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Ichnological signature of Paleozoic estuarine deposits from the Rio Bonito-Palermo succession, eastern Paraná basin, Brazil

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Abstract. Core studies involving sequence stratigraphy, sedimentology and ichnology allowed the recognition of three facies associations and the differentiation among subenvironments within estuarine deposits of the Rio Bonito and Palermo Formations. The ichnological content shows low degree of bioturbation, simple structures of infaunal organisms and low ichnodiversity, characterizing an impoverished-marine association known as *Skolithos-Cruziana,* which denotes brackish-water environments. Salinity is the main paleoecological factor controlling the distribution of the trace fossils in such association. However, oxygenation and energy can be important locally. Monospecific associations of *Planolites* indicate dysaerobic conditions within the substrate or in the water column. Deep or thick-lined burrows indicate high energy. Co-planar surfaces can be locally demarcated by substrate-controlled traces of the *Glossifungites* ichnofacies. The integration of sedimentological and ichnological data allowed the interpretation of the channel, estuary mouth and central basin complexes, suggesting a model of wave-dominated estuaries.

Resumen. SEÑAL ICNOLÓGICA EN DEPÓSITOS ESTUARINOS PALEOZOICOS DE LA SUCESIÓN RIO BONITO-PALERMO, SECTOR ORIENTAL DE LA CUENCA DE PARANÁ, BRASIL. Un estudio abarcando estratigrafía secuencial, sedimentología e icnología en testigos de la secuencia pérmica de la Cuenca de Paraná permitió reconocer tres asociaciones de facies y diferenciar depósitos estuarinos asociados al Miembro Siderópolis de la Formación Rio Bonito y a la Formación Palermo. Las características icnológicas muestran bajo grado de bioturbación, estructuras simples generadas por organismos infaunales y baja icnodiversidad, caracterizando una asociación marina empobrecida del tipo *Skolithos-Cruziana*, típica de ambientes de baja salinidad. La salinidad es el principal factor paleoecológico que controla la distribución de las trazas fósiles en dicha asociación. Sin embargo, la oxigenación y la energía ejercen, en algunos casos, cierto control local. Asociaciones monoespecíficas de *Planolites* están directamente relacionadas a niveles que indican una condición de disaerobia en el sustrato o en la lámina de agua. Trazas verticales profundas o con paredes espesas indican condiciones de alta energía. Superficies co-planares pueden ser localmente demarcadas por la presencia de una asociación de trazas sustrato-controladas de la icnofácies de *Glossifungites*. La integración de datos sedimentológicos e icnológicos posibilitó la interpretación de los complejos de canales, boca de estuario y cuenca central, sugiriendo un modelo de estuarios dominados por olas.

Key words. Ichnology. Estuaries. Salinity. Oxygenation. Permian. Paraná Basin. Brazil.

Palabras clave. Icnología. Estuarios. Salinidad. Oxigenación. Pérmico, Cuenca de Paraná. Brasil.

Introduction

Marine ichnofacies have been the subject of intensive study over the past century. In contrast, an overall understanding of nonmarine ichnofacies was attained only in the 1990's (Buatois and Mángano, 1990, 1993, 1995, 1996, 1998a; Buatois *et al.*, 1997, 1998a; Gierlowski-Kordesch, 1991; Melchor and Poiré, 1992; Pickerill, 1992; Hasiotis *et al.*, 1993; Genise and Bown, 1994a, 1994b; MacNaughton and Pickerill, 1995; Genise *et al.*, 2000). In transitional settings, ichnology has proven to be an important tool for identifying different brackish-water deposits, especially estuarine, which display a characteristic ichnological signature. After the development of sequence stratigraphic concepts, the estuarine successions have been the target for petroleum exploration, mainly because they contain good-quality reservoirs and are surrounded by sediments that allow excellent trapping conditions.

Despite being common in recent transgressive settings, the recognition of estuarine deposits in the geologic record can be problematic if based only on

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lithofacies analysis. Estuarine deposits share characteristics with marine strata, so that proper distinction is only achieved through an integrated approach. Analyses involving sedimentological, ichnological, geochemical and paleontological data were used by some authors to differentiate brackish-water and marine deposits and to refine the related subenvironments (Wightman *et al.*, 1987; Pemberton and Wightman, 1992; MacEachern *et al.*, 1999). In particular, an integrated sedimentological and ichnological analysis, within a sequence stratigraphic framework, has been instrumental to provide reliable interpretations in marine and marginal-marine settings, including the recognition of subenvironments within incised valley-fill systems (*e.g.*, Pattison, 1992; Benyon and Pemberton, 1992; Pemberton and Wightman, 1992; Pemberton *et al.*, 1992; MacEachern and Pemberton, 1994; MacEachern *et al*., 1999; Leroux *et al.*, 1999).

Since the beginning of the 1990´s, ichnology has been used to understand marine and marginal-marine deposits and the related stratigraphic surfaces of the Lower Permian Rio Bonito and Palermo formations (Netto *et al.*, 1991, 2001; Netto, 1994, 2001; Buatois *et al.*, 2001a, 2001b; Tognoli and Netto, 2001; Tognoli, 2002). Ichnology has provided valuable data to differentiate estuarine and shallow-marine deposits, a task that is very difficult on a lithofacies basis alone. The aim of this paper is to document the ichnological signature of estuarine deposits from the eastern portion of the Paraná basin and to test the validity of ichnology in the recognition of Paleozoic incised valley-fill systems.

Ichnology of brackish-water deposits

Ichnology has been an important tool for identifying brackish-water deposits, as demonstrated by several authors (e.g., Goldring *et al.*, 1978; Pemberton *et al.*, 1982; Wightman *et al.*, 1987; Bjerstedt, 1987; Reinson *et al.*, 1988; Benyon *et al.*, 1988; Leckie and Singh, 1991; Netto *et al.*, 1991; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; MacEachern *et al.*, 1992, 1999; Netto and Rossetti, 2000; Tognoli and Netto, 2001; Buatois *et al.*, 2001b, 2001c). According to Pemberton *et al.* (1982), Wightman *et al.* (1987) and Pemberton and Wightman (1992), a number of criteria has been useful in the identification of salinity-stressed suites of trace fossils, including: low ichnodiversity; common occurrence of either monospecific suites or suites dominated by a single trace fossil, both displaying high individual densities; simple and small marine burrows related to infaunal trace makers and mixed vertical and horizontal traces, commonly found in both the *Skolithos* and *Cruziana* ichnofacies.

Although a large number of ichnogenera can be identified in brackish-water deposits, especially feeding and dwelling structures, each subenvironment is characterized by low ichnodiversity suites that reflect the interaction of several ecologic factors, such as energy, oxygenation, substrate texture and pH, within a stressed-salinity environment (*cf.* Ranger and Pemberton, 1992; Pemberton and Wightman, 1992; Benyon and Pemberton, 1992; Pemberton *et al.*, 1992; MacEachern and Pemberton, 1994; MacEachern *et al.*, 1999; Gingras *et al.*, 1999).

