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Large barchanoid dunes in the Amazon River and the rock record: Implications for interpreting large river systems

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ABSTRACT

The interpretation of large river deposits from the rock record is hampered by the scarcity of direct observations of active large river systems. That is particularly true for deep-channel environments, where tens of meters deep flows dominate. These conditions are extremely different from what is found in smaller systems, from which current facies models were derived. MBES and shallow seismic surveys in a selected area of the Upper Amazonas River in Northern Brazil revealed the presence of large compound barchanoid dunes along the channel thalweg. The dunes are characterized by V-shaped, concave-downstream crest lines and convex-up longitudinal profiles, hundreds of meters wide, up to 300 m in wavelength and several meters high. Based on the morphology of compound dunes, expected preserved sedimentary structures are broad, large-scale, low-angle, concave up and downstream cross-strata, passing laterally and downstream to inclined cosets. Examples of such structures from large river deposits in the rock record are described in the Silurian Serra Grande Group and the Cretaceous São Sebastião and Marizal formations in Northeastern Brazil, as well as in Triassic Hawkesburry Sandstone in Southeastern Australia and the Plio–Pleistocene Içá Formation in the western Amazon. All these sedimentary structures are found near channel base surfaces and are somewhat coarser than the overlying fluvial deposits, favoring the interpretation of thalweg depositional settings. The recognition of large barchanoid dunes as bedforms restricted to river thalwegs and probably to large river systems brings the possibility of establishing new criteria for the interpretation of fluvial system scale in the rock record. Sedimentary structures compatible with the morphological characteristics of these bedforms seem to be relatively common in large river deposits, given their initial recognition in five different fluvial successions in Brazil and Australia, potentially enabling substantial improvements in facies models for large rivers.

1. Introduction

Large river systems are defined on the basis of drainage area, channel length, as well as water and sediment discharge (Hovius, 1998), and are the most important agents of sediment transport on Earth (e.g. Potter, 1978; Tandon and Sinha, 2007), accounting for approximately 35% of the sediments delivered to the oceans (Miall, 2006). Although concrete criteria for the recognition of large rivers in the rock record have been proposed (e.g. Miall, 2006; Fielding, 2007), detailed descriptions of such depositional systems are rare in the literature. Additionally, the scarcity of studies on sedimentary processes and products in large river channels hinders the recognition and interpretation of these systems, impacting regional paleogeographical reconstructions, outcrop-scale sedimentological studies and hydrocarbon reservoir geology.

In this way, establishing direct criteria for the recognition of large river deposits is of major importance. Approaches based on relating bedform size and cross-strata set thickness to river scale (e.g. Paola and Borgman, 1991; Leclair and Bridge, 2001; Leclair, 2011) do not directly lead to reliable interpretation of river

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size (e.g. Reesink et al., 2015). On the other hand, difficulties to distinguish between unit bar and large dune deposits bring additional complexity to the interpretation of river scale based on the rock record. The problem is amplified by the scarcity of observational data on deep channel bedform morphology, particularly of Multibeam Echosound (MBES) data, that could be used as a base for comparison of bedform scale distribution in different channels, and potentially reveal detailed 3D bedform morphologies that could be used to refine interpretations of the rock record.

The presence of large-scale cross-strata in fluvial sedimentary successions has been considered by several authors as indicative of large river systems (e.g. Miall, 2006; Fielding, 2007), and estimates of channel depth based on preserved thicknesses of dune cross-strata are often used to constrain river size (e.g. Lunt et al., 2013; Sambrook Smith et al., 2013, but see Reesink et al., 2015 for alternative views).

One main problem with this approach is the difficulty in distinguishing between deposits of large dunes, which thickness is a small fraction of the water depth (Paola and Borgman, 1991; Leclair and Bridge, 2001), and deposits of unit bar forests, which original thicknesses can be similar to the water depth (Sambrook Smith et al., 2006; Reesink and Bridge, 2007). Additionally, compound dunes reported in several active large river channels (e.g. Parsons et al., 2005; Carling et al., 2000; Abraham and Pratt, 2002) can form cross-stratified cosets laterally related to large-scale foresets in the same way as unit bars.

Compound dunes are common features in the thalwegs of channel systems, which include river channels and tidal inlets (e.g. Dalrymple, 1984; Ashley, 1990; Parsons et al., 2005; Svenson et al., 2009; Lefebvre et al., 2011), whereas unit bars are common features in the thalweg of small river systems, but uncommon in the deeper parts of large river channels (Ashworth et al., 2008). In big river systems such as the Brahmaputra unit bars can be observed through satellite imagery and have been described in bar tops (e.g. Ashworth et al., 2000).

Morphologically, unit bars are usually regarded as lobate, non or quasi-periodic and relatively unmodified forms (e.g. Sambrook Smith et al., 2006; Reesink and Bridge, 2007), whereas compound dunes are periodic (Ashley, 1990) and have been commonly reported as straight and sinuous-crested (e.g. Dalrymple, 1984; Carling et al., 2000). More recently, barchanoid compound dune forms have been recognized (e.g. Carling et al., 2000; Ernstsen et al., 2005; Abraham and Pratt, 2002).

Fluvial barchanoid dunes are crescentic shaped bedforms (in plan-view) with arms pointing down-current, being morphologically similar to aeolian barchanoid dunes and also ascribed to limited sediment supply (Carling et al., 2000; Kleinhans et al., 2002). Fluvial barchanoid dunes are distinguished from 3D or undulating dunes in having simple curved crestlines that are higher in the center and tapering toward the arm tips. Fluvial barchanoid dunes are scarcely recorded in the literature, probably due to the lack of 3D bathymetric surveys of river and coastal channel thalwegs. These bedforms were first described in an active fluvial environment as isolated small scale dunes (McCulloch and Janda, 1964). Only recently they have been reported again in the deepest areas of large channels in the Rhine (Carling et al., 2000; Kleinhans et al., 2002) and the Mississippi rivers (Abraham and Pratt, 2002), as well as in the smaller Allier River in France (Kleinhans et al., 2002).

Barchanoid forms may present a symmetric or asymmetric form, with an arm longer than the other (Svenson et al., 2009; Carling et al., 2000). In longitudinal sections, they are usually wedge-shaped, with stoss angles of up to 5° and lee angles that can vary from angle-of-repose to low angles, below 8°, in which case superposed smaller dunes may climb down the lee face. Compound dunes in different environments are documented to have smaller lee angles than small dunes (Dalrymple and Rhodes, 1995; Carling et al., 2000). The length to height ratio is very variable, although maximum heights are observed for given lengths (Ashley, 1990).

Compound barchanoid dunes up to 1 m high were described by Carling et al. (2000) in the Rhine River. The authors proposed a model for the formation of the observed morphology, considering that the dunes grow in height during the rising river stage and then diminish during steady and falling stages, when lee-side deposition is increased by rapidly moving secondary dunes.

