DEPOSITIONAL MODEL OF THE IPIXUNA FORMATION (LATE CRETACEOUS-?EARLY TERTIARY), RIO CAPIM AREA, NORTHERN BRAZIL

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Short Running title: "Depositional model of the Ipixuna Formation, Rio Capim area"

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DEPOSITIONAL MODEL OF THE IPIXUNA FORMATION (LATE CRETACEOUS-?EARLY TERTIARY), RIO CAPIM AREA, NORTHERN BRAZIL

MODELO DEPOSICIONAL DA FORMAÇÃO IPIXUNA (NEOCRETÁCEO-?EOTERCIÁRIO), ÁREA DO RIO CAPIM, NORTE DO BRASIL

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ABSTRACT

Exposures along open quarries located in the eastern Cametá Sub-Basin provide a opportunity to assess further discussion focusing on the depositional environments of the Upper Cretaceous-?Lower Tertiary Ipixuna Formation. The lower part of this unit emphasized herein, known as the “soft kaolin”, consists mostly of kaolinitized sandstones and mudstones that exhibit well preserved sedimentary structures that are particularly favorable for facies analysis and paleoenvironmental reconstructions. The sandstones are chiefly cross-stratified, typically with low angle, locally reverse orientated foresets with reactivation surfaces and/or mud drapes. These characteristics, together with a trace fossil assemblage consisting of *Ophiomorpha, Thalassinoides, Planolites, Teichichnus, Taenidium* and *Skolithos,* conform to deposition in a coastal setting influenced by tidal processes. Although a previous study has documented tidal processes during deposition of the soft kaolin (Santos Jr. and Rossetti, 2003), this paper shows that the influence of tidal currents was much more important than initially proposed. Hence, the kaolinitized deposits are attributed to tidally influenced fluvial channel (Facies Association A), tidal channel (Facies Association B), tidal flat/mangrove (Facies Association C), and tidal sand bar/tidal sandy flat (Facies Association D), all together comprising a tide-dominated estuarine system.

Keywords: soft kaolin, Ipixuna Formation, Cametá Sub-Basin, tide-dominated estuary, sedimentary facies, paleoenvironment.

RESUMO

Exposições ao longo de minas localizadas no leste da Sub-Bacia de Cameá fornecem uma oportunidade única para a condução de discussões focalizando os ambientes deposicionais da Formação Ipixuna (Neocretáceo-?Eoterciário). A porção inferior desta unidade, conhecida como "caulim *soft*", enfatizada neste trabalho, consiste principalmente em arenitos e argilitos caulinitizados que, por serem bem estratificados, favorecem a análise faciológica visando-se reconstruções paleoambientais. Os arenitos são principalmente estratificados cruzados, tipicamente com *foresets* de baixo ângulo e, localmente, orientados bidirecionalmente, além de formarem pacotes definidos por superfícies de reativação/ou filmes de argila. Estas características, juntamente com a assembléia de traços fósseis consistindo em *Ophiomorpha, Thalassinoides, Planolites, Teichichnus, Taenidium* e *Skolithos,* são consistentes com deposição em ambiente costeiro dominado por correntes de maré. Embora estudo prévio já tenha documentado a influência de correntes de maré durante a deposição da unidade correspondente ao caulim *soft*, o presente trabalho mostra que esta influência foi muito mais importante do que inicialmente proposto. Assim, os depósitos caulinitizados estudados são produtos de deposição em ambientes de canal de maré com influência fluvial (associação de fácies A), canal de maré (associação de fácies B), planície de maré/mangue (associação de fáices C), e barra/planície de areia dominada por maré (associação de fácies D), tipificando sistema estuarino dominado por maré.

Palavras-chaves: caulim *soft*, Formação Ipixuna, Sub-Bacia de Cametá, estuário dominado por maré, fácies sedimentar, paleoambiente.

INTRODUCTION

Several mineralogical and geochemical studies (*e.g.*, Truckenbrodt *et al.*, 1991; Kotschoubey *et al.*, 1996, 1999; Souza, 2000) have been undertaken on the Ipixuna Formation (Upper Cretaceous-?Lower Tertiary), which is exposed in the eastern Cametá Sub-Basin. These studies have been motivated by the fact that this unit contains one of the largest kaolin reserves in the world, the Rio Capim kaolin, which has received particular attention due to its high brightness. Despite the economic interest, sedimentologic studies aiming paleoenvironmental interpretations of the Rio Capim kaolin quarries are still inadequate to provide a detailed reconstruction of its mode of deposition.

