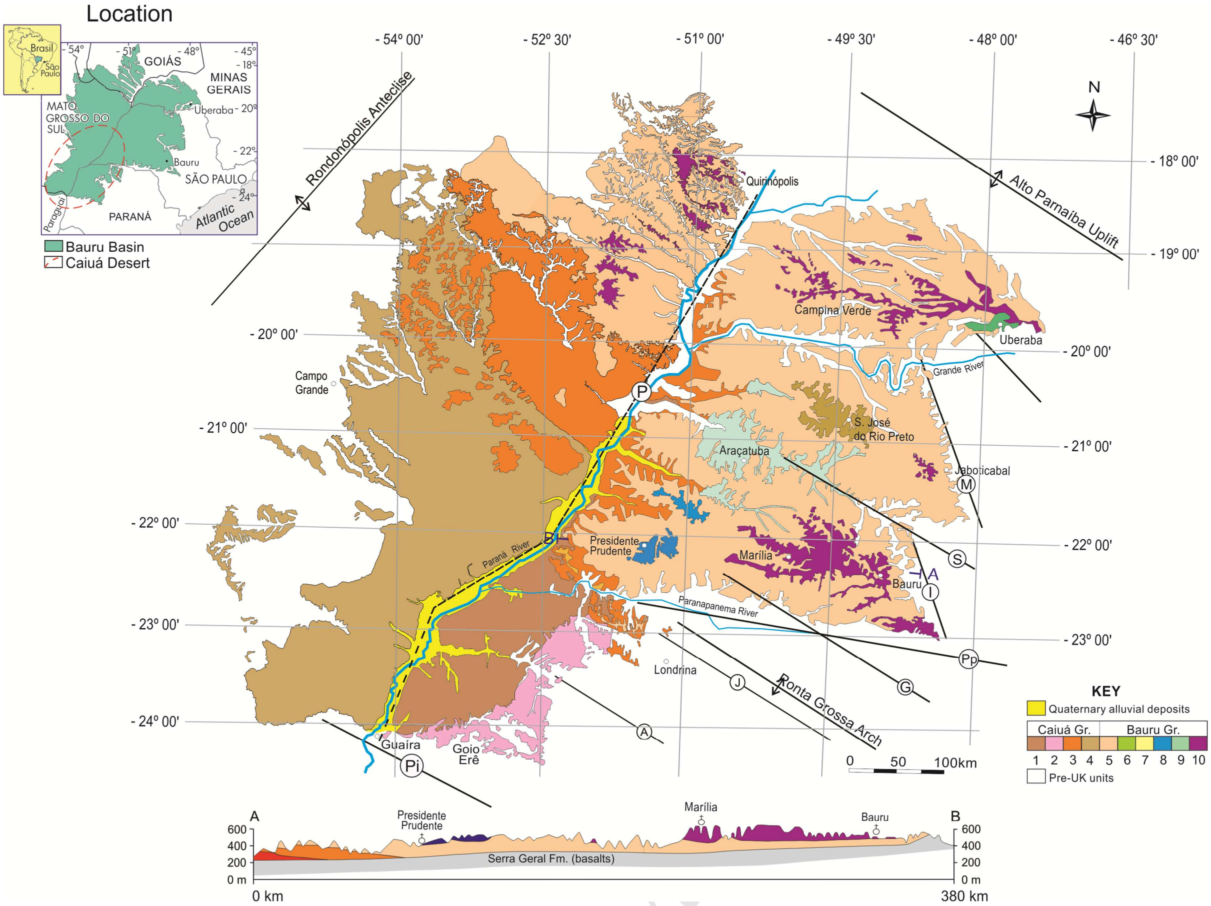
BAURU BASIN					
Lithostratigraphic units/ paleoenvironments	GROUP (flora and fauna)				
	PLANTS	INVERTEBRATES	ICHNOFOSSILS OF INVERTEBRATES	VERTEBRATES	ICHNOFOSSILS OF VERTEBRATES
Paraná River Fm. (Caiuá Gr.) complex of large dunes, inner desert			●dig of arthropods		●footprints of dinosaur (sauropod/theropod) ●footprints of mammals
Goio Êre Fm. (Caiuá Gr.) desert marginal plains (small dunes and wet interdunes)			♦tubes of worms		●footprints (Coelurosaurs)
Santo Anastácio Fm. (Caiuá Gr.) eolian sand sheets plains				●fishes	●rizolites
Uberaba Fm. (Bauru Gr.) braided river system			♦worm/insect tubes	●sauropod dinosaurs ●teropod dinosaurs	♦dinosaur eggs (teropod)
Marília Fm./Serra da Galga Mb. (Bauru Gr.) distal fluvial braided system	●sporocarps of pteridophytes ●carophytas ●spores/pollens of gimnosp./ angiosperms ♦rizolites ♦possible seeds ♦wood of coniferous	●ostracodes ♦gastropods ●bivalves ●conchostracans	♦worm tubes	●fishes ♦anuran ♦lizard ●turtles ♦crocodylomorphs ●sauropod dinosaurs ●teropod dinosaurs	♦dinosaur eggs (sauropod) ■dinosaur eggshells (sauropod) ♦coprolites (sauropods)
Marília Fm./Ponte Alta Mb. (Bauru Gr.) distal fluvial braided system	carophytas ♦rizolites	♦conchostracans ♦brachiopods ♦gastropods ♦bivalves	♦worm tubes	♦fishes ●dinosaurs	♦dinosaur egg (sauropod)
Marília Fm./Echaporã Mb. (Bauru Gr.) eolian plains of sand sheets	●rizolites	●bivalves	●tubes/dig of worms/others arthropods	♦fishes ♦crocodilians ■sauropod dinosaur ■dinosars *indet.*	♦coprolites (reptiles)
São José do Rio Preto Fm. (Bauru Gr.) fluvial braided system	♦rizolites	●ostracodes ●conchostracans ♦gastropods ●brachiopods ♦bivalves		●turtles ■crocodilians ■sauropod dinosaurs ●teropod dinosaurs	♦coprolites (reptiles)
Vale do Rio do Peixe Fm. (Bauru Gr.) Eolian plains of sand sheets and lacustrine deposits	●carophytas ●rizolites	■ostracodes ●conchostracans ♦brachiopods ♦gastropods ●bivalves	●tubes of worms/others arthropods	♦fishes ♦snakes ♦crocodilians ■turtles) ●sauropod dinosaurs ●teropod dinosaurs ■dinosaurs *indet*.	●eggs and eggshells (crocodyliphorms) ●coprolites (reptiles, specially crocodilians)
Araçatuba Fm. (Bauru Gr.) paludial environment	●rizolites	♦conchostracans ♦brachiopods	●tubes of worms/others arthropods	●fishes	●eggs and eggshells (crocodyliphorms) ●coprolites (crocodyliphorms)
Presidente Prudente Fm. (Bauru Gr.)	●rizolites	♦conchostracans	♦worm/insect tubes	♦fishes	

