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Flood-dominated fluvio-deltaic system: a new depositional model for the Devonian Cabeças Formation, Parnaíba Basin, Piauí, Brazil

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ABSTRACT

The depositional model of the Cabeças Formation is re-evaluated in the context of the Devonian paleogeography the Parnaíba Basin, and with particular reference to similarities between the formation's facies associations on t eastern border of the basin and the flood-dominated fluvio-deltaic system facies that have been discussed in rece literature. The widespread occurrence and nature of sigmoidal clinoforms (with asymptotic cross-stratification a climbing ripples) of the Cabeças Formation are here considered as strong evidence of flood-influenced depositio settings. Sandy strata of the Passagem Member, in the vicinity of Pimenteiras and Picos (Piauí State), are interpret as the distal part of fine-grained mouth-bar deposits interbedded with delta-front sandstone lobes showing hummoc cross-stratification. Richly fossiliferous levels, with diverse megainvertebrates and plant cuticles, occur within t delta-front lobes and the distal mouth-bar deposits, reflecting continuation of shallow marine conditions.

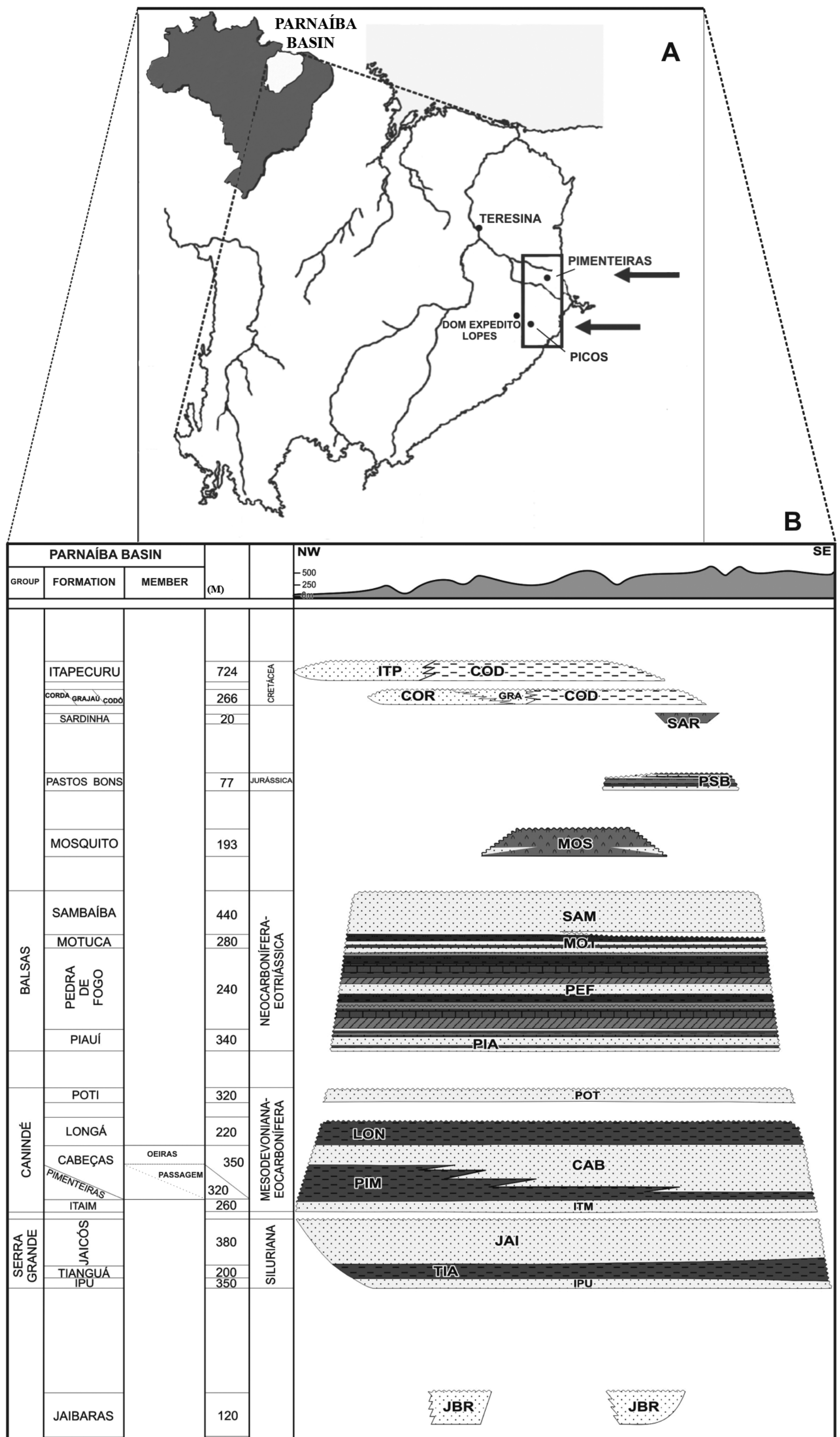
Key words: Parnaíba Basin, Devonian, Cabeças Formation, flood-dominated fluvio-deltaic system, delta-front san stone lobes, mouth-bar deposits, hummocky cross-stratification.

