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The utility of desert sand dunes as Quaternary chronostratigraphic archives: evidence from the northeast Rub' al Khali

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ABSTRACT

The distributions of optically stimulated luminescence (OSL) ages from dunes are affected by palaeoenvironmental changes, complex dune dynamics and sampling strategy. Extracting the relative importance of these factors when interpreting discontinuous OSL chronologies from sand dunes has proven difficult, and is particularly hindered in contexts where the internal sedimentary structures of dunes are not visible. In this study samples for OSL dating were taken from three major dune exposures in the Rub' al Khali, United Arab Emirates, each showing clear internal structure, with the aim of addressing these problems. Specific objectives were to assess how ages of individual sedimentary units represent dune accumulation as a whole, and how the dune record in turn reflects known past environmental changes. Final ages were calculated using the OxCal software package, by incorporating the known relative stratigraphy through the application of Bayesian methods. The results show that stratigraphy alone is not sufficient at these sites to guide OSL sampling; that is, chrono- and lithostratigraphic boundaries do not necessarily coincide. Where chronological hiatuses are present, internal sediment stratigraphy can be a useful tool in identifying potential problems of under-sampling the full dune record. The implications of these findings for reconstructing Quaternary climates from dune chronologies are considered.

1. Introduction

Sand dune systems are important sources of palaeoenvironmental information, and are particularly useful in dryland regions where other archives may be lacking. In response to numerous developments in laboratory and field protocols (e.g. Wintle and Murray, 2006), optically stimulated luminescence (OSL) dating has been increasingly applied to these bedforms. Chronologies of dune activity and stabilisation have been collated and correlated to regional models of past climatic change, enabling the environmental response of local terrestrial systems to be further investigated (e.g. Thomas and Shaw, 2002; Chase and Thomas, 2007). However, whilst these advances have allowed for improved chronologies of palaeoenvironmental change in arid environments, current capacity to interpret ages, and the responses of geoproxies more widely, in terms of understanding past climates remains lacking (Thomas and Burrough, 2012).

Dune archives are complex records of depositional, erosional, accumulation and preservation processes, and this complexity may make them difficult to interpret as palaeoenvironmental records. Hiatuses represent a lack of net accumulation, due to a reduction in sediment deposition and/or an increase in the reworking or erosion of previously deposited units. The reworking of linear dune sediments is dependent upon the balance between the reversals of the crest line in variable wind regimes (Tsoar, 1983; Lancaster, 1985; Wiggs, 2001) and the extent of lateral migration (e.g. Bristow et al., 2000; Tsoar et al., 2004). As a result of the balance of these processes, internal dune structures are inherently discontinuous (e.g. Kocurek, 1998; Munyikwa, 2005). The interaction of many processes that influence dune development and preservation, by directly or indirectly affecting the balance between sediment supply, sediment availability and transport capacity of the wind (Kocurek and Lancaster, 1999), are difficult to distinguish within the sedimentary record. The observable stratigraphy, as the product of their interactions, is therefore not directly related to one specific variable of past climatic change by way of a straightforward process/response model (Kocurek, 1996). In addition, environmental context at a range of spatial scales is crucial in modulating dune response, which may go a long way in explaining the apparent 'inconsistencies' in the terrestrial palaeoenvironmental record, such as in southern Africa (Thomas and Burrough, 2012). Dune form is a product of local as

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well as regional environmental conditions, and different dune forms may not respond in the same way to similar forcing conditions (Chase and Thomas, 2006). Further, it is not necessarily to be expected that forcing conditions will be consistent at regional scales, given the significant spatial and temporal environmental variability observed in drylands, the tropics and subtropics (Thomas et al., 2005; Thomas and Burrough, 2012).

The question of scale is important when interpreting dune structures and chronologies. A numerical model suggests that the resolution of sampling may affect the capacity to distinguish the impact of major externally-forced events, such as regional climate transitions, from stochastic disturbances affecting sediment accumulation and preservation (Telfer et al., 2010). In practice, it has been demonstrated that sampling strategy and resolution can affect the chronology of dune accumulation produced from dated records (Stone and Thomas, 2008). This is particularly significant, given the discontinuous nature of dune sedimentary archives, both temporally and spatially.

Stratigraphic features, where present, can be used to aid environmental interpretation in order to support assessments of chronologies, especially regarding the presence of accumulation hiatuses and whether sampling resolution is sufficient to capture variability in the observable record. The incorporation of all available evidence when interpreting chronologies allows for recognition of a more complex system and a thorough assessment of the meaning of dates in terms of dune development (Fitzsimmons and Telfer, 2008). However, even the use of palaeosols, as stratigraphic features requiring surface stability for their formation, requires caution. The timescale of palaeosol formation may be uncertain as bioturbation may limit constraining the exact timing (Fitzsimmons et al., 2007), the palaeosol may only have formed at certain sites, or part or all of the units may have been subsequently reworked and removed (Munyikwa, 2005; Fitzsimmons et al., 2007). Therefore interpretation of the more obvious dune stratigraphic features is not straightforward, and where these features are not present there is even less information to guide interpretation. Where dune internal structure is not visible, which is more often than not, stratigraphy has also been used to infer dune processes and guide OSL dating with the aid of ground penetrating radar (GPR) (Bristow et al., 2000, 2005, 2007). However, GPR is not suitable for use at all sites, due to subsurface electromagnetic properties, logistical difficulties, or a lack of internal dune structure.