Traditionally known as fluvial to lacustrine in origin (Góes, 1981), the Ipixuna Formation has been more recently related to a coastal depositional system (Santos Jr. and Rossetti, 2003). Sedimentary facies described in that study were attributed to tidal processes. Thereby, several tidally influenced depositional environments were recognized, which collectively led the authors to the interpretation of a wave-dominated estuary. This interpretation was based on the presence of tidal delta deposits along road cuts between the towns of Ipixuna and Paragominas, which were considered correlative to the soft kaolin unit exposed in the kaolin quarries (Santos Jr. and Rossetti, 2003). However, stratigraphic studies have revealed that this unit is more complex than initially thought, encompassing different stratigraphic units attributed to high-frequency depositional sequences (Rossetti, 2004; Rossetti and Santos Jr., 2006). Taking this into account, correlation of the tidal delta deposits with the soft kaolin unit of the Ipixuna Formation in the Rio Capim area is problematic. The continuous kaolin exploitation has resulted in a series of fresh exposures that allow more detailed facies and stratigraphic analyses. As a result, other facies assemblages can be characterized, providing additional elements for a more refined reconstruction of the depositional model.

The goal of this paper is to provide a more complete description of the facies and facies associations of the soft kaolin unit of the Ipixuna Formation. These are based on exposures recently available in two quarries, the IRCC and the PPSA in the Rio Capim area (Fig. 1), in order to furnish a better interpretation of both the sedimentary processes and the depositional environments. Based on these data, it is possible now to assay a wave-dominated estuarine model previously proposed for the soft kaolin.

GEOLOGICAL FRAMEWORK

The Cametá Sub-Basin, together with the Limoeiro, Mexiana and Mocajuba sub-basins, constitutes the Marajó Graben System, located at the mouth of the Amazon River, northern Brazil. These structures were formed by NW–SE and NNW–SSE normal faults, as well as NE–SW and ENE–WSW strike-slip faults during the opening of the Equatorial South Atlantic Ocean (Azevedo, 1991; Galvão, 1991; Villegas, 1994; Costa *et al.*, 2001).

The Cametá Sub-Basin is up to 10 km thick, and includes Cretaceous and Cenozoic deposits (Fig. 2), which are mostly known from subsurface data. The Cretaceous succession includes the Breves Formation (Aptian-Cenomanian) and the Limoeiro Formation (Late Cretaceous), considered to be fluvial and marine transitional in origin (Villegas, 1994). The Tertiary and Quaternary deposits include the Marajó Formation (Paleocene-Eocene) and the Tucunaré Formation (Pleistocene), both formed within marine to transitional environments.

Exposures of Cretaceous rocks in the Cametá Sub-Basin are only found in the eastern margin of the basin, where Albian/Cenomanian deposits are cut by a kaolinitized Upper Cretaceous unit referred to as the Ipixuna Formation. This unit is particularly well exposed in the Rio Capim Kaolin area, where it approaches thicknesses of 40 m and consists of kaolinitized mudstones and sandstones. Previously regarded as a single stratigraphic unit, the Ipixuna Formation has been recently subdivided into two intervals, bounded by a discontinuity surface that is marked by paleosol (Rossetti and Santos Jr., 2003; 2006; Rossetti, 2004). The lower part of the interval corresponds to the deposits referred to herein as the soft kaolin unit. The upper part corresponds to a hard kaolin unit, known as the semi-flint, due to the composition of flint-like fire clay that consist of endured kaolinite showing no plasticity when ground up. An intermediate unit characterized by soft-sediment deformed deposits bounded also by discontinuity surfaces occurs between the soft kaolin and semi-flint at some localities (Rossetti and Santos Jr., 2003). The facies analysis presented herein is focused solely in the soft kaolin unit, which bears the commercially exploited kaolin.

FACIES ANALYSIS OF THE SOFT KAOLIN

The soft kaolin deposits of the Ipixuna Formation in the Rio Capim area correspond to a nearly 20 m thick, fining-upward unit, consisting of kaolinitized, locally lenticular or tabular sandstones, as well as mudstones, and conglomerates. Where the base of these deposits is exposed, an unconformity (cf. Rossetti, 2004) marked by a lag of mudstone clasts and iron-cemented, coarse-grained to pebbly sandstones separates them from the underlying Albian to Cenomanian rocks (Rossetti and Santos Jr., 2003). The top of the soft kaolin unit is also an unconformity, marked by a paleosol that local displays a thin (up to 20 cm thick) interval of lateritic concretions overlain by the semi-flint kaolin unit (Santos Jr. and Rossetti, 2003).