Similar barchanoid compound dunes were observed in the Mississippi River by Abraham and Pratt (2002). Although the authors did not describe the bedforms in detail, MBES image and bathymetric profiles reveal dune heights ranging from 0.6 to 1.5 m and dune lengths up to 60 m, with abundant superposed small dunes on their stoss sides.

Compound dunes in tidal inlet systems, described by Ernstsen et al. (2005, 2006) are characterized by central parts of the crests higher than the arms. Superposed bedforms are larger and coarser-grained, presenting steeper lee angles in the central crest. Celerity is higher on the sides of the compound dunes, what could explain their barchanoid shape.

The present work is aimed at the investigation on deep-channel bed surveys in a selected area of the Amazon River (Fig. 1), which reveals that large, up to 12 m tall, barchanoid dunes are conspicuous features in the thalweg of this large river. This type of bedform is not found in shallow deposits in the region and is not described for small river systems elsewhere. The main objective was to provide new criteria for the recognition of large river thalweg deposits, presenting detailed description and a model for the internal structure of barchanoid dunes. Additionally, examples of preserved structures from the rock record are presented, illustrating the importance of establishing criteria to distinguish large compound dunes from unit bar deposits (see below).

2. Investigated area

The fluvial systems of the Amazon stand out as important elements in Earth surface dynamics, contributing with a significant proportion of the global sediment flux to the oceans. Large rivers with catchments in the Andes, such as the Solimões–Amazonas and Madeira, are responsible for the bulk of the sediment transport in the region. These rivers, together with rivers with large water discharge but lower sediment flux, such as the Negro, Tapajós and Xingu, exert important controls on the distribution of animal and plant species in the region.

The investigated area in the Amazon River is located in the main channel, north of the Careiro Island, 33 km downstream of the confluence between the Solimões and the Negro rivers. The Careiro Island separates the main channel from a local anabranch (Paraná do Careiro, Fig. 1), which has an average minimum low stage discharge of 5100 m^3/s and average maximum high stage discharge of 25,900 m^3/s, according to the Brazilian National Water Agency (AGÊNCIA NACIONAL DE ÁGUAS – ANA). In the main channel minimum discharges occur between October and December, with average minimum annual discharge of 74,100 m^3/s since 1977, varying between 51,500 m^3/s and 102,400 m^3/s. Maximum discharges occur between May and July, with average maximum annual discharge of 178,000 m^3/s, varying between 121,400 m^3/s and 233,000 m^3/s. Discharge variation in one year ranges from 50% of peak discharge (1980 record) to 70% of peak discharge (2009 record). Total suspended sediment discharge at the Manacapuru gauge station, approximately 130 km upstream of the studied area, is around 400 $Mt\,yr^{-1}$ (Filizola and Guyot, 2009).

Bedload grain-size in the Solimões–Amazon river system is markedly similar throughout the 3000 km in Brazilian territory

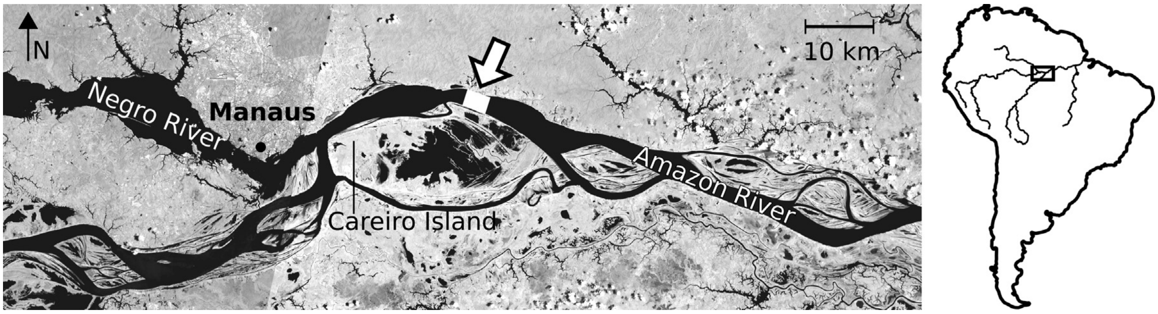

Fig. 1. Surveyed area (white rectangle) in the Amazon River.

(Nordin et al., 1980; Mertes and Meade, 1985; Strasser, 2008), with average grain-size varying between 0.25 and 0.40 mm. Depth-related grain-size variation at one section in Óbidos (Strasser, 2008) presents greater magnitude, with a median of 0.16 mm at nearly 40 m depth and of 0.57 at nearly 60 m depth. In the investigated area, previous study of bedload grain-size shows a median of 0.40 mm, with 60% of the grains between 0.30 and 0.50 mm (Strasser, 2008). In the studied reach the Amazon River, the main channel has a local maximum depth of 78 m. The thalweg is approximately 800 m wide, with depths below 50 m, flanked to the south by the submerged lateral extension of the Careiro Island, dipping nearly 3.5°. To the north, the main thalweg is bounded by a steep erosional surface on Cretaceous sedimentary rocks. A few isolated pinnacles of the same Cretaceous rocks occur in the main channel.

3. Methods

Bathymetric and seismic profiling systems were used to describe channel morphology and shallow stratigraphy. Swath bathymetry sonar systems have been used in the last decades to map and study seafloor morphology, as described in the pioneer work of Hughes-Clarke et al. (1996) and, more recently, to remotely estimate seafloor physical properties (Fonseca and Mayer, 2007). Due to the centimetric depth resolution and overall submetric spatial accuracy, high-frequency sonars have been also used to study 3D morphological features of active river channels (e.g. Parsons et al., 2005).

Bedform morphology and high-resolution bathymetry in a reach of the Upper Amazonas was studied with Multibeam Echosounder (Teledyne-Reson Seabat 7101 system), operating at a frequency of 240 kHz, with 511 beam achieving a resolution of 12,5 mm. Internal structure and distance to channel bedrock were interpreted from seismic images, obtained with a Meridata sub-bottom profiling system using a Boomer profiler operating in the 0.7–2 kHz frequency band, resulting in a resolution of about 0.5 m.

Bed material was collected in 12 sites during the dry season, 3 months after the MBES survey, with a 10 kg Van Veen grab sampler. Grain size analyses were performed with a Malvern Mastersizer 2000 (fractions smaller than 1 mm). Fractions with larger grain-size were estimated based on normalized weight proportion in relation to the whole sample.

