Earth-Science Reviews 150 (2015) 652–665

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Extremes in dune preservation: Controls on the completeness of fluvial deposits

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ARTICLE INFO

Article history:
Received 4 June 2015
Received in revised form 15 September 2015
Accepted 20 September 2015
Available online 25 September 2015

Keywords:
Dunes
Unit bars
Preservation
River deposits
Stratigraphic completeness

ABSTRACT

Understanding sedimentary preservation underpins our ability to interpret the ancient sedimentary record and reconstruct paleoenvironments and paleoclimates. Dune sets are ubiquitous in preserved river deposits and are typically interpreted based on a model that describes the recurrence of erosion in a vertical sequence, but without considering spatial variability. However, spatial variability in flow and sediment transport will change the recurrence of erosion, and therefore dune preservation. In order to better understand the limits of these interpretations and outline the causes of potential variability in preservation potential, this paper reviews existing work and presents new observations of an extreme end-member of dune preservation: 'form-sets', formed by dunes in which both stoss- and lee-slopes are preserved intact. These form-sets do not conform to models that are based on the recurrence of erosion, since erosion does not recur in their case, and can therefore be used to evaluate the assumptions that underpin sedimentary preservation.

New Ground Penetrating Radar data from the Río Paraná, Argentina, show dune fields that are buried intact within larger scale barforms. These trains of form-sets are up to 300 m in length, are restricted to unit-bar troughs in the upper 5 m of the channel deposits, occur in >5% of the mid-channel bar deposits, show reactivation surfaces, occur in multiple levels, and match the size of average-flow dunes. A review of published accounts of form-sets highlights a diversity of processes that can be envisaged for their formation: i) abandonment after extreme floods, ii) slow burial of abandoned dune forms by cohesive clay in sheltered bar troughs and meander-neck cut-offs, iii) fast burial by mass-movement processes, and iv) climbing of dune sets due to local dominance of deposition over dune migration.

Analysis of these new and published accounts of form-sets and their burial processes highlights that form-sets need not be indicative of extreme floods. Instead, form-sets are closely associated with surrounding geomorphology such as river banks, meander-neck cut-offs, and bars because this larger-scale context controls the local sediment budget and the nature of recurrence of erosion. Locally enhanced preservation by the 'extreme' dominance of deposition is further promoted by finer grain sizes and prolonged changes in flow stage. Such conditions are characteristic, although not exclusive, of large lowland rivers such as the Río Paraná. The spatial control on dune preservation is critical: although at-a-point models adequately describe near-horizontal sets of freely migrating dunes in uniform flows, they are unsuitable for inclined dune co-sets and other cases where multiple scales of bedforms interact. Spatial and temporal variations in flow and sediment transport between the thalweg and different positions on larger bar-forms can change the preservation potential of dunes within river channels. Therefore, dune set thickness distributions are likely grouped in larger-scale units that reflect both formative dune geometries *and* bar-scale variations in preservation potential. The multi-scale dynamics of preservation highlighted herein also provides a useful comparison for other sedimentary systems.

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http://dx.doi.org/10.1016/j.earscirev.2015.09.008
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Contents

1. Introduction

Our understanding of bedform preservation underpins many interpretations of sedimentary deposits. Dunes and their preserved deposits provide fundamental information on formative environmental conditions of fluvial, estuarine and marine deposits, within which they are abundant (Allen, 1982; Van Rijn, 1990; Van den Berg and Van Gelder, 1993). The grain size sorting within preserved dune deposits controls permeability and porosity, and therefore heterogeneity within aquifers and hydrocarbon reservoirs (Weber, 1982; Brayshaw et al., 1996; Tidwell and Wilson, 2000; Huysmans and Dassargues, 2010). The scale of subaqueous dunes lends itself to 1:1 scale experimental analysis of preservation processes within timescales that are realistic for process-product studies (Bridge, 1997, 2003). Such experimental studies have led to the development of a single, dominant model of bedform preservation in unidirectional, uniform flows. This model describes the formation of sedimentary beds by recurrence of scour in a vertical column (Fig. 1A; Barrell, 1917; Kolmogorov, 1951) and assumes that the amount of truncation by later erosion is predictable because bedforms occur in predictable size-distributions and, as a consequence, preserve set thicknesses can be used to infer formative bedform heights (Kolmogorov, 1951; Paola and Borgman, 1991; Bridge and Best, 1997; Leclair and Bridge, 2001). However, systematic application of this 'variability-dominated' model typically indicates that this model of dune preservation is not universally applicable (e.g. Jerolmack and Mohrig, 2005; Leclair, 2011; Reesink and Bridge, 2011; Holbrook and Wanas, 2014). Consequently, the stratigraphic completeness of fluvial deposits remains inadequately understood, and the accuracy of paleoenvironmental interpretations that use preserved dune sets may require modification. The present paper thus investigates under what conditions the current quantitative model is applicable, and under what conditions it is invalid or in need of modification.

In order to achieve this goal, the paper first reviews the theory of bedform preservation and the fundamental processes it describes. We then present new observations of extreme dune preservation from the Río Paraná, Argentina, that do not conform to the recurrence-of-scour model. These dune deposits comprise both their stoss- and lee-slopes and are herein referred to as 'intact' forms, or 'form-sets' (cf. Imbrie and Buchanan, 1965). We discuss these observations within the context of diverse accounts of dune form-sets. The absence of erosive truncation after deposition illustrates processes and variables that can modify and potentially dominate dune preservation. Based on this analysis and published accounts of dunes that are preserved intact, some preliminary constraints are presented beyond which the current at-a-point preservation models should not be used for quantitative interpretations. The analysis indicates potential opportunities for a hierarchical approach to dune-set interpretation in which the dune sets are grouped according to formative conditions and position within an alluvial channel.

2. Theory

Cross-stratified sets (or *beds*) are the depositional units formed by the migration of bedforms, and generally consist of a thin, low-angle subunit at the base (*bottomset*) followed by a cross-stratified layer formed on the lee slope of the bedform (*foreset*) (Kleinhans, 2004; Reesink and Bridge, 2007, 2009). In the case of (near-) intact preservation, a thin low-angle subunit may be preserved that was formed on the stoss slope of the bedform (*topset*; cf. Boersma, 1967). Each cross-stratified set is associated with a single bedform (e.g. dune, unit bar), and a stack of inclined sets that form a larger-scale compound group is known as a *co-set* (McKee and Weir, 1953). The association of preserved sets with their formative dunes, and of dunes with their formative flow, relies on understanding both dune morphodynamics and processes of sedimentary preservation (Allen, 1982; Bridge, 2003; Collinson et al., 2006). Bedforms and their preserved sets are known to be associated with a certain range of flow conditions and grain sizes (their 'phase' or 'stability' space) (e.g. Allen, 1982; Southard and Boguchwal, 1990; Van Rijn, 1990; Van den Berg and Van Gelder, 1993; Wan and Wang, 1994; Best, 1996; Schindler et al., 2015). Interpretations of bedform types can therefore be used to constrain formative flow conditions. In addition, the mean direction of the dip of cross-strata and the elongation and shape of dune troughs can also be used to indicate formative flow directions (Slingerland and Williams, 1979; Allen, 1982; DeCelles et al., 1983; Miall, 1996; Bridge, 2003), unless sediment transport is driven by strong lateral velocity gradients. Maximum equilibrium dune heights and scour depths are commonly related to water depth in steady uniform flows (Jackson, 1975; Yalin, 1964; Southard and Boguchwal, 1990; Ashley, 1990; Allen, 1982; Van Rijn, 1990; Best, 2005). This relationship is further evidenced by the growth and decay of dunes during floods, but also further complicated because the lagged development of dunes commonly results in a distinct hysteresis in dune size, bed roughness and sediment transport (e.g. Julien and Klaassen, 1995; Wilbers and Ten Brinke, 2003; Kleinhans et al., 2007). The correlation between flow depth and dune height in natural rivers also varies with grain-size sorting, sediment suspension, supply limitation, bed cohesion, and by acceleration–deceleration and secondary currents generated by bar-scale topography (e.g. Wan and Wang, 1994; Nittrouer et al., 2008; Sambrook Smith et al., 2009; Tuijnder et al., 2009; Leclair, 2011; Claude et al., 2012; Baas et al., 2013; Rodrigues et al., 2014; Schindler et al., 2015). Dune geometries in marine settings also typically