Despite the high degree of kaolinitization, which is primarily due to replacement of lithic grains and detritic clay minerals, the soft kaolin is characterized by well-developed primary stratification, providing the basis for reconstructing the depositional processes and paleoenvironmental settings. Based on geometry, sedimentary structures, grain sizes, and suite of trace fossils, four intergradational facies associations were recognized and attributed to (Figs. 2 and 3): 1. tidally-influenced fluvial channel (Facies Association A); 2. tidal channel (Facies Association B); 3. tidal flat/mangrove (Facies Association C); and 4. tidal sand bar/tidal sandy flat (Facies Association D). Facies Association A, dominant in the base of the studied quarries, grades upward into deposits that show stronger tidal influence producing a typical fining-upward successions. Facies associations B and C are better developed in the PPSA quarry, whereas Facies Association D is more abundant in the RCC quarry.

Facies Association A: Tidally influenced Fluvial Channel

Facies association A (Fig. 3A-E) is up to 5.5 m thick and occurs at the base of the soft kaolin deposits, where it consists primarily of sandstones composed of abundant quartz grains. Intraformational conglomerates and heterolithic mudstones/sandstones are also present. This facies association comprises fining- and thinning-upward packages that are up to 2.5 m thick and are bounded at the base by erosional discontinuity surfaces. Where exposures are laterally continuous, the basal surface of the fining/thinning-upward successions displays a broad concave upward shape, up to 300 m wide (Fig. 3A-D). Trace fossils are very rare in this facies association, including only undetermined vertical burrows.

Three facies are present in this association including, in order of decreasing abundance: tabular/trough cross-stratified or laminated sandstone (Facies St); intraformational conglomerate (Facies Ci); and heterolithic mudstone/sandstone (Facies Ht). The sandstones (Fig. 3E) are, in general, poorly sorted, consist of sub-rounded, coarse- to medium-grained sands, and display tabular and trough cross-stratification or cross-lamination (Facies St), the latter with set thicknesses averaging 0.3 m and less than 5 cm, respectively. The cross sets, which typically decrease in size upward, dip consistently at low angles (typically between 10-20^{o}). Although they dip dominantly to the N/NE, oppositely dipping S/SW cross sets are common in this facies (Fig. 3D). Additionally, reactivation surfaces are abundant and define foreset packages averaging 10 cm thick, which are locally marked by mud drapes (Fig. 2).

Facies Ci is dominantly confined to the base of the fining-upward successions, and consists of poorly sorted conglomerates composed of clasts of laminated mudstones. These average 5 cm in diameter, and occur mixed with poorly sorted quartz granules. Sedimentary structures, where present, are incipient and dominated by crude trough cross stratification and normal grading.

Facies Ht consists of interbedded, fine to very fine-grained sandstones and laminated mudstones that form wavy and lenticular beddings. This facies is only locally found at the top of some fining/thinning upward successions, where it forms beds that are less than 0.4 m thick.

Interpretation: Facies Association A is attributed to tidal-influenced fluvial channels. The presence of deposits with concave upward basal surfaces, though not exclusive to, is suggestive of flow confinement within channels. Where this feature is not present, the fining/thinning- upward facies successions are bounded by sharp, erosional basal surfaces, and attest to deposition during decreasing flow energy, as typical of channel fills. Facies Ci records episodes of highest energy, when channels were scoured into underlying muddy deposits. The muddy accumulations were eroded and re-deposited as lags at the channel bottom. Facies St was formed by migration of small to medium scale, 2D- and 3D-bedforms within channels, and Facies Ht records alternating sand and mud deposition formed as topset beds during channel abandonment.

Facies Association A is attributed to tidal-influenced fluvial channels formed in proximal estuarine areas, near the limits of the fluvial realm. Although weak, tidal currents might reach these inner estuarine areas and rework sediments brought from the fluvial channels. The recognition of this type of setting in the geological record might be problematic (e.g., Ashley and Renwick, 1983; Allen, 1991; Hori *et al.*, 2001; Leckie and Singh, 1991; Dalrymple *et al.*, 1992; Plink-Bjorklund, 2005), particularly where the distribution of the depositional environments throughout a proximal-distal transect cannot be observed, as in the case of the study area. However, the poor sorting, very coarse sand to gravel grain sizes, and scarcity or absence of bioturbation are features that led to claim a fluvial origin for this facies association, distinguishing it from other channel deposits formed under dominant tidal processes (see Facies Association B described below).