4. Results

4.1. Morphology of compound barchanoid dunes

Deep channel areas in the investigated reach, from 42 m to 66 m below high stage water level, are dominated by large-scale compound barchanoid dunes, contrasting with shallower areas, 5 to 32 m deep, where straight- to sinuous-crested simple dunes dominate (Fig. 2). In a transitional domain, from 34 to 57 m depth, following the slope of the subaqueous extension of the Careiro Island bar, large-scale, straight-crested, flow-oblique compound dunes are found. Large-scale compound barchanoid dunes are characterized by arched to V-shaped crestlines, with angles from 70° to 106°, on average, between the nearly straight arms. Despite the apparent lateral continuity of crestlines into straight to lobate dunes, those actually form separate trains with different wavelengths, only randomly connected to the barchanoid crests (Fig. 2). Distances between arm tips of each dune vary between 84–156 m (average of 136 m) for the small train and 270–471 m (average 384 m) for the large train. Crestlines do not systematically vary in height between central and external parts of each bedform, but seem to follow the inclination of the surface on which the bedforms migrate. Barchanoid dunes wavelength has little variation on each individual dune train (standard deviation/mean from 0.20 to 0.36), with a mean of 150 m for the larger dunes train and 61 m for the smallest dunes train. Dune height follows the same pattern, with mean dune height of approximately 5 m for the larger dune train and of 2.2 m for the smaller one. The smallest barchanoid dune is 0.6 m tall, whereas the larger is 8.2 m tall. The dunes are asymmetric in longitudinal profiles, with the proportion of lee-side length to total length averaging 35%. Stoss angles range from 2.2° to 8.0°, with a mean of 4.4°, and 70% of the values between 2.9° and 6.2°. Lee angles are strongly dependent on the position of the considered longitudinal profile of a given barchanoid dune: while steeper profiles are found at the central parts of individual barchanoids, very low dipping surfaces (a few degrees) characterize the downcurrent arms of each barchanoid dune. Interestingly, even the central parts rarely show angle-of-repose lee faces, with only 10% of the dunes showing lee face dips steeper than 20°. Lee faces are often convex upward, displaying planar, higher angle parts near the base of the leeside, and low angle surfaces dominating the upper, convex part of lee faces. The mean dip value for planar, steeper parts of the lee faces is 11.8°, with 50% of the values between 7.4° and 16.2°. The steeper lower part of the lee face represents 20% to 94% of the dune height, averaging 61%.

Superposed bedforms are often found on the stoss of the barchanoid dunes. Those are more frequent and higher in the external arms of each barchanoid dune, commonly showing 0.1 to 0.5 m in height and 2 to 10 m in wavelength. Superposed dune heights tend to be larger near the crest of host barchanoid dunes. Superposed dunes are also found on the lee faces, mainly on the arms of host barchanoid dunes.

Average mean grain size of the whole area covered by the MBES varies from 0.213 to 0.375 mm. Spatial distribution indicates that coarser average grain sizes are located in the deeper thalweg area, whilst finer grain sizes are found in shallower areas, such as deep and shallow bar margins (Fig. 3). There is a clear relationship of average grain size and depth (Fig. 3). This difference is also observed for maximum grain size: granules are exclusively found in thalweg barchanoid dunes and sediment starved thalwegs, whereas shallower areas feature coarse and medium sand (Fig. 2).

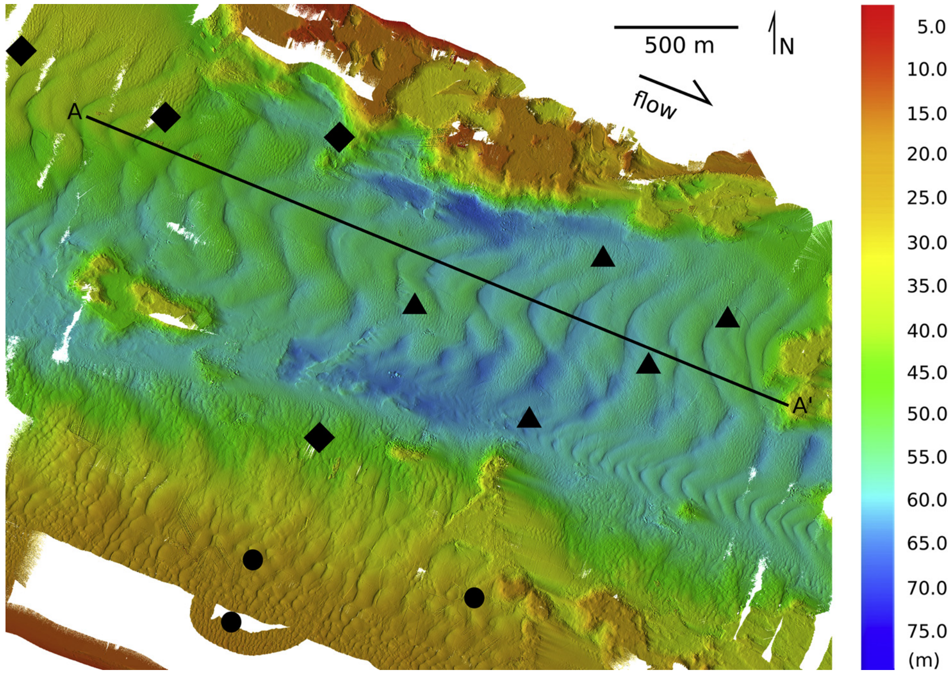

Fig. 2. Multibeam Echosounder (MBES) 3D bathymetric model of the studied reach showing distribution of different types of bedforms in the studied area. Location of seismic survey is shown in the A–A′ line. Location of grain size analysis samples are plotted. Symbols represent maximum grain sizes observed at specified locations: triangles – granule; diamonds – coarse sand; circles – medium sand. Note correlation of maximum grain size with depth.

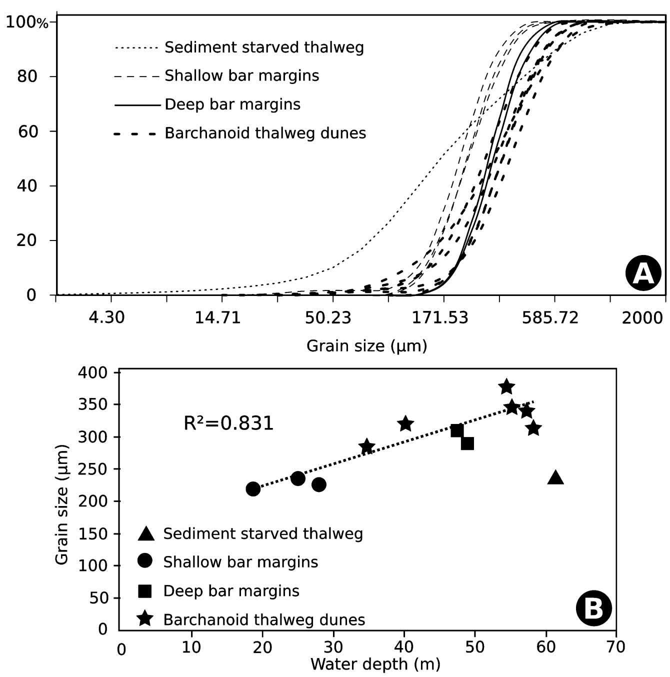

Fig. 3. A) Cumulative grain-size distributions of samples from thalweg barchanoid dunes and other types of bedforms in the investigated area. B) Correlation between average grain-size of individual samples and water depth in the investigated area. Note that grain size from sediment starved thalweg domain was not considered for the construction of the regression line.

