Visualizing bed deformation and sediment dispersal across dune fields

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ABSTRACT: Dunes deform as they migrate downstream over time, and this deformation is enhanced when the dunes are not in equilibrium with the flow. However, we still have an incomplete knowledge of *how* dunes deform. This study presents a cross-correlation method (cf. McElroy and Mohrig, 2009) for the visualization of dune deformation. In this analysis, dune profile length determines the spatial context of the observed deformation, and temporal resolution determines the timescale of the processes that are being visualised. Different deformation patterns indicate different sediment dispersal processes, and highlight that significantly more sediment dispersal processes exist in nature than are included in current explanations and predictions of dune dynamics. The analysis highlights that dunes act as local sources and sinks of sediment within the dune field, thus always involving multiple dunes. This paper provides both a methodology and a theoretical background for the interpretation of dune deformation, variability in sediment transport across dune fields, and enhanced deformation during bedform growth and decay under unsteady flow conditions.

1. INTRODUCTION

Dunes are known to deform continuously in rivers even in cases where the mean geometric parameters have converged to a stable value (McElroy and Mohrig, 2009). Resolving the relative importance of such natural variability, the inheritance of morphology from past events (Allen and Collinson, 1974), and spatial changes in channel morphology (e.g. Jackson 1975; Nittrouer et al., 2008) requires fundamental understanding of the sediment transport processes that cause the dunes to deform. Without understanding these processes, we can neither adequately explain dune development, nor the variability in sediment transport across dune fields. While quantifications of flow over disequilibrium dunes (e.g. Unsworth et al., 2013) and more general approaches to dune deformation are being developed (McElroy and Mohrig, 2009), our understanding of the sediment transport processes and the associated geometrical signatures of dune deformation remain underdeveloped. This paper therefore presents: 1) a method for the quantification and visualization of the geometric changes of dunes, and 2) an overview of sediment transport processes that can incite such geometric changes.

2. BACKGROUND

The growth and decay of dunes in response to changes in flow requires the removal and addition of dunes from the population, which occurs through merger and splitting (Fig. 1 A&B). Merger and splitting can create new dunes with significantly different height-length characteristics and volumes compared to dunes that are in equilibrium with the flow (Fig. 1 A&B; Yalin 1964; Jackson, 1976; Ashley 1990). Thus, these new dunes create defects within the dune pattern: local excesses and deficiencies of sediment. Experimental investigations illustrate that such defect patterns can change the dynamic feedbacks between flow and morphology because bed morphology controls time-averaged flow and turbulence characteristics (e.g. Fernandez et al., 2006), sediment transport rates, and morphological development (Reesink et al., 2014).

2.1. Sediment dispersal processes

Deformation of dunes and enhanced deformation under disequilibrium conditions require sediment to be redistributed over and among dunes (see summary in Figure 1) Bedload sediment can be suspended temporarily and therefore bypass one, or several, dunes (Fig. 1C; e.g. Naqshband et al., 2014). In cases where regions of high velocity and high-turbulence exist within the flow over the dunes (Hardy et al., 2014), sediment transport paths are likely spatially unequal. Sediment dispersal can also be achieved through differential migration of dunes (Fig. 1D; Martin and Jerolmack, 2013), or the introduction and storage of extra sediment by differential scour (Fig 1E; Gabel, 1993). Superimposition of bedforms (Fig. 1F; Best, 2005; Reesink et al., 2014) has been described as the mechanism by which sediment moves over host dunes (Venditti, 2005a), but is also inherent to bedform adaptation in the onset of splitting (Warmink et al., 2014), and as a prerequisite for through-passing of superimposed bedforms (Fig. 1G; Venditti et al., 2005b). Through-passing of superimposed bedforms may redistribute sediment as bedload when the host dunes approach a stable geometry. Dune volume can also be modified by changing dune geometry from a triangular to a humpback profile. Such changes are not captured by simple metrics such as bedform height and wavelength, but do change the flow field over the dunes (Fig. 1H; Reesink and Bridge, 2009). Finally, cross-stream sediment transfer as a consequence of three-dimensional geometry and flow (Fig. 1I; Allen, 1982; Parsons et al., 2005) can also be an important factor in sediment dispersal. These different processes span a range of temporal and spatial scales, and can be expected to result in different ‘geometrical signatures’ in the deformation of dunes.

3. METHODS

Repeat profiles of sand-bed dunes (D_{50}=239 μm) were measured in a 2 m wide x 12 m long flume at 5 minute intervals, using an Aquascat acoustic backscatter sensor (2MHz) that was mounted on a 5 m long automatic traverse (See Reesink et al., 2013 for details). The downstream and vertical height resolutions were 5 mm and 2.5 mm respectively. Data analysis involved cross-correlation of temporally consecutive streamwise bed profiles, with the maximum correlation being used to determine the mean shift of the dune profile. After removal of this shift, the difference between consecutive profiles represents the deformation of the dunes (Fig. 2; McElroy and Mohrig, 2009). This deformation, reflected by local excess deposition or excess erosion relative to the mean profile shift, is an indication of local sediment dispersal and transfer between dunes.

