What is the representative elementary volume of preserved dune deposits?

A.J.H. Reesink *Lancing College, Lancing, BN15 0RW, UK and Energy and Environment Institute, University of Hull, Hull, UK – ajhr@lancing.org.uk*
L. Colombera *School of Earth and Environment, University of Leeds, Leeds, UK and Department of Earth and Environmental Sciences, University of Pavia, Pavia, Italy*
D. Das *Department of Geography, University of Santa Barbara, CA, USA*
R.A. Duller *School of Environmental Sciences, University of Liverpool, Liverpool, UK*
V. Ganti *Department of Geography, University of Santa Barbara, CA, USA*
N.P. Mountney *School of Earth and Environment, University of Leeds, Leeds, UK*
D.R. Parsons *Energy and Environment Institute, University of Hull, Hull, UK*

ABSTRACT: Sediment preservation is a selective process in which preserved dune strata present themselves as the equivalent of short TikTok videos of the rock record, capturing only partial and selective information. By recognising and accounting for this bias, we can unlock the potential of preserved dune strata as a source of information on formative flow and sediment transport conditions. This paper examines the state of knowledge from recent and current publications and highlights three areas that require further systematic research. First, research is needed that examines the links between flow, form, and preserved strata with explicit emphasis on bedform scour. Herein, specific attention is also needed to examine precisely how *process-to-product models* can be used in reverse (*product-to-process*) to interpret the multiplicity of controls that shaped the rock record. Second, *multiple lines of evidence* from, e.g., depositional units associated with, e.g., dunes, bars, and floods can be used to reduce uncertainty in palaeo-hydrological interpretations. Finally, a focus on the definition of *'representative samples for preserved dune deposits'* is needed to resolve the temporal and spatial variability in preservation potential within depositional systems. The broad concepts discussed herein apply widely to all sedimentary systems, and as such, dune preservation presents an exemplary case for the wider analysis of the long-term burial or re-mobilisation of carbon and microplastics in our sediment systems.

1 INTRODUCTION

Preserved dune deposits present a rich record of the past, yet one that is incomplete and inherently biased. Precisely what palaeo-hydrological information is contained in the sedimentary record can only be interpreted reliably after the preservation bias has been quantified. The analysis of dune deposits also has a wider significance for our understanding of sediment preservation. We need to know how to use and adapt process-based and quantitative models of sedimentary preservation if we are to understand, for example, the fate of *microplastics* or predict the rate at which *carbon is sequestered* through burial within sedimentary systems such as mudflats. Thus, there exist two central questions as to what precisely controls dune preservation, and how we can adapt and use the conceptual models accounting for dune preservation for different conditions.

Preserved dune deposits present themselves as the equivalent of short TikTok videos of the rock record, capturing only partial and selective information. The preservation bias that characterises the rock record and is a crux problem in geological investigations (Barrell, 1917; Sadler, 1981; Paola et al., 2018). Recurrence of erosion is a mechanism in the ‘shredding’ of environmental signals (Jerolmack & Paola), and yet dune deposits themselves are used widely and with increasing nuance and success to reveal information on formative hydrological conditions (e.g. Wood et al., 2023; Lyster et al., 2022). These studies demonstrate, but do not constrain, the value of dune sets as palaeo-hydrological indicators.

To visualise how dune deposits are linked to the dynamic evolution of dunes, the morphodynamic feedback (Leeder, 1983) can be extended to include a unit for the sedimentary deposits (Fig. 1). This usefully highlights that the interpretation of dune deposits requires knowledge of hydraulics, and that dune deposits provide invaluable information that helps us constrain the natural form-flow dynamics of dunes. This paper examines this premise and summarises a number of gaps in our understanding of the links between ‘live’ dunes and their preserved deposits in order to define some focal points for future research.