Ichnologic research in brackish-water settings evolved mainly after the work of Howard and Frey (1973, 1975) and Dörjes and Howard (1975). Among several ecological factors, Howard and Frey (1973) noted that salinity and substrate texture influenced some specific ichnocoenoses. This conclusion has fundamental importance for the recognition of brackish-water deposits in the geologic record.

The model was strongly improved with the intensive studies developed in Cretaceous deposits of the Western Canada Sedimentary Basin (*e.g.*, Wightman *et al.*, 1987; Reinson *et al.*, 1988; Benyon *et al.*, 1988; Leckie and Singh, 1991; Benyon and Pemberton, 1992; Pemberton and Wightman, 1992; Pemberton *et al.*, 1992; MacEachern and Pemberton, 1994; MacEachern *et al.*, 1992, 1999; Leroux *et al.*, 1999). Subsequently, studies in modern deposits became necessary to better understand the complexity of estuarine systems, especially the ichnologic characteristics of their different facies and subenvironments. In particular, Gingras *et al.* (1999, 2000) provided valuable data about a modern estuary at Willapa Bay, Washington. These two studies stressed, respectively, firmness profiles associated with tidal-creek deposits and ichnological and sedimentological characteristics of several subenvironments in Willapa Bay. This work helps to understand modern estuarine processes and, consequently, assists in the identification of ancient estuarine deposits in the stratigraphic record.

Research on Paleozoic estuarine deposits and their ichnofaunas has been comparatively rare. However, they show an increase in the last 10 years, particularly in the Late Paleozoic of Brazil and United States (*e.g.*, Netto *et al.*, 1991, 2001; Netto, 1994, 2001; Martin *et al.*, 1998; Buatois and Mángano, 1998b; Buatois *et al.*, 1998b, 1999, 2001a, 2001b, 2001c, 2002; Tognoli and Netto, 2001). Recent data provided by Buatois *et al.* (2001a, 2002) reveal that Permian marginal-marine ichnofaunas are quite different from Carboniferous ones, but show much similarities with their Mesozoic and Cenozoic counterparts. The comparison among brackish-water ichnofaunas through the Phanerozoic will be important to understand the colonization and development of behav-

Figure 1. Location maps of the study area. **A,** The Paleozoic outcrop belts of the Paraná Basin in south central Brazil. **B,** Detailed map showing the location of cored wells on the west of the Guatá Group outcrop belt in Paraná State. / *Mapa de ubicación del área de estudio.* ***A,*** *Faja de afloramientos de la Cuenca de Paraná en el centro sur de Brasil.* ***B,*** *Mapa de detalle mostrando la posición de las coronas al oeste de la faja de afloramientos del Grupo Guatá en el Estado de Paraná.*

ioral patterns in marginal-marine settings. This will provide valuable data to improve the ichnological models that at present allow the recognition of estuarine successions.

Study area and database

The study area is located in the eastern portion of the Paraná State, southern Brazil (figure 1.A). It extends for approximately 250 km along the eastern margin of the Paraná Basin (figure 1.B).

The database comprises 10 cored and logged wells, drilled by Companhia de Pesquisa de Recursos Minerais (CPRM) (Aboarrage and Lopes, 1986). Cores of the Rio Bonito and Palermo formations were described in detail, taking into account sedimentological and ichnological data. The integration of these data with the gamma ray and resistivity logs allowed the recognition of key-surfaces within a sequence stratigraphic framework.

Geological setting

Guatá Group

The Guatá Group was proposed by Gordon Jr. (1947) to include the Rio Bonito and Palermo Beds of White (1908). Coal-bearing deposits are well-known and they have been exploited since the end of the nineteenth century, mainly in the Rio Grande do Sul and Santa Catarina States. Hydrocarbon occurrences are also known from several localities.

This group mostly consists of sandstone, siltstone, mudstone, shale and, more rarely, conglomerate, marl and limestone. Schneider *et al.* (1974) proposed the subdivision of the Rio Bonito Formation in three units, named respectively, from base to top, the Triunfo, Paraguaçu and Siderópolis Members (figure 2).

According to Schneider *et al.* (1974), Aboarrage and Daemon (1975), Castro (1980, 1991, 1999) and Aboarrage and Lopes (1986), the Triunfo Member comprises cross-stratified, moderately to poorly sorted, medium- to coarse-grained, quartzose sandstone. The Paraguaçu Member consists of horizontal laminated, gray to greenish gray siltstone; massive to slightly stratified, well to moderately sorted, fine- to coarse-grained, quartzose sandstone; limestone with algal lamination and dessication cracks; and dark gray shale (Schneider *et al.*, 1974; Schneider and Castro, 1975; Sampaio, 1987; Câmara Filho, 1997; Tognoli, 2002). The Siderópolis Member is composed of massive to cross-stratified, well-sorted, very fine- to medium-grained, quartzose sandstone (Schneider *et al.*, 1974; Sampaio, 1987; Tognoli, 2002). Mudstone, carbonaceous shale and coal beds are present locally (Schneider *et al.*, 1974).

The overlying Palermo Formation is characterized by interstratified mudstone and sandstone, displaying wavy and lenticular bedding and intense bioturbation, burrowed sandstone, unburrowed dark gray shale and, more rarely, coarse-grained sandstone and clast-supported, polymictic conglomerate (Schneider *et al.*, 1974; Habekost, 1978, 1983; Aboarrage and Lopes, 1986; Albuquerque, 1990; Perinotto, 1992; Netto, 1994; Milani, 1997; Tognoli, 2002).

The age of the Guatá Group is still controversial. The lack of biostratigraphic resolution does not allow a precise age for the studied interval. Furthermore, invertebrate fossils and palynological data provide variable ages (Netto, 1994), but stu-

Figure 2. Stratigraphic chart for the Guatá Group in the eastern portion of the Paraná State. / *Cuadro estratigráfico del Grupo Guatá en la porción oriental del Estado de Paraná.*

dies on insect-plant interactions provide a reliable Early Permian age for the Guatá Group (Adami-Rodrigues and Iannuzzi, 2001), assumed herein as Cisuralian.

Regional geology

The Lower Permian Guatá Group is an extensive unit in outcrop and subsurface in the Paraná Basin. At a more regional scale, the Siderópolis Member and the Palermo Formation form a third order depositional sequence, containing both the transgressive systems tract (TST) and the highstand systems tract (HST), as proposed by Tognoli *et al.* (2001) and Tognoli (2002). This sequence overlies the marine to marginal marine deposits of the Paraguaçu Member and is overlain by the transgressive marine shales of the Taquaral Member of the Irati Formation (figure 2).

