

Scales and causes of heterogeneity in bars in a large multi-channel river: Río Paraná, Argentina

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ABSTRACT

To date, published studies of alluvial bar architecture in large rivers have been mostly restricted to individual bar case studies and single locations. Relatively little is known on how the deposition processes and sedimentary architecture of km-scale bars vary within a multi-km reach or over several 100s km downstream. This study presents ground-penetrating radar (GPR) and core data from 11, km-scale bars from the Río Paraná, Argentina. The investigated bars are located between 30 km upstream and 540 km downstream of the Paraná-Paraguay confluence, where a significant volume of fine-grained suspended sediment is introduced into the system.

Bar-scale cross-stratified sets with lengths and widths up to 600 m and thicknesses up to 12 m, which enable the distinction of large river deposits from stacked deposits of small rivers, are only present in half the surface area of the bars. The majority of

these bar-scale sets (~90%) are found on top of finer-grained ripple-laminated bar-trough deposits that are recognised as permeability barriers in sandstone reservoirs. Bar-scale sets make up as much as 58% of the volume of the deposits in small, incipient mid-channel bars, but this proportion decreases significantly with increasing age and size of the bars. Contrary to what might be expected, a significant proportion of the sedimentary structures found in the Río Paraná is similar in scale to those found in much smaller rivers. In other words, large river deposits are not always characterised by big structures that allow a simple interpretation of river scale. However, the large scale of the depositional units in big rivers causes small-scale structures such as ripple sets to be grouped in thicker co-sets, which indicate river scale even when no obvious large-scale sets are present.

The results also show that the composition of bars differs between the studied reaches upstream and downstream from the confluence with the Rio Paraguay. Relative to other controls on downstream fining, the tributary input of fine-grained suspended material from the Paraguay causes a marked change in the composition of the bar deposits. Compared to the upstream reaches, the sedimentary architecture of the downstream reaches in the top ~5 m of mid-channel bars shows (i) an increase in the abundance and thickness (up to m-scale) of laterally extensive (100s of metres) fine-grained layers; (ii) an increase in the percentage of deposits comprised of ripple sets (to >40% in the upper bar deposits); and (iii) an increase in bar-trough deposits and a corresponding decrease in bar-scale cross strata (<10%). The thalweg deposits of the Rio Paraná are composed of dune sets, even directly downstream from the Río Paraguay where the upper channel deposits are dominantly fine-grained. Thus, the change in sedimentary facies due to a tributary

point-source of fine-grained sediment is expressed primarily in the composition of the upper bar deposits.

Keywords

Large rivers, bars, dunes, Río Paraná, facies models, GPR, channel deposits

INTRODUCTION

Although the world's largest rivers dominate the drainage and continental basin sedimentation of the Earth (Potter, 1978; Milliman & Meade, 1983; Schumm & Winkley, 1994; Hovius & Leeder, 1998; Gupta, 2007; Fielding *et al.*, 2012), surprisingly little is known about how these large rivers evolve over time, how they build km-scale bars, whether they produce a characteristic sedimentary architecture, and how this architecture compares to that found in deposits of smaller rivers (Miall & Jones, 2003; Fielding, 2007; Gupta, 2007; Latrubesse, 2008; Sambrook Smith *et al.*, 2009; Ethridge, 2011). Our understanding of modern large rivers also underpins our ability to correctly interpret and characterise large rivers in the rock record (Potter, 1978; Miall, 1996; Miall & Jones, 2006; Fielding, 2007). The increased in land area at times of sea-level low-stand causes rivers to merge into large systems that affect long-term variations in the build-up of the continental shelf (Blum *et al.*, 2013). The dynamics of dunes and bars in the present-day channel of the Río Paraná affect flood heights, control the supply and size dredged aggregates, control localised erosion and hence damage to infrastructure, determine the navigability of the river, and constrain the physical environment of the biota (Amsler & García, 1997; Amsler

& Prendes, 2000; Orfeo & Steveaux, 2002; Amsler *et al.* 2007, 2009; Paoli *et al.*, 2010; Blettler *et al.*, 2012).

Whilst recent studies in large rivers have begun to document the internal architecture of individual, km-scale, mid-channel bars in generally sandy multi-channel rivers (e.g. Bristow, 1993; Stevaux, 1994; Best *et al.*, 2003, 2007; Latrubesse & Franzinelli, 2005; Sambrook Smith *et al.*, 2009; Horn *et al.*, 2012a,b; Valente & Latrubesse, 2012; Rozo *et al.*, 2012), it remains uncertain whether these lithofacies descriptions are representative of the wide range of bar types and channel patterns that characterise large rivers (cf. Ashworth & Lewin, 2012). For example, little work has been undertaken on how the subsurface alluvial architecture varies both within a reach, down-river and following mixing with tributary input of significant fine-grained material (Lane *et al.*, 2008). Past research has shown that sediment load and grain size may be expected to have a pronounced effect on channel and bar stability (Smith & Smith, 1980; Federici & Seminara, 2006; Edmonds & Slingerland, 2010; Nicholas, *in press*), the character of flow and bedforms (e.g., Baas *et al.*, 2009; Kostaschuk *et al.*, 2009) and the relative abundance of small-scale bedforms (Van den Berg & Van Gelder, 1993), yet it is unclear how these processes affect the heterogeneity of the channel deposits in a large river system with a significant tributary input of fine-grained sediment.

This paper presents data from 40 km of Ground Penetrating Radar (GPR) surveys and 30 cores collected on eight, km-scale, bars in a 100 km reach of the Upper Rio Paraná near Corrientes, Argentina, and supplementary data from 10 trenches and 11 cores taken on three bars ~540 km further downstream near Santa Fe (Fig. 1).

Additionally, ~350 m of Parametric Echo Sounder (PES) line are used to illustrate the morphology and composition of the channel bed. The objectives of this paper are to: (i) describe the origin and evolution of a range of bar types, morphologies and sizes in this large multi-channel river, (ii) describe and quantify the variability in alluvial architecture within, and between, bars of different size and origin in a large river, (iii) determine the influence of a major fine-grained tributary input on the bar sedimentology, and (iv) compare the sedimentary deposits of the Río Paraná to that of smaller (< 1 km wide) rivers, and in particular with reference to reservoir properties.

THE RÍO PARANÁ, ARGENTINA

The Río Paraná is one of the world's largest rivers with a drainage basin of 2.6×10^6 km² (Gupta, 2007; Paoli *et al.*, 2010; Fig 1A). The mean annual water discharge of the Río Paraná at Itati (Fig. 1C) is $\sim 12,000$ m³ s⁻¹, increasing to $\sim 17,000$ m³ s⁻¹ at Corrientes, 30 km downstream of the confluence with the Río Paraguay (Fig. 1C). Overbank flow upstream of the confluence occurs at $\sim 19,000$ m³ s⁻¹. Mean annual sediment discharge of the Río Paraná increases from ~ 19 to $\sim 158 \times 10^6$ tons year⁻¹ at the junction with the Río Paraguay, primarily due to the large input of suspended sediment (concentrations between 600 and 1100 mg L⁻¹) supplied from the Río Bermejo tributary (Bonetto & Orfeo, 1984; Lane *et al.*, 2008; Amsler & Drago, 2009). Bed material of the upper reach of the Río Paraná is well sorted, predominantly medium-to-fine sand (average D₅₀ of 26 bed samples is 0.35 mm), although some fine gravel is present in the channel thalweg and on aeolian deflation surfaces on some exposed bars. Mean bed grain size downstream of the confluence near

Corrientes ranges from 0.31 to 0.45 mm (Drago & Amsler, 1998; Amsler *et al.*, 2007). Whilst ~500 km downstream at Santa Fe (Fig. 1D) the mean bed grain size is ~0.30 mm, there is a much higher proportion of fines in the suspended load. Mean slope near Corrientes ranges from 4.9×10^{-5} (m/m, bankfull water-surface slope; Latrubesse, 2008) to 8.5×10^{-5} (m/m, channel slope; Orfeo & Steveaux, 2002). The upper reach of the Río Paraná is regulated by a series of large dams (Orfeo & Steveaux, 2002) although the hydrograph is still characterised by floods of long duration that are typically associated with prolonged rainfall in the headwaters during the austral winter. Channel depths in the thalweg vary between 5 and 12 m with maximum outer bend scours of 25 m at discharges of $\sim 11,000 \text{ m}^3 \text{ s}^{-1}$ (Parsons *et al.*, 2005; Sandbach *et al.*, 2010).