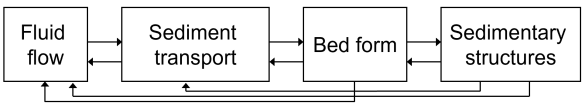

Figure 1. A simple diagram of the morphodynamic feedbacks that control the dynamic evolution of dunes and their deposits – ‘bed form’ includes scour depth.

2 PRESERVATION AS A FUNCTION OF A DUNE SCOUR DISTRIBUTION

To examine preservation, it is useful to first consider some fundamental principles. A preserved dune set, like any sedimentary bed, is defined by its lower and upper bounding surfaces: they are the deepest and second-deepest scour that occurred during the period of its formation. This observation indicates the overriding importance of *the ‘extremes’ in the distribution of scour depths*. However, this notion of extremes is contrasted against the strange ordinariness of the stratigraphic record, and in particular of river channel deposits (Paola et al., 2018).

Because of our ability to create dunes experimentally under a range of conditions, dunes have become quite possibly the most intensely studied case of sedimentary preservation (e.g. Paola and Borgman, 1991; Leclair and Bridge, 2001; Jerolmack & Mohrig, 2005). The analytical and mathematical models of sedimentary preservation (Kolmogorov, 1951; Paola and Borgman, 1991) are based on the premise that the recurrence of erosion (‘random topography’ cf. Paola and Borgman, 1991) can be linked to specific characteristics of the preserved dune-set distribution. This concept – referred to as *variability-dominated preservation* – is widely applicable to all sedimentary systems, and provides a crucial piece of knowledge for ‘hot topics’, such as the fate of microplastics in sediment systemsand carbon sequestration by means of the long-term burial of carbon-rich sediment. A flexible examination of the key premises that underpin this key model has the potential to unlock its application more widely, and a study of dunes has the potential to fulfil this important function.

The classic ‘*variability-dominated model’* of dune preservation (Paola and Borgman, 1991) describes the distribution of preserved sets as a function of the distribution of dune scour (central theory in Fig 2). The core concept of the variability-dominated model is its focus on the tail of the scour-depth distribution. Assumptions are made about the tail of the scour distribution in order to arrive at a quantitative analytical solution that links deposits back to their scour distribution. The procedure of quantitatively linking a scour distribution to the associated strata has been validated through flume-based research (Leclair and Bridge, 2001) and constrained though examination of exceptions to the rule (Reesink et al., 2015). The key weakness of this model appears to be its dependency on our understanding of relative importance of multiple co-operating controls on dune scour (Fig 1.).