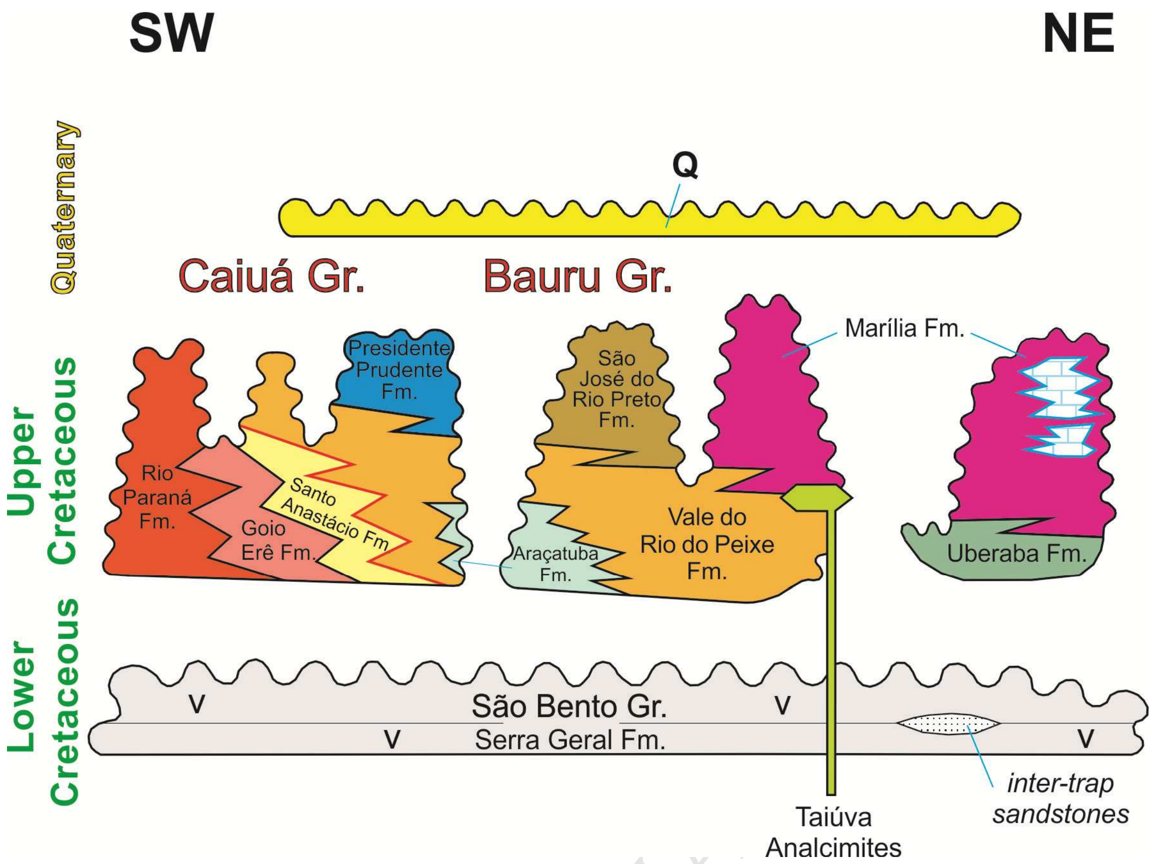
meandering fluvial system		♦brachiopods ♦gastropods ●bivalves		■turtles ♦crocodilian remains ●sauropod dinosaurs ●teropod dinosaurs ■dinosaurs *indet*.	
TYPE OCCURRENCES: ■several/ ●some /♦rare					
SOME **TAXA/PARATAXA DISTRIBUTION (groups of flora and fauna)**	PLANTS	INVERTEBRATES	ICHNOFOSSILS OF INVERTEBRATES	VERTEBRATES	ICHNOFOSSILS OF VERTEBRATES
	Pteridophyta- Class Filicales/gen. *Marsilea* (sporocarp)-(Msg) carophytas- *Chara* sp., *Amblyochara* sp., *Feistiella* sp., *Nitellopsis* sp. (Msg) Gymnosperm - *Dadoxylon* sp. (coniferous)-(Msg)	Ostrachoda- *Metacypris* sp., *Ilyocypris* sp., *Wolburgiopsis* sp., *Paracypria* sp., *Paracypridea* sp., *Mantelliana* sp. (VPX), *Virgatocypris* sp., *Altanicypris* sp. (Msg) Conchostraca - *Palaeolimnadiopsis* sp., *Bauruestheria sancarlensis* (VPX) Gastropoda- *Anodontites price*, *Florenceia peiropolensis*, *Turritela* sp. (Msg); *Physa aridi* (SRP); *Hydrobia prudentinensis, Diplodon arrudai* (PP) Bivalvia- *Anodontites pricei*, *Musculium*? (Msg), *Anodontites paulistanensis* (PP), *Castalia* sp. (VPX)	Ichnogen.- *Arenicolites* sp. (VPX), *Beaconites* sp. (Mec), *Coprinisphaera* sp. (VPX) *Macanopsis* sp., *Palaeophycus* sp. (Arc), *Skolithos* sp., *Taenidium* sp. (Mec, RP)	Fishes- *Lepisosteus* sp. (Msg); *Atractoteus* sp. (VPX); Siluriphorms (Ub); Characiphorms sp., Lepisosteiphorms sp., *Neoceratodus* sp., *Osteoglossidae* sp., *Characoidei indet*. (SA), Order Siluriform, Order Perciform (PP) Anura- *Baurubatrachus pricei* (Msg) Squamata- *Pristiguana brasiliensis* (Msg), Fam. Anilioidea (VPX) Chelonia- *Cambaremys langertoni, Peiropemys mezzalirai, Pricemys caieira* (Msg), *Baruemys elegans* (PP) Crocodylia- A*damantinasuchus navae, Mariliasuchus amarali, Armadilosuchus arrudai* (VPX), *Uberabasuchus terrificus* (Msg), *Sphagesaurus huenei (PP)* *Aelosaurus faustoi, Maxakalisaurus topai, Baurutitan britoi* (VPX), *Trigonosaurus pricei*, *Titanosaurus* sp. (Msg), Fam. Titanosauridae (PP, SRP, Ub, Msg), Fam. Charcarodontosauridae (VPX), Fam. Abelisauridae (Msg, VPX), Fam. Spinosauridae (VPX), Maniraptora (Msg) Aves- Subclass Enantiornithes (VPX) Mammalia- Infraclass Placentalia (VPX)	footprints of large, circular tridactyl footprints, digitigrade, digits with sharp edges tridactyl footprints, digitigrades, tracks with irregular and bipedal gait quadruped track, gait rebound and rounded footprints oofam. Megaloothidae (sauropod eggs and eggshells) oofam. Elongatoothidae (teropod eggs) oofam. Krokolithidae (crocodyliphorm eggs and eggshells) cilindric morphotype (dinosaur coprolites) cilindric morphotype (crocodyliphorm coprolites)

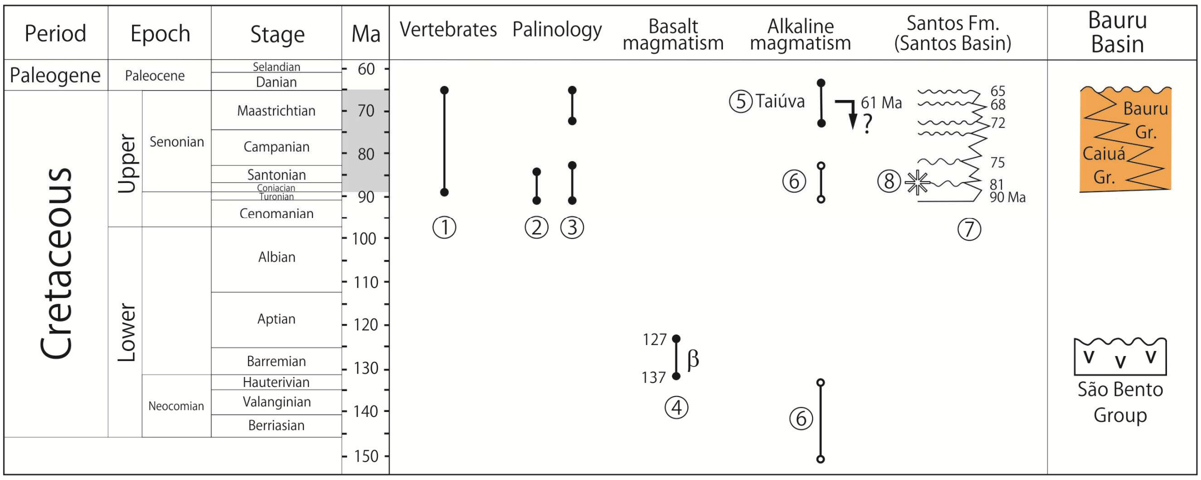
TAPHONOMIC ASPECTS (flora and fauna groups)	filled/molds of roots impressions-fragments of plants parcial plant remains complete plant remains	isolated fragments parcial remains of invertebrates complete remains of invertebrates molds of conchostracans	molds of tubes printing of traces	isolated fragments parcial remains of vertebrates complete remains of vertebrates fossil remains adhered to the sediment	printing of footprint-pads and grippers phalangeal printing of footprint-erosional depressions in unmarked half-moon shape or deformation structures apparent printing of tracks fragments of eggshells impressions-outer/inner eggshells parcial or complete eggs fragments of coprolites parcial or complete coprolites

Key: Arç = Araçatuba Fm., **Mec** = Marília Fm./Echaporã Mb., **Msg** = Marília Fm./Serra da Galga Mb., **PP** = Presidente Prudente Fm., **RP** = Rio Paraná Fm., **SA** = Santo Anastácio Fm., **SRJ** = São José do Rio Preto Fm., **Ub** = Uberaba Fm., **VPX** = Vale do Rio do Peixe Fm.