Figure 3. Simplified stratigraphic framework of the Guatá Group in the Paraná State. **A,** A co-planar surface that represents the initial transgression of the sequence. Note the small pebbles and lithic fragments over the surface. FP-08-PR, 160.8 m. **B,** Re-incision surface within the estuarine channel deposits of the Siderópolis Member. FP-06-PR, 303.5 m. **C,** Co-planar surface demarcated by firmground traces of the *Glossifungites* ichnofacies. FP-06-PR, 300.0 m. **D,** Co-planar surface at the top of the Siderópolis Member. FP-08-PR, 153.3 m. **E,** Transgressive surface of erosion expressed as a wave ravinement surface. Note the occurrence of a substrate-controlled trace fossil of the *Glossifungites* ichnofacies and the associated granules and clasts. FP-08-PR, 122.0 m. / *Estratigrafía del Grupo Guatá en el Estado de Paraná.* ***A,*** *Superficie co-planar que representa la primera transgresión de la secuencia. Nótese las guijas y fragmentos rocosos sobre la superficie. FP-08-PR, 160,8 m.* ***B,*** *Superficie de re-incisión en depósitos de canales estuarinos del Miembro Siderópolis. FP-06-PR, 303,5m.* ***C,*** *Superficie co-planar demarcada por trazas de sustrato firme de la icnofacies de* Glossifungites*. FP-06-PR, 300,0 m.* ***D,*** *Superficie co-planar en el tope del Miembro Siderópolis. FP-08-PR, 153,3 m.* ***E)*** *Superficie transgresiva de erosión expresada como una superficie de ravinamiento por olas. Nótese la presencia de una traza fósil de la icnofacies de* Glossifungites*, suprayacida por granulos y clastos. FP-08-PR, 122,0 m.*

The main stratigraphic surfaces can be picked from well logs, which exhibit abrupt deflections of the gamma ray and resistivity logs (figure 3). The MFS is a consistent marker in the gamma ray log, demarcating the inflexion point that separates the transgressive and highstand systems tracts.

The base of the Sideröpolis Member is a sequence boundary (SB), represented by a co-planar surface (figure 3.A). According to Van Wagoner *et al.* (1990), this type of surface is the result of the amalgamation between lowstand and transgressive erosion or marine flooding (FS / SB). Re-incision surfaces into earlier estuarine deposits can occur (figure 3.B). The unit is limited above by another co-planar surface (figures 3.C, D), locally demarcated by firmground trace fossils of the *Glossifungites* ichnofacies (figure 3.C). This interval corresponds to the deposits of the early TST.

The overlying Palermo Formation, below the maximum flooding surface (MFS), represents the late TST. These deposits are punctuated by transgressive erosion surfaces interpreted as wave ravinement surfaces (figure 3.E). Locally, the MFS can be expressed as a wave ravinement surface, demarcated either by sandy lags or substrate-controlled *Glossifungites* ichnofacies.

The TST is composed mainly by cross-stratified, moderately to poorly sorted, fine- to coarse-grained, quartzose sandstone with a sparse vertical assemblage of trace fossils; thoroughly burrowed silty sandstone, without identifiable sedimentary structures; interstratified mudstone and sandstone, having wavy-lenticular bedding, variable bioturbation degree, coal fragments, sideritic bands and root traces; burrowed mudstone containing synaeresis cracks; unburrowed dark gray shale with high total organic carbon (TOC) content; and low angle, undulatory to parallel-laminated sandstone beds interpreted as hummocky stratification. The facies are forming regional, wave- to storm-dominated parasequences that define a retrogradational parasequence set. The parasequences are limited by transgressive surfaces of erosion, expressed mainly as sandy lags of well to poorly sorted, fine- to very coarse-grained, quartzose to arkosic sandstone, commonly associated with *Thalassinoides*, *Skolithos* and clavate structures with sharp burrow boundaries, revealing the presence of a firmground *Glossifungites* assemblage (Tognoli *et al.*, 2001; Tognoli, 2002).

The highstand systems tract (HST) comprises interstratified mudstone and sandstone, stacked in aggradational parasequence sets. At the top of the succession, the HST shows a coarsening and thickening upward tendency, with predominance of bioturbated fine-grained sandstone. The dark shale of the Taquaral Member unconformably overlie the Palermo Formation. The discontinuity represents a transgressively modified sequence boundary, locally demarcated by trace fossils of the *Glossifungites* ichnofacies (Tognoli, 2002).

Facies analysis

The estuarine deposits of the Guatá Group were recognized based on the integration of sedimentological and ichnological data, within a sequence stratigraphic framework. Three facies associations (FA), namely FA1, FA2 and FA3, indicate three depositional zones within the estuary, known as Channel Complex, Central Basin Complex and Estuary Mouth Complex (figures 4, 5). The Bay Head Delta Complex was not identified in the study area.

Facies Association 1 - Channel Complex. Two facies compose the FA1. They are dominated by sandstone, but mudstone can occur occasionally. Energy is the main stress factor, as denoted by the trace fossil assemblage.

The Channel Facies 1 (CF1) is the dominant one. It comprises quartzose, medium- to coarse-grained, subrounded to rounded, moderately to poorly sorted, trough cross-stratified sandstone (figure 6.A). The beds may reach more than 40 cm in thickness, amalgamated into metric bedsets. Current ripples were not observed and herringbone cross stratification is present locally. Thin, milimetrical mud laminae and drapes are common.

Trace fossils are quite rare and the assemblage is dominated by dwelling structures; deposits are characterized by low degree of bioturbation and low ichnodiversity. *Skolithos*, *Ophiomorpha*, *Thalassinoides* and *Palaeophycus* are the ichnogenera recorded. *Skolithos* consists of very deep burrows, commonly reaching more than 10 cm (figure 6.B). *Ophiomorpha* is less common. Specimens are 1 to 1.5 cm wide and are thickly lined (figures 6.B, C). *Thalassinoides* is associated with muddy layers that occur locally between sandstone beds (figure 6.D).

The cross stratification present in the CF1 indicates sediment transport by currents, while the restricted occurrence of these sandstone beds and the local presence of herringbone cross stratification suggest channelized flows under tidal influence. The deep shafts of *Skolithos* and the thick lining of *Ophiomorpha* corroborate high energy conditions related to continuous sand dune migration under marine or marginal-marine influence. Thin, milimetrical mud laminae and drapes point out to deposition during brief low energy periods, which allow mud mantling of the bedforms. Thus, the CF1 is interpreted as tidal inlet deposits, within the estuary mouth complex.

The CF2 is a lithic, pebbly massive to slightly stratified sandstone. Grains are medium- to coarse-

Figure 5. Litholog of estuarine deposits at FP-08-PR well. Note the relationship, from base to top, between the Central Basin and the Estuary Mouth Complex. Legend is given in figure 4. / *Dibujo esquemático de depósitos estuarinos en el pozo FP-08-PR. Nótese la relación, de la base al tope, entre los complejos de cuenca central de boca de estuario. Leyenda en la figura 4.*

grained, angular to subrounded, moderately to poorly sorted, containing silexite clasts, granules of quartz, lithic fragments and siderite-cemented sandstone pebbles (figure 6.E). The basal contact is always erosive and the beds are 5 to 10 cm thick. Trace fossils were not observed.