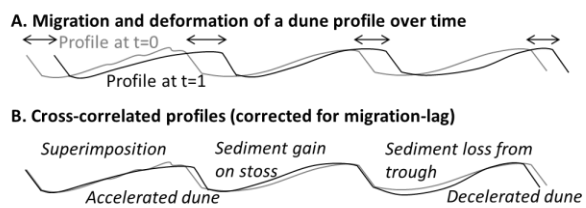

Figure 2. A) Two cross-correlated dune profiles (t0 and t1). B) Systematic deviations from the overall migration indicate that sediment has been dispersed among dunes.

4. PRELIMINARY RESULTS

Figure 3 shows a series of profiles that are coloured by the increase or decrease of erosion relative to the principal profile shift, which can be interpreted as local production or storage of sediment (Fig 2). Labels a and b indicate stoss slopes that act as sinks or sources of sediment relative to the main dune migration (cf. Fig. 1D; Martin and Jerolmack, 2013). Label c indicates an example of the persistence of sediment production in an area where a dune is overtaken and reduced. (Fig. 1A). Label d indicates that subsequent development of a train of superimposed bedforms (Fig. 1F) on the long stoss slope is located in a zone of sediment storage. Neither these superimposed bedforms, nor the zone of deposition of sediment, persists over time. Thus, these relatively large superimposed bedforms are unlikely to be a standard mechanism by which sediment moves across dunes (see Venditti et al., 2005a) and are more likely a signature of local disequilibrium morphology.

5. DISCUSSION

The results show that cross-correlation can be used to visualise the geometric signature of dune deformation. The persistence of zones of erosion and deposition over time, relative to the main migration identified by cross-correlation (Fig. 3), indicates that individual dunes can act as local sources and sinks of sediment within the dune field. Such variability in erosion and deposition affects dune tracking analyses (Ten Brinke et al, 1999), applications of the Exner equation (Paola and Voller, 2005), and interpretations of measured bedload transport rates (e.g. Frings and Kleinhans, 2008).

Dune deformation can only occur when sediment is redistributed over and between dunes. As such, dune adaptation, growth, and decay are the combined characteristic of a population of dunes, and cannot be fully described by a geometric change of a *single* dune.

The dune deformation pattern can be used to interpret sediment transport processes. The outcome of this analysis will depend on the temporal and spatial resolution of the dune profiles and the profile length. At the 5 minute resolution used herein, deformation is dominated by differential migration of lee slopes and stoss slopes that act as local sources and sinks. At larger temporal intervals, an increasing amount of local detail on the change in bed geometry is lost.

The simultaneous operation of multiple processes brings into question the idea that a single relationship can describe the adaptation of dunes to changes in flow. Differential migration and superimposition are known to change between growth and decay, as well as over time (Martin and Jerolmack, 2013). Deformation is known to change between systems, likely in response to grain size (McElroy & Mohrig, 2009). The relative magnitudes of different sediment dispersal processes are not static, but vary in time and space.

Only a few sediment transport processes are currently explicitly captured in predictions of dune development (e.g. Giri et al., 2006; Paalberg et al, 2009; Warmink et al., 2014). The method presented herein can be used to compare the magnitude and spatial signature of deformation between such predictive models and the natural dunes they represent.

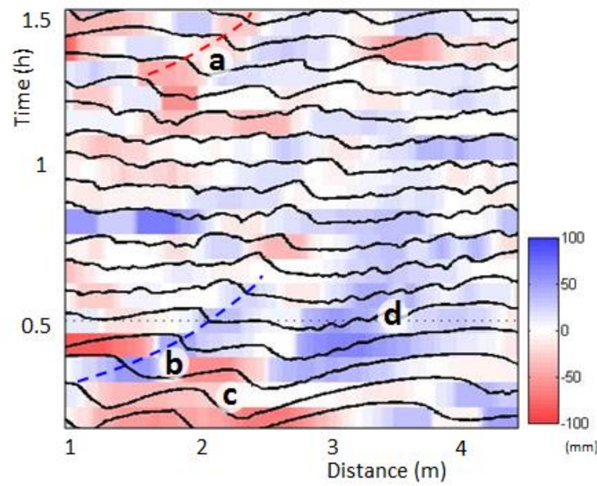

Figure 3. Successive experimental dune profiles, which were sampled at 5-minute intervals, which are coloured according to their difference in elevation after they have been corrected for dune migration (migration lag in a cross-correlation). The difference between the profiles represents excess erosion (red) and deposition (blue) relative to the overall shift of the profile. Flow depth was changed at 0.5 hours from 0.18 to 0.23m, velocity decreased from 0.66 to 0.53 m/s. See text for explanation of labels.

