Complexities of interpreting aeolian linear dune depositional history using luminescence chronology: a case study from the Kalahari

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1. Introduction

Linear dunes are the most ubiquitous of all desert dune types (Lancaster, 1982; Pye and Tsoar, 1990; Bristow et al., 2000) and occur as aeolian bedforms that cover no less than 40 % of the world's desert sand dune areas (Bullard et al., 1995). Despite their omnipresence, however, their origin and long-term development remain inadequately understood (Tseo, 1993; Bullard et al., 1995; Bristow et al., 2000, Wang et al., 2002). Notwithstanding the apparent paucity in details regarding linear dune morphodynamics, the rapid advances that have been made in the development of luminescence dating techniques over the past decade have seen the extensive application of the method in direct determination of the depositional chronologies of linear dune sequences. Such depositional chronologies have invariably been used for palaeoenvironmental reconstruction (Stokes et al, 1997; Thomas et al., 1997; 2002; Blmel et al., 1998; O'Connor and Thomas, 1999; Glennie and Singhvi, 2002). The Kalahari sand sea of southern Africa is one such region where luminescence dating has been applied on linear dune structures. More than 250 luminescence dating ages that have been acquired from six separate studies carried out in the area by various workers (Stokes et al., 1997; Thomas et al., 1997; Blmel et al., 1998; O'Connor and Thomas, 1999; Thomas et al., 2000; Munyikwa et. al., 2000) supposedly indicate multiple episodes of aeolian activity that occurred over the past 100 ka. Due to the absence of environmental markers within the stratigraphy, the timing of the depositional phases have largely been constrained by chronological gaps within dune sequences or, alternatively, from clusters of ages (Stokes et al., 1997) acquired from disparate sites and analyzed statistically for trends. The exact beginnings and ends of these depositional periods, however, vary from study to study and the individual assessments, when analyzed together, generally illustrate incongruent chronological reconstructions. Thus, it has so far been very difficult to create a region-wide Late Pleistocene chronology of the southern African linear dune activity and the associated climatic evolution.

In this paper it is argued that it will not be possible to comprehensively interpret the luminescence chronologies from the Kalahari without first addressing how the linear dune stratigraphic sequences originated and evolved. To demonstrate this rationale, hypothetical scenarios that simulate the progression and preservation of stratigraphical records in lineardune sequences are presented using two different theories that have been advanced to explain origin and development of longitudinal dunes: bi-directional wind regime and helical roll vortices. It is illustrated that linear dune systems that form under bi-directional wind regime are intrinsically inefficient at preserving complete records of their depositional history and this places major constraints for palaeoenvironmental reconstruction using luminescence chronology. When linear dunes form under the influence of helical roll vortices, however, it is shown that the degree of sequence preservation is much higher. It is, thus, demonstrated that different paleoenvironmental conclusions for the Kalahari are arrived at, depending on which theory is applied to explain the linear dune evolution. This construal is not accordant with current approaches that have paid minimal attention the role played by the dune morphogenetic history.

2. Linear dune development

Linear dunes are straight or sinuous crested aeolian ridges with a high axial length to width ratio. The widths may vary from tens of meters to close to 2.0 km and individual dunes may attain lengths in excess of 200 km (Thomas, 1983). Various mechanisms have been proposed to explain the formation of linear dunes but two main theories have received significant focus: the bi-directional wind theory and the helical roll vortices theory.

2.1. Dune sequence development under bi-directional wind regime

Under the bi-directional wind regime, in most cases, the wind approaches a sand body from two different directions, and there usually is a periodic change in the wind direction that is accompanied by episodic swapping of the dune stoss side and lee side (Figure 1). Sand transport up the windward slope of the dune varies with changes in shear stress on the dune surface as a result of variations in wind velocity, slope morphology, wind direction and grain size distribution. Using measurements of sand in transport up the windward slopes of active dunes, various studies (Lancaster et al., 1992, 1996; Frank and Kocurek, 1996; Wang et al., 2002) have confirmed that sand transport rates generally increase up the dune profile towards the crest as a consequence of an increase in shear velocity with distance up the dune slope.

Luminescence dating of aeolian dune sequences approximates burial ages of sediments by assessing the energy that has accumulated in mineral grains since the last zeroing event (exposure to sunlight) and the rateat which this energy is accumulated. In palaeoenvironmental studies, periods during which aeolian sediments were deposited are usually constrained by retrieving samples from the lower and upper sections of a particular stratigraphic unit. Buried soils within the stratigraphy provide environmental markers. When linear dunes form under bi-directional wind influence, however, the periodic reversals of the dune stoss side sand lee side results in the upper part of the dune being constantly mobilized. The degree of reworking would depend on factors such as wind speed, dune morphology and sediment supply. For luminescence dating purposes, reworking of sediments deposited in previous aeolian episodes is undesirable since this makes it impossible to accurately date the period when the episodes would have ended.