It is also interpreted that CF2 records re-incision of channels into previous estuarine deposits during lowstands. As discussed by MacEachern and Pemberton (1994), it is very difficult to discern among the several possible subenvironments, such

Figure 4. Litholog of estuarine deposits at NF-02-PR well. Note the relationship, from base to top, among the three depositional complexes. / *Dibujo esquemático de depósitos estuarinos en el pozo NF-02-PR. Nótese la relación, de la base al tope, entre los tres complejos depositacionales.*

Figure 6. Sedimentological and ichnological aspects of the Channel Complex. **A,** Cross stratification in medium- to coarse-grained sandstone. NF-02-PR, 242,8m. **B,** Deep penetrating *Skolithos* (Sk) and *Ophiomorpha* (Op). Note the thick lining *Ophiomorpha*. NF-02-PR, 244,9m (left) / 243,9m (right). **C,** *Ophiomorpha* associated to cross stratification, indicating a marine influence. NF-02-PR, 242,7m. **D,** *Thalassinoides* (Th) present into a thin, milimetrical mudstone layer. NF-02-PR, 240,7m. **E,** Medium- to coarse-grained sandstone indicating a lowstand re-incision surface into previous estuarine deposits (black arrow). Note the presence of lithic granules (gr) and pebbles (pe). The dark pebble is a siderite-cemented sandstone. NF-02-PR, 239,7m. / *Aspectos sedimentológicos e icnológicos del complejo de canales.* ***A,*** *Estratificación entrecruzada en areniscas de grano medio a grueso. NF-02-PR, 242,8m.* ***B,*** Skolithos *(Sk) largos y* Ophiomorpha *(Op). Nótese el espesor de la pared de Ophiomorpha. NF-02-PR, 244,9m (izquierda) / 243,9m (derecha).* ***C,*** Ophiomorpha *asociada a estratificación entrecruzada, indicando influencia marina. NF-02-PR, 242,7m.* ***D,*** Thalassinoides *(Th) presentes en niveles milimétricos de lutitas. NF-02-PR, 240,7m.* ***E,*** *Arenisca de grano medio a grueso indicando una superficie de re-incision de mar bajo en depósitos estuarinos anteriores (flecha negra). Nótese la presencia de gránulos (gr) y guijas (pe). La guija oscura es una arenisca cementada por siderita. NF-02-PR, 239,7m.*

as tidal channels, tidal inlets or marine-influenced lowstand channels. However, the sedimentary nature of the succession denotes rejuvenation of the system, with derived sediments from the continent. On the other hand, the apparent lack of bioturbation could indicate freshwater influence, although high energy can be invoked.

Facies Association 2 - Central Basin Complex. The facies association 2 comprises four facies, informally named CBF1, CBF2, CBF3 and CBF4. They consist of moderately to poorly burrowed, interbedded or interlaminated sandstone and mudstone. In some cases, either sandtone or mudstone may reach more than 90% of the facies.

The sandstone is quartzose, very fine-to medium-grained, well to moderately sorted and subangular to rounded. The mudstone is light to dark gray, weakly to strongly carbonaceous and display variable silt content.

The Central Basin Facies 1 (CBF1) is the main facies, consisting of moderately to poorly burrowed, interlaminated carbonaceous silty mudstone. They are gray to dark gray in color, reflecting the relative richness in organic matter demonstrated by the Total Organic Carbon (TOC) analyses, which varied from 0.7% to 0.85%. Plant remains are present locally. The sandstone is very fine grained and occur in the mudstone intervals as thin, milimetrical stringers or laminae. They have an abrupt basal contact and consist exclusively of oscillation ripples, where several laminae are juxtaposed. Locally abundant in some intervals, synaeresis cracks are characterized by irregular, crenulated morphologies in vertical sections and elongated, spindle-shaped in plan view.

The ichnologic assemblage displays low ichnodiversity. Simple morphologies are dominant, including small *Planolites*, *Palaeophycus*, *Thalassinoides*, *Teichichnus* and *Chondrites*, commonly associated with synaeresis cracks (figure 7.A, B, C, D). *Skolithos* and *Helminthopsis* are subordinated. Escape structures are rare and usually associated with *Skolithos* in the sandstone laminae.

It is interpreted that CBF1 represents deposition under calm conditions in protected environments, such as bays or lagoons. The oscillation ripples present in the sandstone laminae record the effects of storm events within the estuary. Low degree of bioturbation and small-size trace fossils produced by trophic generalists are characteristic of impoverished *Cruziana* ichnofacies, a diagnostic indicator of salinity-stressed deposits. The associated synaeresis cracks also support the brackish context.

The CBF2 facies occurs interfingered or intercalated with the CBF1 facies throughout gradational contacts. It comprises scarcely burrowed to unburrowed dark gray, carbonaceous mudstones with TOC content greater than 0.9%. Sandstone laminae are absent and synaeresis cracks are rare. The ichnological content involves a monospecific suite of *Planolites*, with low degree of bioturbation (figure 7.D). *Chondrites* occurs in some intervals.

According to Benyon and Pemberton (1992), a monospecific suite of *Planolites* points out to a low oxygenation condition within the substrate. The relative high values of TOC (> 0.9%) indicate the presence of preserved, unoxidized organic matter, supporting the oxygen-depleted conditions suggested by the ichnological analysis. Furthermore, the sporadic occurrence of *Chondrites* and the lack of trace fossils in thin intervals allow recognition of periodic conditions of anoxia, either within the substrate and / or at the sediment-water interface.

On the other hand, the close relationship between the CBF1 and CBF2 and the presence of synaeresis cracks are strong evidence of salinity-stressed conditions. Both oxygenation and salinity may have been harsh to the endobenthic activities of the infaunal organisms. It is very difficult to discern between both factors, but the greater TOC content of the CBF2, if compared with the CBF1, indicates oxygenation as the main limiting factor, whereas the preservation of organic matter is enhanced under low oxygenation conditions.

The sedimentological characteristics and the intrinsic relationship between the CBF1 and CBF2 facies point out to deposition in bays or lagoons, with restricted or absent bottom-water circulation. A seaward enclosure of the estuary during a period of low rainfall, and consequently low fluvial discharge, is adopted herein as a speculative interpretation.

The CBF3 occurs locally and consists of sharp-based quartzose, massive, lower to upper fine-grained sandstone. Mud is present as thin, discontinuous stringers, while carbonaceous detritus and coal fragments are dispersed throughout the facies (figure 7.E, F). Rhizoliths of different sizes are common (figure 7.E, F). Bioturbation is rare and consists of *Palaeophycus*, *Planolites* and *Helminthopsis* (figure 7.E, F). The common occurrence of organic fragments and rhizoliths indicates a proximal, landward position within the estuary. The low degree of bioturbation and the low ichnodiversity suggest deposition in a freshwater-influenced environment. It is interpreted that CBF3 records deposition in a lagoonal margin near the Bay Head Delta Complex.

The CBF4 is the least common facies, occurring only in the FP-08-PR well. It is enclosed within the CBF1 facies interval. It consists of moderately burrowed, upper very fine- to fine-grained, slightly wavy-laminated sandstone that is 1 to 5 cm thick. Thin, milimetrical mudstone laminae occur intercalated within the sandstone intervals. Carbonaceous detritus are locally abundant. Upward, this facies grades into the mudstone of the CBF1.

The trace fossil association is moderately diverse and includes *Teichichnus*, *Thalassinoides*, *Palaeophycus*, *Planolites*, *Skolithos*, *Helminthopsis*, *Chondrites* and rare escape structures (figure 7.G). The relative diversity of the ichnological content and the presence of feeding and dwelling structures indicate a low degree of stress imposed by salinity variations.