The complexity of dune accumulation has led to the suggestion that many hundreds, if not thousands, of samples are required for dating if the major climatic events in the history of a dunefield are to be captured (Telfer et al., 2010). Such an approach is unlikely to be viable in practical terms. On the other hand, dune stratigraphy is seen as a vital guide to the interpretation of dune development, and has been exploited to 'target' OSL sampling of large sets of cross-stratification around inferred unit boundaries (Bristow et al., 2005). Intensive sampling and dating of a dune with an exposed and clear stratigraphy may provide an opportunity to identify and explain the issues that hamper dune chronology development: representativeness and reproducibility. This paper will introduce OSL ages in three sites in the United Arab Emirates (UAE) where the stratigraphy is visible and has been used to guide sampling in the field. The relationship between chrono- and lithostratigraphy will be investigated, and the use of stratigraphy to guide sampling strategies, calculate ages using a Bayesian approach, and interpret resultant chronologies and chronological hiatuses will be assessed.

2. Material and methods

2.1. Sampling sites and strategy

Covering over 600,000 km^2 of the southern Arabian Peninsula, the Rub' al Khali is the earth's largest active sand sea. In the UAE mean annual precipitation is 50–100 mm, with significant variability (Edgell, 2006). The two dominant wind systems in this region are the northwesterly *Shamal* and southwesterly Indian Ocean summer monsoon, which during the early Holocene had a more significant influence on the interior of the Peninsula than today.

The sites are located in the far northeast of the Rub' al Khali in the UAE. Large linear dunes, or 'megaridges', up to 70 m high and 1 km apart, are orientated southwest-northeast and superimposed by smaller secondary linear ridges that are up to 15 m high and orientated towards the southeast (Atkinson et al., 2011, 2012). The dunes are presently partially vegetated. Large sand quarries in the northern UAE have recently revealed the internal structure of dunes within this part of the dunefield (Atkinson et al., 2011). Three sites situated in this context, and part of the same linear megaridge dune system, were sampled for OSL dating (Figs. 1 and 2).

The first two sites, UAE10/1 and UAE10/2, are both located in the same pit near Shwaib (24°47′38.85″N 55°47′24.70″E). The sites are only a few kilometres to the west of the Oman Mountains where alluvial gravels extend towards and underlie the dunes (Atkinson et al., 2011). The third site is within a large sand quarrying excavation pit located off the Emirates Highway (25°39′17.22″N 55°50′50.94″E) approximately 20 km southwest of the city of Ras al Khaimah. These sites have been previously sampled by Atkinson et al. (2011, 2012), and here they were revisited with the specific aim of using the stratigraphy to guide sampling.

Sampling was conducted at a high spatial resolution, bracketing identified structural features. Previous studies have classified aeolian bounding surfaces according to their hierarchical relationships and inferred origin (e.g. Brookfield, 1977; Kocurek, 1981). First-order bounding surfaces and super surfaces represent the migration of interdunes and a cessation of accumulation and preservation due to changing external conditions respectively (Kocurek, 1988). Most of the bounding surfaces across which sampling followed were interpreted to be reactivation (third-order) surfaces representing the periodic erosion of the lee face, following Kocurek (1981). More extensive bounding surfaces sampled at one of the sites (UAE10/2) are interpreted as second-order surfaces, representing formation by the migration of superimposed dunes over the underlying bedform (Kocurek, 1981). However, without a three-dimensional view of the extent of these surfaces their significance as unconformities was unclear. Therefore allostratigraphical units, which are defined by their bounding unconformities, could not be strictly classified. Vertical and lateral sampling of the visible exposures, by sampling above and below bounding surfaces both with depth and horizontally, aimed to investigate the spatial variation in OSL chronologies. This method of sampling was employed in order to tie ages to dune development processes and to assess dating consistency.

2.2. Methods

2.2.1. Sample retrieval

Samples were extracted by scraping away the outer exposed section surface, and hammering in horizontally 12 cm sections of 50 mm diameter opaque plastic tubing. When full, the tube was extracted into a bag, and the inner end capped and sealed. All containers and bags were lightproof.

2.2.2. Sedimentology

Grain size analyses were conducted on raw samples using a Malvern Mastersizer 2000 laser particle analyser and analysed using Gradistat (Blott, 2000). Organic and carbonate contents were estimated using loss on ignition (LOI), following Heiri et al. (2001). Colour analysis was conducted on oven-dried samples using a Munsell colour chart.