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Multi-spatial analysis of aeolian dune-field patterns

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ABSTRACT

Aeolian dune-fields are composed of different spatial scales of bedform patterns that respond to changes in environmental boundary conditions over a wide range of time scales. This study examines how variations in spatial scales of dune and ripple patterns found within dune fields are used in environmental reconstructions on Earth, Mars and Titan. Within a single bedform type, different spatial scales of bedforms emerge as a pattern evolves from an initial state into a well-organized pattern, such as with the transition from protodunes to dunes. Additionally, different types of bedforms, such as ripples, coarse-grained ripples and dunes, coexist at different spatial scales within a dune-field. Analysis of dune-field patterns at the intersection of different scales and types of bedforms at different stages of development provides a more comprehensive record of sediment supply and wind regime than analysis of a single scale and type of bedform. Interpretations of environmental conditions from any scale of bedform, however, are limited to environmental signals associated with the response time of that bedform. Large-scale dune-field patterns integrate signals over long-term climate cycles and reveal little about short-term variations in wind or sediment supply. Wind ripples respond instantly to changing conditions, but reveal little about longer-term variations in wind or sediment supply. Recognizing the response time scales across different spatial scales of bedforms maximizes environmental interpretations from dune-field patterns.

1. Introduction

The striking similarity of aeolian dune-field patterns across Earth, Mars, Venus and Titan demonstrates that self-organization within the complex system of sediment transport gives rise to similar patterns independent of differences in gravity, atmospheric pressure and type of sediment. The well-organized patterns created by dune fields are defined by regular spacing and crestline orientation and provide a means to recognize sand dunes on planetary surfaces. The presence of sand dunes, in turn, implies the production of a sediment size fraction capable of being transported by wind and the presence of surface winds that at some time were capable of transporting sediment (Greeley and Iversen, 1985; Kocurek and Ewing, 2012). Determining specific environmental signals such as wind direction, grain size, sediment supply and source area from well-organized dune-field patterns, however, has proven difficult because these signals are integrated into the organization of the pattern (Rubin and Hunter, 1987).

Approaches to extracting environmental signals from bedform patterns include mapping and measurement of ripple and dune patterns from aerial and satellite imagery (Mabbutt and Wooding, 1983; Fenton et al., 2003; Ewing et al., 2010; Bullard et al., 2011; Silvestro et al., 2013); laboratory and field experiments (Rubin and Hunter, 1987; Rubin and Ikeda, 1990; Kocurek et al., 1992; Reffet et al., 2010; Ping et al., 2014); and computer simulations (Werner, 1995; Bishop et al., 2002; Parteli et al., 2009; Zhang et al., 2010). This range of approaches, paired with increased availability of high spatial- and temporal-resolution data, has highlighted that environmental interpretations from dune-field patterns are maximized by studying variability in dune fields defined by the intersection of different spatial scales of bedforms that coexist within a dune field (Warren and Kay, 1987; Werner, 2003; Ewing and Kocurek, 2010; Bridges et al., 2012; Ayoub et al., 2014; Murray et al., 2014).

This paper examines a range of bedform patterns and processes that coexist in dune fields and that can be used to interpret environmental and climatic conditions within the context of dune-field pattern formation (Werner, 1999). Examples of bedform patterns are shown for Earth, Mars and Titan. The conclusion reached by this paper is that the composite pattern of dunes and ripples in a dune field is dictated by the stage of pattern development and the response time scales of the bedforms to changing environmental boundary conditions. Examining multiple spatial scales of bedforms in the context of the formative boundary conditions maximizes environmental reconstructions and provides a means to extract specific wind and sediment supply signals from dune-field patterns.

1.1. Multi-spatial dune-field pattern analysis

The appropriateness of a multi-spatial approach to pattern analysis arises because aeolian dune-field patterns form over a wide range of

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spatial and temporal scales and in response to environmental boundary conditions that change over wide spatial, temporal and magnitude ranges. Where different scales of bedforms coexist in a dune field, a potentially rich record of pattern forming processes and changing environmental conditions exist.

The coexistence of different spatial scales of bedforms within a dune field can be thought of as occurring within a single type of bedform or between types of bedforms. Within a single type of bedform, patterns emerge through different stages of pattern development by interactions at the fluid-grain, flow-form, and dune–dune scales (Werner, 1999; Kocurek et al., 2010). These different interactions generate distinct bed morphologies, such as dunes, protodunes, lee slope processes and dune defects (Werner, 1999; Murray et al., 2014). These bed morphologies are modified over different time scales, thus creating unique environmental records over a range of time scales. In addition to varying stages of pattern development, distinct types of bedform coexist within a single dune field, such as ripples, coarse-grained ripples and dunes. Different types of bedform arise through different formative mechanisms, respond to environmental changes over different time scales and create unique environmental records (Sharp, 1963; Andreotti et al., 2006; Yizhaq et al., 2012; Murray et al., 2014). Analysis of bedforms at different stages of development and of different types provides a means to recognize environmental changes over different time scales (Fig. 1).