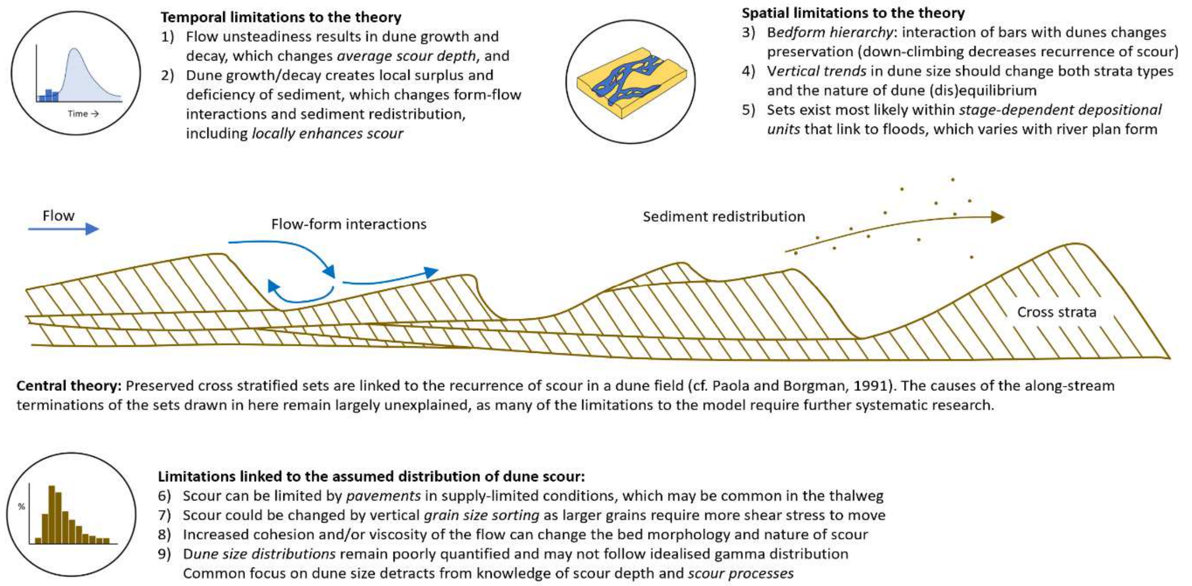

Figure 2. Review of the central theory on how a distribution of dynamically evolving dunes create selectively preserved cross-stratified sets, with a number of limitations.

3 CONSTRAINING THE VARIABILITY-DOMINATED MODEL

In research aimed at constraining the existing models, there have been three recent key advances on how dune morpho-dynamic processes affect preservation potential.

First, the '*unsteadiness hypothesis'* of Leary and Ganti (2020) examines how unsteady flow affects preservation. The greater potential for deep scour when dunes are out of equilibrium with the flow during waning flow stages (cf. Reesink et al, 2018) is likely to create a systematic bias in the preserved strata. The spread in the preserved dune set distribution (covariance) might be an indicator of the degree of disequilibrium between the flow and the dunes.

Second, the '*hierarchy hypothesis*' by Ganti et al. (2020) examines how interactions between dunes and larger-scale morphology such as bars affects preservation. It is well known that dunes decelerate and decrease in size as they deposit sediment on the low-angle lee slopes of unit bars (Reesink et al., 2015). Areas of significant net deposition are not captured properly by the variability-dominated model because the deposits are not the product of a 'distribution'. In decelerating flows, each dune deposits sediment as it *decreases in height downstream (Rubin and* Hunter, 1982). This observation highlights that dune scour, aggradation, and migration are not independent variables, which is problematic for the application of the variability-dominated model. The evidence of zones of net deposition by down-climbing dunes is common in the rock record (e.g. Haszeldine, 1983).

Third, the '*transport stage hypothesis*' by Das et al. (2022) examines how decreased scour at both low and high transport stages affects preservation. Any such change in scour depth affects the recurrence and distribution of dune scour. The conclusion herein is that set thickness may be more sensitive to transport stage than flow depth, and as such, that estimations of palaeo-flow depths based on cross stratified sets may be necessarily low in resolution. Simultaneously, dune sets may be useful as indicators of transport stage, which raises questions about what variables shape the rocks record, and which ones may be interpreted from it.

To test the viability of models derived from such experimental studies, Colombera et al. (in review) examine a large dataset of measurements of preserved cross stratified set thicknesses from different river systems. Their findings indicate that only a quarter of the investigated cases matches expectations based on the idealised variability-dominated model. The majority of the results do not follow the idealised model, nor do they indicate another simple systematic correlation between set thickness statistics and hydrological parameters. Although the absence of a clear relation between cross stratified sets and formative hydrological parameters may be in part due to the nature of a meta-analysis (Colombera et al. in review), it also highlights interesting hypotheses for further research.

First, a multitude of factors act simultaneously to create preserved dune strata (Fig. 3). When there is a multiplicity of factors or processes leading to a single product, a simple inverse interpretation may not be possible (Fig. 3). Instead, multiple parallel lines of evidence may be needed to resolve the uncertainty. Fortunately, a range of options is available, including the use of covariance alongside the mean of set thickness (Leary and Ganti, 2020) and the addition of, among others, analyses of unit-bar sets (Alexander et al., 2020), unit-bar cross strata (Reesink, 2018), and co-sets and other coherent depositional units (e.g. Reesink et al., 2014).