INTRODUCTION

The present-day intracratonic Parnaíba Basin covers an area of ca. 600,000 km^2 in northeastern and north-central Brazil. Devonian lithostratigraphic units of the Parnaíba Basin are, in ascending order, the Itaim, Pimenteira, Cabeças, and lowermost Longá formations (Fig. 1). The Cabeças Formation was proposed by Plummer (1948) for a thick (ca. 100–400 m) sequence of sandstones exposed in the Cabeças locality (known nowadays as Dom Expedito Lopes) on the eastern mar-gin of the Parnaíba Basin (Fig. 1A). Plummer (1948)

stones; from the base upwards, the Passagem, Oei Ipiranga members. Only the first two members a rently accepted, and even these are of problemati ity in terms of their putative lithological discrim (Beurlen 1965, Mabessone 1994).

The Cabeças Formation consists chiefly c grained to pebbly sandstones with asymptotic an mocky cross-stratification, and with subordinat beds of siltstone. The upper part of the formatio prises tillites, striated pavements with faceted, and polished clasts and varvelike rhythmites. Mi


PARNAÍBA BASIN
A
TERESINA
PIMENTEIRAS
DOM EXPEDITO LOPES
PICOS
B
PARNAÍBA BASIN
GROUP
FORMATION
MEMBER
(M)
NW
SE
500
250
ITAPECURU 724
CORDA GRAJAÚ CODÓ 266
SARDINHA 20
PASTOS BONS 77
MOSQUITO 193
SAMBAÍBA 440
MOTUCA 280
PEDRA DE FOGO 240
PIAUÍ 340
POTI 320
LONGÁ 220
CABEÇAS 350
PIMENTEIRAS 320
OEIRAS
PASSAGEM
ITAIM 260
JAICÓS 380
TIANGUÁ 200
IPU 350
JAIBARAS 120
BALSAS
CANINDÉ
SERRA GRANDE
CRETÁCEA
JURÁSSICA
NEOCARBONÍFERA-EOTRIÁSSICA
MESODEVONIANA-EOCARBONÍFERA
SILURIANA
ITP
CÓD
COR
GRA
COD
SAR
PSB
MOS
SAM
MOT
PEF
PIA
POT
LON
CAB
PIM
ITM
JAI
TIA
IPU
JBR
JBR

(Grahn et al. 2006). On the basin's eastern margin, in outcrops around Pimenteiras and Picos (Fig. 1A), marine megafossil faunas indicate a Givetian age (Melo 1988) for the lower part of the Cabeças Formation (Passagem Member).

The Cabeças Formation provides an example of a sedimentary unit whose origin cannot be explained adequately in accordance with classical depositional models. It displays thick sigmoidal clinoforms with asymptotic cross-stratification (*sensu* Zavala 2008) and climbing ripples, here considered to represent the main evidence of the significant flooding in its depositional setting. Climbing ripples are related to traction plus fallout processes generated by a turbulent flow with high suspended load. Recently, this structure has been considered a major sedimentary feature in hyperpycnal deposits, as it manifests the steady migration of sedimentary bedforms while sediment supply is maintained and sedimentation rate is significant (Mulder et al. 2003, Zavala et al. 2006).

Della Fávera (J.C. Della Fávera, unpublished data) has proposed that the Cabeças sandstones were deposited under the influence of tidal currents, based on his observations in the south-central Pyrenees Basin, where sand structures with sigmoids are interpreted as tidal deposits. Subsequently, in 1990, Della Fávera linked the origin of the Eocene Roda Formation in the south-central Pyrenees Basin to that of the Cabeças sandstones. The Roda Formation is now interpreted as a flood-generated deposit (Tinterri 2007). Moreover, tidal influence could hardly be envisaged as substantial in epicontinental basins like the Parnaíba Basin. Della Fávera and Medeiros (J.C. Della Fávera and M.A.M. Medeiros, unpublished data) have interpreted a set of sigmoidal clinoforms in the Cabeças Formation as mega-climbing ripples caused by catastrophic floods.

Episodic sedimentation has been reappraised considerably in recent years, following the intensive discussions of the early 1980s (as detailed by Della Fávera 1984), when the gradualistic character of sedimentation was considered to have prevailed.

The unusual nature of this kind of event in terms

interpretation of some paleoenvironments, such
considered here.