It is interpreted that this facies represents deposition in wave-influenced, shallow-water environment, possibly a lagoonal margin behind the barrier. The abundance of *Teichichnus* indicates low depositional rate. The associated carbonaceous detritus are related with storm events, which breached the barrier and allowed the entrance of marine water into the estuary, increasing the diversity of organisms and, consequently, the recorded ichnodiversity.

Facies Association 3 - Estuary Mouth Complex. Three facies (EMF1, EMF2 and EMF3) comprise the Facies Association 3. These are sandy facies that represent the sediments deposited and preserved on the estuarine side of the Estuary Mouth Complex. The FP-08-PR well records the transition between the Central Basin and Estuary Mouth Complexes (see figure 5).

EMF1 grades upward from the CF1. In so far as sedimentological characteristics are concerned, EMF1 is a quartzose fine- to medium-grained, sandstone, with variable content of mudstone present in some intervals. Drapes are not common and synaeresis cracks were not observed. Bioturbation is of moderate intensity and diversity, including *Teichichnus*, *Thalassinoides*, *Planolites*, *Palaeophycus*, *Skolithos*, *Chondrites* and *Helminthopsis* (figure 8.A).

The relative diversity of the ichnofauna, recording different behaviors, suggests a low salinity-induced stress. The presence of equilibrium traces (i.e. *Teichichnus*) indicates low energy conditions and low aggradation rates. Thus, the EMF1 is interpreted as deposits of the estuary mouth complex near the tidal inlet. The proximity of the tidal inlet allowed the entrance of marine water, supporting a moderately diverse, fairweather ichnofauna.

The EMF2 grades upward from the CBF1. It consists of moderately burrowed, interlaminated mudstone and massive to rippled sandstones, which display a fairweather suite of trace fossils. The dominant ichnogenera are *Thalassinoides*, *Teichichnus*, *Cylindrichnus*, *Palaeophycus*, *Planolites*, *Skolithos* and *Chondrites* (figure 8.B). This facies is commonly interbedded with EMF3 packages. It is interpreted that EMF2 represents deposition in a shallow-water environment, frequently affected by storm events, within the estuary mouth complex.

Upward, EMF3 occurs forming discrete intervals. It comprises erosional-based, wavy laminated fine- to very fine-grained, quartzose, well sorted sandstone with subrounded to rounded grains. Commonly, the top of beds is mantled by thin, milimetrical muddy siltstone laminae, defining stacked fining-upward cycles. Sometimes, the siltstone is absent and the sandstone beds are erosionally amalgamated into centimetric (< 10 cm) bedsets. This facies is bounded above by a transgressive surface of erosion, interpreted as a wave ravinement surface (see figure 3.E).

Burrowing is sparsely distributed. Few ichnogenera are present, including *Thalassinoides*, *Cylindrichnus*, *Palaeophycus*, *Skolithos* and escape structures (figure 8.C). *Helminthopsis*, *Chondrites* and rare *Planolites* occur in the muddy siltstone and overprint an intensely bioturbated background fabric. *Thalassinoides* is the dominant form and occurs throughout the facies, cross-cutting both muddy siltstones and sandstone.

This facies is interpreted as storm-generated deposits. These deposits possibly were formed during major storms, which breached the barrier and allowed the sand to be transported into the estuary. The overlying wave ravinement surface records the ensuing marine transgression.

Conclusions

Ichnology has proven to be a powerful tool for identifying estuarine deposits in the Rio Bonito-Palermo succession. It allows a more reliable differentiation between the brackish-water and the fully marine deposits. However, an integrated approach involving sedimentology, ichnology and sequence stratigraphy is required to better understand the stratigraphic relationships within an estuarine valley-fill system and, consequently, to differentiate among the different subenvironments.

The recognition of the Central Basin and Estuary Mouth Complexes clearly indicate a wave-dominated estuary. Tidal processes can be noted locally, especially in the Channel Complex. Abundant mud drapes and herringbone cross stratification suggest tidal influence.

Figure 7. Sedimentological and ichnological aspects of the Central Basin Complex. **A-C,** Gray to dark gray mudstone displaying a low to moderately diverse ichnofauna of *Thalassinoides* (Th), *Palaeophycus* (Pa), *Teichichnus* (Te), *Planolites* (Pl) and *Chondrites* (Ch). Note the associated synaeresis cracks (sc). **A,** FP-07-PR, 193,7m; **B,** FP-08, 137,6m; **C,** NF-02-PR, 237,25m. **D,** The same ichnofauna overlain by carbonaceous mudstone, containing a monospecific suite of *Planolites*. FP-09-PR, 290,0m. **E,F,** Fine-grained sandstone with rhizoliths (r), carbonaceous detritus and coal fragments (black arrows). Trace fossils are represented by *Planolites*, *Palaeophycus* and *Helminthopsis* (He). FP-07-PR, 198,9m / 198,85m. **G,** Wavy, parallel lamination in fine-grained sandstone. The ichnofauna is moderately diverse, represented by a suite of *Teichichnus*, *Palaeophycus*, *Thalassinoides*, *Chondrites* and *Helminthopsis*. / *Aspectos sedimentológicos e icnológicos del Complejo de Cuenca Central.* ***A-C,*** *Lutitas grises a grises oscuras con una icnofauna pobre a moderadamente diversa de* Thalassinoides *(Th),* Palaeophycus *(Pa),* Teichichnus *(Te),* Planolites *(Pl) y* Chondrites *(Ch). Nótese las grietas de sineresis (sc).* ***A,*** *FP-07-PR, 193,7m;* ***B,*** *FP-08, 137,6m;* ***C,*** *NF-02-PR, 237,25m.* ***D,*** *La misma icnofauna sobrepuesta por lutitas carbonosas, con una suite monoespecífica de* Planolites. *FP-09-PR, 290,0m.* ***E,F,*** *Arenisca de grano fino con raíces (r), detritos carbonosos y fragmentos de carbón (flechas negras). Las trazas son representadas por* Planolites, Palaeophycus *y* Helminthopsis *(He). FP-07-PR, 198,9m / 198,85m.* ***G,*** *Laminaciones paralelas, onduladas, en areniscas de grano fino. La icnofauna es moderadamente diversa, representadas por una suite de* Teichichnus, Palaeophycus, Thalassinoides, Chondrites *y* Helminthopsis.