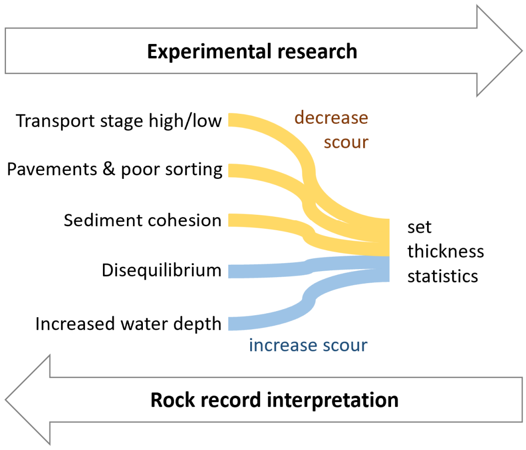

Figure 3. A multiplicity of formative factors complicates the interpretation of the rock record, necessitating the addition of further parallel lines of evidence in an interpretation.

Second, the lack of a clear correlation between preserved sets and hydrological parameters may be linked to the inherent variability within river systems. For example, river depth and width scale to discharge, and as such are perpetually re-adjusting to changes in river flow. Bridge (1993) highlighted that in addition to re-equilibration of the channel, the main zones of scour and deposition change over time and with stage. This notion has since been confirmed and expanded through field studies (e.g. Szupiany et al., 2012; Hackney et al., 2018). Furthermore, floods vary, and all perennial rivers have an ephemeral zone over the bar tops where changes in flow are much greater than those seen in the thalweg (Demyanov et al., 2019). Significant differences in dune development and scour may be expected within rivers.

4 A SIMPLE STOCHASTIC EXAMINATION

For the case of dunes, a major question appears from the recent research: *how much do dune distributions vary, and how are different scour distributions reflected in the sedimentary record?* This paper examines this question through some simple forward modelling. Figure 4 presents two contrasting distributions: 1) a gamma distribution with a

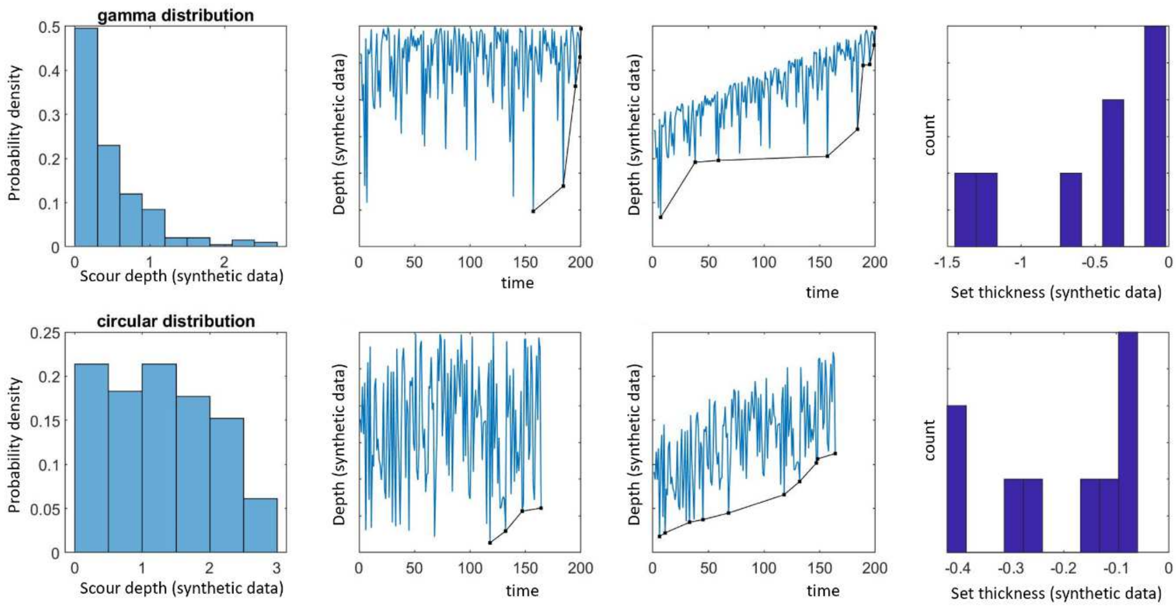

Figure 4. Two contrasting scour distributions (left), the stratigraphy they create under zero deposition and net deposition, and the thickness distribution they leave behind (right).

