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Remote sensing of spatial variability in aeolian dune and interdune morphology in the Rub' Al-Khali, Saudi Arabia

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ABSTRACT

The Rub' Al-Khali aeolian sand sea of south eastern Saudi Arabia – also known as the Empty Quarter – covers an area of 660,000 km^2 and is one of the largest sandy deserts in the world. The region is covered by the latest generation of public-release satellite imagery, which reveal spatially diverse dune patterns characterized by a varied range of dune types, the morphology, scale and orientation of which change systematically from central to marginal dune-field areas where non-aeolian sub-environments become dominant within the overall desert setting. Analysis of geomorphic relationships between dune and interdune sub-environments within 4 regions of the Rub' Al-Khali reveals predictable spatial changes in dune and interdune morphology, scale and orientation from the centre to the outer margins of dune fields. A quantitative approach is used to characterize the complexity present where large, morphologically complex and compound bedforms gradually give way to smaller and simpler bedform types at dune-field margins. Parameters describing bedform height, spacing, parent morphological type, bedform orientation, lee-slope expression, and wavelength and amplitude of along-crest sinuosity are recorded in a relational database, along with parameters describing interdune size (long- and short-axis dimensions), orientation, and style of connectivity. The spatial rate of change of morphology of aeolian sub-environments is described through a series of empirical relationships. Spatial changes in dune and interdune morphology have enabled the development of a model with which to propose an improved understanding of the sediment system state of the modern Rub' Al-Khali desert sedimentary system, whereby the generation of an aeolian sediment supply, its availability for aeolian transport and the sand transporting capacity of the wind are each reduced in dune-field margin areas.

1. Introduction

Significant advances in our understanding of the spatial arrangement of aeolian dune patterns have been made possible through the increasing availability of high-resolution satellite imagery in recent years (e.g. Blumberg, 2006; Hugenholtz and Barchyn, 2010). Aeolian dune-field patterns are a product of self-organizing systems (Kocurek and Ewing, 2005; Wilkins and Ford, 2007; Ewing and Kocurek, 2010a) in which the development of simple or complex distributions of genetically related groups of aeolian bedforms and their adjoining interdunes is characterized by systematic and predictable changes in dune type, size, morphology, orientation and spacing from dune-field centre to dune-field margin settings (Werner and Kocurek, 1997; Kocurek and Ewing, 2005; Ewing et al., 2006; Bullard et al., 2011).

Several previous studies have documented spatial variation in bedform type and associated spatial changes in aeolian lithofacies distributions in desert dune fields (e.g. Breed and Grow, 1979; Sweet et al., 1988; Kocurek and Lancaster, 1999; Atallah and Saqqa, 2004; Baas, 2007; Bullard et al., 2011). However, relatively few studies have attempted to quantitatively document the form of spatial variability of dune and interdune morphology from the centres of aeolian dune-field systems to their margins (Kocurek and Ewing, 2005; Wilkins and Ford, 2007; Ewing and Kocurek, 2010a,b; Kocurek et al., 2010; Hugenholtz and Barchyn, 2010).

This study utilizes the latest generation of public-release satellite imagery to quantify the form of geomorphic relationships between dune and interdune sub-environments in both the central and marginal parts of four modern dunes fields of the Rub' Al-Khali (Empty Quarter) of Saudi Arabia. The overall aim of this work is to document how and explain why dune- and draa-scale aeolian bedforms and their adjoining interdunes systematically change form from central to marginal dune-field areas in terms of their morphology, geometry (scale), orientation and style of bedform linkage (i.e. the extent to which interconnected and amalgamated aeolian bedform complexes are developed). Specific objectives of this research are as follows: (i) to assess the geomorphic complexity and variety of dune types present in the Rub' Al-Khali desert; (ii) to demonstrate and quantify styles of spatial variation in dune

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and interdune type and geometry for a series of major dune fields; (iii) to consider how a series of external factors that collectively define the sediment state of the system act to dictate spatial changes in dune and interdune morphology and geometry.

This research is important because understanding the morphology and architectural distribution of the deposits of aeolian dune and interdune sub-environments serves to constrain the development of models with which to explain the principal controls on desert dune distributions. Further, the establishment of spatial trends in dune morphology and geometry aids the reconstruction of ancient aeolian palaeoenvironments and guides the prediction of sedimentary architecture in subsurface stratal successions. Understanding the morphological complexity present in a range of modern aeolian desert systems is a primary control on preserved stratigraphic complexity and is the first step in developing a series of generic models with which improve our understanding of the mechanisms by which complex sedimentary architectures arise in ancient preserved aeolian successions. Thus, there exists a need to document the morphology of modern desert systems to understand how spatial morphological changes in dune type and size might impact preserved stratigraphic architecture (Mountney, 2012).

1.1. Background

Modern aeolian dune-field systems are composed of complex arrangements of geomorphic elements, including dunes, draa and interdunes, which occur on a range of scales and are characterized by a variety of morphologies and geometries (Warren and Knott, 1983; Kocurek and Havholm, 1993; Lancaster, 1994; Rubin and Carter, 2006; Ewing and Kocurek, 2010a). In many dune-field systems, the form of geomorphic elements and their relationship with adjacent elements varies systematically and predictably as a function of position within the overall aeolian system, especially in downwind directions and from the centre to outer margins of dune fields (Breed et al., 1979; Lancaster, 1983, 1994). Indeed, groups of genetically related aeolian dunes and intervening interdunes represent some best examples of patterned landscapes in nature (Kocurek and Ewing, 2005).