Ancient flood-dominated fluvio-deltaic s
cannot be described and interpreted according
current sedimentological models for fluvial and
sedimentation, because such models are usually
from modern depositional environments domina
"normal" fluvial and marine processes (see ex
discussion in Mutti et al. 1996). The modern ana
these flood-dominated systems could be the sm
medium-sized mountainous rivers described by
man and Syvitski (1992) and the "dirty rivers" of
and Syvitski (1995), which can generate frequent
pycnal flows during a year (Mutti et al. 2000).

Hyperpycnal flows result from a sedimen
fluvial discharge entering a standing body of
mainly during a flood (Mulder and Syvitski 19
hyperpycnal system could be defined as the suba
extension of the fluvial system, delivering a huge
of sediment into a basin, with facies and facie
ciations that depart significantly from classical
Consequently, their deposits and depositional f
could resemble certain characteristics common
fluvial and turbidite deposits (Zavala et al. 2006)

Although hyperpycnal flows are evidently co
at contemporary river mouths (Mulder and S
1995, Mulder et al. 2003), their manifestation
cient deposits has been poorly documented (Za
al. 2006).

A classic example of cataclysmic floods
Channeled Scablands of Washington, U.S.A., wh
undated the Columbia River basin during the
cene. In 1923, J. Harlen Bretz envisaged huge
to explain the immense ripples with wavelength
100 m and amplitudes of 9 m, fluvial bars 120
erratic boulders, and other structures found in the
neled Scablands (Della Fávera 2001). In complyi
the Lyellian concept of gradualism, the scientifi
munity of that time rejected Bretz's model, whi
not fully recognized until 1965.

FLOOD-DOMINATED FLUVIO-DELTAIC SYSTE

fluvio-deltaic sedimentation pertaining to flood-dominated depositional systems.

Mutti et al. (1996) introduced a depositional model for ancient flood-dominated fluvio-deltaic systems, typical of tectonically active basins, but applicable also to interior cratonic basins such as the Parnaíba Basin. These flood-dominated fluvio-deltaic systems can be viewed as developing in elevated catchment basins and short and high gradient transfer zones. In such settings, floods generate sediment-water mixtures that enter seawater as density-driven underflows (hyperpycnal flows).

Flood-dominated fluvio-deltaic systems produce sedimentary units with distinct vertical and longitudinal grading formed during a discrete flood event. These elementary flood-units may diverge considerably from each other due to many local controlling factors such as volume, sediment concentration, duration of individual flood events, type of process, type of sediment involved and depositional setting (Mutti et al. 2000).

Therefore, individual flood-units may vary from, on the one hand, crudely graded, small and lenticular coarse-grained bars produced by the sudden deceleration of low-volume and short-duration flash floods to, on the other hand, graded and comparatively well-sorted and laterally extensive sandstone beds deposited by long-lived and relatively confined hyperpycnal flows (Mutti et al. 2000).

In flood-dominated fluvio-deltaic systems, climatic and minor eustatic variations, generated by orbitally forced cyclicity within the Milankovitch range, are considered the primary factor in controlling sedimentation; see Milliman and Syvitski (1992) and Mutti et al. (1996, 2000) for a detailed discussion. Catastrophic floods can originate only if large amounts of water are available in drainage basins over short time intervals; these could result from breaches of natural dams (including failure of ice dams that blocked large drainage systems), proglacial-lake overflows, subglacial volcanic eruptions, landslide-dam failures, lake-basin overflows and ice-jam floods. Large floods resulting from meteorological conditions and atmospheric water sources played a minor role at least in Quaternary flooding episodes by breaches of natural dams and those that resulted from meteorological phenomena would not be expected to vary appreciably through geologic time. During the so-called "flood epochs", climate and topography are jointly responsible for producing unusually high frequencies of large floods, especially in times of advancing continental ice sheets and rapid changes in sea level (O'Connor and Costa 2004).

According to Mutti (1992) and Mutti et al. (2000), the most common and distinctive depositional unit of a flood-dominated fluvio-deltaic system consists of sharp-based and parallel-sided graded sandstone beds characterized by hummocky cross-stratification (HCS). These sheet-like sandstone beds typically form packets 3-15 m thick, with muddier interbeds that may be richly fossiliferous and bioturbated. These sediments, which are notable for their lateral continuity and their internal cyclic stacking pattern, constitute the typical delta-front facies association of a flood-dominated system.

First recognized by Goldring and Bridges (1973), these deposits were initially named "sublittoral sheet sandstones" and variously attributed to storms, tsunamis, floods, tides, rip and turbidity currents. Mutti et al. (1996) termed the deposits "shelfal sandstone lobes", which were redefined by Mutti et al. (2000) as "flood-generated delta-front sandstone lobes". Vertical and lateral stratigraphic relationships indicate that delta-front sandstone lobes pass basinward into mudstone-dominated prodelta facies, and that their landward equivalents are represented by very distinctive mouth-bar deposits (Fig. 2A).