distinctive concave tail, and 2) a contrasting 'circular' distribution that has a finite, convex tail (a simple Monte-Carlo solution from random data with $x^2+y^2<1$). This simple stochastic modelling as makes it possible to examine how different scour distributions may be reflected within strata in the rock record.

Figure 4 shows that the contrast in the shape of the tail of the scour distribution leads to major differences in the preserved stratigraphy. A long and thin tail (Fig 4. top) is associated with fewer deep scours, and this creates greater gaps in the record, and thicker sets. The more abrupt end of a distribution's tail is associated with smaller gaps in the record, and thinner sets. The contrast between the two different tails of the scour distributions highlights the need to understand the controls on the distribution of dune scour. Dune scour distributions are known to be controlled by a number of contrasting factors, including transport stage, water depth, dune interactions, sediment cohesion, fluid viscosity, and grain-size sorting. Each factor has a different control on dune scour, thus changing the recurrence of scour and the ultimate distribution of associated strata.

The value of simple stochastic analyses is of course limited. The recurrence or erosion is not the same as a 'scour distribution' because dune sequences are not random. For example, scour depth varies with discharge. Furthermore, **'**superimposed' aggradation does not account for the fact that sediment transport occurs through dune migration – aggradation and dune migration are not independent variables. Dune sequences are constrained in time and space. However, the analysis highlights that the shape of the tail and recurrence of the deepest scours are the key. The key focus in the analysis of preserved set needs to shift away from controls on dune scour towards what determines the formation of the deepest scours in a sequence.

One key process, dune interaction, presents itself as a reasonable candidate for a *dune-scour process-hypothesis for dune preservation.* Dunes that grow compete for space, and dunes that decay have to shed sediment and split (Reesink et al., 2018). This simple premise is a foundation for thinking about dune disequilibrium, with notable implications for the nature of dune scour. If we accept that enhanced dunes scour is linked to the dynamic interaction between dunes, then it may follow that dune preservation is controlled by interactions between successive dunes. This has two major implications: 1) additional knowledge is needed on the nature of dune interactions in relation to scour; and 2) if correct, the tail of a dune scour distribution might be dominated by specific conditions – locally enhanced scours – which are hydrodynamically and geometrically constrained, and thus, can be captured as a specific adaptation of the dune scour distribution.

Additional understanding and advances are needed to constrain the temporal and spatial scales of the process to product relationships. We postulate a set of questions to the research community: (i) *at what temporal and spatial scales should we examine the recurrence of dune scour and preserved dune deposits*; (ii) *is there a representative elementary volume* for dune deposits?* Answering these questions requires a holistic flow-form-deposit approach with a focus on the evolution of dune scour, and a recognition that there is an unresolved heterogeneity in preservation potential within river deposits.

* *the smallest volume of preserved dune deposits over which a measurement can be made that will yield a value representative of the whole.*

5 CONCLUSIONS

Knowledge of dune preservation is improving, and this yields increasingly nuanced understanding of rivers in the geological past. However, the current interpretative models remain subject to significant uncertainty. Three areas that require further systematic research are identified. First, our *process-to-product models* and their inverse interpretations (*product-to-process*) require more process-based understanding, which ought to focus on the precise controls on the deepest scours as opposed to scour in general. Second, *multiple lines of evidence* from, e.g., depositional units associated with, e.g., dunes, bars, and floods can be used to reduce uncertainty in palaeo-hydrological interpretations. Finally, a focus on the definition of *'representative samples for preserved dune deposits'* is needed to resolve the temporal and spatial variability in preservation potential within depositional systems.

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