Few aeolian desert sand dunes exist in isolation. Most cluster, with many examples forming large dune fields in which systematic patterns of groups of genetically related dunes can be recognized, in some cases repeating with spatial regularity or with one or more defining attribute of the dune-form changing progressively in a given direction from, say, the centre of a dune field to its margin. Groups of dunes collectively form larger geomorphic elements typically referred to as sand seas, dune fields (Livingstone and Warren, 1996) or ergs (Wilson, 1973). Although Cooke et al. (1993) define the lower size limit for a sand sea at 30,000 km^2, this being an inflexion point on the distribution curve of sand-sea size given by Wilson (1973), in modern usage (post-1995), no lower size limit is formally applied by way of definition.

Dune fields are not necessarily continuously covered with active aeolian sand dunes and most additionally include other morphological bodies of aeolian-derived or aeolian-related sediment deposits, including interdunes, sand sheets (which lack distinctly recognizable larger bedforms), areas of soil cover, lacustrine systems (e.g. playa lakes), and fluvial systems (typically ephemeral), some developed between active aeolian dunes (Lancaster, 1989). Thus, dunes in sand seas, including those in the Rub' Al-Khali, are commonly separated from each other by geomorphic elements whose well-defined shapes are, in part, dictated by the shapes of adjoining dune bedforms of different types (e.g. McKee and Bigarella, 1979).

The construction of aeolian dune-field systems and the spatial variation in the form of their internal components (e.g. dunes and interdunes) from central to marginal areas is governed by numerous controlling parameters that dictate sediment state (Berg, 1986; Kocurek, 1998, 1999; Kocurek and Lancaster, 1999). At a regional scale, the sediment state of aeolian dune fields is defined by separate components of sediment supply, sediment availability and transport capacity of the wind (Kocurek and Lancaster, 1999), and together these factors govern where and when aeolian system construction via the growth of dunes occurs.

1.2. Study area

The Rub' Al-Khali of south-eastern Saudi Arabia – also known as the Empty Quarter – is one of the largest continuous sand deserts in the world and comprises a series of dune fields, some spatially discrete and some merging into neighbouring fields, within which self-organised patterns of aeolian bedforms and adjoining interdunes are developed (Bishop, 2010). The name for the Arabian desert – Rub' Al-Khali or the Empty Quarter – was introduced by the Swiss geographer Burckhardt (1829) in his book "Travels in Arabia" and used later by Doughty (1888). Early research by Thesiger (1949), Beydoun (1966), Holm (1960, 1968), Glennie (1970) and Breed et al. (1979) each documented the presence of different bedform types and noted general spatial variations in dune types between different parts of the overall desert system.

In total, the Rub' Al-Khali covers approximately 660,000 km^2, rising to 776,000 km^2 of continuous active sand cover if adjoining sand seas (e.g. Jafura, Dahna and Nefud in Saudi Arabia) are additionally included (Breed et al., 1979; Edgell, 1989, 2006). Indeed, the wider desert region, which additionally incorporates the Wahiba Sand Sea of the Sultanate of Oman (Laity, 2009), covers an area of 795,000 km^2. Within the main the Rub' Al-Khali, active aeolian dunes and interdunes cover an area of 522,340 km^2 (Edgell, 2006), extending from United Arab Emirates and Oman in the east, to south-western Saudi Arabia and northern Yemen (Fig. 1; Wilson, 1973; Glennie, 2005; Edgell, 2006). The largely unconsolidated sand dune deposits of the Rub' Al-Khali are characterized by large bedforms (dunes and draa), individual examples of which range from 50 to 300 m in height (Brown et al., 1963; Abd El Rahman, 1986; Edgell, 2006), and the majority of which are each separated by broad interdune flats, some up to 5 km in width in dune-field margin settings (Fig. 2). The majority of the Quaternary sediments of the Rub' Al-Khali are composed chiefly of aeolian-reworked Pliocene alluvial sediments (McClure, 1978), though a secondary sand component is likely to have been additionally sourced from local modern alluvial (wadi) sediments (Holm, 1960; Brown, 1960).

The Rub' Al-Khali basin is a combined physiographical and tectonic feature (Bagnold, 1951; Powers et al., 1966; McClure, 1976, 1978; Edgell, 1989; Clark, 1989) that forms a structural depression characterized as an embayment with a structural axis trending from northeast-to-southwest, bordered to the northwest and west by the Arabian Shield, and to the south and southeast by the Hadramawt–Dhofar Arch or Plateau (Fig. 1b). The northern end of Rub' Al-Khali basin opens into the Arabian Gulf through the United Arab Emirates (Edgell, 2006). The desert is additionally constrained by the arc of the Oman Mountains to the northeast and by the Qatar Arch to the northwest (Fig. 1b). The area occupied by active sand seas extends from the United Arab Emirates and Oman in the east, to south-western Saudi Arabia and the area directly north of Yemen.

1.3. Quaternary evolution of the Rub' Al-Khali

The Rub' Al-Khali formed in response to cyclic episodes of aridity driven by climatic fluctuations throughout much of the Quaternary period (Edgell, 1989, 2006; Glennie, 1998; Goudie et al., 2000). The application of optical dating methods to sand samples