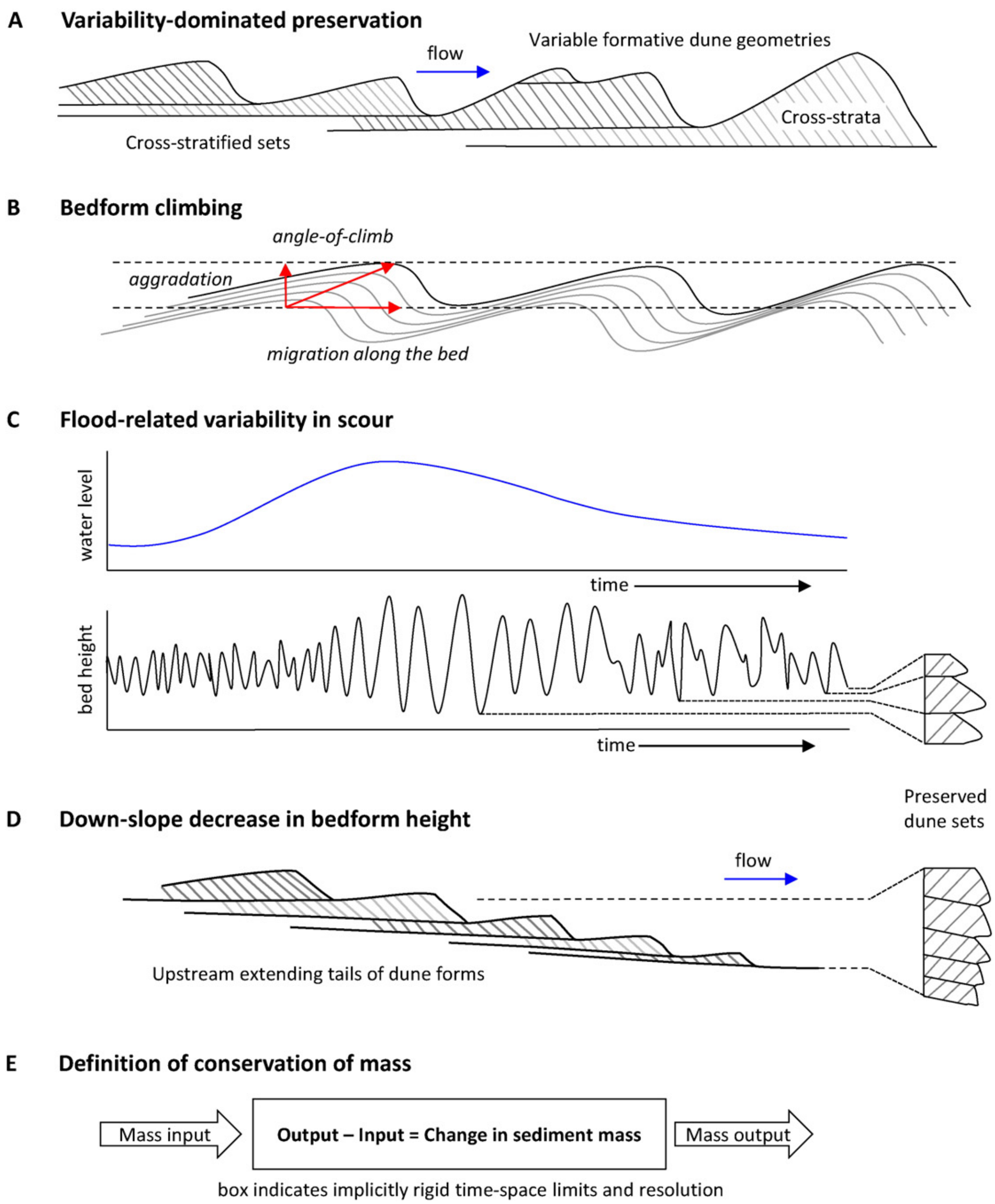

Fig. 1. Illustrations of fundamental processes that control the preservation of dune sets: A) the role of bedform scour variability; B) the role of aggradation as a control on preserved set thickness; C) dune development during a flood wave and its effect on dune preservation (after Kleinhans, 2002); D) decrease in bedform height (and set thickness) as dunes migrate down larger-scale lee slopes (e.g. Rubin and Hunter, 1982); E) schematic diagram of conservation of mass in bedform migration.

indicate that water depth is commonly less important than sediment availability and shear stress distributions (Bartholdy et al., 2005; Hulscher and Dohmen-Janssen, 2005; Parsons and Best, 2013).

Whereas an increasing body of research is devoted to associations between dune forms and their environmental boundary conditions, comparatively little attention has been given to the processes that control the formation and preservation of sets. The geometric parameters of preserved dune sets, such as their height, width, and length, tend to scale to those of their formative bedforms, with both bedform and set dimensions typically resembling either a gamma or a logarithmic distribution (Paola and Borgman, 1991; Drummond and Wilkinson, 1996; Drummond and Coates, 2000; Leclair, 2002; Longhitano and Nemec, 2005). Because dune migration rate is inversely proportional to their size for any given bedload transport rate (Van den Berg, 1987), the skewness of bedform size distributions implies that smaller, faster-moving, dunes regularly become superimposed on larger, slower-moving bedforms (Bridge, 2003; Martin and Jerolmack, 2013; Fig. 1A). The sets that are created by the largest dunes with the deepest scours are therefore more likely affected by superimposed bedforms (Reesink and Bridge, 2007, 2009). Horizontal sets formed by distributions of bedforms are therefore also characteristically truncated at their top, and represent punctuated records with a limited stratigraphic completeness (e.g. Sadler, 1981; Allen, 1982; Rubin, 1987; Bridge, 2003; Collinson et al., 2006; Sadler and Jerolmack, 2014; Mahon et al., 2015). Although most sets are truncated at their top by later erosion, some, known as *form-sets*, retain the shape of their formative bedform, including deposits of the stoss and lee slopes (Imbrie and Buchanan, 1965). Similar to ripple form-sets (Allen, 1970, 1982), dune form-sets can develop under conditions where dunes continue to migrate, maintaining their shape, but where no net erosion occurs because deposition dominates over erosion (Fig. 1B). The ratio of deposition (ms^{-1}) to migration (ms^{-1}) describes the angle at which the set develops during migration relative to the original bed surface, which is termed bedform *climbing*. The term climbing is used herein to describe the motion of the set relative to the original bed surface due to aggradation (Fig. 1B) and is independent of the slope of the host surface along which the bedform migrates. Depending on the relative magnitude of deposition and migration, climbing sets may have erosional stoss slopes (*stoss-erosional*), or can be form-sets (*stoss-depositional*, cf. Rubin and Hunter, 1982). Climbing form-sets are assumed to represent continuous depositional records, with changes in the angle-of-climb often being related to the formative flow and sediment transport history (Sorby, 1859; Jopling and Walker, 1968; Allen, 1970, 1971a, 1971b, 1973). Although some guidelines for the interpretation of climbing ripple sets have been established empirically (e.g. Bouma et al., 1962; Ashley et al., 1982; Arnott and Hand, 1989; Bristow, 1993a), the difficulty often apparent in any analysis of set-climbing is to determine the relative magnitudes of bedform migration and aggradation within a larger geomorphological and flow discharge context (Jopling, 1961; Kneller, 1995). This is especially the case in areas affected by secondary currents that are generated by larger-scale geomorphology, where bedform migration and overall aggradation may not be correlated linearly (Reesink et al., 2014b; Herbert et al., 2015). Migration of a bedform along a downstream-dipping host surface is termed *down-climbing* when the sets experience increased aggradation relative to the inclined bed surface over which they are migrating (Allen, 1982; Bridge, 2003; Reesink and Bridge, 2009, 2011). Stoss-erosional down-climbing sets are commonly found in co-sets that are formed by consecutive bedforms migrating over a low-angle bar-scale slope (e.g. Haszeldine, 1982). Because of their consecutive formation, trends in thickness and sorting between successive sets provide evidence of short-term formative conditions (Rubin and Hunter, 1982). Both form-sets that are completely preserved and form-sets that show continued migration, such as climbing and down-climbing sets, indicate the absence of later erosion. Such absence of erosion thus violates the basic assumptions that underpin models that are based on distributions of variable scour depths (Kolmogorov, 1951; Paola and Borgman, 1991). It is therefore clear that models based on variability in scour depth are not universally applicable, and that the controls on the preservation of dune sets need to be better constrained.

