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Invited review

# Palaeoenvironmental reconstructions from linear dunefields: recent progress, current challenges and future directions

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ABSTRACT

This paper reviews recent progress in the use of linear dunes as ‘geoproxies’ of late Quaternary environmental change, summarises the challenges facing their use, and explores some potential solutions to these challenges. Large areas of the swathes of linear dunes which occupy the continental interior of southern Africa, Australia, and parts of central Asia and southern America currently have limited or negligible aeolian activity. They have been recognised as offering potential information about past environments for more than a century, but only with the widespread application of luminescence dating during the 1990s did they realistically start to offer the prospect of being an extensive, dateable proxy of late Quaternary palaeoenvironments and, possibly, palaeoclimates. Dating aeolian dune sands with luminescence methods is generally (although not always) relatively straightforward. Over the past twenty years, a large number (>1000) of luminescence ages have been added to the global dataset, yet there has also been significant criticism of some of the rationale underpinning much of the interpretation of the records derived. At the landscape scale, developments of arguably equal importance have come from improved geomorphological understanding based on the wider availability of remotely-sensed data and the paradigm of dunefield evolution as a self-organising complex system. Current challenges are identified in three key regions: incomplete understanding of how the process geomorphology of linear dunes affect the accumulation and preservation of sediment, a lack of clarity regarding the temporal and spatial scale of the response in a dynamic environmental setting and uncertainty surrounding the drivers of changing rates of net accumulation. Solutions to these challenges lie within diverse research methodologies. Certainly, further field study is required, with improvement required in understanding system responses to changing environmental stimuli at scales from sedimentological to landscape. In parallel, the full implications of complex systems approaches to aeolian geomorphology for linear dunes lag behind the adoption of the concept to some other dune forms (e.g. barchans); the relationship between observed dune complexity and age from field data complicates previous suggestions that dune patterning may be purely a function of development time. Parallel to this lies the need to improve interpretation of the results of dune geochronological studies; a suggestion is offered which aims to test the statistical significance of dune accumulation time-series by comparison with a modelled system with unchanging external forcing. Despite the initial promise of linear dune records as a revolutionary source of palaeoenvironmental information in drylands, the outcomes to date have been coarse, although still valuable, in resolution. Perhaps the most valuable realization has been that geomorphological understanding of these widespread landforms is incomplete.



## 1. Introduction

The prospect of an abundant archive of dateable palaeoenvironmental information in the world’s arid and semi-arid regions is an appealing one. These dryland areas are typically characterised by a paucity of the resources on which our understanding of late Quaternary environmental change in more temperate zones has been built. The dry climate of the world’s arid zones is not conducive to the formation of bogs or perennial lakes, speleothem formation is at best sporadic, and in many continental regions even the nearest ocean core records may be thousands of kilometres distant. However, it has been noted since the late 19th

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century (e.g. Gilbert, 1890; Russell, 1895; Passarge, 1904) that there is widespread geomorphological evidence that these regions have responded to the climatic fluctuations of the Quaternary in just as dramatic a manner as the higher latitudes. For instance, in many of the world's desert-marginal regions (including central southern Africa, much of Australia, many parts of the central Asian deserts, the Sinai-Negev, and to a lesser extent, the arid margins of both the North and South American continent) extensive fields of vegetated and largely inactive dunes appear to suggest past conditions of greatly enhanced aeolian activity.

Sixty years have passed since E.J. Wayland wrote of the Kalahari's linear dunes that "… one gets the impression that the desert is returning to its own, and in my opinion this impression is no mere idle one. The rains that fixed the dunes (they have been fixed and unfixed more than once) were superimpositions upon a long-lasting desert regime" (Wayland, 1953). The potential for the southern African dunes to serve as geomorphological proxies of environmental change was made explicit by Grove (1969), yet despite the development of absolute radiometric dating methods, and much progress in the understanding of earth systems on long and short timescales, a spatially and temporally detailed understanding of the history of the Kalahari's linear dunefields remains elusive.

This is not a problem confined to the Kalahari. Linear dunes are believed to be the most common form of desert dune (Lancaster, 1995), and they can be found in climatic regimes ranging from the hyper-arid deserts to areas that are presently sub-humid (e.g. parts of the northern China and south-eastern Australia). This range of climatic settings is echoed in a wide range of dune morphologies, from the unvegetated and meandering seif dunes most commonly found in the driest of regions (e.g. Tsoar, 1983, 1984), to densely-vegetated, heavily degraded dunes with little or no aeolian activity occurring at present (e.g. McFarlane et al., 2005). Linear dunes are generally considered to form parallel to the net sand-transporting wind vector (Bagnold, 1941; Tsoar, 1983), and hence are sometimes also referred to as longitudinal dunes. The potential for dunes to act as 'geoproxies' of environmental change, to use an apt term coined by Thomas and Burrough (2012), is most evident from these dunes that exist in climatic regimes not currently conducive to aeolian activity. Although once identified as 'relic' or 'fossil' dunes (e.g. Butzer, 1957; White, 1971; Goudie et al., 1973), such terms are generally better avoided, as it has become increasingly clear that not only do such dunes have the potential to reactivate if climatic conditions are suitable (Forman et al., 1992; Muhs and Holliday, 1995), but also that the line separating 'active' from 'inactive' dunes is not a well-defined one (Livingstone, 1989).