Mouth-bar deposits display considerable variation in terms of geometry and facies types, essentially recording locally prevailing conditions. Depending on the kind of flow, different types of mouth-bars could develop, such as the fine-grained or the coarse-grained mouth bars, ranging from medium to fine sand or boulder and small pebble sized clasts to fine sand, respectively (Mutti et al. 2000).

Facies distribution patterns are thus mainly controlled by the volume of sand trapped at a river mouth and whether sufficient can be liberated to form turbu-

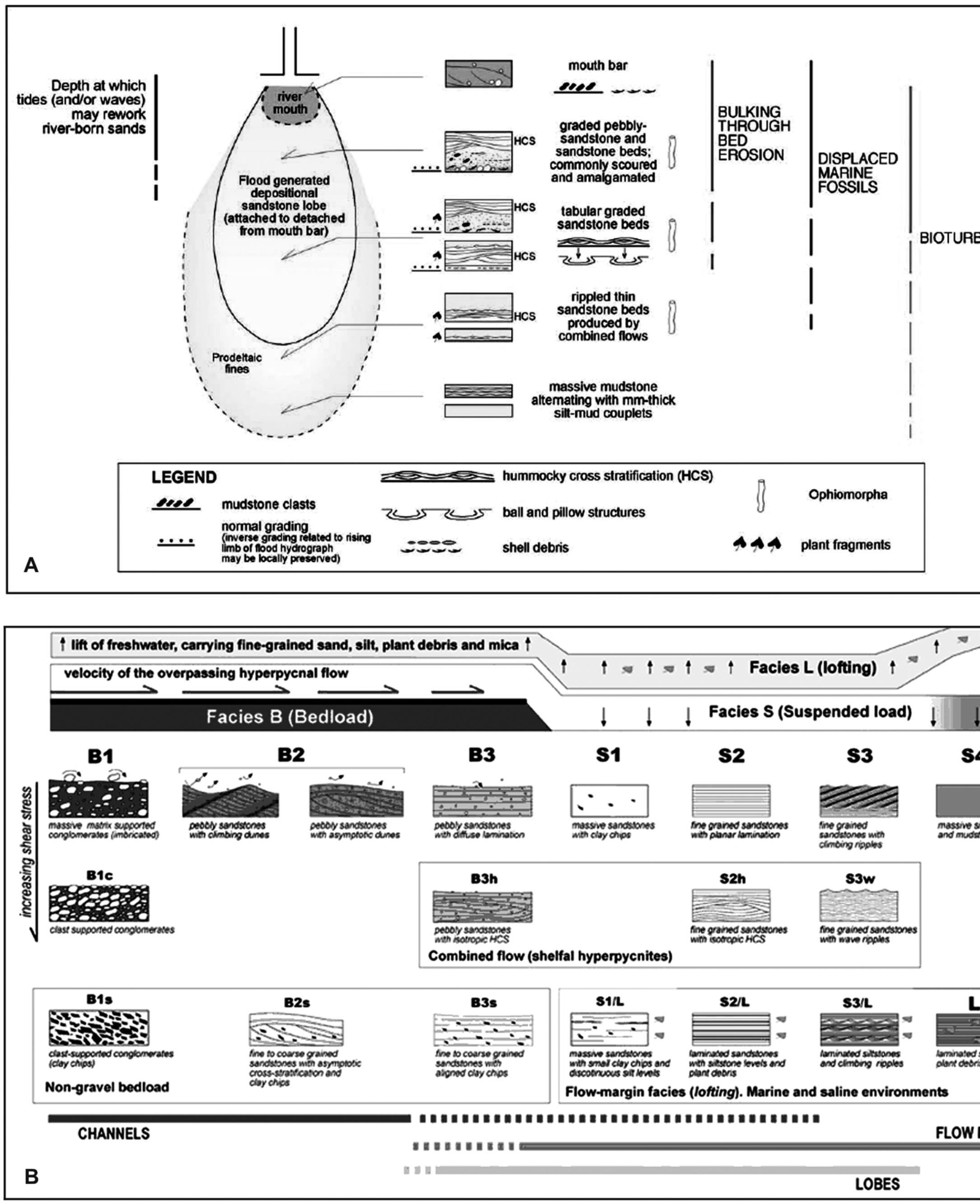


Fig. 2 – (A) Main characteristics of delta-front sandstone lobes in a flood-dominated fluvio-deltaic system (Mutti et al. 2007). (B) Sc diagram showing the genetic interpretation of clastic facies in hyperpycnal systems (Zavala 2008).

ing ripples, mouth-bar deposits most frequently show a typical sigmoidal clinoform bearing asymptotic cross-stratification. This developed at different physical scales as a function of the magnitude and duration of individual flows (Mutti et al. 2000, Zavala et al. 2006).