6. CONCLUSIONS

Dunes deform because sediment is eroded locally and dispersed across the dune field to local zones of deposition. Cross-correlation can be used effectively to visualize local dune deformation, and the geometric patterns that are revealed can be used to identify sediment dispersal processes. A review of sediment dispersal processes highlights that not all natural dune dynamics are captured in our models. This study therefore provides a method and the theoretical background to interpret dune deformation, dune adaptation, and variability in sediment transport over dunes.

7. ACKNOWLEDGMENTS

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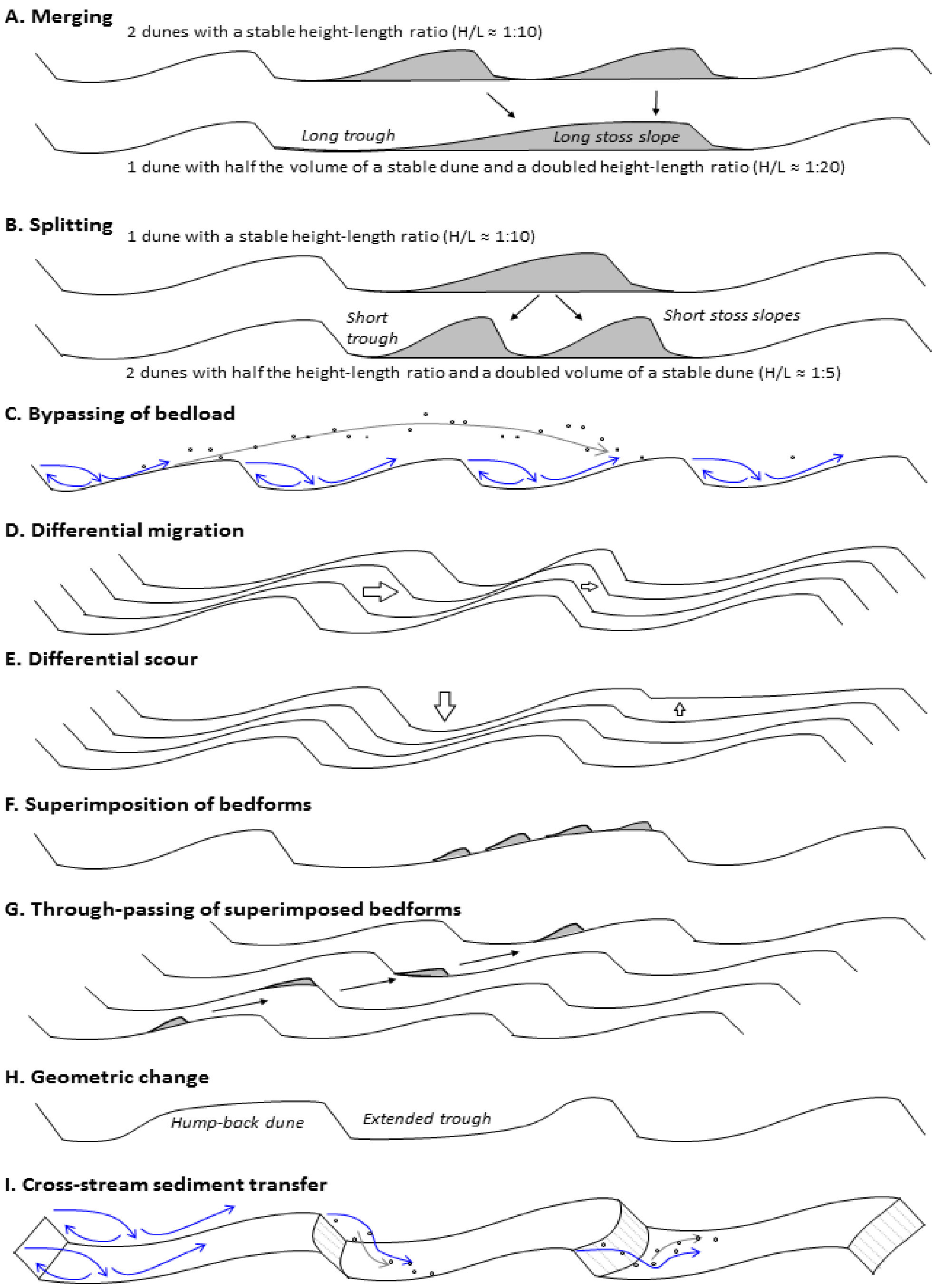

Figure 1. Processes of sediment dispersal over successive dunes. Shaded areas are bedform volumes. Blue arrows are flow. Grey arrows are sediment transport paths.