Figure 8. Sedimentological and ichnological aspects of the Estuary Mouth Complex. **A,** Bioturbated sandstone exhibiting a moderately diverse ichnofauna, with *Thalassinoides* (Th), *Chondrites* (Ch), *Planolites* (Pl), *Palaeophycus* (Pa), *Teichichnus* (Te) and *Skolithos* (Sk). NF-02-PR, 239,7m. **B,** Interbedded mudstone and low angle, wavy sandstone, displaying an opportunistic ichnofauna of *Thalassinoides*, *Teichichnus* and *Palaeophycus*. *Planolites* occurs only in the mudstones. FP-08-PR, 123,5m **C,** An escape structure associated with low angle, wavy laminated sandstone. The top is mantled by mudstone. FP-08-PR, 122,5m. / *Aspectos sedimentológicos e icnológicos del Complejo de Boca de Estuario.* ***A,*** *Areniscas bioturbadas exhibiendo una icnofauna moderadamente diversa con* Thalassinoides *(Th),* Chondrites *(Ch),* Planolites *(Pl),* Palaeophycus *(Pa),* Teichichnus *(Te) y* Skolithos *(Sk). NF-02-PR, 239,7m.* ***B,*** *Lutitas intercaladas con areniscas con laminación ondulada de bajo angulo, exhibiendo una icnofauna oportunista de* Thalassinoides, Teichichnus *y* Palaeophycus. Planolites *aparece solamente en las lutitas. FP-08-PR, 123,5m* ***C,*** *Una estrutura de escape asociada a areniscas con laminación ondulada de bajo angulo. El tope es cubierto por lutitas. FP-08-PR, 122,5m.*

The ichnofauna reveals low diversity, relatively low degree of bioturbation, dominance of small forms, simple structures generated by trophic generalists and occurrence of associated feeding and dwelling trace fossils. These are the diagnostic elements for recognizing brackish-water ichnocoenoses in the rock record.

Three paleoecological factors were the most important controls on the ichnofauna of the Guatá Group. Salinity is the main factor, controlling the distribution and diversity of the tracemakers and, consequently, the ichnofauna recorded. In addition oxygenation is regarded as a limiting factor in the Central Basin Complex. Unburrowed intervals indicate anoxia while monospecific suites of *Planolites* point out to oxygen-depleted conditions. Energy is the predominant paleoecological factor in the Estuary Mouth and Channel Complexes. The majority of the trace fossils are either thickly lined or deeply penetrating, revealing adaptation strategies to high energy conditions.

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References

Aboarrage, A.M. and Daemon, R.F. 1975. *Relatório Integrado dos Projetos:* Carvão no Extremo Norte de Santa Catarina, Prospecção de Carvão no Paraná II, Carvão no Estado de São Paulo. Relatório da CPRM.

Aboarrage, A.M. and Lopes, R.C. 1986. *Projeto A Borda Leste da Bacia do Paraná: Integração Geológica e Avaliação Econômica.* Ministério das Minas e Energia. Departamento Nacional de Produção Mineral. Convênio DNPM-CPRM, Relatório Final, CPRM, SUREG / Porto Alegre. 18v.

Adami-Rodrigues, K. and Ianuzzi, R. 2001. Late Paleozoic terrestrial arthropod faunal and floral successions in the Paraná Basin: a preliminary synthesis. *Acta Geologica Leopoldensia* 24 (52-53): 165-179.

Albuquerque, L.F. A. 1990. Estudo paleoambiental da Formação Rio Bonito em uma seção entre as jazidas de carvão do Iruí e Pântano Grande, Rio Grande do Sul. *Acta Geologica Leopoldensia*, 13: 113-130.

Benyon, B.M. and Pemberton, S.G. 1992. Ichnological signature of a brackish-water deposit: an example from the Lower Cretaceous Grand Rapids Formation, Cold Lake oil sands area, Alberta. In: S.G. Pemberton (ed.), *Application of*

Ichnology to Petroleum Exploration: A Core Workshop. SEPM Core Workshop 17: 199-221.

Benyon, B.M., Pemberton, S.G., Bell, D.D. and Logan, C.A. 1988. Environmental implications of ichnofossils from the Lower Cretaceous Grand Rapids Formation, Cold Lake oil sands deposit. In: D.P. James and D.A. Leckie, (eds.), *Sequences, Stratigraphy, Sedimentology: Surface and Subsurface*. Canadian Society of Petroleum Geologist Memoir 15: 275-290.

Bjerstedt, T.W. 1987. Trace fossil indicating estuarine deposystems from the Devonian-Mississippian Cloyd Conglomerate Member, Price Formation, Central Appalachians. *Palaios* 2: 349-379.

Buatois, L.A. and Mángano, M.G., 1990. Una asociación de trazas fósiles del Carbónico lacustre del área de Los Jumes, Catamarca, Argentina: su comparación con la icnofácies de *Scoyenia*. *5° Congreso Argentino de Paleontología y Bioestratigrafía* (San Miguel de Tucumán, 1990), *Actas* 1, Serie Correlación Geológica 7: 77-81.

Buatois, L.A. and Mángano, M.G. 1993. Trace fossils from a Carboniferous turbiditic lake: implications for the recognition of additional nonmarine ichnofacies. *Ichnos* 2: 237-258.

Buatois, L.A. and Mángano, M.G. 1995. The paleoenvironmental and paleoecological significance of the *Mermia* ichnofacies: an archetypical subaqueous nonmarine trace fossil assemblage. *Ichnos* 4: 151-161.

Buatois, L.A. and Mángano, M.G., 1996. Icnología de ambientes continentales: problemas y perspectivas. *1ª Reunión Argentina de Icnología* (Buenos Aires, 1996), *Publicación Especial* 4: 5-30.

Buatois, L.A. and Mángano, M.G., 1998a. Trace fossil analysis of lacustrine facies and basins. *Palaeogeography, Palaeoclimatology, Palaeoecology* 140: 367-382.

Buatois, L.A. and Mángano, M.G., 1998b. Ichnology of Pennsylvanian estuaries of Kansas: A Paleozoic perspective to ichnofacies modelling of incised valley systems: *15th International Sedimentological Congress* (Alicante, 1998), *Abstracts*: 216-217.

Buatois, L.A., Jalfin, G. and Aceñolaza, F.G. 1997. Permian nonmarine invertebrate trace fossils from southern Patagonia, Argentina: ichnologic signatures of substrate consolidation and colonization sequences. *Journal of Paleontology* 71: 324-336.

Buatois, L.A., Mángano, M.G., Genise, J.F. and Taylor, T.N. 1998a. The ichnologic record of the continental invertebrate invasion: evolutionary trends in environmental expansion, ecospace utilization and behavioral complexity. *Palaios* 13: 217-240.

Buatois, L.A., Mángano, M.G., Maples, C.G. and Lanier, W.P. 1998b. Ichnology of an upper Carboniferous fluvio-estuarine paleovalley: The Tonganoxie Sandstone, Buildex Quarry, Eastern Kansas, USA. *Journal of Paleontology* 72: 152-180.

Buatois, L.A., Mángano, M.G. and Carr, T.R. 1999. Sedimentology and ichnology of Paleozoic estuarine and shoreface reservoirs, Morrow Sandstone, Lower Pennsylvanian of Southwest Kansas, USA. *Current Research in Earth Sciences*. World Wide Web: http://www.kgs.ukans.edu/Current/1999/buatois/buatois1.html

Buatois, L.A., Netto, R.G. and Mángano, M.G. 2001a. Reinterpretación paleoambiental de la formación Rio Bonito (Pérmico de la Cuenca de Paraná) en el yacimiento de carbón de Iruí, Rio Grande do Sul, Brasil: integración de análises de fácies, icnología y estratigrafia secuencial de alta resolución. *Geogaceta* 29: 27-30.