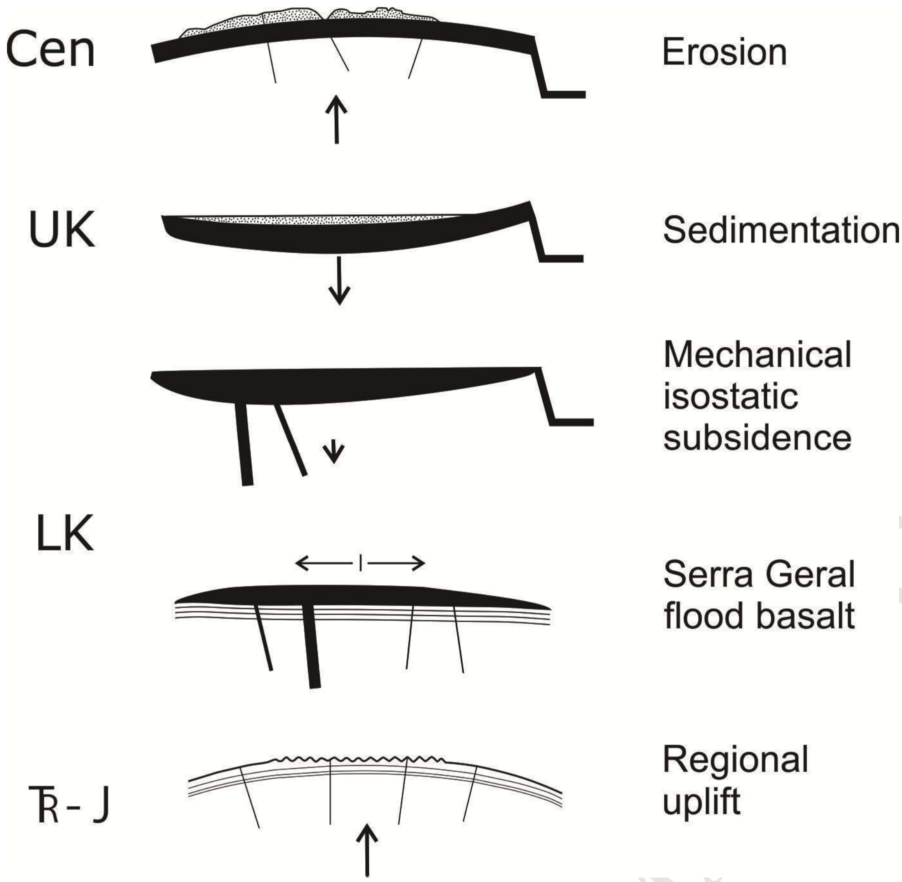


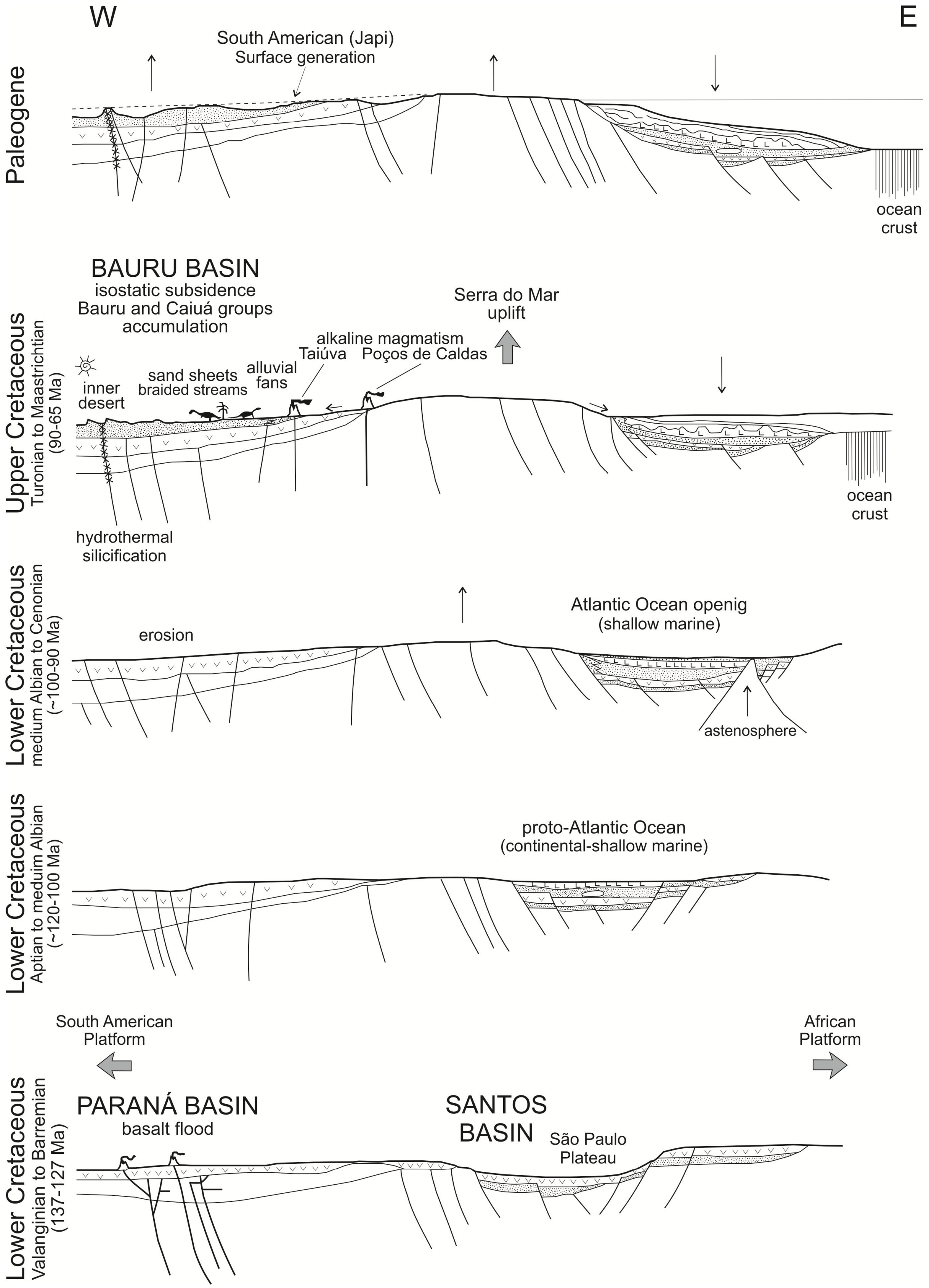
Location
Brasil
São Paulo
GOIÁS
MINAS GERAIS
MATO GROSSO DO SUL
SÃO PAULO
PARANÁ
Paraguai
Atlantic Ocean
Uberaba
Bauru
Bauru Basin
Caiuá Desert
- 54° 00'
- 52° 30'
- 51° 00'
- 49° 30'
- 48° 00'
- 46° 30'
- 18° 00'
- 19° 00'
- 20° 00'
- 21° 00'
- 22° 00'
- 23° 00'
- 24° 00'
N
Rondonópolis Anteclise
Alto Paranaíba Uplift
Ponta Grossa Arch
Quirinópolis
Campina Verde
Uberaba
Grande River
Campo Grande
S. José do Rio Preto
Araçatuba
Jaboticabal
Presidente Prudente
Marília
Bauru
Paraná River
Paranapanema River
Londrina
Guaíra
Goio Erê
KEY
Quaternary alluvial deposits
Caiuá Gr.
Bauru Gr.
1 2 3 4 5 6 7 8 9 10
Pre-UK units
0 50 100km
Serra Geral Fm. (basalts)
0 km
380 km