In Figure 1b, the depiction of a hypothetical scenario shows aeolian sediments that have accumulated during an earlier arid phase (Episode 1) and a soil (Soil A) that develops on the dune during a humid period (Humid Phase I) being reworked during a subsequent arid period (Aeolian Episode II) down to level x. Subsequently, during Humid Phase II, another soil (Soil B) develops in the upper part of the dune profile. The resultant dune sequence, thus, consists of two stratigraphic units

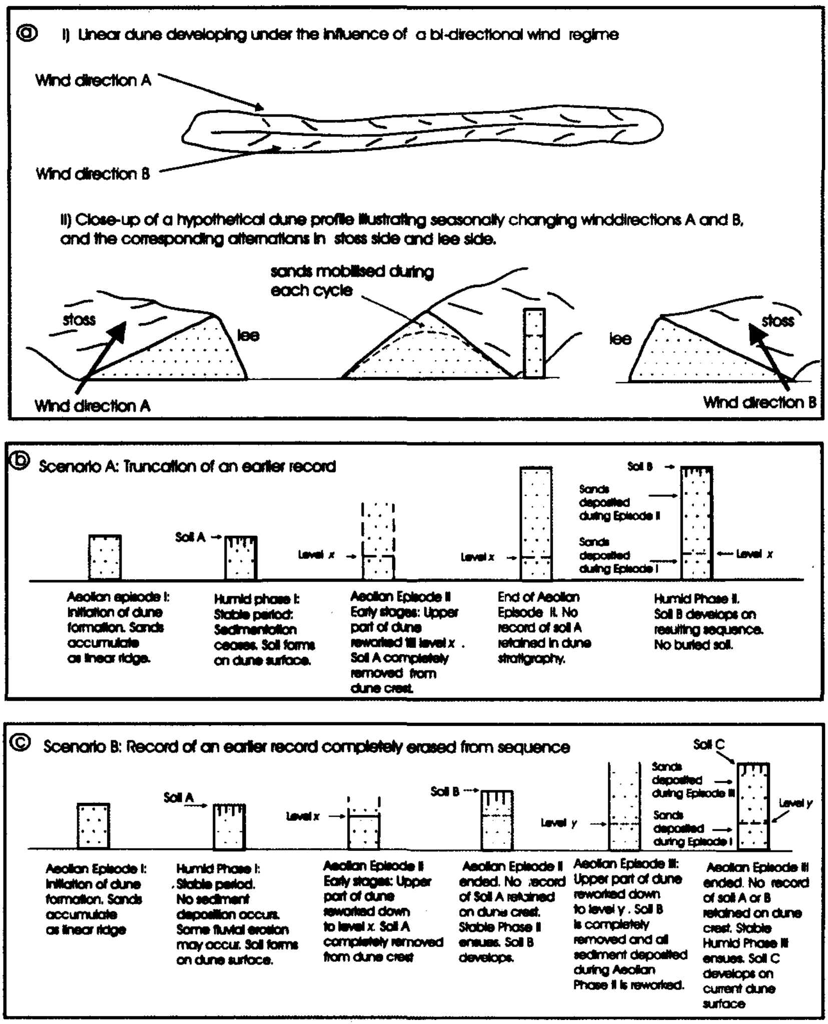

Figure 1 Linear dune development and sequence accumulation under bidirectional wind regime.

that were deposited during two distinct aeolian episodes (Episodes I and II). Because the dune sequence was truncated, a luminescence dating sample retrieved from the upper part of the unit deposited during Episode I is incapable of yielding an age that accurately approximates the end of the aeolian episode. The removal of Soil A from the stratigraphic sequence also erases important evidence of environmental change.

Figure 1c (Scenario B) illustrates an even more intensive case of aeolian reworking. In this instance, deep remobilization results in the complete erasure of the unit deposited during Aeolian Episode II. The sequence seen at the end only contains sediments deposited during Episodes I and III and soils A and B are bothmissing. Thus, in both Scenarios A and B, the resultant sequences are made up of incomplete fragments of the depositional records. Ages obtained from such sequences do not accurately constrain the aeolian episodes and the missing environmental markers make if difficult to speculate on what conditions would have prevailed.

2.2 Dune sequence development under helical roll vortices influence

An alternative theory for the formation of linear dunes postulates that pairs of roll vortices or helical air currents that form in the atmospheric boundary layer during storms and rotate in opposite directions close to the surface are responsible for the formation of linear sand ridges