Subsurface Boomer images reveal that at some points several compound dunes are stacked, most probably forming cosets, summing up at least 18 m of sediments on top of the interpreted Cretaceous rocks (Fig. 4), whereas elsewhere only the thickness of one individual dune can be recognized. Successive large compound dunes climb evidence a clear difference from true barchans migrating on bedrock or pebble lags (e.g. Kleinhans et al., 2002).

4.2. Internal structure and facies model of compound barchanoid dunes

The characteristic morphology of the large compound dunes which dominate the thalweg of the investigated area, integrated to shallow subsurface seismic images, provide elements for the interpretation of the sedimentary structures that would be preserved in similar deposits in the rock record.

Considering that these thalweg bedforms may not leave long term deposits where erosion rate equals deposition rate during bedform migration, their preservation requires either gradual shift or abandonment of the main channel, with progressive burial of the thalweg bedforms by channel fill or bar migration. The long term preservation of these bedforms would be controlled by scour depth variation (Paola and Borgman, 1991), leading to the potential erosion of the upper part of the structure.

In this way, low angle tangential lee-faces in the central parts of the barchanoid dunes would be preserved as low-angle foresets dipping parallel to the current direction, whereas towards the dune arms, preserved foreset orientations would tend to shift towards the central part of the dune, leading to a low angle concave up and downstream cross-stratification pattern. The abundance of superimposed smaller bedforms on the barchanoid dune arms would result in compound cross-strata.

Therefore, the observed morphology would result in two different types of cross-strata sets in the sedimentary record, namely large-scale foresets and inclined cosets, reflecting different profiles in the same bedform (Fig. 5A):

(1) In the central parts of the bedform, longitudinal profiles would tend to be dominated by large-scale tangential foresets, with thicknesses of up to several meters. These large-scale cross-strata would be marked by expressive variation in foreset grain-size due to pre-sorting during the migration of the superposed bedforms on the stoss and upper parts of the lee of larger dunes in a similar way to unit bars (e.g. Reesink and Bridge, 2007). The occasional preservation of the upper parts of the bedform would tend to record a gradual transition from the steeper parts of the foresets to lower angle foreset tops,

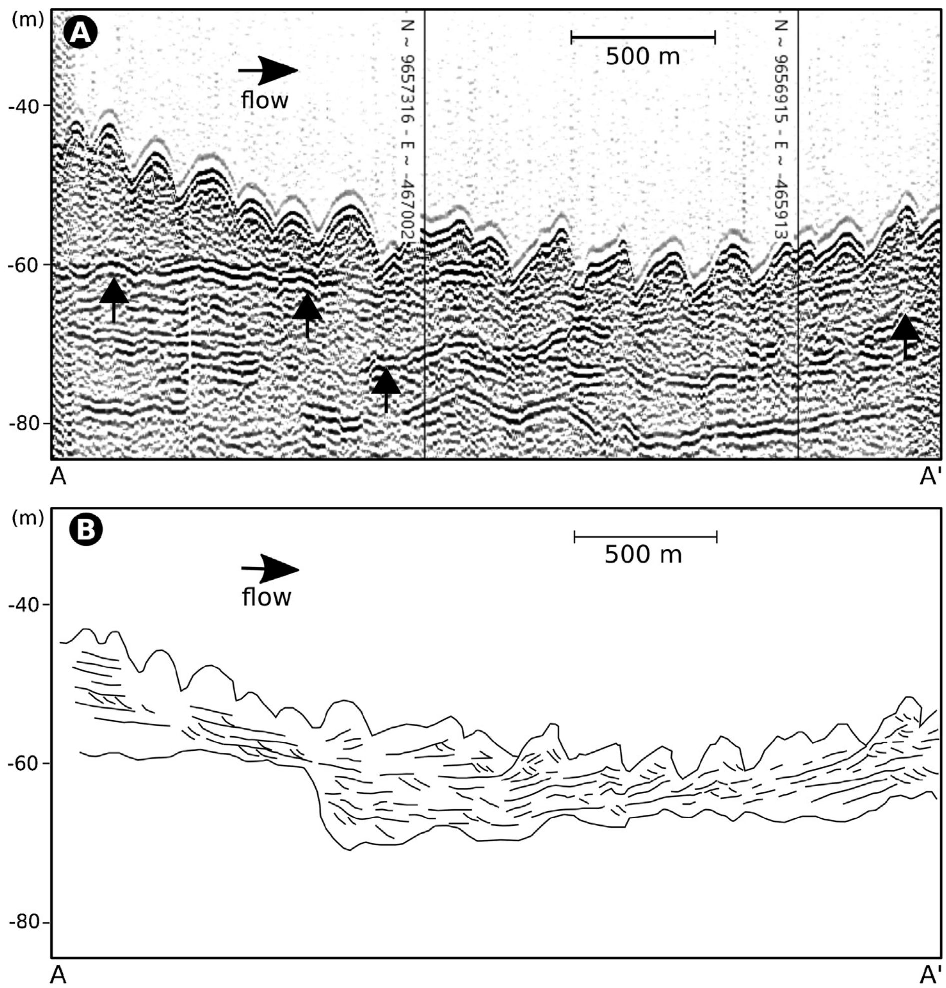

Fig. 4. A) Shallow boomer sub-bottom profile (A–A′, see Fig. 2 for location) parallel to river flow. Reflectors ascribed to the Cretaceous substrate (black arrows) lay several meters below the surface of the studied barchanoid dunes. B) Seismic profile interpretation. Reflectors between the Cretaceous substrate and the river bed are interpreted as sub-horizontal to low-angle dipping cross-strata set bounding surfaces, as well as local preserved cross-strata.