2.1. The ‘variability-dominated’ preservation paradigm

The concepts of recurrence-of-scour, progressive erosion after deposition, the punctuation of the sedimentary record, and stratigraphic (in)completeness, are largely scale-independent. Where short-term deposition rates exceed those of long-term accumulation, vertical sequences of sediment are necessarily incomplete and composed of short records that are broken up by hiatuses (Sadler, 1981). These hiatuses within sedimentary sequences can represent periods of stasis, during which no deposition occurs (Tipper, 2014), or recurrence of erosional scour with variable depths (Fig. 1A, Barrell, 1917; Kolmogorov, 1951). The recognition of the importance of the variability in, and recurrence of, erosive scour is firmly embedded in geological thinking (e.g. Ager, 1973, 1976; Miall, 2014). Over the last century, the ‘variability-dominated’ model has become a paradigm in sedimentary geology, in part because it provides an explanation of how the geological record is punctuated and how depositional units are formed by variable scour over time in areas with no, or negligible, net deposition. In addition, the variability in bedform scour has been shown to be the dominant control on bedform preservation for a considerable range of bedform types and uniform flow conditions (Bridge, 2003). Variations of this variability-dominated model have been experimentally tested for ripples (Storms et al., 1999), dunes (Leclair and Bridge, 2001), upper-stage plane beds (Bridge and Best, 1997), antidunes (Alexander et al., 2001), and bar-scale bedforms (Bridge and Lunt, 2006; Lageweg et al., 2013). This systematic experimental verification and the practical nature of the variability-dominated model have also caused it to become firmly embedded in much further research (e.g. Lunt et al., 2004, 2013; Gibling, 2006; Fielding, 2007; Sambrook Smith et al., 2009), even though alternative models for the interpretation of formative bedform heights are available (Rubin and Hunter, 1982; Kleinhans, 2001, 2002; Blom and Kleinhans, 2008; Reesink and Bridge, 2007; Reesink et al., 2014b). However, the existence of form-sets, and systematic applications of the variability-dominated model, indicate that this model is not universally applicable (Jerolmack and Mohrig, 2005; Leclair, 2011; Holbrook and Wanas, 2014). Importantly, the use of a channel-wide average value to represent vertical aggradation (Bridge, 1997) inherently assumes internal homogeneity within the channel. This use of temporal and spatial limits and resolution makes it simpler to justify the principles of conservation of mass that underpin the variability-dominated model (Fig. 1E). However, the combination of meter-scale deposition from dunes over the course of hours, together with kilometer-scale and multi-year bar and channel migration rates, skips several intermediary scales. For dunes, these intermediary scales include deposition and erosion at the spatial scales of bars and bends and the time-scales of floods, which easily span several orders of magnitude (Lane et al., 2010; Brasington et al., 2000; Lewin and Macklin, 2003). The present paper specifically addresses the issue of such multi-scale dynamics on bedform preservation.

2.1.1. The ‘variability-dominated’ bedform preservation model

In the ‘variability -dominated’ bedform preservation model, the bases of preserved sets are formed by the deepest scours, which are associated with the largest bedforms, and set thickness is given by the difference between the deepest and second-deepest scour (Fig. 1A). Thus, the thickness of sets is a function of the slope of the large-value tail of the bedform thickness distribution, which describes the natural variability in bedform heights. This relation can be expressed as:

$$s = \gamma * \beta \tag{1}$$

in which s is set thickness (m), γ is a constant that describes the relation between the bedform height and trough scour depth, and β represents the variability in bedform height (Bridge, 1997). The value of γ varies between bedforms because the processes and depths of scour vary between bedform types (Bridge, 1997; Bridge and Best, 1997; Alexander et al., 2001; Bridge and Lunt, 2006). β describes the variability in scour depth, as a function of bedform height, and can be derived by fitting a curve to the tail of the probability density function of bedform heights (cf. Bridge and Lunt, 2006). The angle-of-climb of the bedform is added to the thickness associated with the difference in scour depth to account for the overall aggradation (Fig. 1B), and expressed by:

$$s = \gamma * \beta + L * r/c \tag{2}$$

in which L is the bedform length (m), r is the flux of sediment to the bed ($m\,s^{-1}$), and c is the celerity of the bedform along the bed ($m\,s^{-1}$). Rates of erosion and deposition associated with bedform migration typically exceed rates of river channel migration and aggradation by several orders of magnitude (Sadler, 1981; Bridge, 1997; Brasington et al., 2000; Lewin and Macklin, 2003; Lane et al., 2010; Williams et al., 2013). This lends support to a model in which the variability in the recurrence of erosion by bedforms dominates sedimentary preservation. Aggradational and non-aggradational experiments on dunes (Leclair et al., 1997; Leclair and Bridge, 2001; Leclair, 2002, 2006) show that the angle-of-climb (L^*r/c) is negligible for a considerable range of flow conditions because dune celerities (c) are high relative to aggradation rates (r). When the angle-of-climb is small, set thickness is controlled by variability in bedform height and dune sets can be assumed to be approximately a third of the thickest formative dunes (0.28–0.45; cf. Leclair and Bridge, 2001). It is important to note that interpretations based on a single preservation ratio inherently assume that a limited number of preserved dune sets can be used to represent the large-value end of an entire dune population. Numerical simulations suggest that an increase in vertical aggradation may change this preservation ratio (cf. Jerolmack and Mohrig, 2005). Any such increase in sediment deposition is limited in its spatial extent, because the sediment transport gradients that drive deposition are dictated by the conservation of mass (Paola and Voller, 2015; Mahon et al., 2015; Fig. 1E). However, the variability in preservation that is a logical consequence of bar-scale gradients in sediment transport (Szupiany et al., 2012) remains largely unknown. Experiments with ripples (Storms et al., 1999) and dunes (Leclair, 2002, p. 1159) indicate that high rates of upstream sediment feed cause the development of a bar-scale bedform over which smaller bedforms migrate (Fig. 1D). In order to apply Eq. (2), it is assumed that i) the bed level is static; ii) the dune population is large and stable; iii) scour is a stable function of bedform size; iv) values of bedform celerity are sufficiently large, and v) deposition rates are sufficiently low. However, it is well-known that there are a number of naturally occurring situations in which one or more of these assumptions are invalid. Such conflicting observations are analysed herein.

3. Results

3.1. Dune form-sets revealed by Ground Penetrating Radar, Río Paraná, Argentina

A new analysis of >40 km of Ground-Penetrating Radar surveys from mid-channel bars in the Río Paraná, Argentina (Reesink et al., 2014a), indicates that the intact preservation of dunes may be more common than reported in previous work (Ghienne et al., 2010). The methods for the collection and processing of the GPR images used herein are described in detail by Sambrook Smith et al. (2009) and Reesink et al. (2014a). Form-sets can be observed in GPR images if sufficient contrast in electromagnetic properties exist between sediment layers, if the radar is not attenuated or scattered by the overlying sediment, and provided that the forms are sufficiently large relative to the GPR resolution, which is in the order of 0.1–0.2 m for 100 MHz antennae depending on the subsurface velocity (Cagnoli and Ulrych, 2001a; Cagnoli and Ulrych, 2001b).

Systematic delineation of form-sets in the GPR images indicates that dune form-sets are common in the deposits of mid-channel bars in the Río Paraná (Fig. 2; Sambrook Smith et al., 2009; Reesink et al., 2014a). The GPR lines in Fig. 2 are from different bars in the area of the confluence of the Río Paraná and Río Paraguay to 50 km upstream near the city of Itati. In a conservative interpretation, dune form-sets are identifiable in ~5% of the GPR survey, and in 5 of the 9 bars, surveyed upstream of the influence of the influx of fine sediment from the Río Paraguay (Reesink et al., 2014a). This interpretation excludes isolated asymmetrical reflections because asymmetrical mounds and scours are easily misinterpreted as 'dune-shaped'. The lengths of trains of dune form-sets identified in the GPR panels are in the order of 50–300 m, which matches the size of bar-top hollows (Best et al., 2006) and wake zones in the lee of bars (Bridge, 2003) in the Río Paraná. The GPR reflections of many of the dune form-sets can be traced to an upstream bar margin, or are overlain by a distinct unit-bar deposit (Fig. 2, red lines). Some form-sets can be traced to upstream-dipping reflections that are associated with climbing, or down-climbing, structures (Fig. 2, labels Cl, Dc; Allen, 1982; Rubin, 1987). The limited horizontal resolution of the GPR (±0.1 m) prevents distinction between the stoss-erosional or stoss-depositional character of these sets. Moreover, stoss-erosional and stoss-depositional sets typically grade into one another (Allen, 1970, 1982; Ghienne et al., 2010). However, the limited thickness of the 'form-set tails' suggests that a stoss-erosional character of climbing sets is more prevalent. In some cases, multiple

