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Reproducibility and utility of dune luminescence chronologies

Carly L. Leighton [a,*], David S.G. Thomas [a,b], Richard M. Bailey [a]

[a] School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK
[b] Department of Environmental and Geographical Science, University of Cape Town, Rondebosch 7701, South Africa

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ABSTRACT

Optically stimulated luminescence (OSL) dating of dune deposits has increasingly been used as a tool to investigate the response of aeolian systems to environmental change. Amalgamation of individual dune accumulation chronologies has been employed in order to distinguish regional from local geomorphic responses to change. However, advances in dating have produced chronologies of increasing complexity. In particular, questions regarding the interpretation of dune ages have been raised, including over the most appropriate method to evaluate the significance of suites of OSL ages when local 'noisy' and discontinuous records are combined. In this paper, these issues are reviewed and the reproducibility of dune chronologies is assessed. OSL ages from two cores sampled from the same dune in the northeast Rub' al Khali, United Arab Emirates, are presented and compared, alongside an analysis of previously published dune ages dated to within the last 30 ka. Distinct periods of aeolian activity and preservation are identified, which can be tied to regional climatic and environmental changes. This case study is used to address fundamental questions that are persistently asked of dune dating studies, including the appropriate spatial scale over which to infer environmental and climatic change based on dune chronologies, whether chronological hiatuses can be interpreted, how to most appropriately combine and display datasets, and the relationship between geomorphic and palaeoclimatic signals. Chronological profiles reflect localised responses to environmental variability and climatic forcing, and amalgamation of datasets, with consideration of sampling resolution, is required; otherwise local factors are always likely to dominate. Using net accumulation rates to display ages may provide an informative approach of analysing and presenting dune OSL chronologies less susceptible to biases resulting from insufficient sampling resolution.

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Contents

1. Introduction

1.1. Application of luminescence dating to desert dunes

Optically stimulated luminescence (OSL) dating is used to estimate the age of burial of a sample (i.e. the time since the sample was last

* Corresponding author. Tel.: +44 1865 285070; fax: +44 1865 275885.
E-mail address: carly.leighton@ouce.ox.ac.uk (C.L. Leighton).

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exposed to sunlight), and is often applicable to samples with burial ages in the range of 0.1–200 ka. The development and application of OSL dating has provided an increasingly significant archive for the study of past climatic and environmental conditions, and the establishment of depositional histories of landforms, particularly desert dunes. Developments in field and laboratory protocols have enabled the output of a large number of dune ages from many of the world's sand seas. In particular, the application of drilling methods that retain sample integrity has enabled samples to be extracted systematically from deep within dune bedforms, in some cases reaching their basal sediments (e.g. Preusser et al., 2002; Bray and Stokes, 2003; Telfer and Thomas, 2007).

The use of these methods has produced large datasets in which the dune internal structure is often unknown, as opposed to dated stratigraphic sequences where visible information can be used to guide interpretation of dune development (Stone and Thomas, 2008). Alongside reconstructions of Quaternary environmental changes, luminescence dating used in tandem with visible stratigraphy and/or the aid of ground penetrating radar (GPR) has aided understanding of geomorphic processes such as linear dune formation, extension and migration (e.g. Bristow et al., 2005; Hollands et al., 2006; Telfer, 2011). These advances have raised many questions with regard to the utility and interpretation of dune ages, principally related to the discontinuous nature of linear dune records, the representativeness of the accumulation units present in OSL datasets (i.e. sampling strategy-dependence), and the representativeness of sampled dune OSL chronologies for regional palaeoclimatic signals, especially from local 'noisy' records (where local forcing is present as well as regional environmental forcing) (Stone and Thomas, 2008). This paper aims to address some of these issues, including the appropriate spatial scale over which to infer environmental and climatic change based on dune chronologies, whether chronological hiatuses can be interpreted, how to most appropriately combine and display datasets, and the relationship between geomorphic and palaeoclimatic signals.