Facies Association A displays features that cannot be justified exclusively by unidirectional fluvial flows. The bipolar paleocurrent data, coupled with the common reactivation surfaces and mud drapes separating packages of foresets, are features suggestive of some degree of tidal reworking. The dominance of foresets dipping consistently at low angles is a further evidence of tidal influence, as migration of 2D- and 3D-bedforms in tidal settings typically results in cross sets that display low angle dipping foresets (Shanley *et al.*, 1992; Plink-Bjorklund, 2005).

Considering the foregoing interpretation, it is noteworthy that the position of Facies Association A, lying at the base of the soft kaolin unit, is a situation expected when a fluvial system is flooded during a transgression to form an estuarine valley (e.g., Dalrymple *et al*., 1992; Zaitlin *et al*., 1994).

Facies Association B: Tidal Channel

Facies Association B (Figs. 3D, 4 and 5) is up to 10 m thick and consists of : tabular and trough cross-stratified/laminated sandstone (Facies St) and horizontal laminated sandstone (Facies Sh), alternating sandstone and mudstone displaying heterolithic bedding (Facies Ht), and subordinate intraformational conglomerate (Facies Ci). These deposits, which are typically bounded at the base by broad concave upward surfaces with lengths of up to 200 m (Figs. 4A-C), are internally organized into fining- and thinning-upward successions averaging 3 m thick. More rarely, this facies association comprises entire intervals of heterolithic bedding (Fig 4B and C), which are cut internally by multiple erosive basal concave upward surfaces that are locally mantled by intraformational conglomerate.

Facies St consists of moderately sorted, coarse- to very fine-grained, tabular and trough cross-stratified sandstones having grains that are mostly subangular to subrounded. The cross sets, up to 0.3 m thick, consistently display low angle foresets.

Paleocurrent measurements indicate main vectors to the NNE and SSW (Fig. 3D). A typical feature of Facies St is stacked packages of foresets averaging 5-10 cm thick that are defined by reactivation surfaces and/or mudstone drapes. Facies St locally grades laterally into fine- to very fine-grained, horizontal laminated sandstone (facies Sh). The sandstones are, in general, moderately sorted with subrounded grains and form packages that are 0.1-0.2 m thick, and commonly bounded by mud drapes.

Facies Ht comprises alternating layers of medium- to fine-grained sandstone and mudstone, forming wavy, lenticular and flaser bedding, that might dip at low angles (*i.e.*, $>10^{o}$). Individual lithological packages are up to 20 cm thick. Thicknesses of sandstone and mudstone beds are not constant upwards, rather varying progressively into alternating thicker and thinner bundles, the latter displaying a higher concentration of mud layers (Fig. 4D and E). The sandstone layers are moderately to well sorted. Thicker sandstone layers are internally characterized by plane parallel stratification, cross stratification, or are structureless. Locally, cross strata display oppositely dipping foresets. The mudstone and siltstone may display parallel lamination or appear massive.

Facies Ci occurs locally, typically mantling concave upward surfaces. It consists of sub-angular to sub-rounded mudstone and sandstone intraclasts up to 20 cm in diameter. Facies Ci is generally massive, or displays crude trough cross-stratification and normal grading.

A typical feature of Facies Association B is the abundance and variety of trace fossils, including *Thalassinoides, Planolites, Teichichnus, Taenidium* and *Skolithos* (Fig. 5).

Interpretation: Like facies association A, Facies Association B was also formed by confined flows within channels, as indicated by the basal concave upward erosional bounding surface. The internal organization, configuring thinning- and fining-upward successions formed by the upward gradation from intraformational conglomerates to sandstones and into heterolithic bedding of sandstone and mudstones, attests to deposition during waning flow, typical of channels prone to lateral accretion.

Internal features that favor channel deposition under the influence of tidal currents include: 1) an abundance of reactivation surfaces and mud drapes within cross sets; 2) oppositely dipping foresets; 3) low-angle dipping cross sets; and 4) alternating thicker and thinner packages of sandstones and mudstones within the heterolithic facies. Generation of all these structures requires fluctuating current energy, as occurs most typically in tidal settings In particular, the successions of alternating thicker and thinner bundles of the heterolithic facies are attributed to sediment aggradation under influence of tidal currents that vary in strength and duration on a daily and monthly basis. The alternations of sandier and muddier packages may be related to neap-spring tidal variations (Nio and Yang, 1991). The typical fining/thinning upward successions suggest that tidal channels filled up more or less continuously during rising sea level (Dalrymple *et al*., 1992).

The proposed deposition by tidal processes in brackish water conditions is consistent with the ichnologic assemblage described in this facies association. The low-diversity association of *Ophiomorpha, Thalassinoides, Planolites, Teichichnus, Taenidium* and *Skolithos* is consistent with deposition in nearshore settings influenced by stressed environmental conditions (Benynon and Pemberton, 1992; MacEachern and Pemberton, 1994; Pemberton *et al.*, 2001; Uchman *et al.*, 2004).