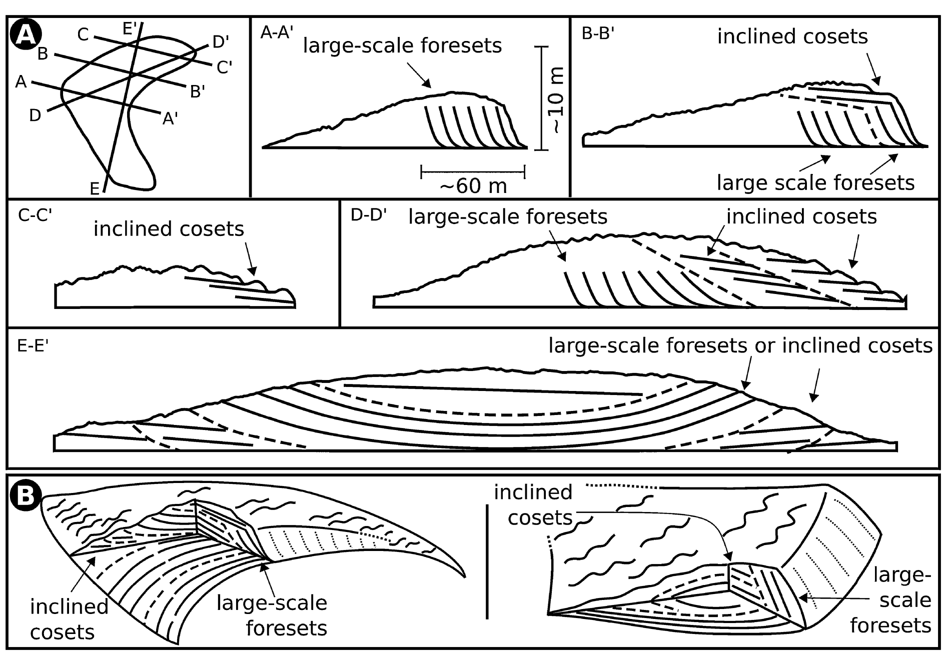

Fig. 5. A) Interpreted sedimentary structures and bounding surfaces internal to the studied barchanoid dunes in different profile orientations. Upper left corner: plan view of an ideal barchanoid dune, 60 to 180 m in wavelength, showing the position and orientation of the depicted profiles, with vertical exaggeration of 6 times. B) Simplified ideal morphology and internal structure of Thalweg Barchanoid Dunes (left) compared to Unit Bars (right). Vertical exaggeration is comparable to profiles in A.

in some cases with inclined cosets showing smaller individual cross-strata sets recording the down-climbing superposed bedforms (Fig. 5A, A–A′ and B–B′ sections).

(2) Longitudinal profiles of the large barchanoid dune arms would be dominated by inclined cosets with internal cross-strata sets a few decimeters thick (Fig. 5A, C–C′ section). Cross-strata set bounding surfaces would be inclined a few degrees, and their dip direction would be controlled by the local orientation of the lee face of the host bedform and the angle of climb of the smaller bedforms (Almeida et al., 2016). Thickness of the whole coset would be nearly the same of the related foreset at the central part of the host bedform.

(3) Profiles orthogonal to the current direction would show a broad (hundreds of meters wide) trough cross-stratification, with the steeper part of the foresets in the inner trough transitioning outward and upward to lower angle foresets and inclined cosets (Fig. 5A, E–E′ section). Dip directions measurements of host dune foresets show a dispersion of more than 120°, with higher angles in the direction of flow and lower angles in oblique directions.

Lateral variations between both types of preserved cross-strata are expected in profiles oblique to the current direction, therefore cutting through both the central and lateral parts of the bedform (e.g. Fig. 5A, D–D′ section). Additionally, an increase in the frequency of superposed smaller bedform is expected during low stages, whereas a dominance of steeper foreset is expected at high stages, potentially leading to temporal variations between avalanche foresets and down-climbing coset observable in longitudinal profiles.

Potential preservation of large barchanoid dunes in the rock record can be expected where these thalweg elements are buried beneath migrating bars or abandoned channel fills. Climbing of barchanoid dunes is strongly suggested by the seismic profile from bar fronts, where downstream migrating barchanoid dunes stack forming tens of meters high macroforms (Fig. 4). Additionally, in most of the Solimões and the Amazon rivers, mid-channel and bank-attached bars frequently grow or migrate over the thalwegs, thus potentially covering the barchanoid dunes. Finally, several kilometers long abandoned channel reaches in both rivers point to the potential long term preservation of complete channel fill successions, with large barchanoid dunes at the bottom.

4.2.1. Criteria for the distinction of large compound dune from unit bar deposits

Unit bars have been interpreted from similar large-scale cross-strata, and the distinction of large compound dunes and unit bar deposits in the rock record is not straightforward. Unit bars may have a similar architecture to large compound dunes, defined by superposed smaller bedforms climbing up the stoss, and by variable geometries on the lee side of the host bedform, including large simple, often angle of repose, lee faces and local low angle surfaces with superposed downclimbing bedforms. Current knowledge about the occurrence, depositional processes, internal structures and preservation of both types of bedforms is not enough to establish universal criteria for the discrimination between unit bar and large compound dune deposits. Nevertheless, some striking morphological differences may be used to distinguish preserved deposits of unit bars from the here described large compound barchanoid dunes. Unit bars are usually lobate, contrasting with barchanoid large dunes. The position of the large compound barchanoid dunes in the thalweg of the main channel is also a marked characteristic, often related to distinctively coarser grained sediment than the other sub-environments in the same system. Additionally, whereas dunes are periodic bedforms, unit bars are quasi- or non-periodic bedforms (e.g. Smith, 1978; Sambrook Smith et al., 2006) with lengths proportional to the flow width and heights comparable to bankfull depth (e.g. Reesink and Bridge, 2007).

In this way, large barchanoid dunes can be distinguished from unit bar deposits in the rock record based on the following criteria:

(1) Large barchanoid dunes occur in thalwegs and therefore are preserved at the base of channel elements, covering erosional surfaces and frequently being coarser grained than the overlying succession. Unit bars with large-scale foresets are common in shallow parts of the fluvial system (e.g. Ashworth et al., 2008) and have not been observed on large river thalwegs.

(2) Large barchanoid dunes result in cross-strata slightly concave up and slightly to strongly concave downstream (locally V-shaped), with a tendency to preserve large-scale simple foresets on the central part of the structure passing, towards the external part of the structure, to low angle inclined cosets composed of smaller scale cross-strata sets (Fig. 5B). Temporal variations between simple foresets and inclined cosets are also expected. Although local preservation of concave unit bar foresets is possible, the common lobate geometry of unit bars implies a more frequent preservation of apparently tabular or even convex up and downstream cross-stratification.

The periodicity of the large barchanoid dunes contrasts with unit bars, and the presence of local climbing surfaces between large-scale cross-strata can be used as criteria to distinguish between dunes and unit bars.

5. Validation of facies model from the geological record

5.1. Cretaceous fluvial deposits in the Tucano Basin

Early Cretaceous fluvial successions in the Tucano Basin, São Sebastião and Marizal formations, are interpreted as the record of a regional scale fluvial system infilling a deep rift basin during the initial stages of the opening of the South Atlantic (e.g. Costa et al., 2007; Figueiredo, 2013; Freitas, 2014; Figueiredo et al., 2016).

Several meters thick inclined cosets are the dominant element in the architecture of both units, and the preservation of outsized cross-strata sets up to 5 m thick have been previously interpreted mostly as unit bar deposits (Figueiredo, 2013; Freitas, 2014; Figueiredo et al., 2016; Almeida et al., 2016), with local suggestion of compound dunes (Figueiredo, 2013).

Some of these large-scale cross-strata sets and inclined cosets match the here proposed criteria for the interpretation of large compound barchanoid dune deposits, indicating that at least some of the deposits previously interpreted as unit bar products might reflect bedforms developed in channel thalwegs much deeper than the preserved thickness of individual bedforms.

In the São Sebastião Formation, local cosets with trough-shaped set bounding surfaces indicate concave-downstream lee faces of a larger host bedform with down-climbing smaller dunes (Fig. 6). Large cosets are up to 5 m thick and the internal inclined cross-strata sets are 15 to 35 cm thick, suggesting several meters high compound dunes. The position of such cosets near the base of channel elements corroborates the interpretation of thalweg compound barchanoid dunes.