Perhaps the single most important development in the use of dunes as geoproxies has been the development of luminescence dating as a means of absolute age control for the burial of certain minerals, most notably quartz (Singhvi and Porat, 2008). Understanding of the temporal evolution of dunefields had been hampered by extremely poor dating control, due to the lack of material for alternative dating methods (such as radiocarbon) and the poor preservation of both internal and relative stratigraphic context. Luminescence dating took twenty years of sporadic development to attain a degree of maturity, from Singhvi et al.'s (1982) landmark use of thermoluminescence to directly date the sands of the Thar Desert, to Murray and Wintle's (2000) refinement to Optically Stimulated Luminescence (OSL) methods using the Single Aliquot Regenerative (SAR) protocol. Although development in luminescence dating methodology continues apace today, the SAR protocol for optical dating of aeolian quartz usually offered a routine and 'off-the-shelf' method when applied to desert sands, which are often considered an ideal medium for the technique. Linear dunes appeared to offer the greatest potential for preserving a long record of past aeolian activity, as their relative immobility on the landscape was seen to offer a chance for sediment to accumulate as 'stacked' records (e.g. Gardner et al., 1987; Readhead, 1988; Nanson et al., 1992b; Stokes et al., 1997; O'Connor and Thomas, 1999).

As the size of the suites of ages from dunes grew, and the rigour of the sampling strategies increased, dune ages began to make a significant contribution to a number of syntheses of dryland regions, drawing from a wide range of palaeoclimatic and palaeoenvironmental archives, and covering parts of Africa (Thomas and Shaw, 2002; Gasse et al., 2008; Chase and Brewer, 2009), Australia (Hesse et al., 2004; Fitzsimmons et al., 2013), Asia (Feng et al., 2006) and the whole southern hemisphere (Munyikwa, 2005a). Although in Australia the record of dune activity and palaeoclimate had generally been seen as broadly coherent (e.g. Hesse et al., 2004; Fitzsimmons et al., 2007b), southern Africa was proving more problematic. Instead of providing a panacea in resolving apparently conflicting evidence in the existing palaeoclimatic record (e.g. Thomas and Shaw, 2002), a number of studies began to suggest that the use of dunes as a palaeoenvironmental or palaeoclimatic proxy may not be as straightforward as was once hoped. Questions were raised as to exactly what dune accumulation records were a proxy for (e.g. Chase and Thomas, 2007; Chase, 2009), and whether existing sampling strategies were adequate to account for the evident gaps in preservation (e.g. Telfer and Thomas, 2007; Stone and Thomas, 2008). Many aspects of the difficulties of attempting such syntheses have been recently summarised by Thomas and Burrough (2012), who suggest that much of the contradictory evidence in the syntheses may be a function of spatial or temporal extrapolation. In short, the use of dunes as geoproxies of Late Quaternary environmental and/or climatic change is not straightforward.

This paper aims to summarise recent developments in the use of linear dunes as geoproxies, outline the key issues which are currently challenging attempts to derive palaeoenvironmental data from dunefields of the world, and offer a few potential solutions to these challenges.

### *1.1. Scope of this review*

The emphasis of this review is on linear dunes specifically, principally as they have been the main focus of work to date, as their perceived stability has been seen to have the most potential to offer long-term records (Thomas, 2013), and also as they are amongst the most widespread and abundant of desert dune types (Lancaster, 1995). Such long-held assumptions have recently received support from experimental modelling (Reffet et al., 2010), which have demonstrated greater long-term inherent stability in linear morphologies than barchanoid transverse dunes. Linear dunes are broadly synonymous with the term 'longitudinal dunes', with the former definition based on purely geomorphic grounds, whilst the latter offers a morphogenetic perspective. Neither term is unproblematic, as transverse dunes and coastal dune cordons are frequently 'linear' in planform. Similarly, whilst it is often assumed that linear dunes form longitudinal to net annual sand transport potential, this can be complicated by several factors. For instance, Atkinson et al. (2011) demonstrated that two sets of dunes in the Eastern Rub al'Khali, which are currently perpendicular to each other, are both likely to have been formed longitudinally to the prevailing wind regime at the time of their main period of accretion. Reffet et al. (2010) also simulated co-existent transverse and longitudinal dunes in experiments under alternating wind regimes at the critical value of 90°. When alternating winds diverged by more than 90° longitudinal dunes were formed and when winds diverged by less than 90° transverse dunes formed (Reffet et al.,