Considering the proposed tidal channel interpretation for Facies Association B, the inclined heterolithic strata (Facies Ht) are related to lateral accretion on tidally influenced point bars, with sandstones and mudstones recording high and low tidal flow stages, respectively. This type of deposit is usually associated to the presence of channels with high sinuosity (Thomas *et al.*, 1987; Smith, 1988; Fenies and Faugères, 1998; Nouidar and Chellaï, 2001; Mack *et al.*, 2003; Gao, 2004; Plink-Bjorklund, 2005).

Sedimentary and biogenic features similar to the ones recorded here have been found in association with many tidal channel deposits described in the literature (*e.g.*, Clifton, 1983; Smith, 1988; De Boer, 1989; Leckie and Singh, 1991; Nio and Yang, 1991; Plink-Bjorklund, 2005).

Facies Association C – Tidal Flat/?Mangrove

Facies Association C (Fig. 4A) is better developed in the PPSA quarry, is up to 5 m thick, and records the finest deposits of the soft kaolin unit. It consists essentially of tabular packages of distinctively yellow to red colored, highly bioturbated, heterolithic-bedded sandstones and mudstones. These deposits are laterally continuous for up to 1 km and are intergraded with facies associations B and D.

This association is internally characterized by an overall fining- and thinning-upward succession, and consists of only two facies: heterolithic mudstone/sandstone (Facies Ht) and mudstone (Facies M). Like Facies Association B, Facies Ht, represented mostly by *linsen*, is organized into several minor cycles of 0.3-0.4 cm. Then form packages of sandstones and mudstones that progressively change their thickness, varying from thicker to thinner upward (Fig. 3). Facies M consists of thicker packages of mudstones displaying only streaks of coarse-grained siltstones and very fine-grained sandstones.

Facies Association C is highly bioturbated, mainly recording traces that are comparable to those of the previous association. One except on is the absence of *Skolithos* and *Ophiomorpha.*

Interpretation: Facies Association C is interpreted as the record of tidal flat settings, which might have been associated with mangroves, though root marks were not recognized probably to the intense kalinitization. A tidal flat is consistent with the intergrading of this facies association with Facies Association B (Tidal Channel) and Facies Association D (Tidal Sand Flat/Sand Bar). Deposition in a flat-lying area is suggested by the tabular geometry and great lateral continuity of the association. The mudstones indicate deposition from suspensions in low energy environments, while the heterolithic deposits conform to a setting with alternating traction sediment transport and deposition from suspensions (Collinson, 1996). In addition to a genetic association with other tidal deposits, the upward change in thickness of sand/mud bundles of the heterolithic facies attests to tidal currents as the main depositional process.

The sole occurrence of heterolithic deposits and mudstones in Facies Association C suggests intertidal and supratidal deposition. The progradation of heterolithic deposits into mudstones produces a vertical fining-upward succession, consistent with tidal flat progadation (Klein, 1985). The thickness of the tidal flat succession in the study area indicates a macrotidal regime, with a minimum paleotidal range of 5 m.

The ichnologic assemblage is used as a further confirmation of the proposed depositional setting. Hence, like Facies Association B, the trace fossils are typical of estuarine environments. The absence of *Ophiomorpha* and *Skolithos* is due to decreases in energy, as these traces are more common in high-energy environments. *Ophiomorpha* and *Skolithos* are also typical of areas subjected to high sedimentation mobility (Zonneveld *et al.*, 2001; Malpas *et al.*, 2005; Savary *et al.*, 2004).

Facies Association D – Upper Flow Regime Tidal Sand Flat/Sand Bar

Facies Association D (Fig. 6A-G), up to 5 m, is very widespread in both of the studied quarries, where it grades laterally and vertically into facies associations B and C (Figs. 1 and 2). Like Facies Association C, these deposits are laterally continuous, forming tabular packages that are bounded at the base by either planar or only slightly undulating (though not erosive) surfaces. These deposits might also be lenticular, with lenses up to 0.4 m thick and 6 m long. Fining- and thickening-upward cycles are present.