In the Marizal Formation, several examples of 5 to 15 m thick fining-upward elements, bounded by erosional surfaces at the base, present abundant cross-strata cosets, often inclined, composed of coarse sandstone grading upward into medium to fine sandstone dominated by small scale cross-strata sets, with local mudstone lenses and plane-bedded sandstone deposits. These successions are interpreted as complete preservation of channel bases, thalweg

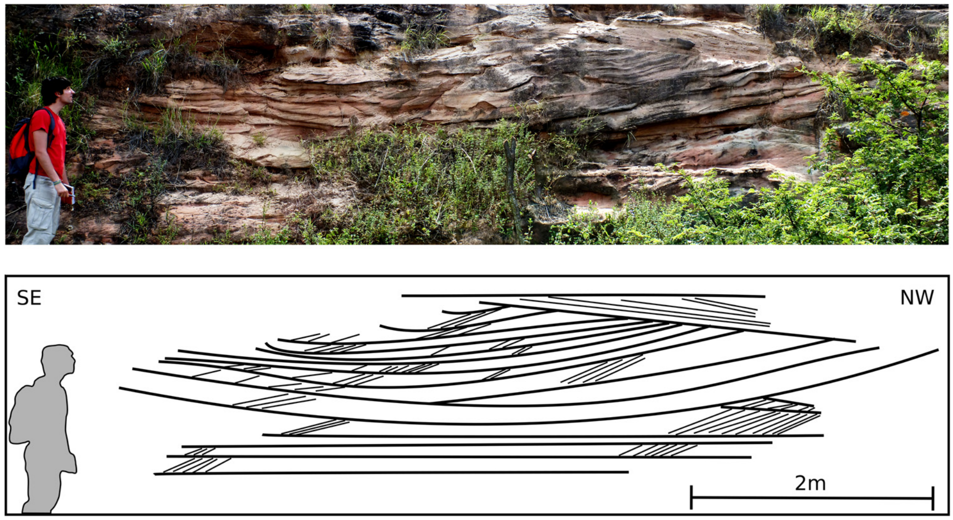

Fig. 6. Trough-shaped cross-strata set bounding surfaces in the São Sebastião Formation interpreted as deposits of large barchanoid dunes. Early Cretaceous, Tucano Basin, NE-Brazil.

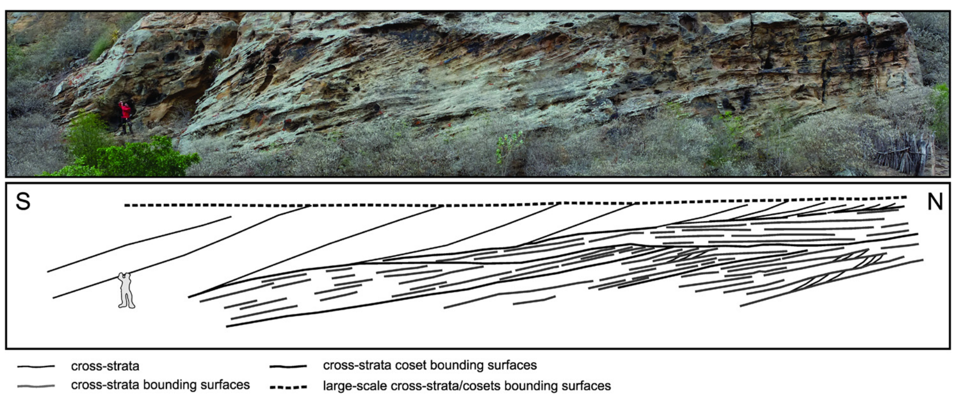

Fig. 7. Large-scale cross-strata and laterally related inclined cross-strata sets in the Marizal Formation. Early Cretaceous, Tucano Basin, NE-Brazil.

facies, bar accretion elements and finally aggradational bar tops (Freitas, 2014; Figueiredo et al., 2016; Almeida et al., 2016).

At several locations, up to 5 m thick cross-strata sets, with 15° to 25° dipping foresets in granule-bearing coarse sandstone, are found near the base of the interpreted channel fill succession, passing laterally to cross-strata cosets composed of decimetric tabular cross-strata sets (Fig. 7). The position at or near the base of fining-upward cycles, on top of major erosional surfaces, and the compatible structure to the here proposed facies model strongly suggest these are the deposits of large-scale compound dunes in fluvial thalwegs.

5.2. *Silurian fluvial deposits in the Parnaíba Basin*

Sandstone-dominated fluvial successions of the Serra Grande Group (Silurian, Parnaíba Basin, northeastern Brazil) were deposited in a broad sag basin covering different elements of the Late Neoproterozoic Brasiliano orogeny (e.g. Pedreira et al., 2003). The lowermost unit in the Serra Grande Group (Ipu Formation) as exposed in the northeastern part of the basin, is dominated by erosional-based 10 to 15 m thick fining-upward sandstone successions, capped by centimetric to decimetric mudstone deposits (Fig. 8). Near the lower erosional surfaces, abundant 1 to 2.5 m thick trough cross-strata pass laterally to and from trough-shaped cross-strata sets composed of 0.1 to 0.35 m thick tabular and trough cross-strata (Fig. 8). Local superposition of two individual large-scale cross-strata sets suggests periodical bedforms. Finer-grained (medium to fine sandstone) laterally continuous inclined cosets of trough and tabular cross-strata form meter-scale elements covering the lower succession dominated by large-scale cross-strata sets. Both the position and the overall structure of these lower successions are compatible to the here proposed model for large-scale barchanoid compound dune deposits.

5.3. *Triassic Hawkesbury Sandstone, southeastern Australia*

The Hawkesbury Sandstone, deposited during the Triassic in the Sydney Basin and currently exposed in southeastern Australia, is interpreted as the geological record of a large-scale fluvial system (e.g. Miall, 2006; Fielding, 2007). This interpretation is mainly ascribed to the common occurrence of large-scale (up to 8 m thick, commonly 2 to 3 m thick) cross-strata within cross-strata coset-dominated, medium to coarse-grained, sandstone successions (Conaghan and Jones, 1975; Rust and Jones, 1987; Miall and Jones, 2003), superbly exposed on coastal cliffs near Sydney.