First described by Mutti et al. (1996), sigmoidal clinoforms produced by flood-generated flows are typically expressed by sigmoidal sets of cross-laminae which markedly thin and flatten downcurrent and are truncated upcurrent by a flat or slightly convex-upward erosional surface, produced by the bypassing of a turbulent flow. Sigmoidal clinoforms are readily distinguishable from those of tidal origin, inasmuch as the distinctive features of tide-dominated facies, like mud drapes and current reversal, are unrepresented in flood-dominated sediments.

The presence of hummocky cross-stratification (HCS) may also cause uncertainties in the interpretation of flood deposits. Flood-generated delta-front sandstone lobes have usually been mistakenly identified as storm-dominated nearshore and shelfal deposits, mainly because of the pervasiveness of the HCS. However, combined-flow conditions are inherent in the dynamics of flood-generated flows, particularly in those flows entering seawater as hyperpycnal flows. Hence the interpretation of the HCS origin has changed from the classic storm-layer theory of Harms et al. (1975) to that involving turbidites generated by a hyperpycnal flow (Mutti et al. 1996). Hyperpycnal flows behave essentially as shallow-water turbidity currents, and, except for the occurrence of HCS, locally abundant fossil debris and bioturbation, these flows produce facies tracts very similar to those generated by turbidity currents in a deep-water environment (Mutti et al. 2007).

Basinward of mouth-bar and delta-front regions, where the bulk of sand is trapped, flood-dominated fluvio-deltaic systems grade into prodeltaic mudstones with interbedded fine-grained sandstones. The delta-front is considered the terminal depositional zone of these systems, with facies deposited by hypopycnal flows (buoyant plumes) and low-density hyperpycnal flows (Mutti et al. 2003). Hypopycnal flows can form

Zavala et al. (2008) interpreted the deposits of low-density hyperpycnal flows as lofting rhythmites, where rhythmic sand-silt couplets containing abundant plant material are interbedded with massive to laminated tabular sandstone lobes (the delta-front sandstone lobes *sensu* Mutti et al. 2000). Lofting rhythmites accumulate from a lofting plume, which characterizes hyperpycnal inflows in marine environments. When the flow gradually deposits part of its suspended load, the freshwater current will ascend from the substrate through buoyancy reversal, forming lofting plumes charged with fine-grained sediments, plant debris and micas.

Alternatively, the interbedded sandstone lobes result from traction plus fallout processes, and often show vertical facies recurrences, which are interpreted as evidence of deposition from flow fluctuations in long-lived and quasi-steady hyperpycnal flows. In contradistinction to classic models of turbidity sedimentation, coarse-grained materials are not transported at the flow head, but are transported at the flow base as bedload (Zavala 2008).

The facies tract proposed by Zavala (2008) comprises three main genetically related facies groups, termed B, S and L. These correspond to bedload, suspended load and lofting transport processes, respectively (Fig. 2B).

Facies B (bedload) is the coarsest grained and relates to shear and frictional drag forces induced by the overpassing long-lived turbulent flow. Three main subcategories are identified, termed B1 (massive or crude bedding conglomerates), B2 (pebbly sandstones with asymptotic cross-stratification, with the subdivision B2s, characterized by fine to coarse grained sandstones with asymptotic cross-stratification and clay chips) and B3 (pebbly sandstones with diffuse planar lamination and aligned clasts). Facies S is essentially fine grained, and reflects the gravitational collapse of sand-size materials transported as suspended load. Four S facies sub-types are recognized: S1 (massive sandstones), S2 (parallel-laminated sandstones, with the subdivision S2h, characterized by fine grained sandstones with isotropic HCS), S3 (sandstones with climbing ripples) and S4 (massive grained sand, silt, plant debris and micas) are lifted from the substrate and are re-deposited as laterally extensive silt/sand couplets (Zavala 2008, Zavala et al. 2008).

A NEW DEPOSITIONAL MODEL FOR THE CABEÇAS FORMATION

The depositional paradigm of the Cabeças Formation is re-evaluated here with reference to the Devonian paleogeography of the Panaíba Basin, and to similarities between the formation's facies associations on the eastern side of the basin and the flood-dominated fluvio-deltaic system facies described in recent literature.

The widespread occurrence and nature of sigmoidal clinoforms in the Cabeças Formation (i.e., sandstones, several meters thick, bearing asymptotic cross-stratification and climbing ripples, without the distinctive features of tide-dominated facies, like mud drapes and current reversal) are here considered to constitute persuasive evidence of flood-influenced depositional settings.

The set of sigmoidal clinoforms attributed to mega-climbing ripples from some outcrops of the Cabeças Formation (e.g., BR-343 Highway, km 168.5, near Piracuruca, Piauí) signifies a water depth of 50 m during flooding, due to the ripple geometry with 10–15 m ripple-spacing and height of 2 m (Della Fávera and Medeiros 2007).