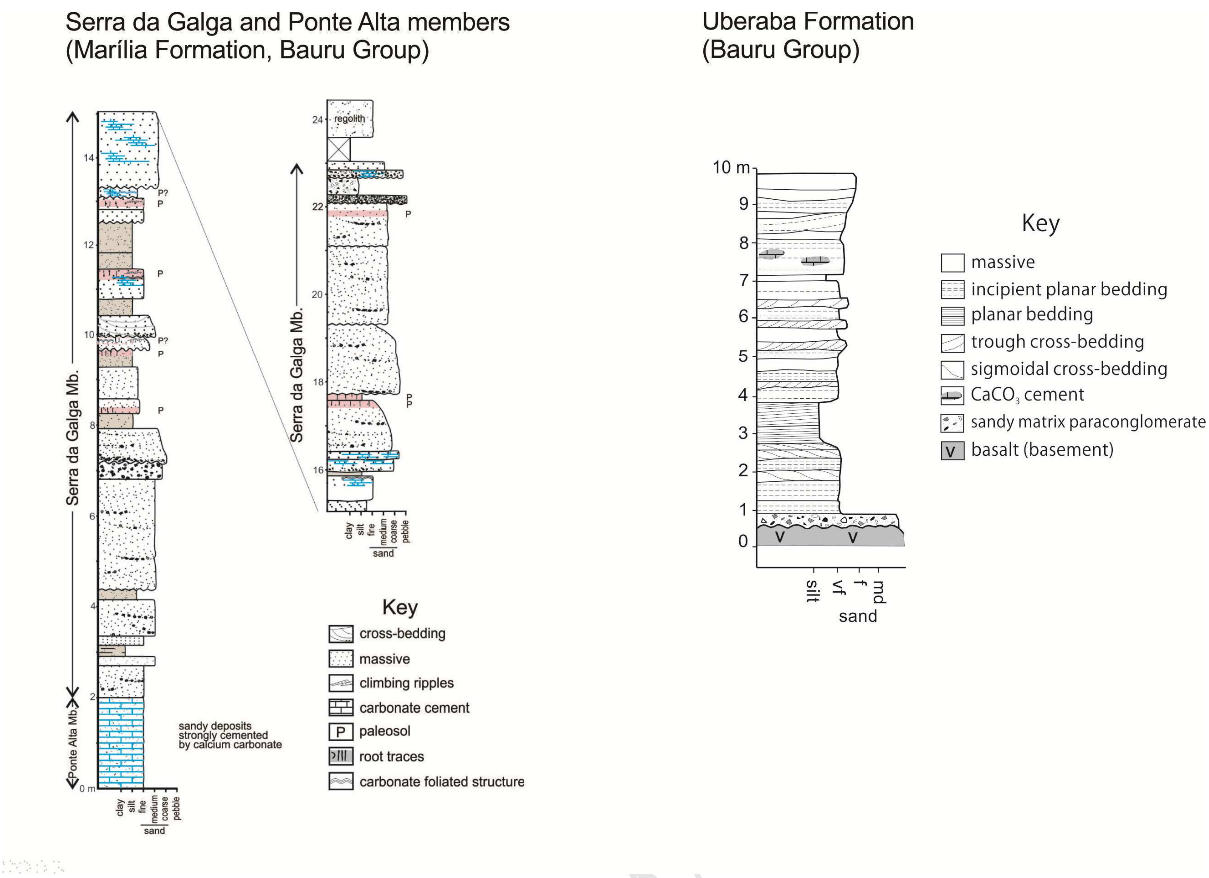

SW
NE
Quaternary
Q
Caiuá Gr.
Bauru Gr.
Upper Cretaceous
Presidente Prudente Fm.
São José do Rio Preto Fm.
Marília Fm.
Rio Paraná Fm.
Goio Erê Fm.
Santo Anastácio Fm.
Araçatuba Fm.
Vale do Rio do Peixe Fm.
Uberaba Fm.
Lower Cretaceous
São Bento Gr.
Serra Geral Fm.
Taiúva Analcimites
inter-trap sandstones



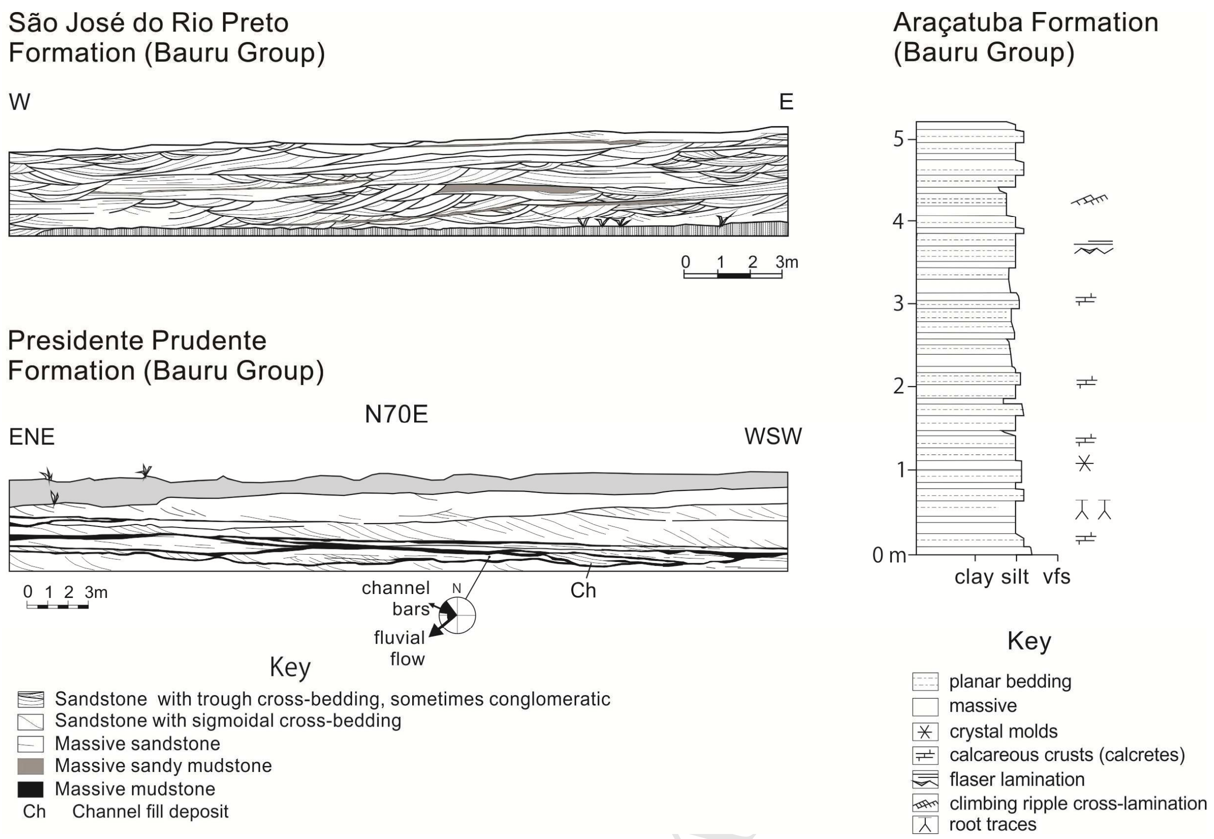
Key: ①Huene (1939), ②Lima et al. (1986)/Mitsuro Arai (1994, oral comunication), ③Dias-Brito et al. (2001), ④Turner et al. (1994), ⑤Coutinho et al. (1982), ⑥Almeida & Melo (1981), ⑦Moreira et al. (2007), ⑧Alves et al. (1994).