A remarkable characteristic of the Hawkesbury Sandstone large-scale cross-strata is the curved trace of the foresets in plan view, concave in the palaeoflow direction (Fig. 9A). The morphology of these preserved bedforms intrigued Conaghan and Jones (1975) who could not reconcile their observations with data available from active rivers, known to be dominated by "irregularly lobate, sinuous or linguoid" bedforms at that time. To interpret these

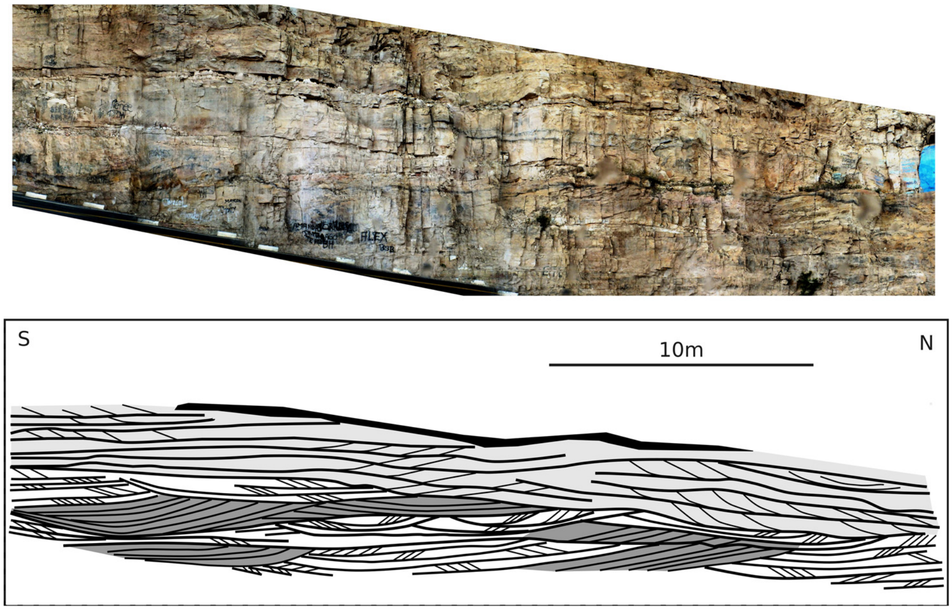

Fig. 8. Large-scale trough cross-strata and trough-shaped cross-strata sets in the Serra Grande Formation interpreted as deposits of large barchanoid dunes. Silurian, Paraíba Basin, NE-Brazil.

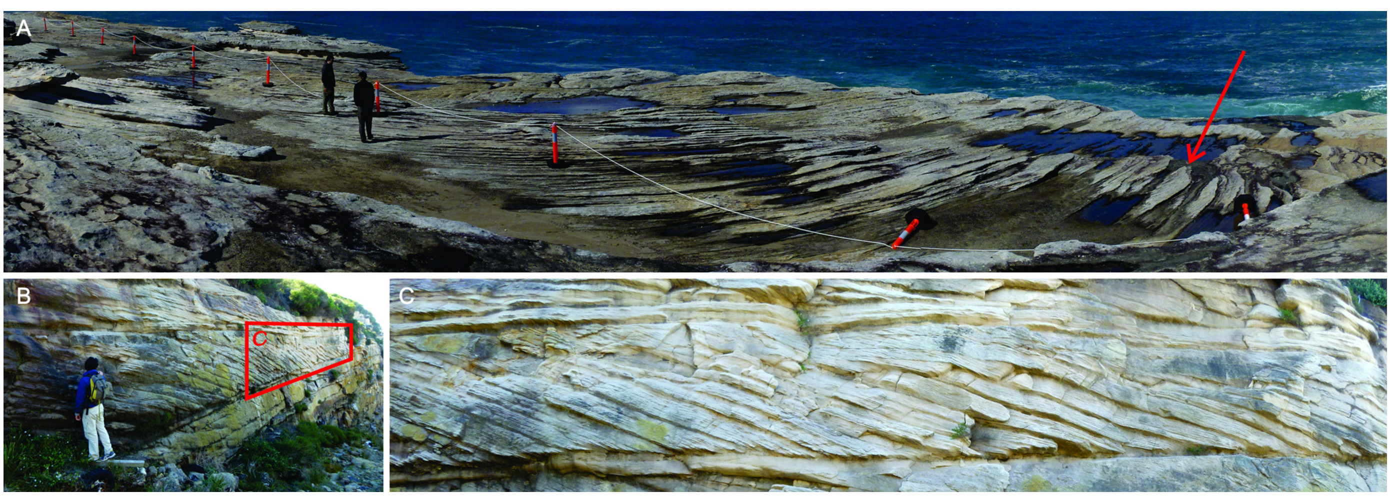

Fig. 9. Examples from the Hawkesbury Sandstone. A) Concave downstream large-scale cross-strata. Note the lateral transition from large-scale cross-strata to compound cross-stratification (red arrow). B) and C) Large-scale cross-strata displaying smaller preserved cross-stratifications from superposed bedforms migrating near the host dune brink point.

sedimentary structures, Conaghan and Jones (1975) envisaged the occurrence of lunate or catenary forms in the thalwegs of the Brahmaputra River, inferring these bedform geometries from "patterns of surface turbulence above the completely submerged flood-stage sandwaves".

The occurrence of large-scale tangential foresets, slightly concave up and slightly to strongly concave downstream (Fig. 9A), above channel base erosional surfaces, point to an origin on migrating barchanoid dunes. Large-scale foresets laterally related to cosets and separated by large-scale cross-strata set bounding surfaces indicate periodicity of the formative bedforms, corroborating the above interpretation.

Lateral transitions between large-scale foresets and cosets can be observed both in plan view and in vertical sections (Fig. 9A, red arrow, and C), reflecting spatial relationships between these two types of cross-strata characteristic of barchanoid dunes. Local preservation of bedform tops suggest transitions from superposed bedform cross-strata to large-scale foresets at the brink point of compound dunes (Fig. 9C).

5.4. Neogene deposits in the western Brazilian Amazon

Exposures of Plio–Pleistocene sand-dominated successions, including the Içá Formation and possibly younger Pleistocene deposits are found at the margins of the Solimões River, in the western Brazilian Amazon (e.g. Rossetti et al., 2005; Horbe et al., 2013). These comprise more than 15 m thick fining-upward cycles, beginning at erosional surfaces cutting through the Miocene to Pliocene Solimões Formation, and composed of lower granule and intraclast-rich coarse sandstone, passing upward to very fine cross-laminated sandstone, heterolithic beds and mudstone lenses. The succession is dominated by 0.6 to 1.5 m thick inclined cosets of trough and tabular cross-strata, with isolated meter-scale thick trough cross-strata occurring locally, overlying major erosional surfaces (Fig. 10).