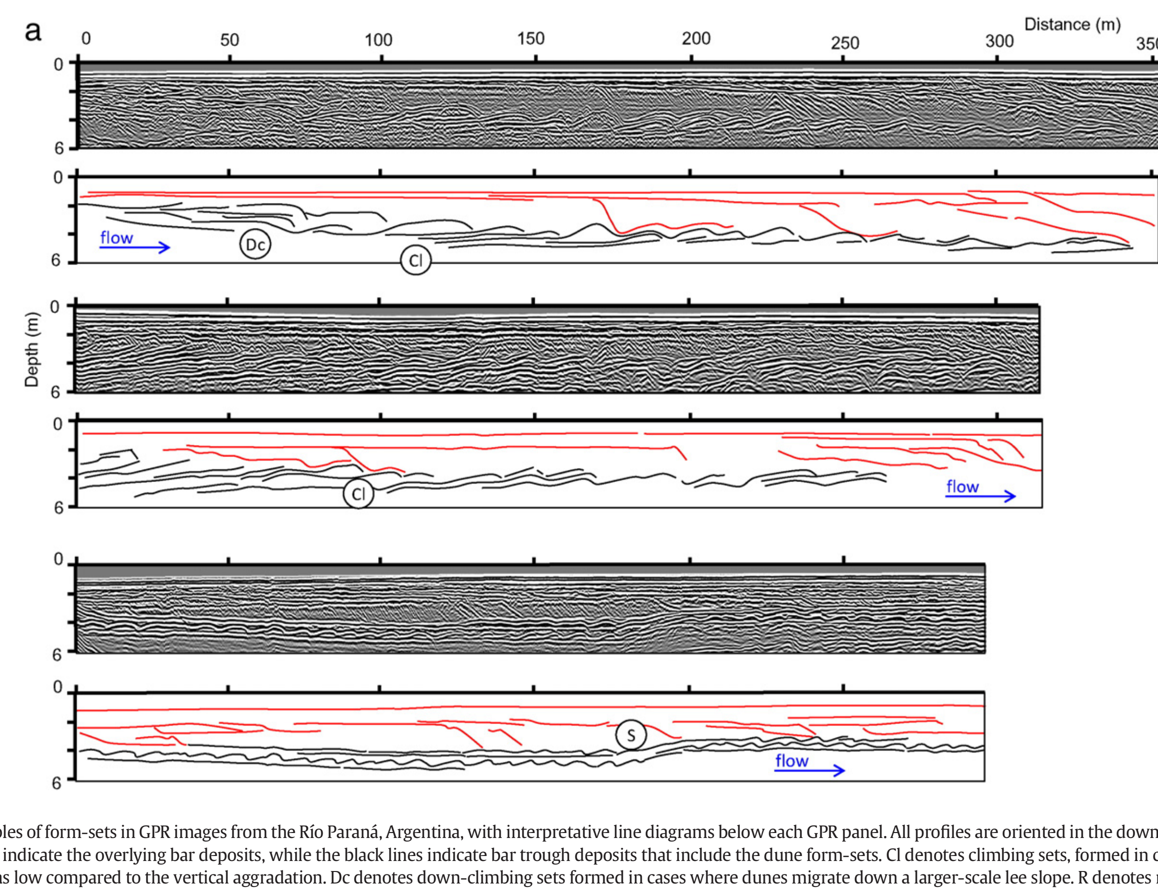

Fig. 2. Examples of form-sets in GPR images from the Río Paraná, Argentina, with interpretative line diagrams below each GPR panel. All profiles are oriented in the downstream direction. The red lines indicate the overlying bar deposits, while the black lines indicate bar trough deposits that include the dune form-sets. Cl denotes climbing sets, formed in cases where dune migration was low compared to the vertical aggradation. Dc denotes down-climbing sets formed in cases where dunes migrate down a larger-scale lee slope. R denotes reactivated form-sets, and S denotes superimposed dune fields, both of which imply multiple periods of activity of the dune form-sets.

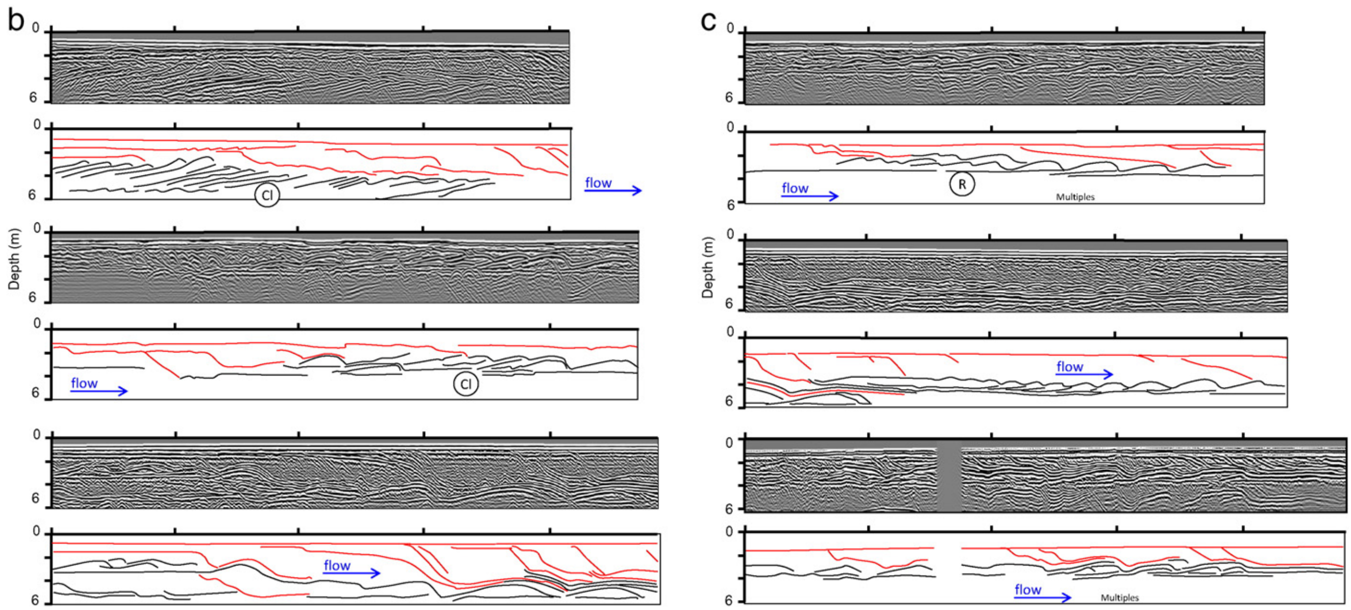

Fig. 2 (*continued*).

dune-fields are preserved on top of one another (Fig. 2, label S), whereas in other cases, form-sets appear to have been remobilized without significant erosion of the original form (Fig. 2, label R). Sediment cores taken with a Van-der-Staay suction corer indicate that the overlying sediment is not consistently composed of cohesive clay (D_{50} of bar trough fines typically 60–150 μm), which is further corroborated by the ability of the GPR to image structures below the form-sets (Fig. 2). The heights of the dunes identified in the GPR images compare well with dune heights measured from echo-sounder data collected in April 2008 in near-average flow conditions (Fig. 3; discharge at Itati gauge ~11 500 $m^3\ s^{-1}$). Thus, the form-sets are neither significantly larger, nor smaller, than dunes formed in average flow conditions. The lengths of the dune form-sets themselves are likely to be exaggerated in the two-dimensional GPR profiles, but measured lengths are between 5 and 50 m. This is in reasonable agreement with height-length ratios below 0.06 described in the literature (Bridge, 2003) and matches other observations from bathymetric surveys undertaken nearby in the Río Paraná (Parsons et al., 2005). No form-sets were found deeper than 5 m below the exposed bar-tops, even though the GPR reflections are visible beyond this depth. Thus, these intact dune form-sets appear to be characteristic of the upper parts of mid-channel bar deposits in the Río Paraná and are not characteristic of the deeper parts of the channel and thalweg.

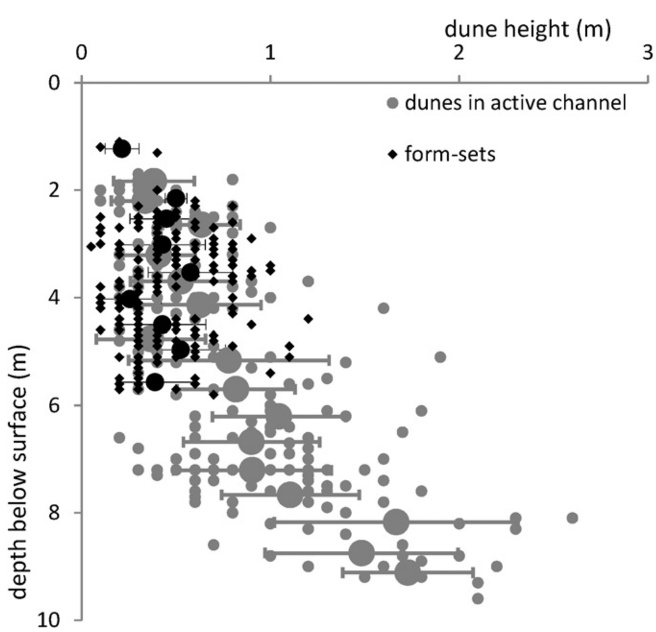

Fig. 3. A comparison of the heights of active dunes (Río Paraná near Corrientes) plotted against flow depth relative to the water surface during a near-average flow, and thicknesses of all form-sets identified in the GPR images with respect to the height of the bar surface. Error bars are standard deviation around means calculated per half meter depth interval.