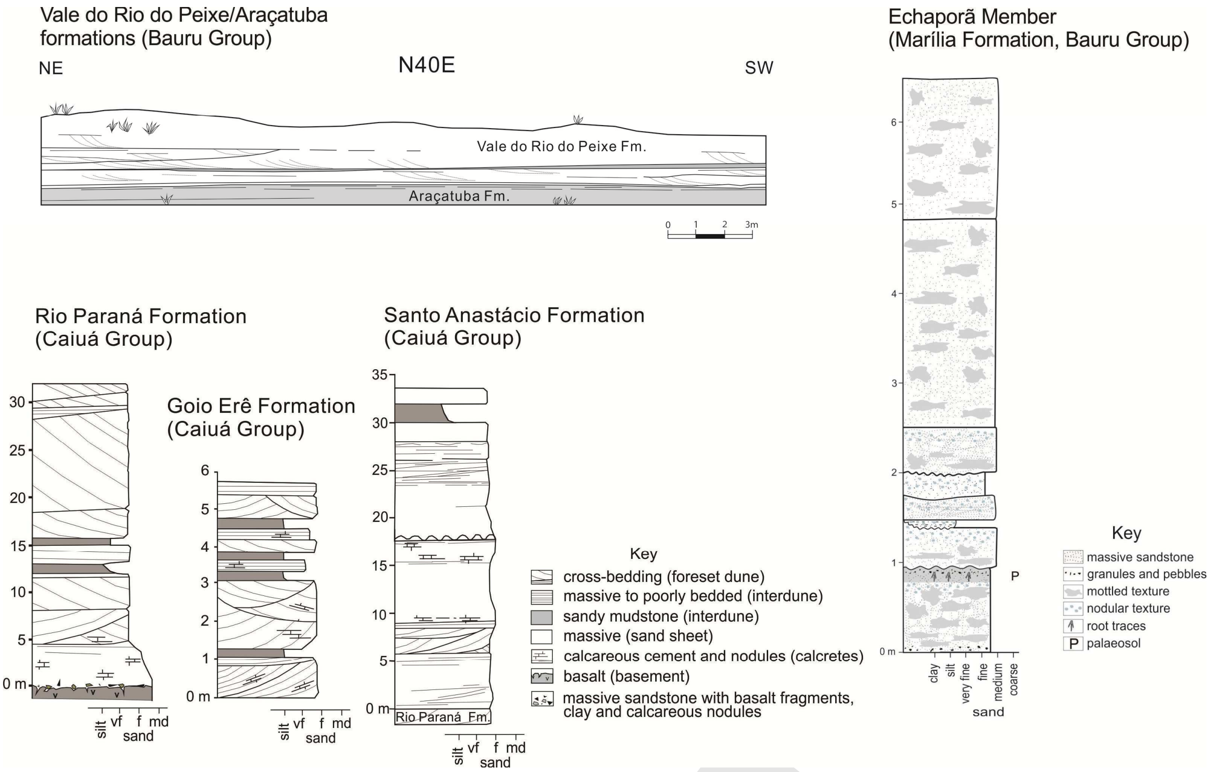

Cen
Erosion
UK
Sedimentation
Mechanical
isostatic
subsidence
LK
Serra Geral
flood basalt
Ʀ - J
Regional
uplift

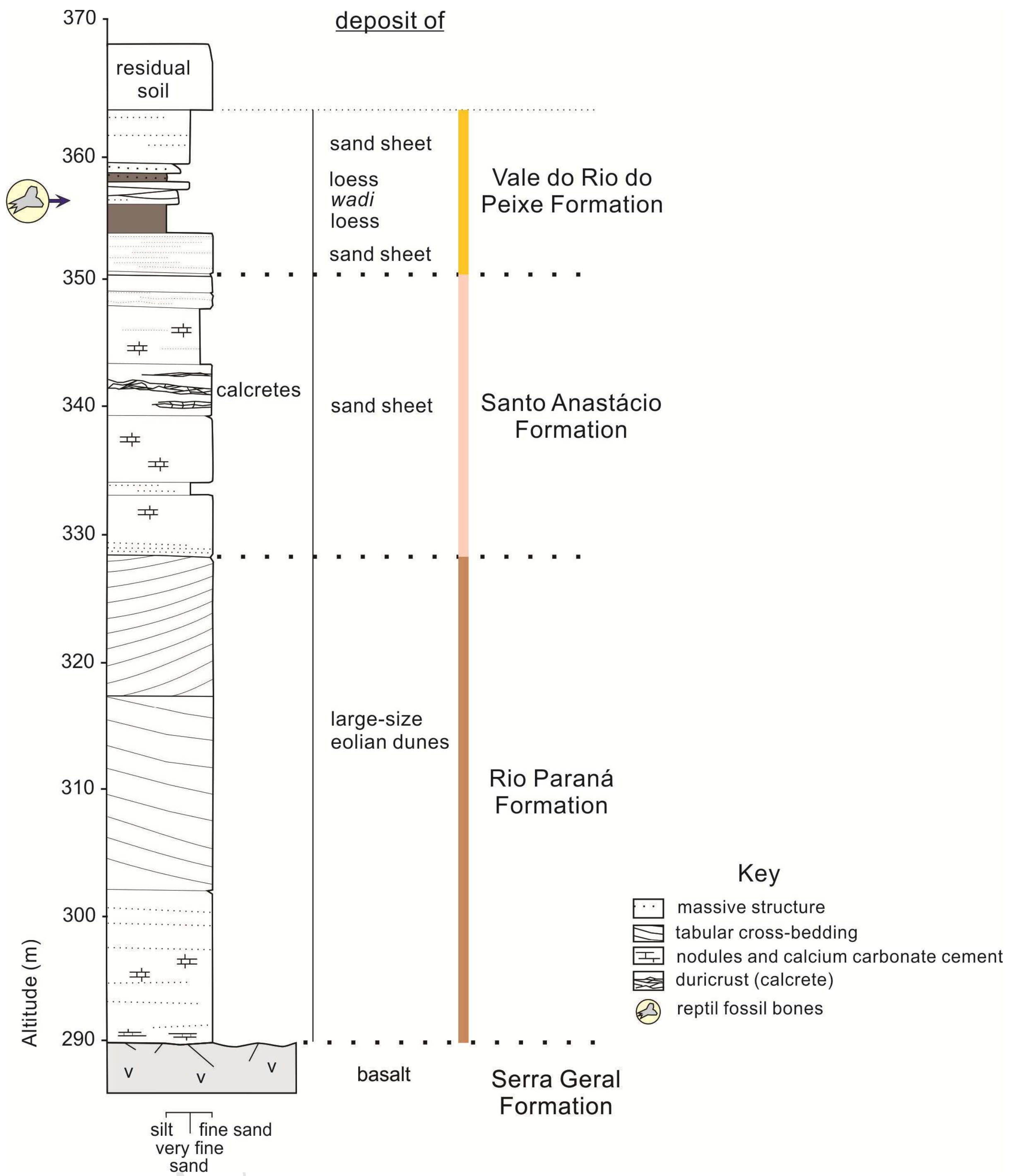

W
E
Paleogene
South American (Japi)
Surface generation
ocean
crust
Upper Cretaceous
Turonian to Maastrichtian
(90-65 Ma)
BAURU BASIN
isostatic subsidence
Bauru and Caiuá groups
accumulation
Serra do Mar
uplift
alkaline magmatism
Taiúva
Poços de Caldas
alluvial
fans
sand sheets
braided streams
inner
desert
hydrothermal
silicification
ocean
crust
Lower Cretaceous
medium Albian to Cenonian
(~100-90 Ma)
erosion
Atlantic Ocean openig
(shallow marine)
astenosphere
Lower Cretaceous
Aptian to meduim Albian
(~120-100 Ma)
proto-Atlantic Ocean
(continental-shallow marine)
South American
Platform
African
Platform
Lower Cretaceous
Valanginian to Barremian
(137-127 Ma)
PARANÁ BASIN
basalt flood
SANTOS
BASIN
São Paulo
Plateau