In the studied reach between Itati and Santa Fé, the Río Paraná is a multi-channel river that contains mid-channel bars of unconsolidated sand as well as stable vegetated bars that divide flow up to bankfull stage, and could therefore be described as an anabranching river (Nanson & Knighton, 1996; Latrubesse, 2008; Ashworth & Lewin, 2012). Near Itati (Fig. 1C), the width of the primary channel (1.7 ± 0.7 km) is larger than that of the bars (0.5 ± 0.6 km) and about five times the width of smaller secondary channels (0.3 ± 0.2 km). Sandy bars in the Río Paraná are typically bank-attached, transverse or medial bars (Santos & Steveaux, 2000) with migration rates of $\sim 50 \text{ m year}^{-1}$, that reach up to 130 m year^{-1} near the Paraguay-Paraná junction. Significant portions of the floodplain and stable mid-channel bars are densely vegetated with mature shrubs and trees, with trees establishing themselves on exposed bars within decades. The outer bank edges of the primary channel are relatively straight, but a bathymetric survey of a 38 km reach

immediately upstream of the Paraná-Paraguay junction shows a dominantly sinuous, meandering thalweg with a wavelength of ~12 km (Ramonell *et al.*, 2002; Sandbach *et al.*, 2012). Outcrops of cemented Pleistocene sediments are found in places throughout the main study reach, notably on the south-east (left) river bank. Outcrops can cause local constriction and acceleration of flow and hence accentuate the deepest thalweg scours against the left bank. The river bed of the Río Paraná is dominated by dunes at all flow stages (Amsler & Prendes, 2000; Parsons *et al.*, 2005; Kostaschuk *et al.*, 2009; Shugar *et al.*, 2010). Parsons *et al.* (2005) report large dunes with mean heights of 2 m and wavelengths of 64 m with smaller superimposed dunes with heights up to 0.3 m and wavelengths up to 10 m in the deeper parts of the channel near Corrientes at a discharge of 11,000 m³ s⁻¹. However, much larger dunes with heights up to 6.5 m and wavelengths of 320 m have been observed in the Río Paraná during the historic large flood of 1983 (Amsler & Garcia, 1997). Ripples are present in shallow water and are common on near-emergent bar tops, and aeolian re-working is widespread on sparsely vegetated, exposed bar tops.

STUDY REACHES

Data are presented herein from three study sites: (i) a reach from 30 km upstream of the Paraná-Paraguay confluence to 4 km downstream of the junction, which is not influenced by the fine-grained input from the Rio Paraguay; (ii) a reach from 9 km to 74 km downstream of the confluence where the input of fine sediment is more significant, and (iii) a reach much further downstream (520-540 km) near Santa Fe where the Paraguay and Parana waters are fully mixed (Lane *et al.*, 2008) (Fig. 1,

Table 1). Previous descriptions of the Río Paraná near, or within, the upstream study reach are given in Parsons *et al.* (2005, 2007, 2009), Amsler *et al.* (2007), Lane *et al.* (2008), Sambrook Smith *et al.* (2009), Kostaschuk *et al.* (2009) and Shugar *et al.* (2010), Nicholas *et al.* (2012). Five mid-channel bars were investigated in the upstream study area (**Fig. 2A-E**, prefix U): three bars were located upstream from the confluence (at distances relative to the Paraná-Paraguay confluence of -30, -8 and -7.5 km), and two located close to the confluence (at +1 and +4 km downstream) but with only limited influence from the confluence. Three mid-channel bars were studied that were influenced by the confluence (**Fig. 2F-H**, prefix C) and were located +9, +73 and +74 km downstream of the confluence. Cores and trenches from three more bars much further downstream were also studied of the confluence (+520 to +537 km; **Fig. 2I-K**, prefix D). The eleven bars were selected to maximise the differences in size, age and location with respect to the Paraná-Paraguay confluence and to establish any broader upstream-downstream trends (**Table 1**).

METHODS

Ground-penetrating radar (GPR) surveys

Approximately 40 km of common-offset GPR surveys were collected (**Table 1**) using a Sensors and Software SmartCart© carrying a Pulse-EKKO PRO system with 100 MHz antennae. Surveys were collected mostly in a rectangular grid except where vegetation blocked access (**Fig. 2**). Eight stacked traces were collected at every shot point, with the shot points being triggered by the cart's odometer wheel at ~0.1 m spacing. GPR lines were corrected for any topographic variation by interpolation of

points ~100 m apart on lines surveyed using a Leica differential Global Positioning System (dGPS) operating in Real-Time Kinematic mode (RTK), which had relative positional errors of ± 0.02 m horizontally and ± 0.03 m vertically. Post-processing of the GPR data in Seismic Unix included application of a zero-phase, sine-tapered bandpass filter with polygon frequency values of 10, 50, 250 and 600 MHz. Loss of reflection amplitude with depth was reduced by the application of a time-varying gain. A Stolt-migration based on a single subsurface velocity was applied to reduce the effect of refraction hyperbolae. The radar velocity was determined from Common Mid-Point surveys (CMP's) using normal move-out corrections as well as velocity semblance analyses, and by comparison of the common-offset profiles with core logs. These three different methods yielded consistent results. Two-way travel time was then converted to depth using a constant velocity, derived separately for the upstream bars and confluence bars, of 0.05 m ns^{-1} and 0.08 m ns^{-1} respectively. The associated wavelengths are in the order of ~ 0.125 m upstream and ~ 0.2 m downstream, with maximum vertical resolution a quarter of these wavelengths (Sheriff & Geldart, 1982). The higher radar velocity in the downstream bars from the confluence is attributed to the increase in fine-grained sediment in the deposits (Neal, 2004; Baker *et al.*, 2007). Strong attenuation of the radar signal prevented the collection of GPR profiles of sufficient depth from the bars near Santa Fe and from those dominated by the influence of the Rio Paraguay (Table 1).

Classification and description of radar facies

The primary radar facies that characterise the deposits of the Río Paraná in the main study reach are shown in Table 2. The three key radar facies used here match the previous descriptions of the deposits of a km-scale bar by Sambrook Smith *et al.*

(2009), which is bar U4 in the present study. The only difference herein is that Facies 1 is subcategorised by the angle of reflections rather than set thickness (Sambrook Smith *et al.*, 2009) because this provides a better match between the radar reflections and the true sedimentary structures observed in cores (cores were not available in the earlier study by Sambrook Smith *et al.*). A brief description of each radar facies and their sedimentary interpretation is given below and examples of the radar facies are shown in Table 2 and Fig 3.