The distributional patterns among the Cabeças Formation's sigmoidal clinoforms bearing asymptotic cross-stratification (the mouth-bar deposits) and the interbedded hummocky cross-stratified tabular sandstones (the delta-front lobes) reflect the density and transformations experienced by these turbidite-like flows.

High-density turbulent flows, in which the unidirectional component of the hyperpycnal flow predominates, are responsible for the deposition of the flood-generated mouth-bars and for the sigmoidal clinoform's genesis. Basinward, the delta-front lobes with HCS (where the oscillatory component of the hyperpycnal flow prevails) would result from low-density turbulent flows bypassing the high-density deposits and carrying their suspended load to more distal regions. Finally, when the flow gradually deposits part of its suspended

producing rhythmic sand-silt couplets with ab plant material (i.e., constituting facies L of Za al. 2008).

As a result, the Cabeças Formation's delt sandstone lobes with HCS (corresponding to fac of Zavala 2008, see Fig. 2B) would onlap the stones bearing asymptotic cross-stratification (co ble to facies B2s of Zavala 2008) and reach dee gions. Depending on flow efficiency, these delt lobes could remain attached (in the case of less e flows) or be detached (efficient flows) from the imal mouth-bar deposits (Mutti et al. 2000, Za al. 2000).

In the Passagem Member, the fine-grained stone lobes with HCS contain an allochthonous blage with diverse and plentiful megainvertebrate 3B) consisting mostly of terebratulid brachiopo tentaculitids, together with rare bivalves and trilo

Mouth-bar deposits of the Cabeças Formatio sagem Member) are exposed in the eastern bo the Parnaíba Basin: notably, in the Oiti regio nicipality of Pimenteiras, Piauí) and in the vici Picos (Fig. 4). These deposits are interpreted he the distal component of a fine-grained mouth-ba in a flood-dominated fluvio-deltaic system. Vertic tions of these outcrops in the Pimenteiras and Pico are composed of two portions.

The downstream section, the mouth-bar slope prises medium- to fine-grained sandstones with bedding and climbing ripple cross-lamination in ded with massive to laminated siltstones at its ba current ripples at its top (Fig. 4A).

The upstream portion is characterized by asymptotic cross-stratification of pebbly to fine-g sandstones (Fig. 4B). These mouth-bar deposit erosional features such as mudstone clasts and ar dant para-autochthonous megainvertebrate asse (Fig. 3A). The megafossils consist chiefly of *chonetes comstocki* (Rathbun, 1874), associate spiriferid, terebratulid and lingulid brachiopo valves, tentaculitids, trilobites, crinoids and gastr