Transversal sections of the latter structure display concave-up large-scale foresets passing upward to concave-up sets of smaller scale cross-strata, recording the temporal change from an avalanche lee face to a lower angle lee with downclimbing super-

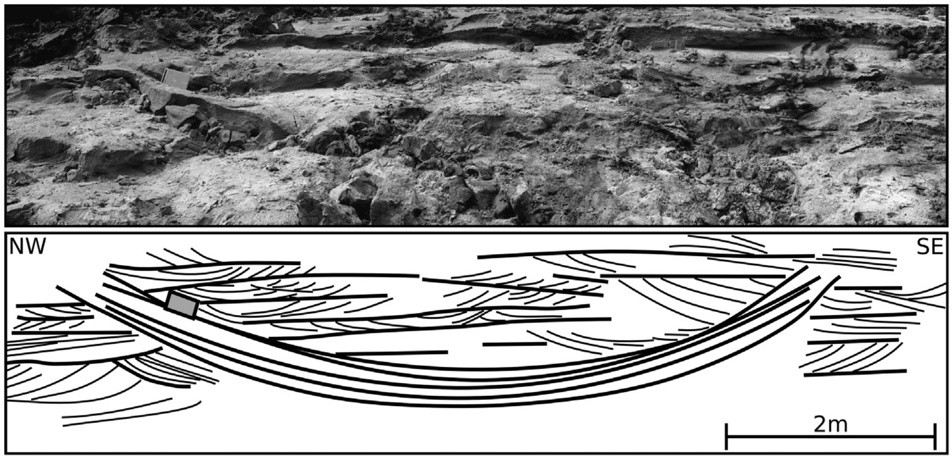

Fig. 10. Large-scale, concave-up cross-strata adjacent to inclined cosets, above and below, in the Içá Formation, interpreted as deposits of large barchanoid dunes. Neogene, Western Amazon, Brazil.

posed bedforms. The relative small size of these structures, up to 1 m thick and 3 to 5 m wide, differs from what is expected to be the record of large-scale barchanoid dunes observed in the modern thalweg, suggesting a smaller channel.

6. Discussion

The particular morphology of large barchanoid dunes, their occurrence exclusively on the thalweg of major channels and the distinctive characteristics of the examples from the rock record point to marked differences from other large-scale cross-strata systems described in the literature. This could justify the definition of a new architectural element, helping the description and interpretation of Channel Thalweg Bedforms.

The observed dune morphology seems to indicate reworking of large barchanoid dunes by the migration of superposed bedforms, with the supposedly original angle-of repose lee sides being progressively modified by later accumulation of sediment (e.g. Kostaschuk and Villard, 1996) derived from smaller dunes migrating up the stoss of the larger bedform (e.g. Reesink and Bridge, 2007). In this way, low angle lees would result from changes in flow conditions, when the larger bedforms cease to be active, although additional data on actual flow velocities and temporal evolution of these large barchanoid dunes is necessary to elucidate this point.

Recognizing the deposits of large compound barchanoid dunes in the rock record can be useful in the characterization of large river deposits. These bedforms have been reported in large rivers thalwegs in the Rhine and the Mississippi rivers (Carling et al., 2000; Abraham and Pratt, 2002). In the present study, the characterization of the morphology and interpreted internal structure of large compound barchanoid dunes in the thalweg of the Amazon River enabled the interpretation of similar deposits in the rock record, bringing the possibility of interpretation of deep channels that could otherwise be mistaken for unit bar deposits of much shallower channels, since unit bars tend to reach the water level whereas thalweg dunes are one order of magnitude smaller than the formative water flow depth.

In all above presented examples of possible barchanoid compound dunes from the rock record, the deposits are found at or near the base of fining-upward elements which are three to five times thicker than the individual large-scale cross-strata. Such scale relationship corroborates the interpretation of those cross-stratified deposits as products of the migration of dunes instead of unit bars.

Even smaller barchanoid compound dunes, in the range of a few tens of meters wide and approximately one meter high, such as those found in the Rhine and the Mississippi rivers and those interpreted for the Plio–Pleistocene of Western Amazon, seem to be absent in small rivers, and can be used to interpret regional scale fluvial systems. Larger structures such as those recognized in the Parnaíba and Tucano basins, as well as in the Hawkesbury Sandstone, indicate greater water depths.

The apparent relationship between large rivers and thalweg barchanoid dunes is probably due to the combined effect of two factors: (i) greater local shear stresses in deep currents compared to shallower ones, resulting in greater transport efficiency and consequently leading to relatively starved sediment domains in the deepest thalwegs; (ii) lack of water-depth control over bedform height (due to the deep water column), enabling huge variations in dune crest height along crest lines, and consequently causing such mobility differences that the greater celerity of the smallest parts results in the formation of nearly current parallel arms disrupted from the central part of these bedforms (e.g. Ernstsen et al., 2005).

Although no method for the estimation of formative water depth based on preserved barchanoid compound dune cross-strata set thickness can be proposed at the moment, future studies on modern large rivers can be used to build a database that could elucidate such matter, considering variations on flow conditions and bedform grain-size in different systems. Discriminating thalweg bedform deposits and their properties in the rock record will probably lead to better correlation with water-depth than that achieved in studies considering all types of dunes (e.g. Paola and Borgman, 1991; Leclair and Bridge, 2001; Jerolmack and Mohrig, 2005; Bartholdy et al., 2005).

For now, a comparison of the morphology of thalweg bedforms in Amazon rivers with the preserved structures in Neogene deposits in the Western Amazon can be useful in the qualitative determination of the relative size of fluvial systems in the region and their spatial and temporal distributions, with important implications for models considering the role of large river systems in the evolution of the biodiversity in the region.

7. Conclusions

MBES images from a selected reach of the Amazon River revealed the presence of large barchanoid compound dunes along the channel thalweg. Whereas simple small branchanoid dunes have been rarely described in small rivers (e.g. McCulloch and Janda, 1964; Kleinhans et al., 2002), large compound bedforms have been recognized only in thalwegs of large rivers, such as the Rhine and the Mississippi. Therefore, the interpretation of similar bedforms from the rock record brings the possibility of recognizing ancient large river deposits.

The two trains of barchanoid dunes described in the Amazon River are restricted to the deepest areas of the channel. The dunes are characterized by V-shaped crest lines and convex longitudinal profiles. These dunes present 133 to 471 m between the tips of each arm; mean wavelength of 150 m for the largest train, and of 61 m for the smallest; mean dune height respectively of 5 m and 2.2 m. Lee side angles are characteristically low: a few degrees on the dune arms and less than 20° degrees at the dune center. Lower lee angles are related to superimposition by secondary dunes on the stoss side.

Based on morphology of compound dunes, expected sedimentary structures resulting from the preservation of large barchanoid compound dune deposits are broad, large-scale, low-angle, concave up and downstream cross-strata, passing laterally and downstream to inclined cosets. Examples of such structures from large river deposits in the rock record are found in the Silurian Serra Grande Group and the Cretaceous São Sebastião and Marizal formations in Northeastern Brazil, as well as in the Triassic Hawkesbury Sandstone in Southeastern Australia and the Plio–Pleistocene Içá Formation in the Amazon. All these deposits are found near channel base surfaces and are somewhat coarser than the overlying fluvial deposits, favoring the interpretation of a thalweg depositional setting.

The recognition of large barchanoid dunes as bedforms restricted to river thalwegs and probably to large river systems brings the possibility of establishing new criteria for the interpretation of fluvial system scale in the rock record. Sedimentary structures compatible with the morphological characteristics of these bedforms seem to be relatively common in large river deposits, given their initial recognition in five different fluvial successions in Brazil and Australia. In this way, further studies on active barchanoid dunes and their deposits are needed to test the hypothesis of their relationship with river scale, and may result in substantial improvements in facies models for large rivers.

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