(1A) Large-scale high-angle and (1B) medium-angle inclined reflections

Facies 1 is characterised by sets of dipping reflections with angles $>6^\circ$. Sets of facies 1 can commonly be traced laterally for several hundreds of metres (up to 400 m) and have thicknesses of 2 m on average with a maximum observed thickness of 12 m. The study herein subdivides radar facies 1 into high-angle (1A; Table 2; Fig. 3A, C-D, G-H) and medium-angle (1B; Table 2; Fig. 3A-C, E-H) reflections. Large-scale (*cf.* Bridge, 1993a), high-angle reflections (facies 1A) exceed 20° and are characteristically straight with low amplitudes. Large-scale, medium-angle reflections (facies 1B) vary in angle between 6° and 20° and are typically more irregular in shape with higher amplitudes. Facies 1A is associated primarily with angle-of-repose cross-strata formed by grainflows on large-scale dune or bar slopes (Reesink & Bridge, 2007, 2009) and may include compound reflections (Reesink & Bridge, 2011). Facies 1B represents large-scale inclined co-sets: stacks of inclined small- and medium-scale sets. Such co-sets are interpreted as formed by ripples and dunes migrating over steep topography (e.g. a unit-bar lee slope; Haszeldine, 1982). Thus, both facies 1A and B represent bar-margin accretion, and are consequently

commonly observed adjacent to one another and grading into one another (Fig. 3A, C, H, label I).

(2) Near-horizontal, undular, discontinuous and chaotic reflections

Facies 2 (Fig. 3A-B, D-G, label 2) is composed of near-horizontal ($<6^\circ$) reflections that may be chaotic (Fig. 3C, F, label II), discontinuous (Fig. 3C, E, label III) or contain m-scale trough shapes (e.g. Fig. 3A, label IV). The lateral extent of these reflections is less than 60 m and amplitudes are not usually higher relative to surrounding reflections. The symmetry and continuity of the reflections in facies 2 are highly variable and typically grade both laterally and vertically. Trough-shaped reflections within facies 2 are up to 2 m high and are up to 50 m long, less than the thicknesses and lengths of sets of facies 1. These trough-shapes are primarily attributed to the trough-shapes of dune sets. Facies 2 also includes asymmetrical reflections that resemble complete dune profiles (Fig. 3E-F, label V), and are interpreted as trains of dunes that were abandoned and did not undergo any great reworking before being buried under subsequent sediment. Facies 2 includes reflections from both the individual bounding surfaces of sets with sizes larger than the radar wavelength (dunes, small unit bars) and reflections that relate to grain-size variations within stacks of sets smaller than the radar wavelength (ripples, small dunes). Thus, facies 2 is associated with near-horizontal medium- and small-scale sets that are attributed to dunes and ripples respectively.

(3) Laterally-extensive, high-amplitude reflections

Facies 3 comprises laterally-extensive reflections (up to 1 km and approaching the lengths of the bars) that have distinctively higher amplitudes relative to adjacent

reflections (Fig. 3A-H, label 3). Facies 3 is commonly associated with loss of the radar signal below the reflection. These reflections represent laterally-extensive bounding surfaces within the bars that are primarily transitions from relatively coarse-grained bar-margin deposits (mean 0.33 mm in cores) to underlying layers of finer-grained ripple-sets (mean 0.18 mm in cores), with limited thicknesses, which are deposited in the bar troughs and during low-flows. The distinct contrast in grain size at the top of the fine-grained bounding layers generates high-amplitude GPR reflections, with the observed loss in radar amplitude directly underneath these high-amplitude reflections being associated with attenuation of the signal by fine-grained sediment such as clay (Neal, 2004; Baker *et al.*, 2007).

Calculations of distribution of facies

All GPR data were interpreted as illustrated in Fig. 3H, with reflections assigned a facies classification based on the criteria outlined above and summarised in Table 2. The radar facies were identified from vertical profiles with ~0.1 m spacing between shot points, and these data were then used to calculate the mean, standard deviation and distribution of the facies (% of all facies that were identified in the GPR images, hence volume) and the presence/absence of facies (expressed as a percentage of the bar area investigated). Maps of facies distributions were constructed by spatial averaging using a 200 x 200 m square window (i.e. larger than the spacing of the survey lines) (Fig. 4). The thickness of the reflections associated with facies 3 has been determined from the cores in this study because GPR alone does not provide accurate measurements of the thickness of fine-grained layers, since these are of the same order of magnitude as the radar wavelength. The mean thickness of silts and very-fine sands (0.2 ± 0.2 m) from the core observations is

therefore used to quantify and estimate the proportion of fine-grained layers represented by facies 3 in the GPR images.

Coring

In order to ground-truth the GPR and provide information on the sedimentary architecture of the deposits at resolutions higher than provided by the GPR, 30 cores of the bar sediments were taken on GPR lines. Cores were obtained using a modified Van der Staay suction corer with a diameter of 0.06 m (Van de Meene *et al.*, 1979; see Fig. 2; Table 1). In addition, 11 cores were taken in mid-channel bars near Santa Fé (Fig. 1D) in order to sample the bar deposits where the water and sediment of the Río Paraguay are more fully mixed with that of the Río Paraná and where GPR provided no data. Van der Staay suction coring works well in sand (Ashworth *et al.*, 2011), but did not work well in deposits that were dominated by silt and clay. Cores retrieved from the sandy bars had an average length of 4 m and a combined length of 149.3 m. The cores were sawn in half lengthwise and epoxy peels made of one half. Sediment-samples were taken from selected locations within the cores and grain-size distributions determined by dry sieving and grain sizing obtained using a Malvern Laser Mastersizer 2000. Detailed logs of the sedimentary structures were constructed by analysis of the epoxy peels following the methodology outlined by Bridge (2003) (Fig. 5, Fig. 10).

RESULTS

The development and approximate age of the investigated bars (Fig. 2) were established from their appearance in Landsat images (Band 1-3) that were taken between 1972 and 2010 (Fig. 6). The composition of the bars observed in the GPR

images (Fig. 3, Fig. 7, Fig. 8) and cores (Fig. 5, Fig. 10) is expressed as maps of frequency of occurrence of different facies (Fig. 4). The results are summarised in Table 1 and general and contrasting patterns in the composition and their relation to bar development are discussed below.

Evidence from GPR

Overall, facies 1A, 1B, 2, and 3 make up ~20, 17, 56 and 7 % of the entire investigated volume. Facies 2 and 1B make up the largest part of the deposits, which supports the suggestion that small- and medium-scale sets, and in particular dune sets, are the most abundant sedimentary structures in bars within multi-channel rivers (e.g. Best *et al.*, 2003; Skelly *et al.*, 2003; Bridge & Lunt, 2006; Sambrook Smith *et al.*, 2006; Bridge, 2009; Ethridge, 2011). In contrast to the volumetric analysis, 2D spatial analysis shows that, whereas facies 2 and 3 are found in nearly the entire investigated area (97 and 98%; Fig. 9), the bar-margin deposits represented by facies 1A and 1B are found in only approximately half (45 and 49%) of the investigated area.

Subdivision of the results per bar shows that the mean volumes of facies 1A, 1B, 2 and 3 range between 4-58, 0-48, 38-70, and 2-12% for different bars (Fig. 9). In contrast, the areal coverage of facies 1A, 1B, 2 and 3 ranged between 8-100, 0-90, 87-100 and 92-100% respectively. Facies 2 comprises most of the deposits and is ubiquitous. Facies 3 is also found nearly everywhere, but represents only a small proportion of the sediments. Facies 1A and 1B, which represent horizontal progradation of bar margins, may comprise up to half of the volume of a bar, but are

spatially limited in their extent (Fig. 4). These spatial contrasts in bar composition can be associated with the nature of the bars' development (Table 1).

Facies 1A and 1B are particularly prominent in the newly-emergent incipient bars (e.g. for U3: 1A is 58% of volume and 100% of area). Large-scale sets of facies 1A and 1B were also present lower down in the centre of the larger bars (U2 and U4). Analysis of satellite images (Fig. 6A-C) confirms that these sets formed by downstream-migrating bar margins during the earlier stages of the bar development. These observations suggest that the downstream migration and amalgamation of unit bars is common in the early stages of bar development.