3.1.1. Interpretation of the GPR form-sets

The stacking of multiple preserved dune fields in a vertical sequence suggests that multiple events are involved. The match between the dimensions of the preserved dune fields and measured dune heights in a near-average flow also indicates that the preserved dunes are unlikely formed during singular, extreme floods, during which the largest dunes may grow to 6.5 m in height in the Río Paraná (Amsler and Garcia, 1997). All form-sets are found in the upper part of the channel deposits even though GPR reflections are visible well below the lowest form-set. The elevated location of the dune form-sets, and their association with bar deposits, suggest that form-sets may occur in the sheltered, non-uniform, flow zones in the lee of bars. No form-sets were found preserved in the deposit of the channel thalweg, where flow is perennial and more uniform. Instead, the abandonment and burial of dune fields and local climbing of dune sets is restricted to the upper 5 m of bar deposits that exceed 10 m in thickness because the depth of the thalweg nearby varies between 10 and 40 m (Parsons et al., 2005; Sambrook Smith et al., 2009; Reesink et al., 2014a, 2014b). The restricted occurrence of form-sets also appears likely, because bar top and bar lee regions can be expected to experience the largest temporal and spatial changes in flow velocity and direction when flow is routed differently over and around the bars in response to changing stage levels (Bridge, 1993, 2003; Ashworth, 1996; Darby and Delbono, 2002; Miall, 1996; McLelland et al., 1999). The proportion of the deposits within which form-sets are found also matches the observations of Ashworth (1996) for the onset of significant steering of the flow around bars once bar height exceeds *c.* 55% of the thalweg depth. In addition to significant changes in flow, the burial of dunes in bar lee regions also requires sufficient sedimentation from suspension without re-initiating periods of bedload transport. The Río Paraná experiences large and prolonged changes in flow stage, which explains both rapid abandonment of dunes and the persistence of slow burial by fine-grained sediment.

4. Discussion

4.1. Abandoned and buried dune form-sets

Although there are few published examples of dune form-sets, the existing accounts indicate that intact preservation occurs through different mechanisms and for a diverse range of boundary conditions (Rust and Jones, 1987; Turner and Monro, 1987; Carling, 1996; Sambrook Smith et al., 2009; Ghienne et al., 2010; Martinius and Van den Berg, 2011). Two key controls on intact preservation of dunes are their abandonment and burial. Abandonment of dunes occurs when bedload transport ceases. Abandoned dunes exposed on bars are common in many river systems and easily found in aerial imagery (Fig. 4A-C; Collinson, 1970; Allen, 1982; Bristow, 1993a; Miall, 1996; Bridge, 2003). Large spatio-temporal changes in flow occur across bar-scale morphology in response to overall changes in discharge, and these spatial changes across bars are known to differ in their relative and absolute magnitude from those in the thalweg (Bridge, 1993, 2003; Ashworth, 1996; McLelland et al., 1999). Large absolute changes in flow depth and velocity are conducive to dune abandonment, which is illustrated by dunes that are exposed on bar surfaces (Fig. 4), by the GPR data from the Río Paraná (Fig. 2), and by the existence of large abandoned dune forms that are associated with Pleistocene megafloods (e.g. Carling, 1996; Carling et al., 2002). Furthermore, floods propagate through river channels as waves, such that the largest water-surface slopes occur during the rising stages of floods and the smallest water-surface slopes occur during the waning stage (e.g. Van Rijn, 1990; Reesink et al., 2013). The bed shear stress that drives sediment transport is a product of water depth, water-surface slope and turbulence (Bridge, 2003). Abandonment of peak-flood dunes may be promoted by decreased bed shear stresses during the waning flood stage in cases where the flood-wave slope is large relative to the mean bed slope. It follows that dune abandonment is likely to differ between shallow and steep upland rivers (abandonment likely dominated by changes in flow depth), deep and low-gradient lowland rivers (a decrease in bed slope may promote abandonment), and tidal systems (where flow is driven by the slope of the tidal wave). These kinds of spatial and temporal variations in hydrological controls remain poorly understood and require further systematic research. Abandoned and exposed dunes are a surficial feature, such that their occurrence can be interpreted as a state of prolonged 'stasis' (Tipper, 2014). Nonetheless, abandoned megaflood dunes are known to persist in the landscape over geological timescales (e.g. Carling, 1996; Carling et al., 2002). As such, megaflood dunes are a good example of the natural variability in the durations of sustained (comparatively) low flow episodes that follow formative floods.

Buried form-sets provide evidence that abandoned dunes can be preserved within fluvial and estuarine deposits. Martinius and Van den Berg (2011; Fig. 5A) show an example of a bedform that was buried rapidly by a faintly-laminated deposit generated by a breach failure composed of fine sand. Rapid burial by such a mass-movement process relies on the presence of an unstable channel bank (Van den Berg et al., 2002) to locally and temporally increase the sediment load settling from suspension, and does not necessarily require the dunes to be inactive at the time of burial. In addition to such rapid burial, alluvial bedforms are also known to be buried slowly under fine-grained sediment with low settling velocities, such as may occur following their abandonment in oxbow-lakes, bar troughs, levees and on floodplains (Figs. 5B; 2; Rust and Jones, 1987). Sambrook Smith et al. (2009) present an example of intact dunes within mid-channel bars, similar to those in Fig. 2, which they attribute to abandonment of dunes followed by burial under cohesive clay that prevents the later recurrence of erosion. Such slow burial by clay indicates that deposition from suspension can continue even though bed-load transport has ceased. The continuation of sediment transport and burial will depend on the shape and nature of the hydrograph, such as magnitude of the recession- and base-flow of a

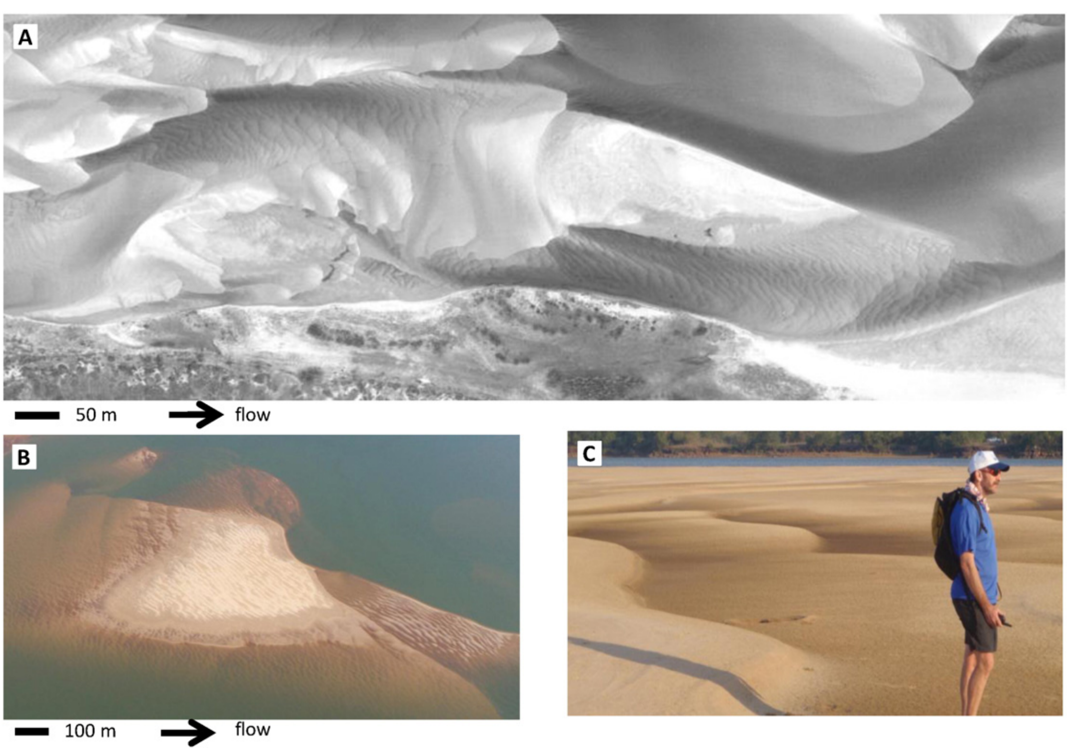

Fig. 4. Examples of abandoned dunes. A) Aerial photographs of abandoned dune fields in areas sheltered by bars, South Saskatchewan River, Canada. B and C) Abandoned dunes on mid-channel bars, Río Paraná, Argentina.

