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Morphodynamics, boundary conditions and pattern evolution within a vegetated linear dunefield

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ABSTRACT

The controls on the evolution of linear dunefields are poorly understood, despite the potential for reactivation of dunefields, which are currently stabilized by vegetation, under the influence of 21st century climate change. The relative roles of local influences (i.e. boundary conditions) and morphodynamic influences (i.e. emergent properties) remain unclear. Chronostratigraphic and sedimentological analyses were conducted on two pairs of linear dunes exhibiting different spatial patterning in the Strzelecki Desert of central Australia. It was hypothesized that morphodynamic influences, via pattern-coarsening, would mean that dunes from the simpler pattern, defined in terms of the frequency of defects (i.e. junctions and terminations), would be more mature, older landforms. Optically Stimulated Luminescence (OSL) dating of full-depth, regularly-sampled profiles was used to establish accumulation histories for the four dunes, and supported by sedimentological analysis to investigate possible compositional differences and similarities between the dunes. Whilst three of the dunes (the two more simply-patterned dunes, and one of the more complex dunes) have accumulation histories beginning between ~100 ka and 150 ka, and document sporadic net accumulation throughout the last interglacial/glacial cycle to the late Holocene, one of the dunes (with relatively complex patterning) reveals that the majority of the dune accumulation (>7 m) at that site occurred during a relatively short window at ~50 ka. There is no clear sedimentological reason for the different behaviour of the younger dune. The data suggest that small-scale and essentially stochastic nature of the aeolian depositional/erosional system can overprint any large-scale morphodynamic controls. The concept of dating landscape change by pattern analysis is thus not supported by this study, and would require very careful interpretation of the scales being considered. This further suggests caution when interpreting dune chronostratigraphies palaeoenvironmentally, as different dunes are able to respond very differently to the same external stimulus (e.g. climate). In the case studied here, a mechanism is proposed to account for the rapid accumulation of the anomalous dune by avulsion of the local aeolian accumulation from one dune ridge to another.

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1. Introduction

Linear dunes, when viewed from above in planform, are one of the world's most strikingly organized landscapes, yet the controls on patterning within dunefields in general and, in this case, linear dunefields are still poorly understood. In addition to being found in some of the world's hyper-arid deserts (e.g. Sahara), linear dunes are a widespread component of the landscape across many semi-arid and arid lands, such as central Australia and central southern Africa, in less-active forms. Yet understanding of the formation and evolution of linear dunes at the landform and landscape scale is still far from complete. Absolute dating with luminescence methods has revealed that these landforms often maintain their position on the landscape over $>10^4$ years, yet may still experience substantial aeolian activity and reworking at decadal to centennial timescales (Telfer, 2011; Roskin et al., 2014). Whilst some linear dunes may be formed by sediment transport orthogonal to the dune trend by lateral deflation from local sands (Hollands et al., 2006; Rubin et al., 2008; Fitzsimmons et al., 2009), it is also evident that they can grow by downwind extension (Telfer, 2011; Lucas et al., 2015); and can also migrate laterally (Nanson et al., 1992a; Bristow et al., 2000). Some of these apparent contradictions may be resolved by consideration of the concept that linear dunes are self-organising phenomena, operating within the complex morphodynamic system formed by interactions within and between the turbulent atmospheric boundary layer and an erodible loose-sand

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substrate. As such, it is not to be expected that such landforms necessarily have singular and unique formational routes, but that the observed planform patterns might be the result of equifinality; part of the non-equilibrium worldview of Philips' 'perfect landscape' concept (Phillips, 2007). The concept of dune morphologies as attractor states within the phase-space of this system was proposed by Werner (1995), and has since been developed by numerous others (e.g. Eastwood et al., 2011; Ewing et al., 2006; Kocurek and Ewing, 2005). Different dunefield patterns may thus represent the outcomes of different trajectories, or different stages along a trajectory, through the phase-space of the complex aeolian system. The concept of attractor states can be extended not just to differences between gross dune morphologies (e.g. between transverse, barchans and linear forms), but also between different patterns within linear dunefields.

Understanding the development of linear dunefields is important for a number of reasons. Firstly, there have been suggestions that some of the world's linear dunefields (e.g. the Kalahari), which are currently largely inactive and host to extensive rural pastoralism, could be subject to intense aeolian reactivation by the end of the current century under the influence of anthropogenic climate change (Thomas et al., 2005), and yet the processes of dune remobilisation are poorly understood. Secondly, attempts to use linear dunes as archives of palaeoenvironmental change have been hindered by poor understanding of the geomorphology of these landforms (Chase, 2009; Hesse, 2010; Thomas and Burrough, 2012; Zarate and Tripaldi, 2012; Telfer and Hesse, 2013). If there is to be hope of exploiting linear dunes as geoproxies of useful past environmental information, improved understanding of their landscape-scale behaviour is needed.