Although facies 1 was also prominent near visible large-scale slopes at the tails of the larger, older bars (U1, U2 and U4; Fig. 4), two of the larger, older bars (U5 and C2) had no significant bar-tail sets >1 m thick but possessed low-angle slopes at the edge of the bars that represent a record of more gradual, vertical aggradation. Thus, although continued growth by horizontal progradation of bar-scale slopes is possible (e.g. large set in U1 and bar tails in U1, U2 and U4), the style of deposition may change during a bar's development to include increased proportions of vertical aggradation (Bristow, 1987). Bar U1 represents an extreme example of such differing styles of composition: the right half of U1 formed by a migrating bar front and the left half formed by in situ vertical aggradation (Fig. 4; Fig. 5A,B).

Vertical associations of the facies indicate that facies 1A and 1B are mostly underlain by facies 3 (91, 80%; Table 3). This preferential association indicates that channel deposits characteristically comprise bar-scale sets with laterally-extensive fine-

grained bottomsets at their base (Fig. 5D, F; Fig. 10E, F). Although facies 1A and 1B are nearly always underlain by facies 3, facies 3 is also found in association with facies 2 (66 percent). Clearly, fine-grained bounding surfaces can have different origins (e.g. low-flow deposits) and need not be formed and preserved uniquely in the bar troughs. The observed reduction in the volumetric abundance of facies 1A downstream from the confluence (C1-3; only 4% of the deposits) may be partially caused by an increase in fine-grained bar-trough deposits. Finer-grained sediment is carried further beyond the brink point of bedforms and is commonly deposited on low-angle slopes (Facies 1B; 48% in C3) and in the trough (Boersma, 1967; Jopling, 1965). Such a relative increase in trough deposits and low-angle slopes is matched by a corresponding decrease in facies 1A.

Evidence from cores

Cores from the upper 5 m of the deposits support observations from the GPR in showing a wide diversity of structures within individual bars and an excellent agreement between GPR reflections and the sedimentary structures. When viewed as a downstream transition from the upstream bars (U1-U5) above the Río Paraguay confluence to those just downstream of it (C1-C3) and much further away (D1-3) some clear trends can be identified in the bar-top sediments from these cores (Table 5). The downstream bars have a larger proportion of ripple sets (mean 43%, range 15-56%) in comparison to the upstream bars (mean 31%, range 2-43%) and the proportion of dune and bar sets is smaller in the downstream bars (mean 32%, range 19-42%) relative to the upstream bars (mean 47%, range 21-98%). This difference in larger-scale sets matches to the lower abundance of bar sets in the GPR of the downstream bars (Bars C2,3, Table 1), which comprise 8% of the downstream

deposits and 20% of the upstream deposits (Fig. 9). In addition to differences in the relative proportions of sedimentary structures, grain size analyses show that the downstream cores and trenches contain a larger proportion of fine-grained material (Table 4). Grain size distributions are typically >90% sand with $D_{50} > 250 \mu\text{m}$ in the upstream sites where there is no influence from the input of fines from the Rio Paraguay. Where the waters of the two rivers become well mixed downstream of the junction, the percentage of silt/clay in the bar sediments can reach 31% with a D_{50} as low as $141 \mu\text{m}$. This increased proportion of fine-grained sediment is found throughout the deposits in the bar-tops and occurs both as local deposits of several metres thickness and interbedded with coarser-grained bedload dominated deposits (Fig. 10A, C, D). The increased occurrence of interbedded fine and coarse deposits is illustrated by the increased number of dunes that occur as solitary sets, interbedded with other structures instead of in stacks of dune sets in the bar-top sediments (e.g. Fig. 5 and Fig. 10A). Whereas only 15% of the dune sets in the upstream reach are found as solitary sets or interbedded with other sedimentary structures, this proportion rises to 35% in the downstream reach. The increased deposition of fines therefore increases the heterogeneity of the deposits and reduces the number of dunes in (uninterrupted) co-sets in the upper portions of channel fill/bar sequences.

Additional evidence of channel deposits: Parametric Echo Sounder (PES)

Because of the limited depth of the cores and of the GPR in some locations, the information contained in the current dataset has a bias towards the upper bar deposits. Of course, the persistent presence of dunes in the deeper parts of the channel (Amsler & García, 1997; Drago & Amsler, 1998; Amsler & Prendes, 2000;

Parsons *et al.*, 2005; Amsler *et al.*, 2007; Kostaschuk *et al.*, 2009; Shugar *et al.*, 2010) does provide some evidence to infer that dune sets may be abundant in the lower parts of the deposits of the Río Paraná. Yet, in the absence of actual subsurface data, such inference provides only a suggestion. For example, GPR was unsuccessful at bar C1, and repeated coring attempts indicated that the upper 5.5 metres were composed of very soft mud. The only core retrieved from the coarser-grained bar head of C1 is composed primarily of ripple-sets. Thus, the upper bar deposits are dominantly fine-grained and ripple-laminated. To establish if these facies are representative of sediments lower down within the profile, an InnomarTM (SES-2000 light) Parametric Echo Sounder (PES) was used to undertake a preliminary survey in the channel adjacent to C1. The principles of the PES are described fully by Wunderlich and Müller (2003) and Sambrook Smith *et al.* (*in press*), but in brief, its most important feature is an ability to generate a broad array of acoustic frequencies; the lower frequencies provide details of the subsurface structure while the higher frequencies are able to record the bed surface as is standard for common echo-sounders. The PES survey shown in Fig. 11 indicates that the channel bed is dominated by dunes 1-2 m high with smaller superimposed bedforms on their stoss slopes of ~0.2 m high. Although this acoustic-based technique is fundamentally different from the electromagnetic based GPR technique, the reflections generated by contrasting sediment strata generate similar facies (Table 2). Notably, the subsurface PES reflections show the bounding surfaces of preserved sets below the dune forms. Distinct dune sets visible in PES images show sets with thicknesses in the order of 0.3 and up to 1.5 m. The PES reflections show that the thalweg deposits in the reach that is most strongly influenced by fine sediment input from the Río Paraguay are also composed of sandy dune sets, and

hence are comparable to the deposits of the sandier upstream reach. Clearly, the fine-grained bar tops observed in the field contrast with the deposits of the adjacent thalweg observed by the PES. Thus, the sudden increase in fine-grained sediment from the Río Paraguay confluence is expressed in a structural change in the bar top deposits, but does not necessarily change the nature of the thalweg deposits.

DISCUSSION

Heterogeneity of large river deposits

As Miall (2006) and Fielding (2007) highlight, the lack of sedimentological data from large rivers has meant there are no universally-accepted criteria for the recognition of their deposits in the rock record. However, both Miall (2006) and Fielding (2007) point out that the vertical dimensions of cross-stratification can be a useful indicator of large rivers. This suggestion is supported by the GPR studies of single bars in the Jamuna River (Best *et al.*, 2003) and Rio Paraná (Sambrook Smith *et al.*, 2009) where thick sets of bar-margin facies (radar facies 1A in this paper) were reported of 8 m and 6 m respectively. Likewise, in one of the most commonly quoted examples of large river deposits preserved in outcrop, the Hawkesbury Sandstone, Miall and Jones (2003) report that cross-stratified sets of 2-3 m thickness are common with a maximum of 7 m. The GPR data in this study confirm that cross-stratified sets with average thicknesses of 2 m and up to 12 m are common, comprising up to 20% of the overall deposits. Thick cross-stratified sets were readily identified in cores (Figs 5A, D, E and 9E) and can indeed be used as indicators of river scale. However, this study also revealed an abundance of sedimentary structures with scales similar to those found in small rivers and a high degree of variability and clustering of

structures within the deposits. This heterogeneity poses a significant obstacle to interpretations of scale and sedimentary composition of river deposits, which underpin facies models, paleo-environmental interpretations, and predictions of permeability, porosity and connectivity of sandstone reservoirs and aquifers. The present paper is based on a much broader range of bars than previous studies and therefore permits a fuller consideration of the scales and causes of heterogeneity in bar deposits in the Río Paraná. The sedimentology of the investigated deposits varies (i) within bars, (ii) between bars of varying morphology, size and history, and (iii) as a result of a major fine-grained tributary input (Fig. 12). These factors and (iv) the similarity with smaller river systems, in particular with reference to reservoir properties, are discussed below.