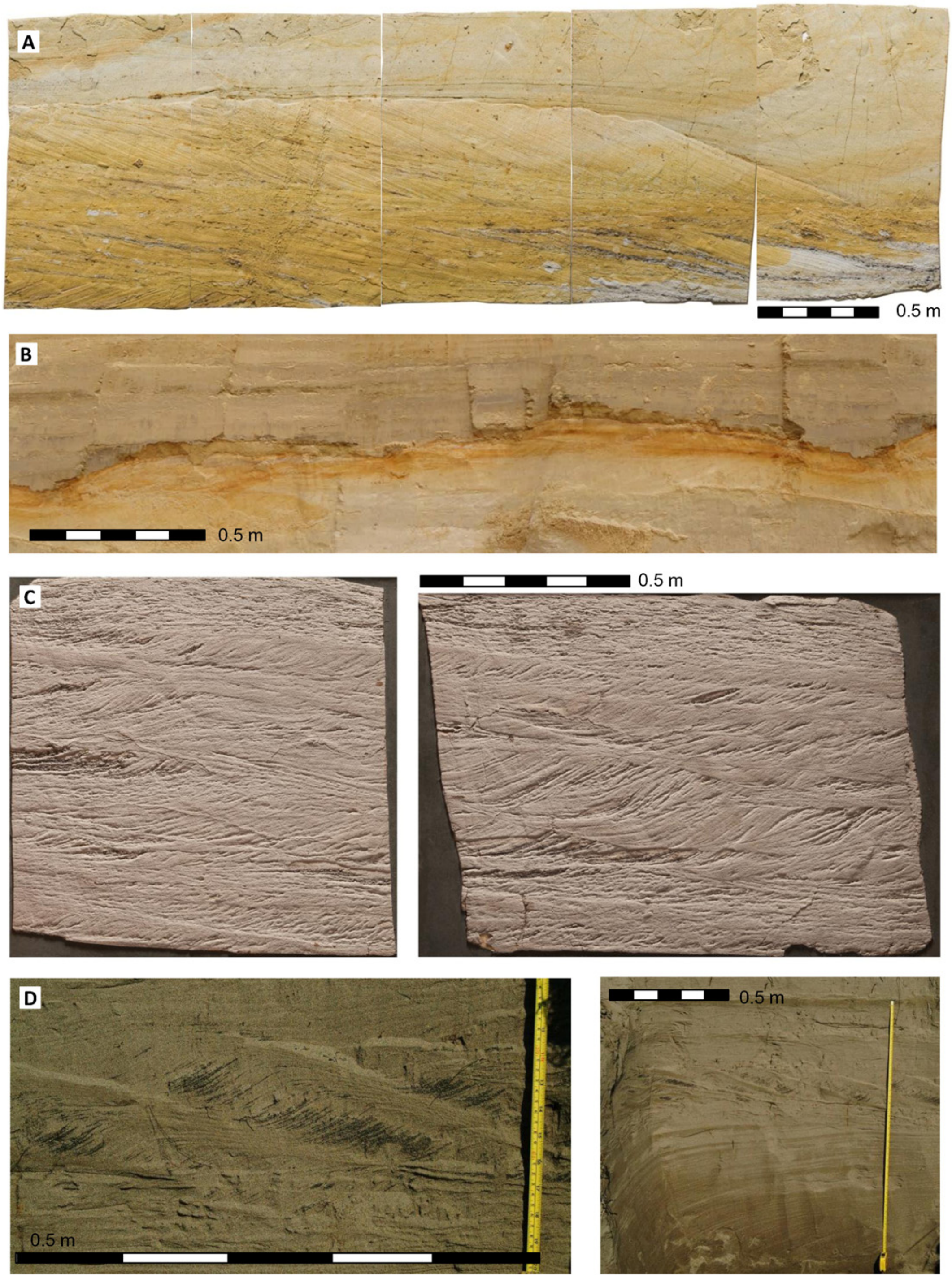

Fig. 5. Examples of form-sets. A) Lacquer peels of a preserved dune deposits within a river channel that are buried underneath turbidite deposits that originated from a channel bank breach failure (see Martinius and Van den Berg, 2011; their Fig. 3.5.8). B) Form-sets preserved under fine-grained deposits in an Oxbow lake that was abandoned suddenly. Flow right to left. Mid-Pleistocene deposits near Brüggen, Germany. Height of the dunes is approximately 0.1 m. C) Lacquer peels of climbing dune sets from lower Pliocene deposits, Tagebau Hambach, Germany. Note that the topsets cannot be traced consistently through-out the profile, which indicates variations between stoss-erosional and stoss-depositional styles of dune climbing. The two peels are adjacent to each other and represent a 45° corner, which implies that the actual inclinations of the strata and bedding are steeper than apparent in these photographs. D) Small, approximately 0.1 m high, stoss-depositional climbing dunes preserved in medium sand deposits (approx. 250 μm) of the braided South Saskatchewan River, Canada. Flow right to left, close-up section about 1 m long. Black grains are organic particles deposited on the dune lee slopes. Note the climbing dunes lie above a series of low-angle, bar-scale, downstream-dipping strata (lower 0.5 m of the section, right photo). These low-angle strata represent sedimentation on the downstream side of a bar, with the climbing dunes thus developing in this region of decelerating flow with locally enhanced vertical rates of sedimentation.

river, which may be large and long-lived in lowland rivers like the Río Paraná (Ashworth and Lewin, 2012; Plink-Björklund, 2015), but negligible or zero and of short duration in smaller rivers with flashier hydrographs. In addition, the potential for burial by fine-grained sediment is larger when suspended sediment concentrations are high. High rates of deposition may be common locally in sheltered areas, such as bar troughs (Fig. 2) and abandoned meander bends (Fig. 5B). Settling of sediment from suspension can also be temporally high, such as during the waning stages of floods (Bristow, 1987; Alexander and Fielding, 1997; Bridge, 2003; Fielding, 2006; Sambrook Smith et al., in press). Further systematic research is required to fully investigate the processes and magnitudes of sediment fallout during waning flows, the spatial geometry of the flow field and sediment transport paths, and their relation to varying flow depth and water surface slope. Local bypassing and deposition of sediment is proportional to the absolute sediment transport rate and hence greater during larger discharges, and is promoted by a greater propensity for sediment to be suspended (Ws/U*; where Ws is the settling velocity of sediment and U* is the fluid shear velocity; Szupiany et al., 2012; Nicholas, 2013; Naqshband et al., 2014). Significant time may be involved in the burial of dunes under a thick cohesive clay layer because the settling velocity of clay is typically low and suspended sediment concentrations are relatively low in most river systems. Sufficient time to allow the slow burial of form-sets by fine-grained sediment without the recurrence of erosion is more likely when changes in flow velocity are sustained over long periods of time. Such sustained periods of comparable discharge are common in the Río Paraná and other large, seasonal, lowland rivers, and less common in smaller rivers where individual, short-lived, storms can dominate the hydrograph. Thus, the observations of form-sets in the deposits of the Río Paraná indicates that their formation is associated with the local geomorphology, and promoted by prolonged changes in discharge and high rates of deposition of fine-grained sediment.

4.2. Climbing and down-climbing form-sets

In addition to dunes that are abandoned and buried, dune form-sets are found with geometries that indicate continued migration, as preserved in climbing sets (Figs. 1B; 2 label Cl; 5 CD; Ghienne et al., 2010) and down-climbing sets formed by dunes migrating down a larger-scale lee slope (Fig. 1D; Fig. 2 label Dc). Climbing and down-climbing form-sets demonstrate that continued bedform migration does not automatically generate scour that will erode the stoss slope and the upper part of the bedform. When sediment transport continues, variable scour may occur at smaller spatio-temporal scales within the sediment transport layer on the stoss slope, even though there is no net erosion. In such cases, only the average stoss-slope geometry is preserved, and evidence of higher-frequency scour recurrence is likely present within the stoss-slope deposits, similar to the case of dunes migrating over the tops of bars (Fig. 6). Set climbing is commonly described for the case of ripples (Sorby, 1859; Boersma, 1967; Allen, 1970, 1971a, 1971b; Collinson, 1970) and is common in bar troughs where migration rates are low and deposition rates from suspended bed material are high (Jopling, 1961; Reesink and Bridge, 2011). Set climbing is also commonly described for bar tops and overbank areas when flow velocities drop during the waning stage of a flood and net aggradation may substantially increase in specific locations (Bristow, 1993a; Fielding et al., 1999; Bridge, 2003; Sambrook Smith et al., in press). Such local sediment fallout during waning flow is not purely due to temporal variability in sedimentation related to a decrease in discharge, which would reflect the changes in sediment concentration within the flow. Instead, the local fallout of suspended sediment is likely the result of temporarily increased spatial gradients in sediment transport. The precise nature of such spatio-temporal sediment-transport gradients, and their associated sediment transport pathways, remains poorly understood. In contrast to climbing ripple sets, observations of climbing dune sets are relatively rare (Fig. 5 CD; Rubin and Carter, 2006; Fielding, 2006; Ghienne et al., 2010). Ghienne et al. (2010) highlight that the potential for development of climbing dune sets increases with larger suspended bed material transport rates. However, the diversity of form-sets identified herein indicates that these structures need not be unique to extreme events, but rather can be linked to spatial changes in flow velocity as controlled by larger-scale bed topography. Numerical simulations of dune migration (Jerolmack and Mohrig, 2005) indicate that a steady rain of sediment may cause dune sets to 'climb'. Although their study does not specify the spatial limits or physical causes of decreased migration and/or increased aggradation, it highlights the importance of local bypassing and the sediment transport paths that control local sediment transport rates as essential factors in set climbing (Ghienne et al., 2010; Szupiany et al., 2012; Naqshband