This facies association differentiates from the previous association on the basis of predominance of horizontally stratified sandstones (Fig. 6A), with subordinate heterolithic deposits (Facies H). The sandstone consists of three facies: horizontal-laminated to low-angle dipping cross-stratified sandstones (Facies Shl), tabular- and trough cross-stratified sandstones (Facies St), and climbing current ripple cross-laminated sandstones (Facies Sc). These facies are characterized by well-sorted, well-rounded, fine-to very fine-grained sandstones, displaying high concentrations of heavy minerals on plane beddings (Fig. 6B). Sets in Facies Shl, which dominates in this association, ranges in thickness from 0.4-0.5 m, indicating northward paleoflows. An interesting feature of Facies Sc is the abundance of parting lineations, which indicate a NE/SW azimuth for paleoflow (Fig. 6C). Other features associated with Facies Shl are pinch and swell structures and symmetrical (oscillation) ripple marks. In addition, undulating laminations displaying internal truncations are common and form broad scours or swales with either symmetrical or asymmetrical geometries (Fig. 6D). Facies Sc occurs only locally, being characterized by tabular or highly undulating lower set boundaries. Facies St and Sc are subordinate, and intergrade with facies Shl. Facies St alternates rhythmically with Facies Shl, resulting in individual packages 10-20 cm thick.

Heterolithic mudstone/sandstone (Facies Ht), alternating with trough cross-stratified sandstone (Facies St), occurs as lenses averaging 0.5 m thick and 8 m long. These are interbedded with the tabular sandstone described above. The sandstones show well-rounded, well sorted, fine- to medium-grained sand, and display cross lamination and small- to medium-scale cross stratification. Locally, cross sets with abundant reactivation surfaces and highly undulating set boundaries are present. Facies Ht and St are typically arranged into coarsening- and thickening- upward successions.

Trace fossils dispersed in this facies association consist of *Thalassinoides, Ophiomorpha, Skolithos, and Planolites* (Fig. 6E-G).

Interpretation: Facies Association D is interpreted as tidal sand bar/sand flat deposits, based on prevalence of tabular sandstones internally displaying horizontal to low-angle dipping stratification. These characteristics imply deposition along a shallow flat area. The abundance of parting lineation in Facies Shl indicates that sediment accumulation took place during prevailing upper-flow-regime conditions (Reineck and Singh, 1980; Yagishita *et al.*, 2004). The rhythmic alternation of Facies Shl and Facies St indicates fluctuating conditions from upper to lower flow regime. Considering the overall proposed depostional setting, these facies might have been the product of tidal processes. The presence of swell and pinch, symmetrical ripple marks, and the large swales indicate frequent wave reworking (*e.g.*, de Raaf *et al.*, 1977). In particular, scours similar to the ones described here (Figure 6C) are common in nearshore areas that have undergone periods of higher energy flow, suggesting storm wave reworking (*e.g.*, Bourgeois, 1980; Cheel and Leckie, 1993; Hori *et al.*, 2001; Plink-Bjorklund, 2005). The abundance of heavy minerals is consistent with flux and reflux.

The above mentioned characteristics, added to the gradation of Facies Association D with the other facies associations described herein support deposition in an upper flow regime tidal sand flat depositional setting (see also Klein, 1985; MuCubbin, 1988; Plink-Bjorklund, 2005).

The lateral gradation of tidal sand flat deposits with sandstone lenses displaying fining- and thickening-upward cycles are suggestive of significant volume of sand accumulation along a series of tidal sand bars. Many ancient tidal sand bars are recorded by similar upward-coarsening lenticular sandstone bodies (Houthuys and Gullentops, 1988; Dalrymple, *et al.* 1992; Reading and Collinson, 1996; Willis, 2000; Heap *et al.*, 2004). Tidal bars are commonly recorded in association with upper flow regime tidal sand flat deposits in confined areas along coasts dominated by high tidal velocities (Dalrymple *et al.*, 1992; Plink-Bjorklund, 2005).

The ichnological assemblage, represented by disperse traces of mostly *Thalassinoides* is in agreement with the proposed setting, since these traces form typically in nearshore areas undergone to episodic or constant environmental changes (Wightman *et al.* 1987; MacEachern and Pemberton 1992; Pollard *et al.* 1993; Gowland 1996).

DISCUSSION OF THE DEPOSITIONAL SYSTEM

The new facies data presented herein confirms tidal currents as the main process responsible for deposition of the soft kaolin unit of the Ipixuna Formation. Evidence for tidal processes includes the abundance of cross sets with reactivation surfaces, commonly mantled by mud drapes, the local presence of tidal bundles, and reversed foresets. The ichnological assemblage represented by low diversity of traces, consisting of *Thalassinoides, Planolites, Teichichnus, Taenidium, Skolithos* and *Ophiomorpha,* attests a nearshore setting with stressing water conditions due to the mixture of marine and freshwater inflows. This, together with the variety of facies associations interpreted above, is consistent with a tide-dominated estuarine model (Fig. 7).