Variability within bars: systematic clustering of facies

A key point to emerge from the results presented herein is that the presence of thick cross-stratified sets, which is diagnostic in interpretations of river scale, is spatially-restricted. Although radar facies 1A and 1B locally dominate bar composition, their presence is restricted spatially to roughly half the investigated area (Fig. 4, Fig. 5, Fig. 9). Thus, although a sample section may have no diagnostic, thick cross-stratified sets; this does not imply that the deposits are not related to a large river. This point is illustrated by the contrasting structures found in e.g. two cores from the upstream bar U1 (Fig. 2A, Fig. 5A-B): while one core displays a thick set of facies 1 associated with migration of a bar lee slope (Fig. 5A), the other shows pervasive ripple sets associated with slower flow in the lee of the bar (Fig. 5B). Fortunately, the presence of this and other thick ripple co-sets suggests that the size of large-scale depositional units, other than bar-scale strata, can also be used to indicate river

scale. Similar to large-scale sets, the thickness of ripple co-sets relates to the distribution of large-scale depositional units, which is an indicator of river scale. River deposits are generally considered to be composed of a limited number of large-scale depositional units (Bridge, 1993b, 2003) and this characteristic is supported by the GPR analysis in this study (Fig. 7). The stacking of a limited number of large-scale units appears scale-independent (Fielding, 2007), and pronounced spatial clustering of sedimentary facies related to bar morphology is also observed in much smaller rivers (Sambrook Smith *et al.*, 2006; Horn *et al.*, 2012a,b).

Variability between bars: effects of bar evolution

The most relevant comparison here is between bars U1, U2 and U3 as these are all located in the same reach, are active sandy bars with little vegetation cover and have similar grid-based GPR datasets. Hence all aspects of within-bar variability, discussed above, should be accounted for. Figure 9 shows that there is a systematic increase in the percentage of facies 1A from 20%, to 27% and then 58% with increasing age and size. The Landsat images (Fig. 6A-B) show that bars U1 to U3 vary in age with U1 and U2 being much older and larger than U3 (Table 1). Based on an analysis of several rivers, Sambrook Smith *et al.* (2009) suggested that the time scale over which bars develop would influence their facies distributions, and this conclusion is supported herein. Small incipient bars with a simple morphology and a short history of development, such as U3, are dominated by facies 1. As bars grow and age, the abundance of facies 1 in the bars decreases (e.g.U3 and U2). This proportional decrease in bar-scale cross strata is attributed to erosion of the original bar-scale set, and/or, to further deposition of smaller-scale sets by ripples and dunes as bars grow with age. Consequently, larger bars are composed of a mosaic of

different types of structures and, relative to their larger size, include a larger proportion of small- and medium-scale sets. Thus, the angle-of-repose bar-scale sets of the incipient bars are progressively reworked, and, bar compositions reflect an increasing range of temporal and spatial boundary conditions as the bars grow and evolve over time.

Variability between reaches: effects of a fine-grained tributary input

Downstream variability in the alluvial architecture of large sand-bed rivers over distances of hundreds of kilometres and including the effects of tributary inputs has not been studied extensively. However, examples from the Rhine, Mississippi and Ganges rivers suggest that subtle, downstream fining in large sand bed rivers is a common phenomenon (Frings, 2008). For example, for the Ganges River, Singh et al. (2007) demonstrate that over approximately 2000 km, the grain size distribution of this sand-bed river changes from predominantly medium and fine sand upstream to fine sand, very fine sand and silt/clay downstream. Conversely, the grain-size differences between the reaches investigated in the Rio Paraná can, for a large part, be attributed to the tributary input of the Rio Paraguay (Table 4). Assessment of the effect of this input of fine-grained sediment on the bar sedimentology is complicated by the inherent variability of the deposits, which relates to the location within a bar and the age of the bar as discussed above. In addition, the onset of any changes in sedimentary composition varies as a function of the dynamics that control the mixing of the sediment from the Río Paraná and Río Paraguay (Lane et al., 2008). GPR data from bars C2 and C3, located at 73 and 74 km downstream from the confluence, still yield viable GPR data that indicate a change in proportional composition relative to the upstream bars (Table 1, Fig. 4, Fig. 9). At >520 km

downstream, near Santa Fé, the evidence from the bars is restricted mostly to the upper bar deposits (25-33% of the upper bar/channel fill sequence) because GPR surveys near Santa Fe (bars D1-D3) were not possible. The interpretations from this area are based on shallow cores and trenches, though it is noted that consistent attenuation of the radar signal itself also provides an important clue as to the composition of the upper bar deposits. The most prominent changes in sedimentary architecture in the bar-top sediments near Santa Fé relate to the introduction of fine-grained material by the Río Paraguay:

- 1) an increased proportion of ripple sets (> 40% of deposits), both as thick co-sets and interbedded with other structures
- 2) a decrease of unit-bar foresets (< 10% of deposits) relative to unit-bar trough deposits
- 3) an increase in the abundance (> 10% silt/clay in grain size distribution) and thickness of fine-grained sediment layers (up to several metres thick), many of which are likely to have bar-scale extents

Although thick sets of cross-strata (i.e. facies 1A) normally provide a focus with respect to the deposits of large rivers, one of the most striking features of the cores presented herein is the relative abundance of ripple sets within the upper 4-5 m of the bar deposits (Table 5). Large proportions of ripple-sets are also found in the upstream reach, but are related to localised flow deceleration in response to the morphological development of the mid-channel bars. In the downstream reach, the presence of ripple-sets is far more pervasive throughout the upper bar deposits and is also found in the troughs of individual dune sets.

Comparison with smaller rivers and effects on reservoir properties

The variability of facies in the investigated bars has many similarities to that described from much smaller river systems (Allen, 1983; Skelly *et al.*, 2003; Lunt & Bridge, 2004; Sambrook Smith *et al.*, 2006; Horn *et al.*, 2012a,b), where channel deposits are also composed of a limited number of large-scale depositional units and where bar morphology also results in pronounced spatial clustering of the sedimentary facies. This potential scale-independent character of the large-scale architecture (cf. Fielding, 2007) does not imply a similarity in the relative abundance of large-scale elements, nor of sedimentary structures within them, as these are known to vary significantly between different systems (Hickin, 1993; Miall, 1996; Bridge, 2009).

The persistent presence of facies 3 as the bounding layers that delineate the large-scale units within the bars compares to observations from smaller river systems and has significant implications for the connectivity of the higher-permeability elements within the deposits. Channel-scale, laterally-continuous, fine-grained deposits (2) are observed in cutbanks near Santa Fe (e.g., Fig. 10C), and in the cores (Fig. 5, Fig. 10F) and radar facies 3 in the GPR images (e.g. Fig. 3, Fig. 7). Larue and Hovadik (2006) discuss how connectivity within a reservoir can be reduced by compartmentalization associated with local muddy deposits, specifically where: (1) a mud drape covers the channel base, (2) laterally-continuous horizontal muds are located within a channel, and (3) inclined mud units are found (e.g. Lynds & Hajek, 2006; Martinius & Van den Berg, 2010). The dominant association of facies 1 (unit-bar sets) with underlying fine-grained layers in both the upstream and downstream reaches (Table 3; Fig. 5D,F; Fig. 10F) suggests that stacking of unit-bar deposits plays a key role in the development of baffles to flow that could ultimately reduce

reservoir connectivity in channel deposits. In addition, the increased abundance of fine-grained layers found downstream from the confluence with the Río Paraguay implies that such a significant point-source change in a large river system with a long downstream-fining distance (cf. Frings, 2008) may result in a marked change in reservoir quality.