Lofting related facies (Zavala et al. 200

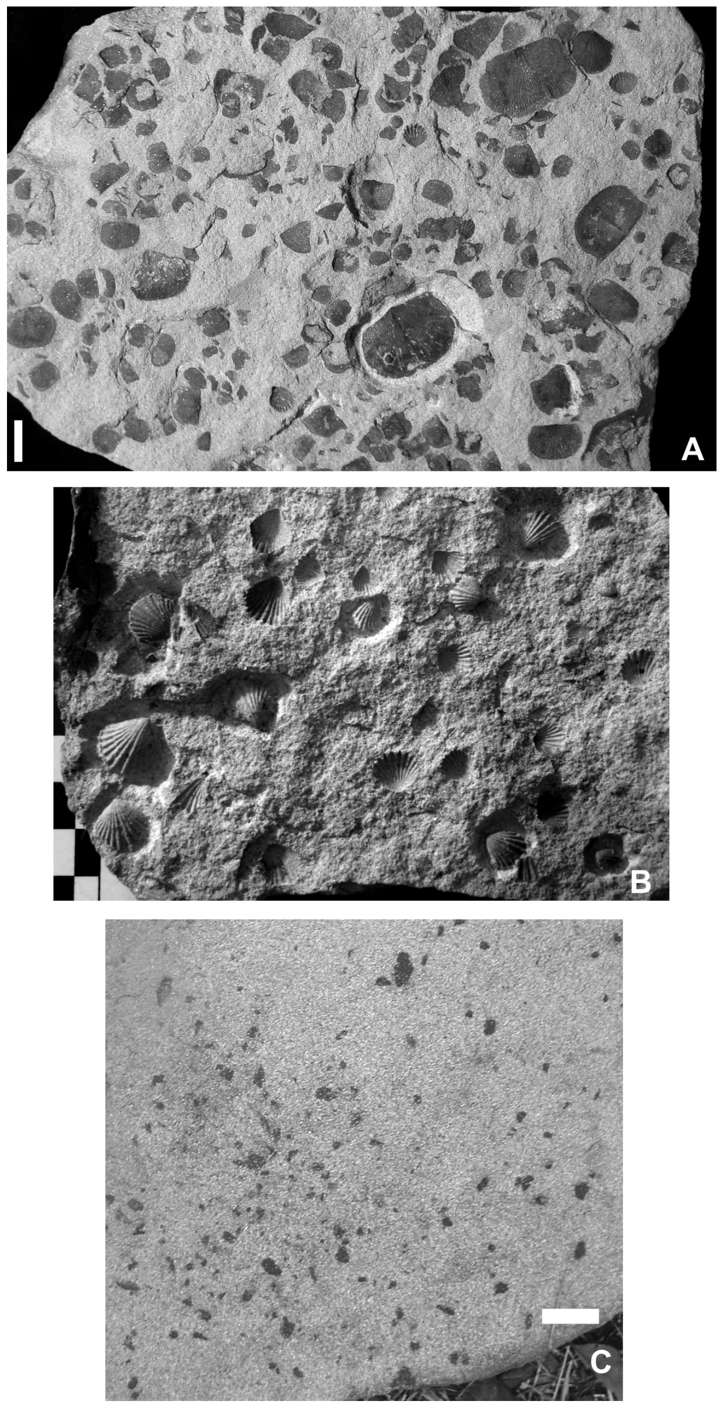


Fig. 3 – (A) Marine megainvertebrate assemblage typical of the distal mouth-bar deposits, dominated by *Pleurochonetes comstocki*. (B) Ma-

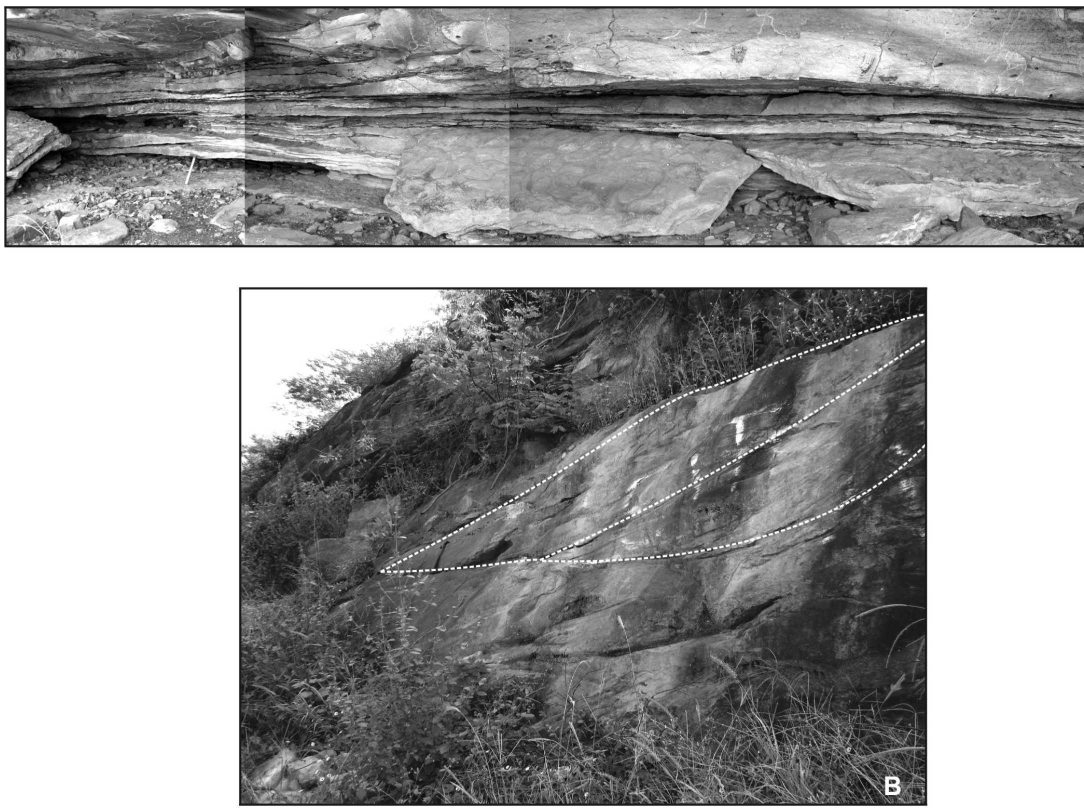


Fig. 4 – (A) Mouth-bar deposits in the Passagem Member, Oiti region (Pimenteiras, Piauí State), showing plane-bed laminae, climbi cross-lamination and current ripples, interbedded with massive to laminated siltstones. (B) Sigmoidal clinoform typical of the upper m portion, Passagem Member, BR-316 Highway, km 308, near Picos, Piauí.

1990). These rhythmites are interbedded with massive to laminated tabular sandstone lobes (the delta-front sandstone lobes) and distal mouth-bar deposits.