Buatois, L.A., Netto, R.G. and Mángano, M.G. 2001b. Paleoenvironmental and sequence stratigraphic analyses of Lower Permian marginal to shallow marine coal-bearing successions of the Paraná Basin in Rio Grande do Sul, Brazil, based on ichnological data. *Ciência-Técnica-Petróleo* 20: 171-176.

Buatois, L.A., Gingras, M.K., MacEachern, J.A., Mángano, M.G., Martin, A.J., Netto, R.G., Pemberton, S.G. and Zonneveld, J.P. 2001c. Colonization of brackish-water environments through time: evidence from the trace-fossil record. *VI International Ichnofabric Workshop* (Isla Margarita & Puerto La Cruz, 2001). *Abstracts*: 18-19.

Buatois, L.A., Mángano, M.G., Alissa, A. and Carr, T.R. 2002. Sequence stratigraphic and sedimentologic significance of biogenic structures from a Late Paleozoic marginal-to open-marine reservoir, Morrow Sandstone, subsurface of southwest Kansas, USA. *Sedimentary Geology* 152: 99-132.

Câmara Filho, L.M. 1997. Estratigrafia de Seqüências do Grupo Guatá na faixa aflorante do sudeste paulista. *Dissertação de Mestrado, Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas,* Rio Claro-Brasil, 221 p.

Castro, J.C. 1980. Fácies, ambientes e seqüências deposicionais das formações Rio do Sul e Rio Bonito, leste de Santa Catarina. In: *31º Congresso Brasileiro de Geologia* (Balneário Camboriú, 1980). *Anais*: 1: 283-299.

Castro, J.C. 1991. A evolução dos sistemas glacial, marinho e deltaico das formações Rio do Sul e Rio Bonito / Membro Triunfo (Eopermiano), sudeste da Bacia do Paraná. *Tese de Doutoramento, Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas*, Rio Claro-Brasil, 147 p.

Castro, J.C. 1999. Estratigrafia de Seqüências das formações Campo Mourão (parte superior) e Taciba, Grupo Itararé, e do Membro Triunfo, Formação Rio Bonito, no leste da Bacia do Paraná. *Tese de Livre Docência, Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas* , Rio Claro-Brasil, 64 p.

Dörjes, J. and Howard, J.D. 1975. Fluvial-marine transitional indicators in an estuarine environment, Ogeechee River-Ossabaw Sound: *Senckenbergiana Maritima* 7: 137-179.

Genise, J.F. and Bown, T.M. 1994a. New Miocene scarabeid and hymenopterous nests and Early Miocene (Santacrucian) paleoenvironments, patagonian Argentina. *Ichnos* 3: 107-117.

Genise, J.F. and Bown, T.M. 1994b. New trace fossils of termites (Insecta: Isoptera) from the Late Eocene-Early Miocene of Egypt, and the reconstruction of ancient isopteran social behaviour. *Ichnos* 3: 155-183.

Genise, J.F., Mángano, M.G., Buatois, L.A., Laza, J.H. and Verde, M. 2000. Insect trace fossil associations in paleosoils: the *Coprinisphaera* ichnofacies. *Palaios* 15: 49-64.

Gierlowski-Kordesch, E. 1991. Ichnology of an ephemeral lacustrine/alluvial plain system: Jurassic East Berlim Formation, Hartford Basin, USA. *Ichnos* 1: 221-232.

Gingras, M.K., Pemberton, S.G. and Saunders, T., 1999. The ichnology of Modern and Pleistocene brackish-water deposits at Willapa Bay, Washington: variability in estuarine settings: *Palaios* 14: 352-374.

Gingras, M.K., Pemberton, S.G. and Saunders, T. 2000. Firmness profiles associated with tidal-creek deposits: the temporal significance of *Glossifungites* assemblages. *Journal of Sedimentary Research* 70: 1017-1025.

Goldring, R.G., Bosence, D.W.J. and Blake, T. 1978. Estuarine sedimentation in the Eocene of southern England. *Sedimentology* 25: 861-876.

Gordon Jr. 1947. Classification of the gondwanic rocks of

Paraná, Santa Catarina and Rio Grande do Sul. *Departamento Nacional de Produção Mineral, Divisão de Geologia e Mineralogia, Notas Preliminares e Estudos*, Rio de Janeiro, 38: 1-20.

Habekost, N.T. 1978. Paleoambientes da Formação Palermo no sudeste de Santa Catarina, Brasil. *Acta Geologica Leopoldensia* 4: 4-177.

Habekost, N.T. 1983. Paleoambientes da Formação Palermo na região central do Rio Grande do Sul, Brasil. *Acta Geologica Leopoldensia* 16: 43-113.

Hasiotis, S.T., Aslan, A. and Bown, T.M. 1993. Origin, architecture and paleoecology of the early Eocene continental ichnofossil *Scaphichnium hamatum* - integration of ichnology and paleopedology. *Ichnos* 3: 1-9.

Howard, J.D. and Frey, R.W. 1973. Characteristic physical and biogenic sedimentary structures in Georgia estuaries. American Association of Petroleum Geologists Bulletin, 57: 1169-1184.

Howard, J.D. and Frey, R.W. 1975. Regional animal-sediment characteristics of Georgia estuaries: *Senckenbergiana Maritima* 7: 33-103.

Leckie, D.A. and Singh, C. 1991. Estuarine deposits of the Albian Paddy Member (Peace River Formation) and lowermost Shaftsbury Formation, Alberta, Canada. *Journal of Sedimentary Petrology* 61: 825-849.

Leroux, M.S. and MacEachern, J.A. 1999. Style contrast of estuarine incised valley complexes: ichnological and sedimentological analysis of valley trends in the Glauconite Member and Viking Formation, Central Alberta. *Canadian Society of Petroleum Geologist - Petroleum Society Joint Convention, Abstracts* 99-127C.

MacEachern, J.A. and Pemberton, S.G. 1994. Ichnological aspects of incised valley fill systems from the Viking Formation of Western Canada Sedimentary Basin, Alberta, Canada. In: R.W. Dalrymple, R. Body and B.A. Zaitlin (eds.), *Incised valley fill systems: origin and sedimentary sequences*. SEPM Special Publication 51: 129-157.

MacEachern, J.A., Raychaudhuri, I. and Pemberton, S.G. 1992. Stratigraphic applications of the *Glossifungites* ichnofacies: Delineating discontinuities in the rock record. In: S.G. Pemberton, (ed.), *Applications of Ichnology to Petroleum Exploration*: A Core Workshop. SEPM Core Workshop 17: 169-198.

MacEachern, J.A., Stelck, C.R. and Pemberton, S.G. 1999. Marine and marginal marine mudstone deposition: paleoenvironmental interpretations based on the integration of ichnology, palynology and foraminiferal paleoecology. In: K.M. Bergman and J.W. Snedden (eds.), *Isolated shallow marine sand bodies: sequence stratigraphic analysis and sedimentologic interpretation*, SEPM Special Publication 64: 205-225.

MacNaughton, R.B. and Pickerill, R.K. 1995. Invertebrate ichnology of the nonmarine Lepreau Formation (Triassic), southern New Brunswick, eastern Canada. *Journal of Paleontology* 69: 160-171.