Finally, this study shows the sensitivity of the observed sedimentary heterogeneity to the definition of the spatial domain of the study. Based on the most distinctive findings from this investigation, [Figure 12](#) separates the sedimentary heterogeneity according to the variability within bars, between bars, and between reaches in response to the fine-grained sediment addition by the Río Paraguay. Clearly, the scale of a study affects the diversity in boundary conditions and the associated heterogeneity in the deposits. Single bars are unlikely to provide an adequate picture of a river system. Yet, increasing the physical extent of the studied domain can, both gradually or abruptly, increase the inclusion of fundamentally different controls on sedimentary deposition. In this study, the internal coherence in the distribution of sedimentary structures varied abruptly as a function of clustering of structures caused by bars' development processes and history, abruptly in response to a local point-source input in fine-grained sediment, and gradually in response to more gradual changes in slope and mixing of waters. Thus, the heterogeneity in bar deposits, and hence the facies models that describe that heterogeneity, are scale-sensitive.

CONCLUSIONS

Ground-penetrating radar and core data from 11, km-scale bars over a ~600 km downstream length of the Rio Paraná show that the channel deposits are composed of 3 principal GPR facies. Facies 1 represents bar-scale sets with heights up to 12 m and lengths up to 600 m that are internally composed of angle-of-repose cross strata (Facies 1A: 8-58% of the investigated volume) or inclined dune- and ripple co-sets (Facies 1B: 0-48%). Facies 2 represents significant volumes of near-horizontal dune and ripple-scale sets (32-60%). Facies 3 represents laterally-extensive layers of finer-grained ripple sets (2-12%).

- 1) Between 32 and 91% of the investigated depositional structures of the Rio Paraná is similar in scale to those found in smaller rivers. In other words, big river deposits are not consistently characterised by big structures that facilitate a straightforward interpretation of river scale. However, many of the smaller dune- and ripple sets are stacked in thick co-sets that do scale to river size.
- 2) Bar-scale cross strata and bar-scale inclined co-sets (Facies 1A and B) are overwhelmingly found on top of layers of finer-grained ripple-sets (Facies 3) that are deposited in the lee of migrating bars. The systematic presence of these laterally-extensive fine-grained layers will limit the connectivity of depositional units with higher permeabilities.
- 3) The bar-scale sets with angle-of-repose cross strata (Facies 1A) that are the most reliable indicators of a river's scale are restricted spatially to half of the bar-surface area and occur predominantly in the smaller, more recently formed bars. This reduction of bar-scale cross strata in older and larger bars is attributed to combinations of reworking and changes in the styles of accretion as the bars evolve over time.

- 4) Relative to other controls on downstream fining, the point-source input of fine-grained sediment from the Rio Paraguay causes a marked change in the upper bar deposits. The increased presence of fines manifests itself as an increased abundance, and thickness, of laterally-extensive fine-grained layers; as an increased abundance of ripple sets, and; as a proportional reduction of bar-scale angle-of-repose cross strata. In contrast to the bar-top deposits, the thalweg of the Río Paraná is covered with m-scale dunes and its deposits are composed of dune sets even in areas where bar-top deposits are dominantly fine-grained. Thus, changes in the sedimentary architecture and the permeability characteristics of km-scale bars due to a fine-grained tributary input are expressed primarily in the composition of the bar-top deposits.

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FIGURE CAPTIONS

Fig. 1. Location of A) the study site, B) the two study reaches and the study bars within the reach around C) the Paraguay-Paraná confluence and D) near Santa Fe.

Fig. 2. Oblique aerial views of the investigated bars also showing the GPR survey lines and core locations. Arrows indicate flow direction. More details are in Table 1.

Fig. 3. GPR profiles with facies interpretations: examples from U1 (A,B), U2 (C), U3 (D), U4 (E), U5 (F), C2 (G) and C3 (H). Labels: [I] horizontal transition between facies 1A and 1B. [II], [III] and [IV] are facies 2 with chaotic, discontinuous, and trough-shaped geometries of the reflections, and [V] are complete dune profiles. Colours in (H) are facies interpretations: red is facies 1A, yellow is facies 1B, green is facies 2, and blue lines are facies 3.

Fig. 4. Maps of spatial averages of GPR facies percentages (vertical sum of a single facies divided by the vertical sum of all facies within 200 x 200 m windows shifted in 20 m increments) for bars where GPR surveys were undertaken. See text for explanation of labels A-O.

Fig 5. Core logs from the investigated bars: (A) bar head of U1, (B) left wing of U1, (C) bar head of U2, (D) right bar tail of U2, (E) U3, (F) bar head of U5 and (G) bar tail of C2. Also shown are associated photos from each of the cores (H-N).

Fig. 6. Landsat images (Bands 1, 2 and 3) showing the temporal development of bars. Note that discharges vary between images but most images are at low flow.

Fig. 7. Along-stream and cross stream GPR profiles and interpretation of the geometry of the bounding surfaces in U1 (A-D), U2 (E-H), U5 (I-L) and C2 (M-P).

Fig. 8. GPR fence-plot and cores of U3 (Fig. 2E) showing an internal composition of a small and new bar that is dominated by large-scale cross-strata (facies 1A).

Fig. 9. Matrix of distributions of the percentage of facies within the bars (vertical proportion). Means and standard deviations are given per graph and visualized by stars with error bars. The percentages of the investigated surface-area where the facies are found are given in the pie-charts (with values).

Fig 10. A) Trench from bar D3 showing interbedded dune sets, ripple co-sets and clay layers. B) Trench from bar D2 showing angle-of-repose unit-bar sets, note the contrast in grain-size sorting in the cross strata and compare with that from further upstream (see Fig. 5H). C) Cutbank from bar D1, note the locally deformed cross strata at the base of the exposure and also the fine-grained horizon that extends over hundreds of metres. D) Core log from bar D1. E) Core log from bar D2. F) Core log from bar D2. See fig. 2 for locations of trenches and cores.

Fig. 11: A) Parametric Echo Sounder (PES) profile showing channel bed surface morphology and subsurface architecture from the channel adjacent to C1. PES reflection surfaces reveal: reactivation surfaces within dunes and deposits characterised by sets composed of (C, α) high-angle, relatively straight, low-amplitude reflections: interpreted as angle-of-repose cross strata formed by dunes,

and (C, β) co-sets composed of lower-angle, higher-amplitude internal reflections with less regular geometries: interpreted as stacks of inclined cross-stratified sets formed by dunes migrating down the reduced lee slope of a larger host dune or bar.

Fig. 12: Overview of the scales and causes of heterogeneity in bars in the Río Paraná, Argentina.