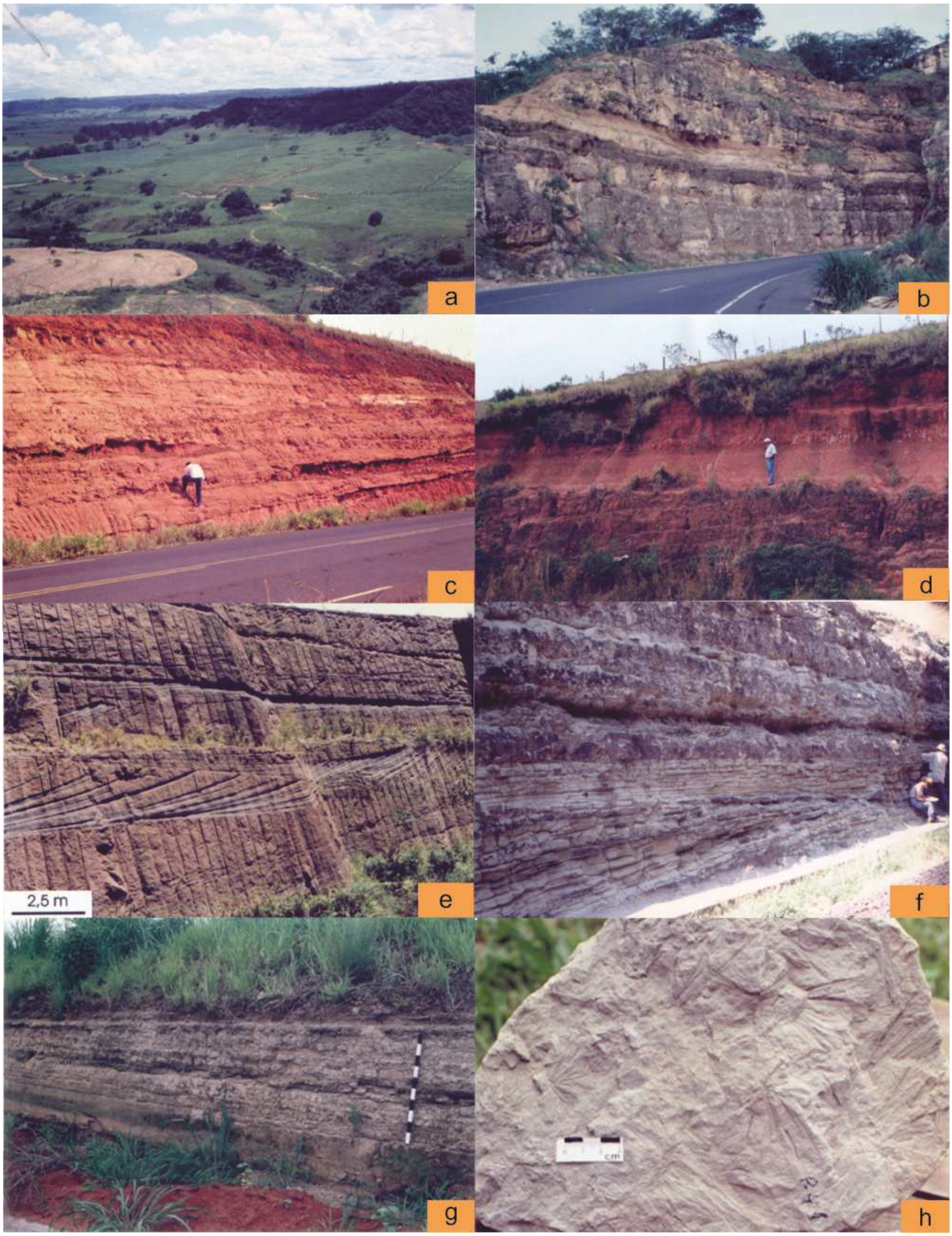
Serra da Galga and Ponte Alta members
(Marília Formation, Bauru Group)
Serra da Galga Mb.
Ponte Alta Mb.
sandy deposits strongly cemented by calcium carbonate
regolith
clay
silt
fine
medium
coarse
pebble
sand
Key
cross-bedding
massive
climbing ripples
carbonate cement
paleosol
root traces
carbonate foliated structure
Uberaba Formation
(Bauru Group)
10 m
silt
vf
f
md
sand
Key
massive
incipient planar bedding
planar bedding
trough cross-bedding
sigmoidal cross-bedding
CaCO3 cement
sandy matrix paraconglomerate
basalt (basement)