Paleogeographically, the Parnaíba Basin was situated during Devonian time at Lat. 40°–60°S (according to Isaacson et al. 2008), experiencing intermittent glacial conditions during its first sedimentary cycle (Late Ordovician through Early Mississippian).

A glacial origin was initially proposed by Moura (1938) for Devonian diamictites penetrated by wells in the Tapajós River area of the Amazonas Basin, and Kegel (1953) was the first to interpret the diamictite as a tillite, based on the texture of cores recovered from Petrobras CL-1-MA well in the Parnaíba Basin.

Furthermore, glacial and periglacial conditions

Crowell (1985), Loboziak et al. (2000), Stree (2000), Caputo et al. (2008) and Isaacson et al. Caputo (1985) proposed that during the late Fr early Famennian the glaciers were restricted to regions and that during subsequent Famennia they advanced over the Parnaíba, Amazonas an mões basins.

In addition to the latest Famennian glaciati denced by the upper Cabeças Formation, Cap al. (2008) speculated about the possibility of an glaciation at the Frasnian-Famennian boundary considered that the regressive sandy and conglor beds within the Pimenteira Formation could si small-scale glaciation. However, the erosional quences of the major late Famennian glaciation

The glacial conditions of the Late Devonian (Frasnian-Famennian) could well have been preceded by small-scale upland glaciation during the late Middle Devonian (Givetian). This could at times have generated floods in the Parnaíba Basin, by breaching of natural dams or meteorological circumstances. The extremely effective flows triggered by such flood events would enter seawater as hyperpycnal flows, thus generating the flood-dominated fluvio-deltaic system facies documented in the previous section.

CONCLUDING REMARKS

Ongoing climate changes are at the forefront of current scientific and public debate (Eyles 2008, O'Connor and Costa 2004). Turning to the geological past, the widespread interest in cyclic climatic fluctuations and ancient episodic events, such as catastrophic floods, emphasizes the vital necessity of obtaining much more detailed information concerning the origin of these events and their resultant facies associations.

The fluvio-deltaic systemic models proposed by Mutti et al. (1996, 2000, 2003, 2007), Zavala et al. (2000, 2006, 2008) and Zavala (2008) can be applied in this new hypothesis about the deposition of the Cabeças Formation along the eastern border of the Parnaíba Basin, thus facilitating a reassessment of its paleoenvironmental setting, including the influence of floods. The deposits of this fluvio-deltaic system dominated by rivers in flood are here considered as having been generated by hyperpycnal flows operating as shallow-water turbidity currents.

The shallow marine faunas of the Cabeças Formation are preserved in the distal mouth-bar deposits and proximal delta-front lobes, in particular the facies of the Passagem Member near Pimenteiras and Picos. The hyperpycnal flows triggered by fluvial floods caused a mixing of megainvertebrate skeletal remains from different shallow-water communities; these latter can be distinguished according to the taphonomic signatures represented in the fossil assemblages. Hence, these data provide an objective basis for taphonomic and paleoecologic analyses of the Cabeças Formation's Devonian taphonomic analysis of diverse megafossils (Fürsich et al. 2005, Astibia et al. 2005, Dominici and Kowalke 2007). Furthermore, the model could assist in paleoenvironmental reconstructions (Torricelli et al. 2006) and in reassessment of depositional settings in other Brazilian epicontinental basins, including the Paraná Basin (Vesely 2007).

In contrast to the considerable knowledge that has accrued concerning the latest Famennian glaciation (Caputo et al. 2008), the nature, extent and precise dating of other possible Devonian glaciations in the Parnaíba Basin, and their effects on the dynamics of depositional systems, clearly warrant further investigation.

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RESUMO

O modelo deposicional da Formação Cabeças é reinterpretado no presente estudo com base no contexto paleogeográfico da Bacia do Parnaíba durante o Devoniano e na similaridade entre as fácies encontradas na Formação Cabeças com as fácies características dos sistemas flúvio-deltaicos dominados por inundações. O tipo das clinoformas sigmoidais (com estratificação cruzada assintótica e laminação cruzada cavallizados nos arredores das cidades de Pimenteiras e Picos, são interpretados como o componente distal de um tipo de barra de desembocadura com a predominância de arenitos finos a conglomeráticos, intercalados com lobos arenosos tabulares de frente deltaica com estratificação cruzada *hummocky*. Diversos intervalos fossilíferos, com abundantes macrofósseis de invertebrados e fragmentos vegetais, ocorrem tanto nos lobos de frente deltaica quanto nos depósitos distais de barra de desembocadura, ainda no contexto de um paleoambiente marinho raso.

Palavras-chave: Bacia do Parnaíba, Devoniano, Formação Cabeças, sistema flúvio-deltaico dominado por inundações, lobos de frente deltaica, depósitos de barra de desembocadura, estratificação cruzada *hummocky*.

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