Table 1. Background details of the investigated bars, their development observed in LandSat images, key observations from the GPR results, and sedimentary structures observed in cores.

| Bar | Geomorphology & historical development (Figs 2 and 6) | Ground Penetrating Radar (Figs 3, 4, 7, 8) | Sedimentary structures in cores (Figs 5, 10) |
|---|---|--|---|
| U1 <ul style="list-style-type: none"> • 30 km upstream^a • ~6 years^b • 0.58 km^{2c} • 8.3 km GPR • 13 cores | <ul style="list-style-type: none"> • Amalgamation in 1997 of two bars 0.5x0.3 and 0.3x1.7 km, approx. 1 km upstream is followed by migration of a bar front towards vegetated islands (Fig. 6 A1-3) • Stalling of the bar front just upstream of vegetated islands forms the current bar's right wing (Fig. 6 A3) • Gradual in-situ growth of the left bar wing causes enclosure and decrease in through-flow of water in the lee of the bar (Fig. 6 A3-5) | <ul style="list-style-type: none"> • Set of facies 1A with a thickness of ~8 m is present in the right wing (Figs. 3A, 7A-D), lateral extent of >600 x >300 m (Fig. 4 label A) • Downstream decrease in facies 1A thickness and increase of near-horizontal reflectors that can be traced to the inclined reflectors: association of the bar trough with the foresets (Fig. 7C-D) • The left wing contains a 4 m thick unit of upstream-dipping facies 1B (Fig. 3B) with a lateral extent of 550 x 200 m (Fig 4, label C) and associated with complete dune forms, facies 2 | <ul style="list-style-type: none"> • The right wing is composed of a large set of angle-of-repose strata of which the base is not observed in the cores overlain by some small and medium-scale sets (Fig. 5A) • The left wing and bar centre are composed of thick units of ripple-sets with some medium-scale dune sets (Fig. 5B) • Trenches and cutbanks are dominated by dune deposits |
| U2 <ul style="list-style-type: none"> • 8 km upstream^a • ~7 years^b • 0.43 km^{2c} • 13.3 km GPR • 10 cores | <ul style="list-style-type: none"> • Developed from a 0.1 x 1 km, elongated bar that detached from the left bank in 1997 (Fig. 6B) • Coalesced with one or more unit bars migrating towards the left bank in 1999-2001, generating a winged shape • Continues to migrate downstream and develop its own elongated wings | <ul style="list-style-type: none"> • Large-scale sets of facies 1A lower in the bar head (Fig. 4 label E) • Stacking of units of facies 1A and 1B migrating to the bar centre from left and right (Fig. 7G-H) • Wings dominated by facies 1A (Fig 4. label D) • Facies 2 is dominant in the upper deposits and the bar flanks (Fig 4, label G) • Local abundance of facies 3 (Fig. 4 label H) likely an artefact of GPR attenuation in the bar centre (Fig. 7G) | <ul style="list-style-type: none"> • Cores from bar head and flanks characteristic contain a variety of ripple-co-sets and larger-scale sets associated with dunes and small unit bars • Distinct association of unit-bar forests with underlying fine-grained trough-deposits that include clay layers |
| U3 <ul style="list-style-type: none"> • 7.5 km upstream^a • ~2 years^b • 0.025 km^{2c} • 1.5 km GPR • 2 cores | <ul style="list-style-type: none"> • Initially attached to U2 during low flow (Fig. 6 B4) • Likely detached by a chute cut-off after 2001 | <ul style="list-style-type: none"> • The internal structure is dominated (58%) by two amalgamated sets of facies 1A (Fig. 3D, Fig. 8) | <ul style="list-style-type: none"> • Cores composed of a large-scale set overlain by a few medium- and small-scale sets and underlain by fine-grained trough-deposits that include clay layers |

Scales and causes of heterogeneity in bars in a large multi-channel river

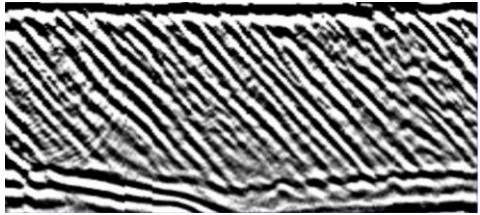
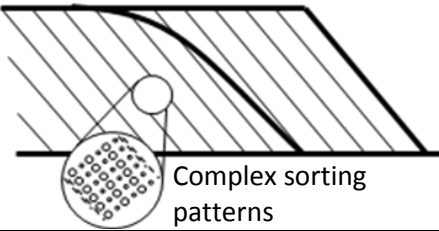
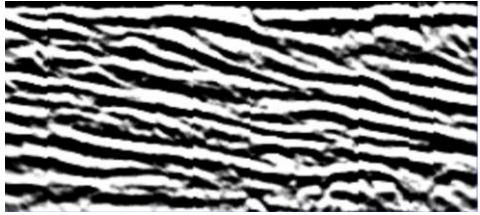


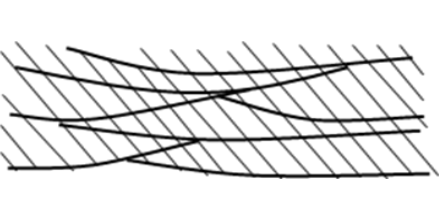

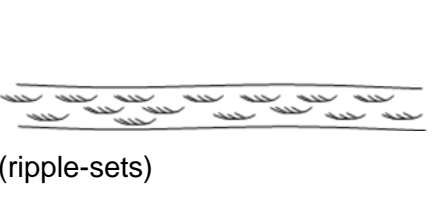
| | | | |
|---|---|--|---|
| <p>U4*</p> <ul style="list-style-type: none"> • 1 km^a downstream • ~15 years^b • 2.5 km^{2c} • 4.4 km GPR • no cores | <ul style="list-style-type: none"> • Developed by amalgamation of bars in the period of 1977-1991 (Fig. 6 C1-2) • Remained in present location since mid 1970's • Dune forms common on flanks and bar head (Szupiany <i>et al.</i>, 2009) • Lateral accretion of large bedforms onto the bar develops its wings in 1995-96 and 2001 (Fig. 6 C3-4) | <ul style="list-style-type: none"> • Two sets of facies 1A and 1B in the bar head of 4 and 5 m thick respectively below 4-6 m of facies 2 (Fig. 4 label J) • Facies 1 dominates the bar tail (Fig. 4 label K) • Facies 2 dominant in the bar head and flanks | <ul style="list-style-type: none"> • No cores |
| <p>U5</p> <ul style="list-style-type: none"> • 4 km^a downstream • ~27 years^b • 1.0 km^{2c} • 5.5 km GPR • 1 core | <ul style="list-style-type: none"> • Not reached by Río Paraguay sediment • Formed from symmetrical bar 1km upstream in 1973 • Remained in present location since 1981 • Characterised by amalgamation of unit bars – mosaic-like development (Fig. 6 C2-5) | <ul style="list-style-type: none"> • Data restricted to unvegetated right side • Facies 3 more abundant than other upstream bars (Fig. 4 label L), characteristically laterally extensive (Fig. 7I-L), and dissecting the deposits into bar-scale units with typical sizes of 30-600 m • Facies 2 dominant | <ul style="list-style-type: none"> • Bottomsets of unit-bar deposits contain clay (Fig. 5M) • Large-scale unit (unit bar) composed internally of a mix of dune- and ripple-sets (Fig. 5F) |
| <p>C1</p> <ul style="list-style-type: none"> • 9 km^a downstream • ~1 year^b • 0.085 km^{2c} • - km GPR • 1 core | <ul style="list-style-type: none"> • Developed in 2007 in a <1km wide anabranch that is dominated by the silt-laden waters of the Río Paraguay (Fig. 2H) • Has remained in place since 2007, gradually elongated to ~1km • Bar surface dominated by silt | <ul style="list-style-type: none"> • GPR attempted, but radar signal was attenuated | <ul style="list-style-type: none"> • Unsuccessful coring attempts in too soft sediments • Retrieved core contained 36% ripple sets, 30% unidentifiable disturbed sediments, and cross-stratified sands • Abundant deformation observed in trench faces |
| <p>C2</p> <ul style="list-style-type: none"> • 73 km^a downstream • ~4 years^b • 1.4 km^{2c} • 5.8 km GPR • 3 cores | <ul style="list-style-type: none"> • Located where Río Paraná and Río Paraguay are intermittently mixed (Fig. 1) • Bar head appeared in 1999, became vegetated in 2004 when the bar tail developed (Fig. 6D) • The present size of the bar tail was reached in 2007 | <ul style="list-style-type: none"> • GPR on 1.3 x 0.7 km bar tail, part of a 2.0 x 1.0 km compound bar (Fig. 2F) • Facies 1A uncommon and restricted to small 10-100 m sets, facies 1B more common (Fig. 4 label N) • Facies 3 common and laterally extensive as in upstream bars (Fig. 4 label O; Fig. 7M-P) | <ul style="list-style-type: none"> • Cores show abundance of ripple sets (67%) and only one 0.5 m thick large-scale set (Fig. 5G,N) underlain by a thick ripple co-set |
| <p>C3</p> <ul style="list-style-type: none"> • 74 km^a downstream • <1 year^b • 0.025 km^{2c} | <ul style="list-style-type: none"> • Exposed during low flow in 2008 • This incipient bar developed as an elevated part of a lobate lee slope that extends from the tail of C2 (Fig. 2G) | <ul style="list-style-type: none"> • Composed of a single large scale set that is dominated by facies 1B (Fig. 3H) • Underlain by a strong laterally extensive reflector below which no structures are observed | <ul style="list-style-type: none"> • No cores |