A previous study of the Ipixuna Formation had tentatively suggested the action of tidal currents during its deposition. This paper, however, demonstrates that tidal processes were much more significant than initially thought and controlled most of the sediment accumulation in all of the depositional environments identified in the soft kaolin unit. In addition, mapping of new exposures has led to a more complete characterization of the various facies associations and their spatial relationships.

A proposed correlation of the tidal deposits of the Ipixuna Formation from the studied quarries exposed along the Road BR-010, located 60 km apart, led to the proposal of a wave-dominated estuarine system for the soft kaolin unit (Santos Jr. and Rossetti, 2003). The data presented herein, however, support depositional settings that are more consistent with a tide-dominated estuarine model. A possibility exists, thus, that the tidal delta deposits present along the Road BR-010 are not correlatable with the soft kaolin unit. These tidal delta deposits might correspond to either an adjacent depositional system or a part of a barrier complex associated with the subsequent stage of the estuary evolution with increased influence of wave action.

The genetic association of tidal-influenced fluvial channel, tidal channel, tidal flat/mangrove, and tidal sand bar/tidal sandy flat deposits, is typical of tidal dominated estuarine system for the soft unit (*e.g.,* Woodroffe *et al.*, 1989; Leckie and Singh, 1991; Dalrymple *et al.*, 1992; Harris *et al.*, 1992; Chappell and Woodroffe, 1994; Mulrennan and woodroffe, 1998; Hori *et al.*, 2001; Heap *et al.*, 2004; Plink-Bjorklund, 2005). An abundance of tidal channel deposits that interfinger with sand bar and upper flow regime sand flat deposits are more commonly recorded in tide-dominated estuaries formed along mesotidal to macrotidal coast (Klein, 1985; Houthuys and Gullentops, 1988; Buatois and Mangano, 2003). Tidal bar and sand flat deposits had been previously recognized in the study area, but were thought to be volumetrically subordinate, have formed when upper flow regimes developed within channels (Santos Jr. and Rossetti, 2003). The newly available exposures reveal, however, that they constitute one of the main facies associations of the soft kaolin unit, second only to tidal deposits.

The distribution of the studied deposits, both vertically and laterally, provides information for interpreting the estuary evolution. The tidal-influenced, fluvial-channel deposits (Facies Association A), which are dominant near the base of the kaolin unit, attest to formation in inner estuarine areas. These deposits characterize the transition between fluvial and tidal sedimentation, thus displaying characteristics that are inherent from both fluvial and tidal processes (Dalrymple *et al.*, 1992; Hori *et al.*, 2001; Cooper, 2002). Features diagnostic of tidal processes, such tidal bundles, are scarce or even absent from such settings due to the interference of fluvial influx (Leckie and Singh, 1991; Hori *et. al.*, 2001; Cooper, 2002; Heap *et al.*, 2004). The velocity fluctuation of tidal currents results in highly unsteady flows, producing frequent reactivation surfaces with mud drapes, as observed in Facies Association A. The abundance of these surfaces separating foreset packages that are only few cm thick facilitates the differentiation of tidal influence from other disturbances in fluvial system (*e.g.*, seasonal fluctuations; Ladipo, 1988; Thorez *et al.*, 1988).

The overall vertical gradation from tide-influenced fluvial channel (Facies Association A) to tidal channel (Facies Association B), tidal flat/mangrove (Facies Association C) and tidal sand bar/sand flat deposits (Facies Association D) records upward increasing tidal influence. As a result, features attributed to, or even diagnostic (*e.g.*, tidal bundles) of tidal currents become progressively more abundant upward, as do the trace fossils *Thalassinoides, Ophiomorpha, Planolithes, Teichichnus, Taenidium* and *Skolithos*, typical of coastal settings. The upward increase in tidal influence is also associated with a progressive increase in mud abundances, resulting in thinning- and fining- upward successions. Such facies arrangements are related to a rise in relative sea level during transgression.

Inclined heterolithic stratification (HIS) in association with tidal channel deposits is expected in meanders of straight-meandering-straight channel segments, typically formed in central estuarine areas of tidal-dominated estuaries (*e.g.*, Nichols and Biggs, 1985; Leckie and Singh, 1991; Dalrymple *et al.*, 1992; Reading and Collison, 1996; Plink-Bjorklund, 2005). The more frequent occurrence of tidal channel deposits in the PPSA quarry might suggest that, when transgression took place, this area was located closer to the central estuary.