1.1. Morphodynamic effects: pattern coarsening within linear/longitudinal bedforms

Modelling and experimentation suggests that the concept of pattern coarsening, whereby highly disorganized patterns become simpler over time, is likely to be a dominant control (Ewing et al., 2006; Andreotti et al., 2009; Ewing and Kocurek, 2010; Fourriere et al., 2010). Rubin and Ikeda (1990) observed pattern coarsening in linear ripples in flume experiments. Studies from other components of the Earth system which demonstrate self-organizing characteristics, ranging from semi-arid vegetation (Barbier et al., 2006; Kefi et al., 2007; Scheffer et al., 2009), to fluvial geomorphology and channel form (Hooke, 2007) also suggest that pattern coarsening can affect systems as diverse as vegetation patchiness and fluvial sedimentation (Seminara, 2009). In linear dunefields, pattern evolution results from the formation, migration and annihilation of defects, and typically results in upwind-branching (or downwind-converging) networks of junctions, although the evolution of pattern is complex due to the highly inter-related nature of defect location and movement (Werner and Kocurek, 1999). Using a probabilistic numerical model, these authors were able to demonstrate that defects migrate through the dunefield (upwind-facing defects migrating downwind, and vice-versa), and that in their simulation, 50 ka was sufficient to eliminate all defects. Such rates, however, are likely to be highly dependent on additional factors stabilizing the dunes, such as vegetation.

Although there is sound theoretical justification for expecting pattern coarsening to be observed in the remarkable spatial patterning of desert dunes, there is little field validation of the phenomenon in comparison to the wealth of observations from models. Beveridge et al. (2006) is a notable exception and demonstrated changing wind regimes during the late Pleistocene and Holocene have resulted in multiple generations of dunes of different morphologies. In part, this is due to the timescales involved in pattern reorganisation within dunefields. Whilst landscape-scale experimentation of unvegetated dunefield has revealed that they may form and organise on timescales of months-years (Ping et al., 2014), vegetated linear dunefields are known to have formed over Late Quaternary timescales (e.g. Telfer and Hesse, 2013). As landscape-scale experimental plots such as that of Ping et al. (2014) have substantial logistical challenges, space-time substitutions offer another solution to the challenge of investigating such slow-forming landscapes (Ewing and Kocurek, 2010). Qualitatively, pattern coarsening has been observed in some linear dunefields; the widely spaced, rarely-branching dunes of the northern Kalahari are known to be in general older, more mature landforms (Thomas et al., 2000; Thomas et al., 2003; McFarlane et al., 2005) compared to those of the intricately-patterned southern Kalahari (Telfer and Thomas, 2007; Stone and Thomas, 2008). Indeed, this raises the further question as to whether such landscapes are prone to de-coarsening, or pattern degradation, either locally or at a regional scale. However, comparisons of globally available data on dune pattern morphometric analysis with geochronological data from the published literature suggest that pattern coarsening alone does not appear to explain the diversity of morphologies observed (Telfer and Hesse, 2013).

1.2. Boundary controls: Local spatial variability within the dunefield

Whilst models such as Werner and Kocurek's (1999) are able to entirely control boundary conditions, in reality the process of pattern evolution is likely to be influenced by a wide range of boundary conditions. Beveridge et al. (2006) note the role of heterogeneity of sediment supply, which has long been recognised as a control on dune morphology. Sediment supply, along with topography has also been recognised as being implicit in linear dunefield pattern evolution in the vicinity of dry valleys in the southwestern Kalahari (Bullard and Nash, 1998, 2000). The southwestern Kalahari also demonstrates localized variability which has been attributed to vegetation, and the role of both grazing and fire on the landscape (Bullard et al., 1995). Throughout the Strzelecki dunefield, there is also more localized variability related to topographic and hydrological obstructions, as well as the nature of the substrate (Fitzsimmons, 2007). Whilst we have attempted to minimize such variability in our chosen study sites in order to explore the relative roles of autogenic and allogenic influences, it is not possible to entirely control such factors in reality.

1.3. Aims and rationale

This study therefore aims to investigate the relative roles that internal (morphodynamic) and external (boundary condition) factors play in process of pattern development over time in linear dunefields. It is hypothesized that morphodynamic pattern coarsening might exert a first-order control on the age and nature of linear dune accumulation. Two nearby (~15 km) pairs of linear dunes from the Strzelecki desert, central Australia, each pair from an area with markedly different planform patterning, were therefore sampled for geochronological (using Optically Stimulated Luminescence, OSL, dating) and sedimentological analyses. Pattern complexity is defined here in terms of the number of defects to pattern (i.e. junctions and terminations) per unit area (and is thus also influenced by dune spacing). Sites were selected in close proximity to each other in order to minimize the possible effects of other controlling variables, such as past variations in climate; it can be assumed here that such changes are synchronous between the pairs of sites.

1.4. Study area

The Strzelecki desert is characterized by vegetated linear dunes and occasionally other dune forms, at the eastern edge of the Lake Eyre basin (Fig. 1) (Fitzsimmons, 2007). Interdunes are sometimes sandy, sometimes have clay soils and pans (both of which are seen at the study sites; Fig. 2), and some are composed of stony (gibber) pavement (Fitzsimmons, 2007). The main Strzelecki dunefield is centred around the tri-state boundary of New South Wales, South Australia and Queensland, to the south and west of the town of Innamincka. As part of the whorl of continental dunes that characterize the continental interior of Australia, it consists primarily of linear dunes with net annual sand-transporting wind from the south and southwest (Jennings, 1968;

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