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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