Scales and causes of heterogeneity in bars in a large multi-channel river

| | | | |
|---|---|--|--|
| <ul style="list-style-type: none"> • 0.5 km GPR • no cores | | | |
| D1 <ul style="list-style-type: none"> • 520 km^a downstream • >38 years^b • 1.25 km^{2c} • - km GPR • 6 cores | <ul style="list-style-type: none"> • Located where waters of the Río Paraná and Río Paraguay are mixed • Submerged bars visible in early images, but first emerged in 1999 as a relatively short and wide bar and gradually became elongated • Vegetated from 2000 onwards (Fig. 6E) • Sandy parts restricted to bar head and left side | <ul style="list-style-type: none"> • GPR attempted, but radar signal was attenuated | <ul style="list-style-type: none"> • The 6 cores contained 46% ripples sets and 32% larger-scale sets but no bar-scale sets • Dune-sets were typically interbedded with finer-grained ripple sets (Fig. 10D) • Cut-banks on the right side contained more dune sets (Fig. 10C) and laterally-extensive clay layers and soil horizons of up to 0.4 m |
| D2 <ul style="list-style-type: none"> • 535 km^a downstream • <1 year^b • 0.09 km^{2c} • - km GPR • 5 cores | <ul style="list-style-type: none"> • Low-lying bar exposed at low flow has been in its current location since 2006 | <ul style="list-style-type: none"> • GPR attempted, but radar signal was attenuated | <ul style="list-style-type: none"> • 5 cores contained 32% ripples and 23% dune sets. • 2 bar-scale sets (20% of core length) were underlain by fine-grained bottomsets that coarsen-upward into its angle-of-repose strata (Fig. 10 E,F) • Trenches revealed bar-scale cross strata with contrast in grain size between 50-60 µm and 190-310 µm (Fig. 10B) |
| D3 <ul style="list-style-type: none"> • 537 km^a downstream • >38 years^b • 1.25 km^{2c} • - km GPR • no cores | <ul style="list-style-type: none"> • Sandy bar tail attached to large vegetated island 2 km downstream from D2 and has been in its current location since the earliest satellite images | <ul style="list-style-type: none"> • GPR attempted, but radar signal was attenuated | <ul style="list-style-type: none"> • Two trenches revealed medium-scale sets interbedded with co- and return-flow ripple-sets and clay layers with grain sizes of 40, 230, and 280 µm respectively (Fig. 10A) |

^a relative to the confluence of the Río Paraná and Río Paraguay; ^b approximate age at the time of the survey (2008); ^c Bar area measured at 11400 m³ s⁻¹ in December 2008; * Studied by Sambrook Smith *et al.* (2009)

Table 2. Classification scheme of GPR facies described in this study (see also Fig. 3)

| Facies | GPR facies description | Sedimentary interpretation - structures | Genetic interpretation - bedforms | Examples of GPR lines* | Conceptual sketch of 2D structures | |
|--------|--|---|--|--|--|---|
| 1 | A | >50% of reflections are steeper than 20° Commonly straight and relatively low amplitude | Large-scale angle-of-repose cross strata with complex pre/re-sorting patterns (see text) | Primarily avalanche deposition at angle-of-repose bar slopes. Could also include some very large dunes |  |  Complex sorting patterns |
| | B | >50% of reflections >6° and <20° Commonly irregular and higher amplitude | Co-sets of inclined small- and medium-scale sets | Primarily dunes and ripples migrating over bar-scale slopes below-the angle-of-repose |  |  |
| 2 | >50% of reflections <6° with undular, discontinuous, or chaotic shapes | Near-horizontal small- and medium-scale sets, may include large-scale cross strata with insufficient contrast in properties to generate reflections | Primarily dunes and ripples migrating over near-horizontal surfaces (e.g. channel floor, bar-top) |  |  | |
| 3 | High-amplitude, laterally-extensive reflections, commonly associated with loss of radar signal | Primarily near-horizontal fine-grained layers of small-scale sets, distinct contrasts in grain size | Large-scale bounding surfaces such as unit-bar bottomsets and low-flow stage deposits, commonly finer-grained, not limited to clay |  |  (ripple-sets) | |

* Images have heights of 2 m and lengths of 20 m

Table 3. Percentages of vertical associations of facies calculated from the ~0.1 m spaced vertical profiles.

| (a) | | Overlying facies | | | |
|-------------------|----|------------------|----|----|----|
| | | 1A | 1B | 2 | 3 |
| Underlying Facies | 1A | | 2 | 17 | 17 |
| | 1B | 2 | | 17 | 18 |
| | 2 | 7 | 18 | | 65 |
| | 3 | 91 | 80 | 66 | |

Table 4: Percentages silt and clay, sand and gravel, number of samples, and median grain sizes of the investigated bars. Note the downstream increase in clay.

| bar | silt/clay% | sand% | gravel% | n | D ₅₀ (µm) |
|-----|------------|-------|---------|----|----------------------|
| U1 | 1 | 99 | 0 | 26 | 263 |
| U2 | 2 | 96 | 2 | 56 | 315 |
| U3 | 0 | 99 | 1 | 16 | 361 |
| U5 | 9 | 90 | 1 | 27 | 348 |
| C1 | 31 | 69 | 0 | 13 | 141 |
| C2 | 11 | 89 | 0 | 26 | 244 |
| D1 | 13 | 87 | 0 | 37 | 237 |
| D2 | 12 | 88 | 0 | 25 | 251 |
| D3 | 23 | 77 | 0 | 3 | 181 |

Table 5: Core lengths and percentages of sedimentary structures in the cores.

| Cores | core length | ripples | dunes | bars | low-stage plane bed | upper-stage plane bed | unknown or deformed |
|------------|-------------|---------|-------|------|---------------------|-----------------------|---------------------|
| all | 152.95 | 35 | 26 | 16 | 1 | 0 | 22 |
| upstream | 95.37 | 31 | 27 | 20 | 0 | 0 | 22 |
| downstream | 57.58 | 43 | 24 | 8 | 2 | 0 | 24 |
| U1 | 51.09 | 43 | 11 | 22 | 0 | 0 | 23 |
| U2 | 35.33 | 19 | 51 | 12 | 0 | 0 | 18 |
| U3 | 4.99 | 2 | 26 | 72 | 0 | 0 | 0 |
| U5 | 3.96 | 16 | 21 | 0 | 0 | 3 | 60 |
| C1 | 4.20 | 36 | 25 | 0 | 8 | 0 | 30 |
| C2 | 13.01 | 15 | 15 | 4 | 1 | 0 | 24 |
| D1 | 19.93 | 46 | 32 | 0 | 2 | 0 | 20 |
| D2 | 20.44 | 32 | 23 | 20 | 1 | 0 | 25 |