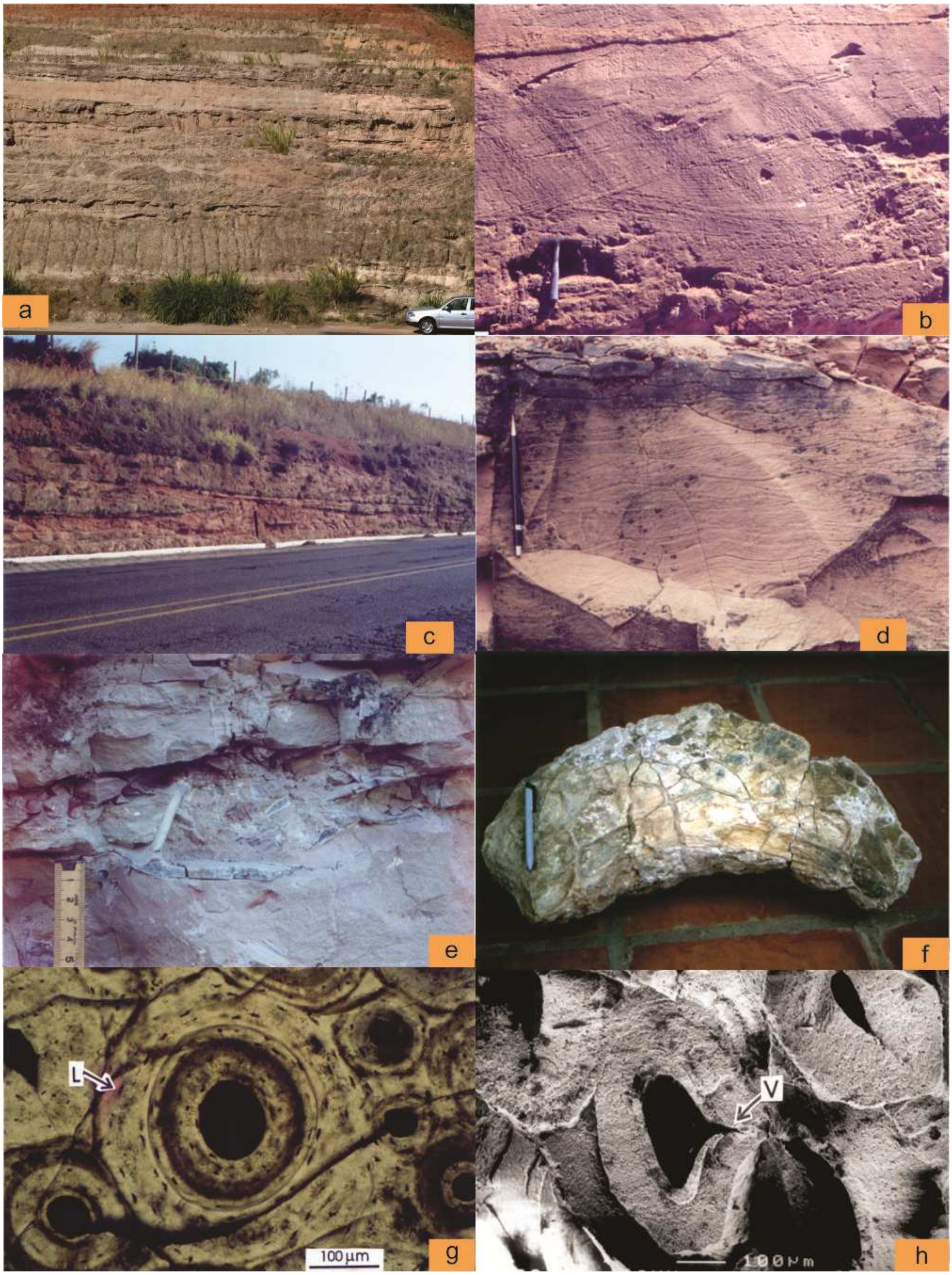

São José do Rio Preto
Formation (Bauru Group)
W
E
0 1 2 3m
Presidente Prudente
Formation (Bauru Group)
N70E
ENE
WSW
0 1 2 3m
channel
bars
N
fluvial
flow
Ch
Key
Sandstone with trough cross-bedding, sometimes conglomeratic
Sandstone with sigmoidal cross-bedding
Massive sandstone
Massive sandy mudstone
Massive mudstone
Ch Channel fill deposit
Araçatuba Formation
(Bauru Group)
5
4
3
2
1
0 m
clay silt vfs
Key
planar bedding
massive
crystal molds
calcareous crusts (calcretes)
flaser lamination
climbing ripple cross-lamination
root traces

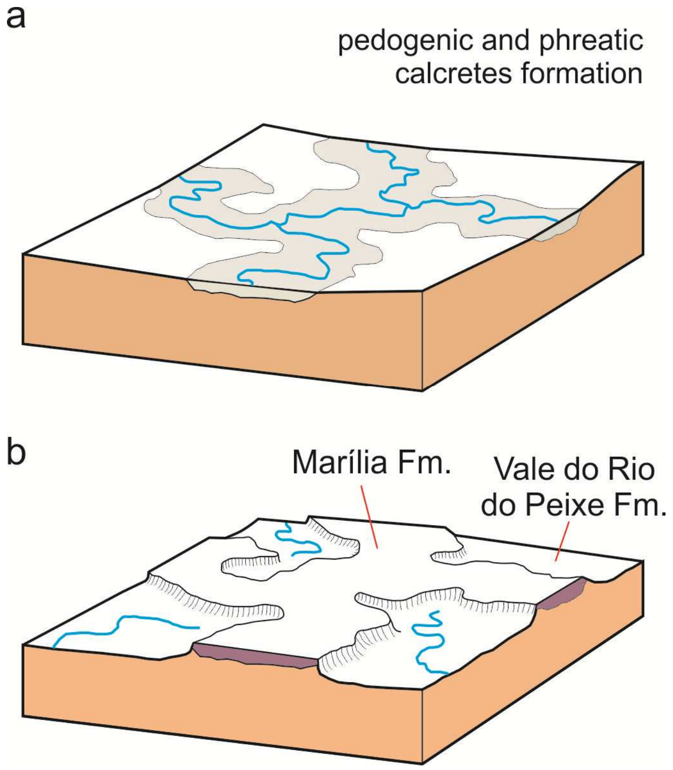

Vale do Rio do Peixe/Araçatuba
formations (Bauru Group)
NE
N40E
SW
Vale do Rio do Peixe Fm.
Araçatuba Fm.
0 1 2 3m
Echaporã Member
(Marília Formation, Bauru Group)
Rio Paraná Formation
(Caiuá Group)
Goio Erê Formation
(Caiuá Group)
Santo Anastácio Formation
(Caiuá Group)
Rio Paraná Fm.
silt vf f md
sand
Key
cross-bedding (foreset dune)
massive to poorly bedded (interdune)
sandy mudstone (interdune)
massive (sand sheet)
calcareous cement and nodules (calcretes)
basalt (basement)
massive sandstone with basalt fragments, clay and calcareous nodules
clay silt very fine fine medium coarse
sand
P
Key
massive sandstone
granules and pebbles
mottled texture
nodular texture
root traces
palaeosol