Martin, A.J., Buatois, L.A. and Mángano, M.G., 1998, A tale of two estuaries: an ichnologic comparison of early and late Paleozoic estuarine sequences (USA): *15th International Sedimentological Congress* (Alicante, 1998). *Abstracts*: 534.

Melchor, R. and Poiré, D. 1992. Invertebrate and tetrapod ichnocoenoses from a Permian fluvial/lacustrine sequence: Carapacha Formation, La Pampa province, Argentina. *IV Reunión Argentina de Sedimentología* (La Plata, 1992). *Actas* 2: 247-257.

Milani, E.J. 1997. Evolução tectono-estratigráfica da Bacia do Paraná e seu relacionamento com a geodinâmica fanerozóica do Gondwana sul-ocidental. *Tese de Doutoramento, Universidade Federal do Rio Grande do Sul, Instituto de Geociências*, Porto Alegre-Brasil, 2 vol.

Netto, R.G. 1994. A paleoicnologia como ferramenta de trabalho na seqüência sedimentar Rio Bonito/Palermo. *Tese de Doutoramento, Universidade Federal do Rio Grande do Sul, Instituto de Geociências*, Porto Alegre-Brasil, 272 p.

Netto, R.G. 2001. Icnologia e Estratigrafia de Seqüências. In: H.J.P.S. Ribeiro (ed.), *Estratigrafia de Seqüências: Fundamentos e Aplicações*, Editora UNISINOS: pp.219-259.

Netto, R.G. and Rossetti, D.F. 2000. Salinity changes measured by ichnofabrics: a key to identify estuarine systems. *31st International Geological Congress* (Rio de Janeiro, 2000). *Abstracts*.

Netto, R.G., Santos, M.A.A. and Nowatzki, C.H. 1991. Permian trace fossils on estuarine sequences at Rio Grande do Sul State, Brazil. In: *13th International Congress on Carboniferous and Permian Geology and Stratigraphy* (Buenos Aires, 1991). *Abstracts*: 98.

Netto, R.G., Buatois, L.A., Mángano, M.G. and Balistieri, P. 2001. *Gyrolithes* em depósitos permianos: uma adaptação para sobrevivência em ambientes salobros? *4° Reuníon Argentina de Icnología / 2° Reunión de Icnología del Mercosur* (San Miguel de Tucumán, 2001). *Resúmenes*: 60.

Pattison, S.A.J. 1992. Recognition and interpretation of estuarine mudstones (Central Basin Mudstones) in the tripartite valley-fill deposits of the Viking Formation, Central Alberta. In: S.G. Pemberton (ed.), *Applications of Ichnology to Petroleum Exploration, A Core Workshop*. SEPM Core Workshop 17: 223-249.

Pemberton, S.G., Flach, P.D. and Mossop, G.D. 1982. Trace fossil from the Athabasca oil sands, Alberta, Canada. *Science* 217: 825-827.

Pemberton, S.G. and Wightman, D.M. 1992. Ichnological characteristics of brackish water deposits. In: S.G. Pemberton (ed.), *Applications of Ichnology to Petroleum Exploration, A Core Workshop*. SEPM Core Workshop 17: 141-167.

Pemberton, S.G., Reinson, G.E., MacEachern, J.A. 1992. Comparative ichnological analysis of Late Albian estuarine valley-fill and shelf-shoreface deposits, Crystal Viking Field, Alberta. In: S.G. Pemberton (ed.), *Applications of Ichnology to Petroleum Exploration, A Core Workshop*. SEPM Core Workshop 17: 291-317.

Perinotto, J.A.J. 1992. Análise estratigráfica da Formação Palermo (P) na Bacia do Paraná, Brasil. *Tese de Doutoramento, Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas*, Rio Claro-Brasil, 2v.

Pickerill, A.K. 1992. Carboniferous nonmarine invertebrate ichnocoenoses from southern New Brunswick, eastern Canada. *Ichnos* 2: 21-36.

Ranger, M.J. and Pemberton, S.G. 1992. The sedimentology and ichnology of estuarine point bars in the McMurray Formation of the Athabasca Oil Sands Deposit, northeastern Alberta, Canada, In: S.G. Pemberton (ed.), *Applications of Ichnology to Petroleum Exploration: A Core Workshop:* SEPM Core Workshop 17, 401-421.

Reinson, G.E., Clark, J.E. and Foscolos, A.E. 1988. Reservoir geology of Crystal Viking field, Lower Cretaceous estuarine tidal channel-bay complex, south-central Alberta. *American Association Petroleum Geologist Bulletin* 72: 1270-1294.

Sampaio, R.F. 1987. Análise faciológica e estratigráfica dos membros Paraguaçu e Siderópolis da Formação Rio Bonito, sul-sudeste da Bacia do Paraná. *Dissertação de Mestrado, Universidade Federal de Ouro Preto, Escola de Minas*, Ouro Preto-Brasil, 111p.

Schneider, R.L. and Castro, J.C. 1975. *Análise estratigráfica, se-*

dimentológica e possibilidades petrolíferas da Formação Rio Bonito no sudeste da Bacia do Paraná. PETROBRAS / DEX-PRO. *Relatório interno*. 39 p.

Schneider, R.L., Mühlmann, H., Tommasi, E., Medeiros, R.A., Daemon, R.F. and Nogueira, A.A. 1974. Revisão Estratigráfica da Bacia do Paraná. In: 27°I *Congresso Brasileiro de Geologia* (Porto Alegre, 1974). *Anais* 1: 41-65.

Tognoli, F.M.W. 2002. Análise estratigráfica e paleoicnológica do Grupo Guatá no leste paranaense. *Dissertação de Mestrado, Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas*, Rio Claro-Brasil, 90 p.

Tognoli, F.M.W. and Netto, R.G. 2001. Ichnofabric patterns of wave-dominated estuarine deposits from the Permian of the Paraná Basin, Brazil. *4° Reuníon Argentina de Icnología / II Reunión de Icnología del Mercosur* (San Miguel de Tucumán, 2001). *Resúmenes*: 74.

Tognoli, F.M.W., Mochizuki, A.H. and Castro, J.C. 2001. Discordâncias e reservatórios associados do Grupo Guatá nas margens leste e nordeste da Bacia do Paraná. *Ciência-Técnica-Petróleo* 20: 185-192.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M. and Rahmanian, V.D. 1990. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops. *American Association of Petroleum Geologists*, Methods in Exploration Series 7: 1-55.

White, 1908. *Relatório sobre as coal measures e rochas associadas no sul do Brasi*l. Rio de Janeiro. Comissão de Estudos das Minas de Carvão de Pedra no Brasil. 300 p.

Wightman, D.M., Pemberton, S.G. and Singh, C. 1987. Depositional modelling of the Upper Mannville (Lower Cretaceous), east central Alberta: implications for the recognition of brackish water deposits. In: R.W. Tillman and Weber, K.J. (eds.), *Reservoir Sedimentology*. Society of Mineralogists and Paleontologists Special Publication 40: 189-220.

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