On the other hand, the higher abundance of Facies Association D in the RCC quarry suggests a location nearer to the coast, as elongate sand bars associated with upper-flow-regime sand flats are typical of the seaward areas in tide-dominated estuaries (Dalrymple *et al.*, 1992). The common occurrence of wave-generated structures (i.e, symmetrical ripple marks and truncating, low-angle dipping cross lamination) in facies association D conforms to an outer estuarine location (Dalrymple *et al.* 1992).

The soft kaolin deposits in the Rio Capim Kaolin area were formed during a period of rise relative sea level, with the RCC quarry recording an increased proximity to nearshore areas relative to the PPSA quarry. The tide-dominated estuary formed along a broad WNW-ESE paleocoast, as proposed by the dominant NNE/SSW and NE/SW paleocurrent data obtained from the in-channel deposits.

CONCLUSION

The presence of sedimentary structures attributed to tidal processes coupled with trace fossil assemblages consisting of *Thalassinoides, Planolites, Teichichnus, Taenidium, Skolithos* and *Ophiomorpha,* suggest that the soft kaolin unit of the Ipixuna Formation in the Rio Capim Kaolin area was formed dominantly under the influence of tidal processes. In addition to facies associations consisting of tidal-influenced fluvial channel, tidal channel, tidal flat/mangrove, and tidal sand bar/tidal sand flat, these characteristics support a tide-dominated estuarine interpretation. The distribution of facies associations, represented by tide-influenced fluvial channel deposits that grade upward into other facies associations denoting increased tidal energy, indicates that deposition took place during a transgression. The increased occurrence of tidal channel, tidal flat/mangrove deposits in the PPSA quarry, and of tidal sand bar/tidal sandy flat in the RCC quarry reveals that the latter was located closer to the nearshore area. During the Late Cretaceous, the paleocoast was positioned circa 240 km landward of the present coast, as a result of relative sea-level rise. This depositional context must be taken into account when discussing the origin of the soft kaolin in the Rio Capim area.

ACKNOWLEDGEMENTS

This paper was financed by the CNPq (Grant #474978/2001-0). Logistic support was provided by the Goeldi Museum. The Imery-Rio Caulim Capim-IRCC and Pará-

Pigmentos S/A-PPSA are acknowledged for their permission to access the kaolin quarries. The geologists Carlos Henrique L. Bastos and Sá Pereira are thanked for the companionship and many discussions in the field. The authors appreciated the careful review of Dr. James McEarchern and Dr. Murray Gingras, who contributed to significantly improve the final version of the manuscript.

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LIST OF FIGURES

Close-up photograph of tidal-influenced fluvial channel deposits (Facies Association A), showing foreset packages with mud drapes (arrows).

Fig. 4: Tidal channel (Facies Association B) and tidal flat/mangrove (Facies Association C). A) Geologic section illustrating the spatial relationship between facies associations B and C. Note the gentle concave upward surface that defines the base of a tidal channel deposit. B) General view of a heterolithic tidal channel deposit (man = 1.65 m tall). Dark color = muddier deposits. C) Detail of the sharp, erosional base of a heterolithic tidal channel. D) Heterolithic deposits typical of facies associations B and C, illustrating a vertical succession attributed to tidal bundles. These consist of rhythmically alternating sandier (spring) and muddier (neap) cycles (S=spring; N=neap). Mud couplets attributed to ebb/flood fluctuation are locally present in some spring cycles (black arrows), and undetermined trace fossils are common (white arrows).

Fig. 5: A-D) Details of trace fossils representative of tidal channel (Facies Association B) and tidal flat/mangrove deposits (Facies Association C): *Thalassinoides* (Th), *Planolites* (Pl), *Teichichnus* (Tc), *Taenidium* (Ta) and *Skolithos* (S).

Fig.6: Upper flow regime tidal sand flat/sand bar (Facies Association D). A) General view of an outcrop illustrating tabular sandstones with horizontal to low-angle dipping cross stratification (Facies St) (man=1.65 m tall). B) Horizontal lamination with laminae highlighted by heavy minerals. C) Sandstone with parting lineation

(pencil oriented parallel to paleoflow). D) Undulating lamination forming scour or swales locally filled by mudstone (white arrows). E-G) Trace fossils, representative of the upper flow regime tidal sand flat/sand bar. *Thalassinoides* (Th), *Planolites* (Pl) and *Skolithos* (S) and *Ophiomorpha* (Op).

Fig. 7: Schematic block diagram depicting the tidal dominated estuarine depositional model (after Dalrymple *et al.*, 1992) proposed for the soft kaolin in the Rio Capim area. (1=profile in the RCC quarry; 2=profile in the PPSA quarry).