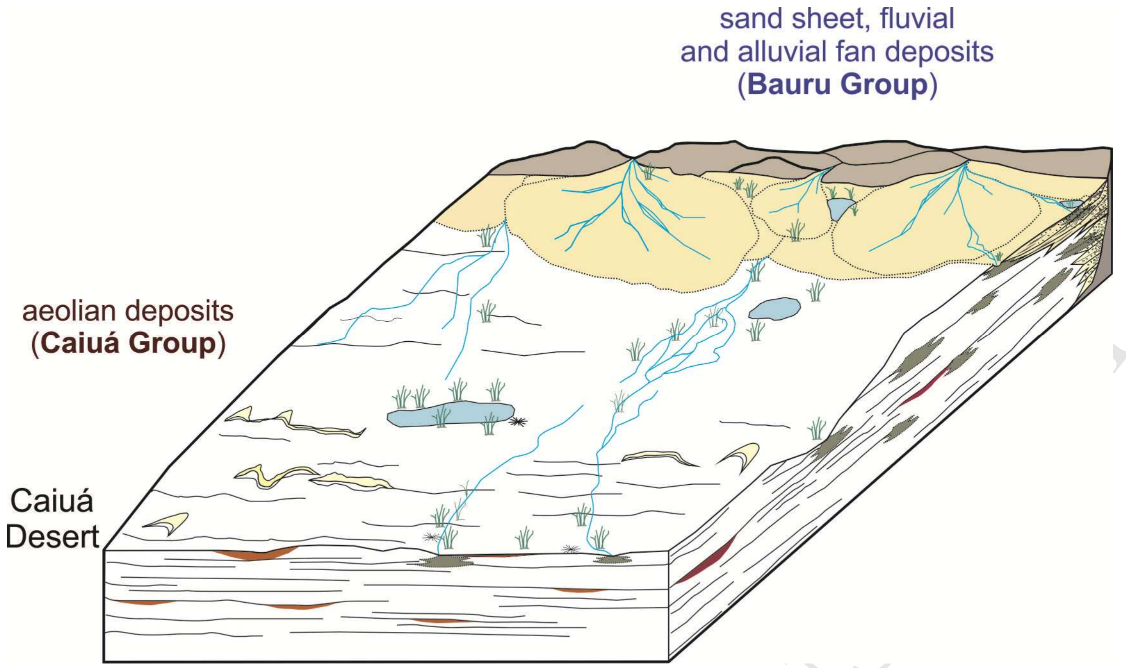


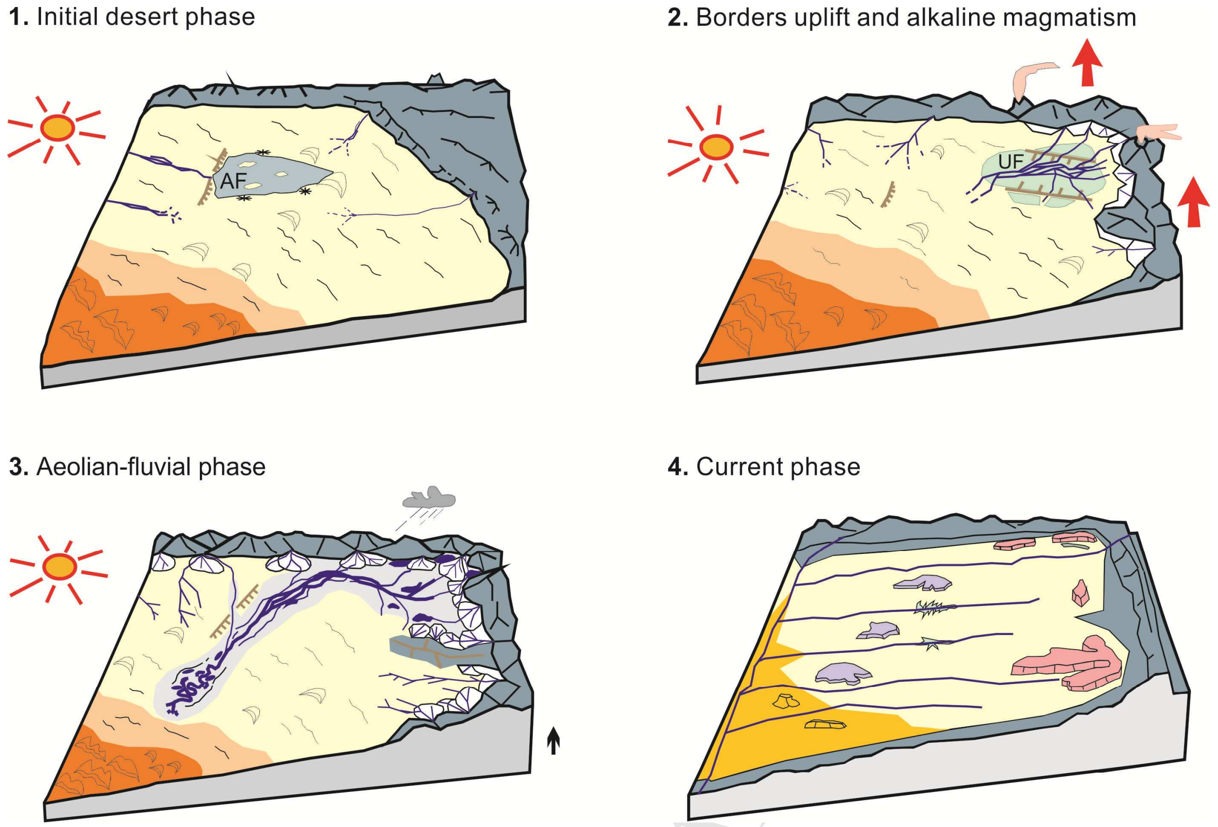
Altitude (m)
370
360
350
340
330
320
310
300
290
deposit of
residual soil
sand sheet
loess
wadi
loess
sand sheet
Vale do Rio do Peixe Formation
calcretes
sand sheet
Santo Anastácio Formation
large-size eolian dunes
Rio Paraná Formation
basalt
Serra Geral Formation
silt
fine sand
very fine sand
Key
massive structure
tabular cross-bedding
nodules and calcium carbonate cement
duricrust (calcrete)
reptil fossil bones

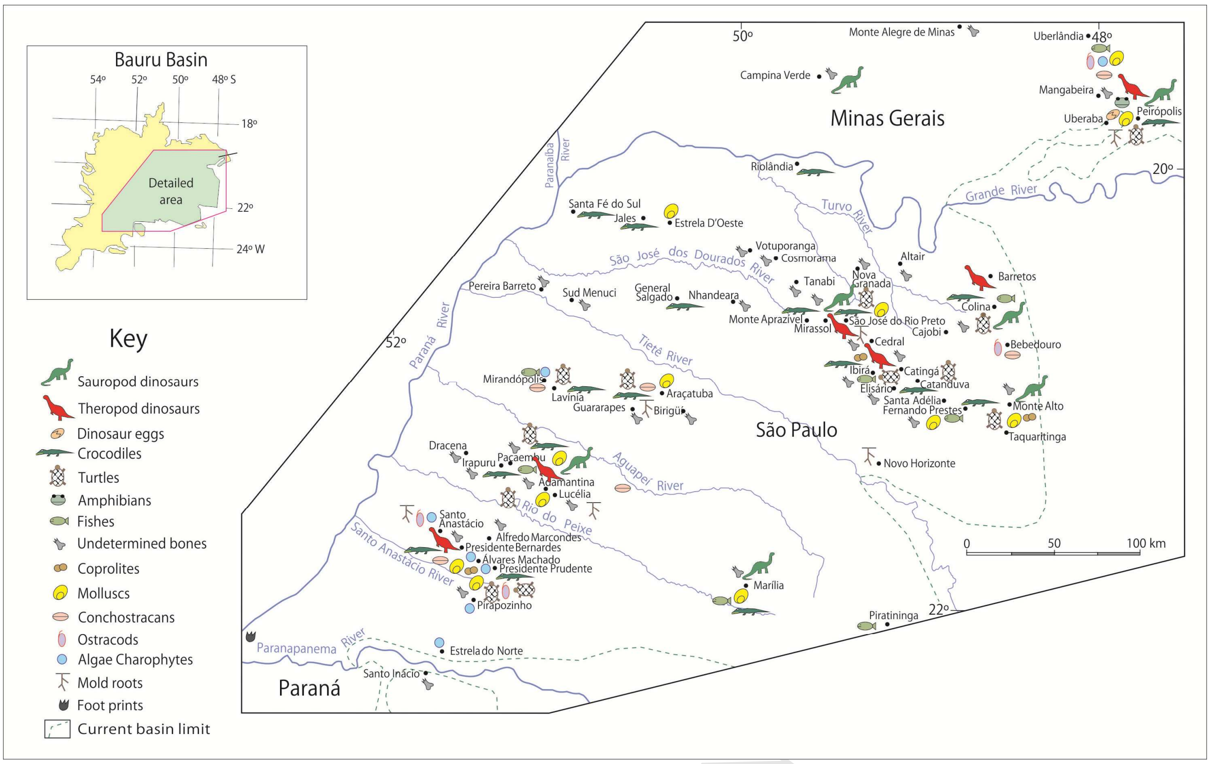

a
b
c
d
2,5 m
e
f
g
cm
h


a
b
c
d
e
f
L
100 µm
g
V
100µm
h


a
pedogenic and phreatic
calcretes formation
b
Marília Fm.
Vale do Rio
do Peixe Fm.


sand sheet, fluvial
and alluvial fan deposits
(Bauru Group)
aeolian deposits
(Caiuá Group)
Caiuá
Desert


1. Initial desert phase
AF
2. Borders uplift and alkaline magmatism
UF
3. Aeolian-fluvial phase
4. Current phase



Bauru Basin
54º
52º
50º
48º S
18º
22º
24º W
Detailed area
Key
Sauropod dinosaurs
Theropod dinosaurs
Dinosaur eggs
Crocodiles
Turtles
Amphibians
Fishes
Undetermined bones
Coprolites
Molluscs
Conchostracans
Ostracods
Algae Charophytes
Mold roots
Foot prints
Current basin limit
Minas Gerais
São Paulo
Paraná
50º
52º
48º
20º
22º
0
50
100 km
Monte Alegre de Minas
Uberlândia
Campina Verde
Mangabeira
Uberaba
Peirópolis
Riolândia
Santa Fé do Sul
Jales
Estrela D'Oeste
Votuporanga
Cosmorama
Altair
Barretos
Tanabi
Nova Granada
Pereira Barreto
Sud Menuci
General Salgado
Nhandeara
Monte Aprazível
Mirassol
São José do Rio Preto
Colina
Cajobi
Bebedouro
Cedral
Ibirá
Catingá
Catanduva
Elisário
Santa Adélia
Fernando Prestes
Monte Alto
Taquaritinga
Mirandópolis
Lavínia
Araçatuba
Guararapes
Birigüi
Novo Horizonte
Dracena
Irapuru
Paraemau
Adamantina
Lucélia
Santo Anastácio
Alfredo Marcondes
Presidente Bernardes
Álvares Machado
Presidente Prudente
Pirapozinho
Marília
Piratininga
Estrela do Norte
Santo Inácio
Paranaíba River
Grande River
Turvo River
São José dos Dourados River
Tietê River
Paraná River
Aguapeí River
Rio do Peixe
Santo Anastácio River
Paranapanema River

Manuscript highlights

The paper tells about the Bauru Basin stratigraphy and its depositional environments. We think that is significant because in the Upper Cretaceous continental basin that where lived the main Brazilian dinosaurs, matter of the special JSAES issue. The paper should be of interest to readers in the areas of Paleontology, Stratigraphy and South American Geology.