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

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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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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 indicate that water depth is commonly less important than sediment