Dune-field pattern boundary conditions, such as sediment supply, availability and wind transport capacity and direction change over a wide range of time scales (Fig. 1). Sediment supply, as the source material for dune fields (e.g. Kocurek and Lancaster, 1999), may be generated instantaneously, as with impact shattering, or over much longer time scales, as with uplift, weathering and erosion of bedrock (see review in Kocurek and Ewing, 2012). Sediment availability within a dune field may change spatially or temporally because of surface moisture, coarse lag, vegetation, binding, cementation, biologic or evaporite crusts (Kocurek and Lancaster, 1999). Changes in the wind transport capacity and direction may occur because of turbulent gusts (Frank and Kocurek, 1994), diurnal winds (Hunter and Richmond, 1988), storm winds (Hunter et al., 1983; Elbelrhiti et al., 2005), katabatic winds (Howard, 2000; Bourke et al., 2009; Ewing et al., 2010), monsoonal winds (Weijian et al., 1996; Loope et al., 2001; Mason et al., 2009), seasonal winds (Hummel and Kocurek, 1984; Kocurek et al., 1992), decadal to centennial wind events (Hugenholtz and Wolfe, 2005; Jewell and Nicoll, 2011; Lancaster and McCarley-Holder, 2013), millennial events (Hanson et al., 2010), and orbital cycles (e.g. tens of thousands of years), such as Milankovitch cycles (Warren and Allison, 1998; Lancaster et al., 2002) (Fig. 1).

The range of winds acting upon a dune field is typically complex despite relatively simple dune-field patterns that may emerge. Analysis of the wind patterns reveals the signal lost by looking at one scale of pattern, implies a rich climate record and motivates the need to for multi-scale pattern analysis. For example, White Sands Dune Field in New Mexico, USA displays a simple crescentic dune pattern that is nearly transverse to the overall wind regime (Fig. 2), but the wind

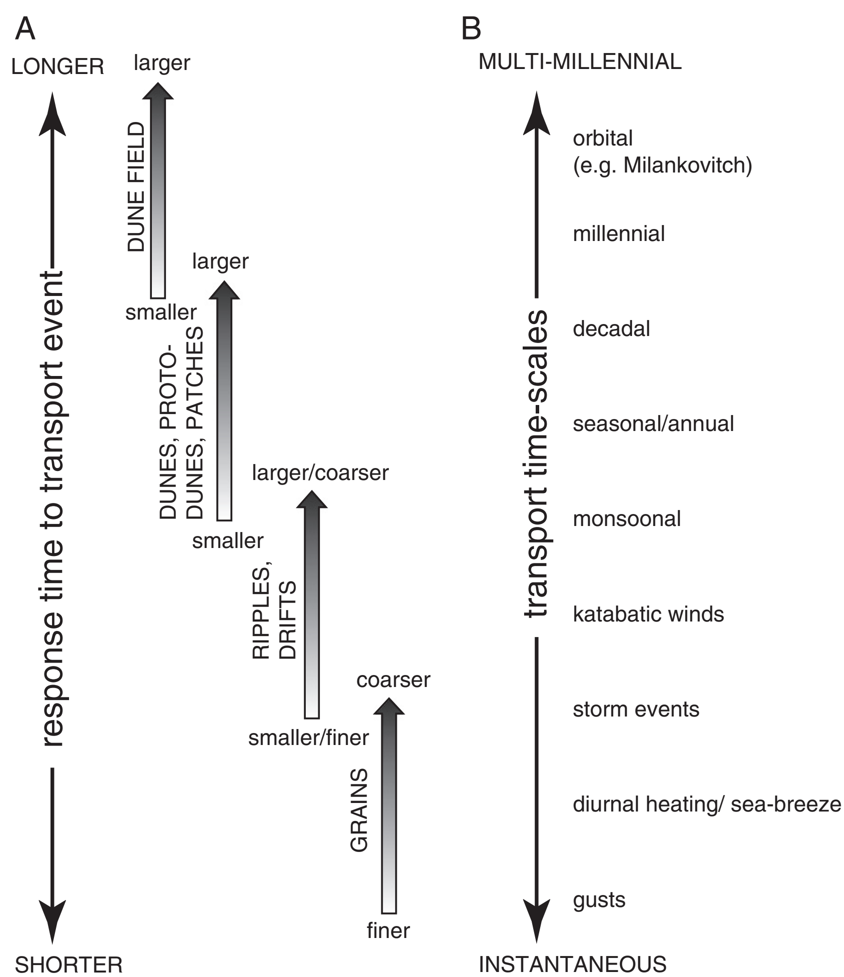

Fig. 1. Schematic showing (A) relative response time scales of different spatial scales of bedforms and (B) different time scales of transport events. Though much overlap occurs in the space and time scales of bedforms and transport events, the range highlights the potential record contained in different bedforms responding over different temporal scales within a single dune field.