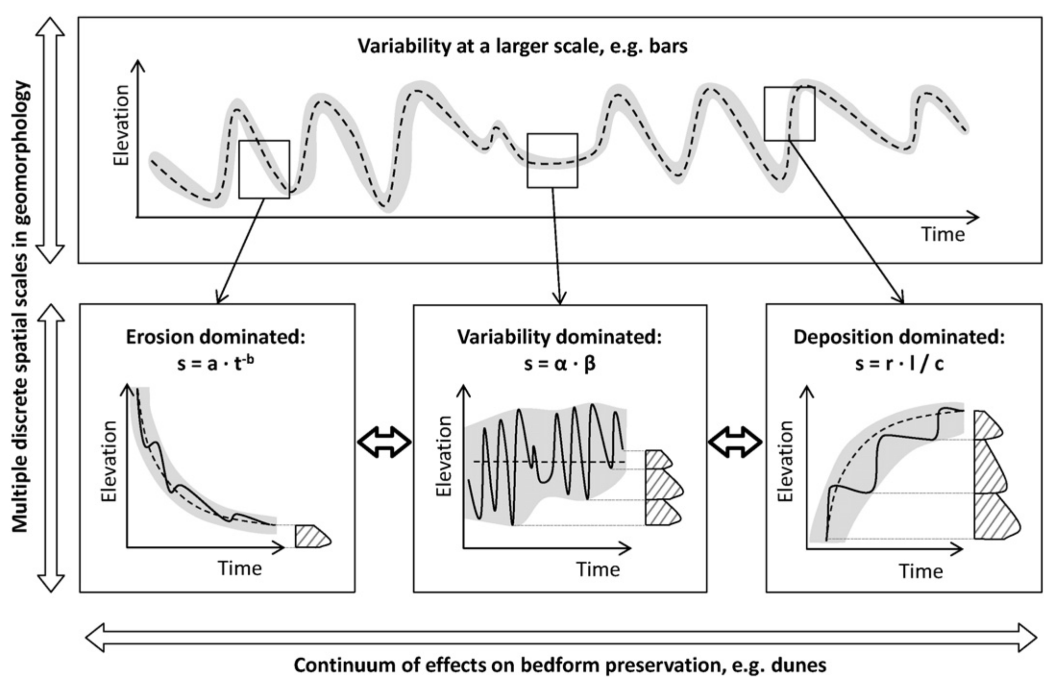

Fig. 6. Three paradigms for preservation in a sedimentary system (delimited in time and space) that experiences variability in erosional scour that is: dominance of erosion of a deposit (e.g. Gilluly, 1969), dominance of variability as a control on thickness distributions (e.g. Paola and Borgman, 1991), and dominance of deposition (e.g. Sorby, 1859; Allen, 1970). Equations are presented as examples of different shapes of trends described in literature, but are likely to vary between locations, times, and geomorphic settings. *s* is the thickness of the preserved layer (m), *a* and *b* are constants that describe the exponential loss of sedimentary strata over time, *t* is time, γ is a constant that describes the relation between the bedform height and trough scour depth, and β represents the variability in bedform height, *L* is the bedform length (m), *r* is the flux of sediment to the bed (m s^{-1}), and *c* is the celerity of the bedform along the bed (m s^{-1}).

et al., 2014). Observations from modern channels indicate that superimposed dunes that migrate down the lee slope of a host bedform decelerate and decrease in size (Pretious and Blench, 1951; Rubin and Hunter, 1982; Amsler and Gaudin, 1994; Parsons et al., 2005; Reesink and Bridge, 2007, 2009; Kostaschuk et al., 2009). This decrease in size, illustrated in Fig. 1D, indicates the deposition of sediment by the superimposed bedforms, which is consistent with a decrease in the transport capacity of the flow in the deceleration zone of the host bedform. The superimposition of bedforms is common in nature (Rubin and McCulloch, 1980), typically enhanced by bedform adaptation in unsteady and non-uniform flows (Kleinhans, 2002; Wilbers and Ten Brinke, 2003; Kleinhans et al., 2007; Martin and Jerolmack, 2013) and linked to the coexistence of different bedform types, such as dunes superimposed on bars (e.g. Haszeldine, 1982). The reactivation surfaces and inclined co-sets that are the sedimentary evidence of down-climbing are common in modern alluvial deposits (Collinson, 1970; Jackson, 1976; Rubin and Hunter, 1982; Reesink and Bridge, 2011), in GPR images (Best et al., 2003; Lunt et al., 2004; Sambrook Smith et al., 2006, 2009; Reesink et al., 2014a) and in the rock record (e.g. Jones and McCabe, 1980; Allen, 1982, 1983; Haszeldine, 1982; Røe and Hermansen, 1993; Bristow, 1993b; Willis, 1993a, 1993b, 1993c; Miall, 1996). Reactivation surfaces are bounding surfaces that can be associated with successive superimposed bedforms (Collinson, 1970; Allen, 1982; Miall, 1996; Reesink and Bridge, 2011). Trends within such successive dune sets therefore provide short records of the geometry of the host and superimposed bedforms, which can be used for qualitative and quantitative interpretations of formative flow and sediment transport conditions (e.g. Reesink and Bridge, 2011; Almeida et al., 2015a, in review). However, in core interpretations, the genetic association of successive sets, and hence the interpretation of formative host bedforms, may not be possible.

4.3. Using form-set analysis to constrain 'variability-dominated' preservation

Form-sets indicate situations where erosion does not recur, and thus invalidate the basic tenet behind models that assume that scour recurs and varies in depth over time (Eq. (2); Paola and Borgman, 1991; Leclair and Bridge, 2001). The analysis of form-sets indicates multiple processes that can affect models that assume variability in scour. For example, when dunes are abandoned, their celerity is zero and Eq. (2) becomes unusable. Climbing dune sets also illustrate that the orientation of the set does not need to equal the orientation of the river bed over which the formative dune once migrated. This discrepancy poses a problem when attempting to interpret the angle of the formative host surface of down-climbing and up-slope migrating dune sets. The discrepancy between set angle and formative bed surface angle requires a systematic investigation. In addition, the 'variability dominated' model assumes a stable probability density function in order to produce a preservation ratio (Kolmogorov, 1951). Yet, consistent changes in the size of down-slope migrating dunes show that such bedform-size distributions change in time and space. Although a preservation ratio can be used in such cases, it must not be derived by assuming a single, idealized probability density function (pdf) of scour depth (cf. Lageweg et al., 2013). The pdf of scour distribution also changes temporally in response to floods. Dune sets in the thalweg of a river may therefore represent only a restricted proportion of flood peaks and waning stages during which the dunes were at their largest (Fig. 1C; Kleinhans, 2001, 2002). Thus, near-horizontal beds in the sedimentary record may represent a temporally selective subset of the total of all flow conditions. The pdfs of set thicknesses that related to deposits of the thalweg are indeed known to differ from the overlying dune sets (Holbrook and Wanas, 2014), although the relative roles of different controlling factors that affect dune size and scour in the thalweg, such as supply limitation, secondary flow, and stage variability, require further systematic research. The pdf of scour distributions is modified differently in cases where dunes migrate into an area of flow deceleration. In cases where all dunes produce successive sets as they migrate down a bar-scale slope, the preserved sets will represent all dunes and not only a selection of the largest dunes (Haszeldine, 1982; Rubin and Hunter, 1982; Reesink and Bridge, 2009, 2011). Furthermore, the flow fields of the host and superimposed forms are known to interact (Fernandez et al., 2006; Reesink et al., 2014b), and these hydrodynamic interactions affect the relation between the heights and scour depths of the superimposed bedforms (e.g. McCabe and Jones, 1977; Reesink and Bridge, 2007, 2009; Warmink et al., 2014). The sediment transport processes on the leeside of the host bedform will also alter in association with the evolving flow field, causing a spatio-temporal variation in both deposition rate and local sediment bypassing (Jopling, 1961; Allen, 1982; Kostaschuk et al., 2009). Both experiments and field data indicate that down-climbing increases the preservation potential as it causes deposition on the host lee slope to dominate over the recurrence of erosion by the superimposed bedforms (Reesink and Bridge, 2009, 2011). In natural deposits, dune-set distributions are likely to reflect varying proportions of their formative dune distributions in response to spatial variations in flow, and are likely to reflect different formative dune distributions due to temporally varying flow conditions. In summary, down-climbing is common in rivers, its deposits are commonly preserved, and the dynamics of down-climbing violate the assumed constancy of the height distribution (β), change the relation between bedform shape and scour (γ), decrease bedform lengths (L), increase the flux of sediment to the bed (r) and decrease bedform celerity (c). It is therefore reasonable to assume that preservation ratios derived from the variability-dominated bedform-preservation model (Eq. (2)) cannot be applied in a straightforward way to non-uniform conditions, such as occur on downclimbing surfaces with bedform superimposition, and are unlikely to be suitable for unsteady flows.