1.2. Linear dunes as discontinuous records of dune development

Linear dunes are frequently used in Quaternary palaeoenvironmental studies due to their widespread occurrence, relative morphological stability, and tendency to preserve longer-term records of sediment accumulation and environmental change (Nanson et al., 1992; Kocurek, 1998). As 'accumulating' dunes, linear dunes are important geoproxy records (Thomas and Burrough, 2012). These records have been interpreted as relating to changes in a number of external forcing conditions, including moisture, windiness and sediment supply (e.g. Kocurek and Lancaster, 1999). For example, Lancaster et al. (2002) interpret 'generations' of linear dunes in the western Sahara Desert with different orientations and discrete age populations as being formed under different wind regimes. However, in addition to regional, environmental forcing sediments can still be subject to reworking during active phases; for example, by the upper sections of a dune being mobilised and deposited further along the dune body, or through an element of lateral migration impacting on longer term morphological stability (e.g. Bristow et al., 2000; Tsoar et al., 2004; Telfer, 2011). Consequently, accumulated records are inherently discontinuous, and this can hinder the interpretation of clusters of ages and the chronological gaps between them. The question of whether a hiatus in the dated sedimentary record represents a period of reduced dune accumulation or an erosional event is a significant one, and one that may be unanswerable, at least at the scale of the individual dune. These complex issues will be discussed further in this section.

The extent of reworking is dependent upon the processes underlying linear dune formation, which are to some degree still under debate (Munyikwa, 2005; Hollands et al., 2006; Bristow et al., 2007b; Telfer, 2011). Classification systems have been developed to describe the morphological variability of linear dunes (e.g. Bullard et al., 1995; Fitzsimmons, 2007), which is suggestive of the complexity of linear dune formation and their variability of form. However, these processes have clear implications for the sedimentary structure preserved, and hence the chronologies that may be obtained. Gaps in understanding the fundamental controls of linear dune formation complicate understanding of individual dune development and their relation to dunefield dynamics, and, in turn, how past environmental conditions are reflected in the landscape at these two scales of analysis.

The most widely accepted theory of linear dune formation is in the context of bimodal wind regimes, which generate or extend other dunes into elongated bedforms orientated parallel to the resultant direction of sand transport (Tsoar, 1984, 2001; Wiggs, 2001; Rubin and Hesp, 2009). In general there is net deposition on the plinth, which is relatively stable, and on the lee side of the dune, where gravity becomes the dominant mode of grain transportation, whilst the windward slope is active with net erosion reaching a maximum at the crest (Tsoar, 1983; Lancaster, 1985; Wiggs, 2001). The stability of the bedform is maintained by a balance between the seasonal reversals of the crest line and alternation of the windward and lee side, which must respond to this alternation of erosion and deposition (Lancaster, 1985; Wiggs, 2001; Munyikwa, 2005). The level of reworking during each wind reversal, as the balance between erosional and depositional processes, is a function of multiple influences including wind speed and direction, slope morphology and sediment supply, and will determine the nature and level of continuity of the sequence (Munyikwa, 2005).

In a consideration of the impact of these processes upon luminescence-dated sequences, Munyikwa (2005) argued that there is considerable potential for previously deposited sediments to be completely lost from the sedimentary sequence (depending on the depth to which reworking occurs), whilst the end of periods of aeolian accumulation are also unlikely to be well constrained as a result of reworking. Further, a longer imbalance between the two dominant wind directions may lead to slow lateral migration of linear forms, as evidenced in luminescence-dated sequences from the northern Namib Sand Sea (Bristow et al., 2005). Interdune sediments and the lower slopes of linear dunes do not necessarily record all periods of aeolian activity and therefore cannot be targeted for dating in a response to the concern over reworking of the crest, which in turn raises questions of the completeness of records of accumulation in light of evidence, at least in some dunefields, of the potential contribution of lateral migration to longer term dune development. This model of linear dune formation may therefore explain the discrepancies between chronologies of different dunes within a dunefield by their incompleteness, as a result of local conditions and their impact upon the extent of reworking of sequences (Munyikwa, 2005).

Other formation mechanisms have also been suggested, with varying implications for the preservation of stratigraphic sequences. The generation of helical roll vortices and creation of parallel linear dunes in zones of updraft suggests a net depositional system with more optimistic implications for the dating of sequences, but this model of formation has not been supported by field evidence (Wang et al., 2004; Munyikwa, 2005). The wind-rift hypothesis of linear dune formation places importance upon erosion in proximal sources for the supply of material, which is then deposited laterally or obliquely onto nearby dunes, rather than the importance of long distance sediment transport resulting in dune elongation (Hollands et al., 2006). This model is supported by the dating of linear dunes and sedimentological evidence in the Simpson Desert, which suggests that dunes have not extended by more than a few kilometres, and that vertical accretion is a dominant process within the basin (Hollands et al., 2006; Cohen et al., 2010). In the southwest Kalahari, OSL dating provides evidence for extensional growth, certainly at the scale of 10 km, but that localised reworking of sediment at any point in the dune, without resultant dune extension, has been and still is a regular occurrence (Telfer, 2011).

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