4.4. Ways forward in the analysis of subaqueous dune preservation

Despite the sensitivity of the assumptions that support a variability-dominated model to non-uniform and unsteady conditions, systematic experimental verification has shown that the variability-dominated model is versatile and adaptable (Leclair and Bridge, 2001; Bridge and Lunt, 2006; Lageweg et al., 2013). Flow across bar tops appears sufficiently steady and uniform to produce near-horizontal dune sets that are similar to those developed in flume experiments (Reesink and Bridge, 2011). Restricting the application of preservation ratios to near-horizontal dune sets (e.g. $<6°$ cf. GPR facies in Sambrook Smith et al., 2006) and contrasting them against inclined dune sets may therefore present a first-order solution. The analysis of down-climbing dune sets and Eq. (2) highlights that preservation potential is particularly sensitive to changes in flow and sediment transport around bars. Locally increased deposition on bars (Lane et al., 2010; Brasington et al., 2000) produces larger-scale trends on which dune preservation is superimposed (Fig. 6). Preservation potential and the preserved set distributions can therefore be expected to vary between different regions of a channel, such as the thalweg, bar flanks, bar top, bar trough, and lee- and stoss slopes (Fig. 6). Dune-set distributions are likely grouped into bar-scale depositional units that reflect these different locations, and this may provide a simple solution for interpretations and predictions. However, it is well-established that bedforms of different scales interact hydrodynamically, even though few studies have been devoted to multi-scale processes such as bedform development in non-uniform flow (Fernandez et al., 2006; Best et al., 2013; Reesink et al., 2014b). Little knowledge is currently available on the effects of the planform morphology, or vertical flow acceleration and deceleration, on sediment transport, dune geometry, and bedform preservation potential. Moreover, although the present synthesis primarily highlights various effects of bar-scale geomorphology, bedform preservation is clearly a spatio-temporal issue (Bridge, 1993; Kneller, 1995). The spatial distributions of flow and sediment transport change as the river bed deforms over time, and respond markedly to changes in stage (Fig. 1C; Bridge, 1993, 2003; Ashworth, 1996; McLelland et al., 1999; Rodrigues et al., 2014). Individual floods are known to produce identifiable bar-scale units of deposition (Bridge, 1993, 2003) and may dominate the preservation of dune sets in the thalweg because of the growth and decay of dunes during floods (Kleinhans, 2001, 2002; Wilbers and Ten Brinke, 2003; Kleinhans et al., 2007). This implies that dune sets are grouped within identifiable units that represent comparable, or systematically changing, boundary conditions and dune-size distributions. Channel deposits are composed of a three-dimensional mosaic of such depositional units that form locally and over multiple floods (cf. Longhitano and Nemec, 2005; Ashworth et al., 2011; Lunt et al., 2013; Holbrook and Wanas, 2014). Such depositional units are commonly described from outcrops, but may be very difficult to identify in cores. The presence of depositional units that represent both comparable flow conditions *and* comparable preservation potential justifies a stratified approach in interpretations of dune preservation, bar-scale dynamics and stage-dependent deposition. Alternatively, systematic trends within set distributions might be compensated for by increasing the size of the sample, and hence considering a larger number of dunes and a broader range of conditions. Such an increase in sample size may stabilize the scour depth distribution, but inherently extends the temporal and spatial scales of the analysis. Formative dune size cannot be interpreted from an individual partially-preserved dune set in a reliable way without a consideration of its larger-scale context.

At the scale of an entire river reach, the variability in preservation potential depends on the channel planform, because dune preservation varies in response to bar-scale morphology (Fig. 6). Considerable variability in sedimentary architecture is known to exist between bars in the same reach (Sambrook Smith et al., 2006; Lane et al., 2008; Ashworth et al., 2011; Horn et al., 2012; Reesink et al., 2014a, 2014b). Variability in locally enhanced dune preservation is tied to this variability in bar morphology, such that a deposit of a few hundred meters in width or length may not be an adequate representation of the behavior of the entire river reach. Furthermore, local deposition from suspension promotes bedform burial and climbing and therefore increases preservation potential (Eq. (2)). The likelihood of locally enhanced dune preservation therefore ought to be larger for finer sands, when settling velocity is low relative to stream power, and when grain density is low (e.g. carbonate sands). These variables are known to change between reaches. In the Río Paraná, the abundance of form-sets can be associated with its hydraulic regime, the relatively fine grain size relative to its stream power, and the morphology of its bars. Thus, preservation potential is linked to the larger-scale geomorphology, is sensitive to the definition of scales, and is more variable than commonly assumed. The controlling factors and the resultant variability in locally enhanced dune preservation likely vary between reaches, between bars, and across bars, and this warrants further systematic research.

4.5. Implications for other scales and sedimentary systems

The above discussion highlights that preservation and stratigraphic completeness are controlled by the recurrence of erosion and deposition, and adhere to the conservation of mass, which is scale-independent (e.g. Barrell, 1917; Kolmogorov, 1951; Mahon et al., 2015; Fig. 1E). In fact, the ideas behind the general model depicted in Fig. 6 are originally derived from studies that range from a continental scale to individual bedforms (Barrell, 1917; Kolmogorov, 1951; Gilluly, 1969; Middleton, 1973; Allen, 1982; Rubin and Hunter, 1982; Paola and Borgman, 1991; Tye, 2004; Wilkinson et al., 2009). The multi-scale dynamics of preservation highlighted herein therefore also provides a useful context for other scales and systems. For example, tectonic motion approximates a random walk (Wilkinson et al., 2009) such that incisional channels at the base of a basin-fill sequence should be the most likely to be preserved in the geological record just as the bases of sets are the most likely parts of dunes to be preserved. Whether variability in scour also controls the volumetric abundance of facies depends on the processes that control depositional trends and the recurrence of scour at regional scales (Gibling, 2006; Weissmann et al., 2010; Hartley et al., 2010; Sambrook Smith et al., 2010; Fielding et al., 2012; Latrubesse, 2015–in press). Analysis of preservation is sensitive to the definition of temporal and spatial scales and multi-scale interactions. In a multi-scale system, individual scales do not need to have identical depositional/erosional trends (Fig. 6). For instance, a bar may be eroded in a channel that experiences net deposition, but which is located in an erosional basin. Temporal and spatial scales of sedimentary systems are linked by sediment transport: a small deposit can be eroded much faster than a large deposit. Consequently, a small depositional system is more likely to be lost over geological timescales than a very large transfer system, because large systems contain much greater volumes of sediment and therefore develop more slowly (Nittrouer et al., 2008, 2012; Latrubesse, 2015–in press). It is also unlikely that preservation is well represented by a single preservation ratio: large-scale spatial trends in deposition exist between the sediment source and depositional sink (Schumm, 1981, 1977; Holbrook and Wanas, 2014). Thus, the multi-scale model of preservation of dunes on bars (Fig. 6), and its limitations as a consequence of scale-definitions and scale-interactions, may provide a framework analysis of other sedimentary systems.

5. Conclusions

This paper presents examples of extreme cases of dune preservation, where these subaqueous bedforms are preserved intact within alluvial deposits. The abundance of intact dune fields revealed by GPR investigation of mid-channel bars in the Río Paraná, indicates that dune form-sets are more common than previously believed, and highlights the significance of bar-scale geomorphology as a control on dune preservation. Other descriptions of form-sets described in previous studies invoke rapid burial by mass-movement processes from collapsing river banks, or slow burial by cohesive clay in areas sheltered to the main flow, such as in the lee of bars and in oxbow lakes, as key processes. Downslope migration of dunes on bars influences dune height, wavelength, bedform shape and scour depth, the flux of sediment to the bed, and overall bedform migration rates: all the basic variables known to control bedform preservation. Intact form-sets indicate that sedimentary preservation varies spatially and temporally within river channels. As a consequence of such spatial variation, dune-set populations reflect both formative dune sizes *and* variable preservation potential. Dune sets are therefore likely grouped within larger-scale units that correspond to the thalweg, bar flanks, bar top, and lee and stoss slopes of larger-scale alluvial morphology. Locally increased preservation potential is likely promoted by finer grain size and by prolonged changes in stage. The sensitivity of preservation potential to scale-definitions and the multi-scale dynamics highlighted in this paper may provide a useful comparison for a wide range of sedimentary systems.

Acknowledgements

This paper evolved over many years and many discussions with supporting colleagues. We would especially like to thank John Bridge for his critique and support. We are indebted to Steve Darby, the Paraná Research Team, and in particular to Phil Ashworth, Greg Sambrook Smith, Stuart Lane and Andrew Nicholas for their support. The collection of the GPR data from the Río Paraná was supported by grant NE/E016022/1 funded by UK Natural Environment Research Council (NERC) to Ashworth, Best, Lane, Parsons and Sambrook Smith. The aerial photograph and photos of form-sets from the South Saskatchewan River are part of a larger collection assembled with support by grants NER/A/S/ 2003/00538 and NE/D005701/1 from the UK Natural Environment Research Council (NERC) to Ashworth, Best, Lane, Parsons and Sambrook Smith. Dave Rubin, Robert Dalrymple, Jaco Baas, Phil Allen and Adrian Hartley are thanked for inspiring questions and comments.

The quality of the paper was improved based on three anonymous reviews and the advice of the editors, Chris Fielding, and Paul Carling.

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