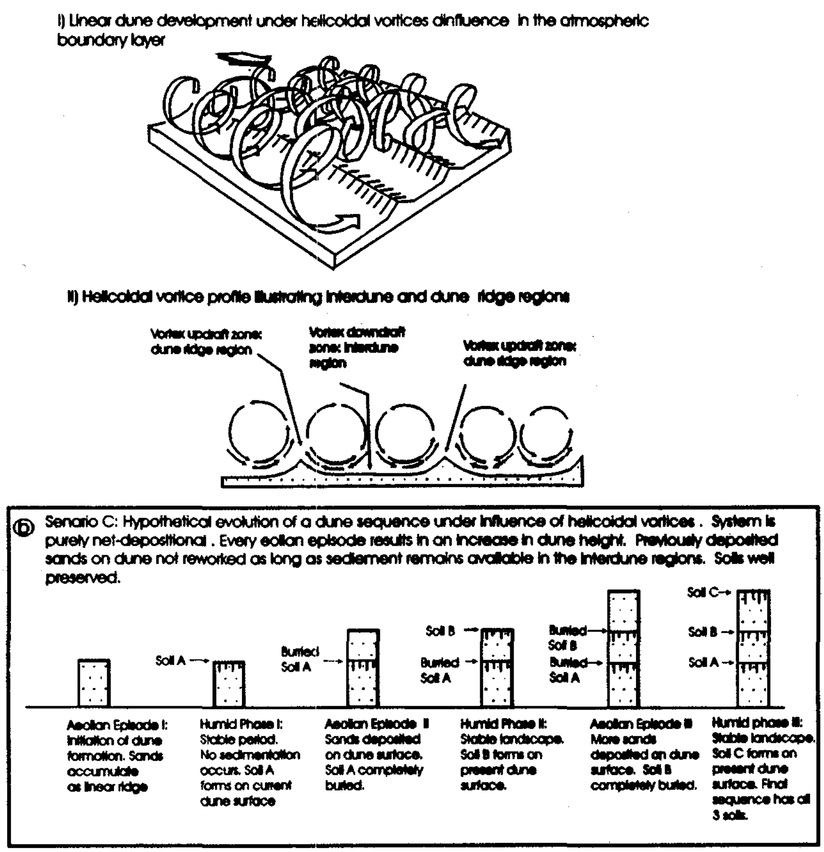

Figure 2 Linear dune and sequence accumulation under influence of helical roll vortices

that extend in the direction wind flow (Figure 2). The helical air currents are generated by the lateral component of flow shear that arises from the deflection of mean flow shear by the Coriolis force (Tseo, 1993).

Sediment transport under the influence of helical vortices is largely determined by the configuration of the helical air currents at the interface with the terrain (Figure 2 (II)). For a particular pair of helical vortices, the downdraft zone is characterized by diverging currents that transport sediment outwards to create the interdune region. At the vortex updraft, air currents from adjoining vortex pairs converge, depositing the sediment removed from the interdune zone to form ridges. The forward spiral mortion of the vortex imparts both a lateral and forward velocity component as they move. Thus, the dune grows both vertically and horizontally in the downwind direction. As long as sediments are available in the interdune zone and the water table low, therefore, the dunes will continue to grow vertically and horizontally. Dune sequence preservation, thus, is far greater than under the bi-directional wind regime. Hypothetical Scenario C illustrates episodes during which three discrete sedimentary units occur, interspersed with three separate humid phases during which soils (Soils A,B,C) develop in the upper parts of the prevailing stratigraphy. As long as sediments are available from within the interdune regions, and the water tables low, the system would remain net depositional and very limited reworking of sediments deposited in previous episodes would occur. Luminescence dating samples collected from the bottom and upper parts of stratigraphic units within such sequences provide reliable constraints of the durations of both the arid periods and the humid phases during which the soils form.

3. Study area

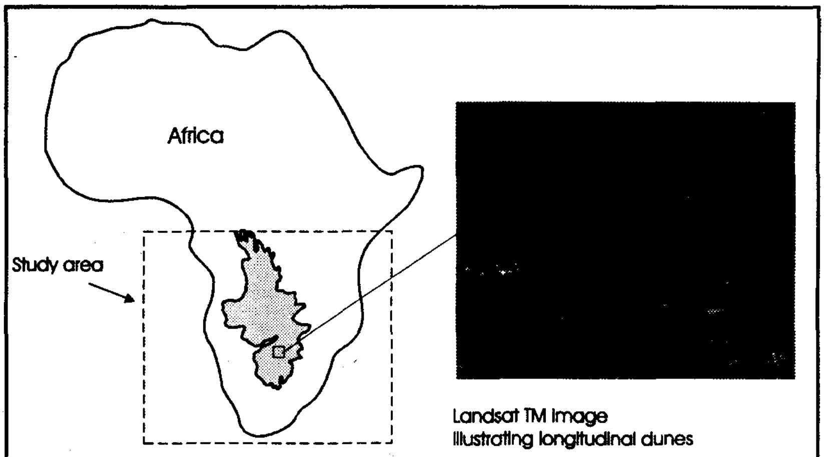

Figure 3 Location of study area

The Kalahari Sands mantle a region stretching from the 5 to the 28 S latitudes in Southern Africa (Figure 3) and they are thought to constitute the world's largest continuous aeolian sand body (Stokes et al., 1997). Surface expression of the sands is in the form of longitudinal dunes that attain lengths of up to 160 km. The present climate in the region is semi-arid and, with the exception of a few localities, the dune structures are inactive and support considerable vegetation. The aeolian deposits are, however, indicativeof past periods during which the climate in the region was less humid. Prior to 1995, very little information was known about the chronology of the environmental evolution within the Kalahari but since 1997, six major luminescence dating studies (Stokes et al., 1997, 1998; Thomas et al., 1997, 2000; Blmel et al., 1998; O'Connor and Thomas, 1999; Munyikwa et al., 2000) have been carried out in the area producing in excess of 250 ages. However, the results from the individual studies do not portray a uniform picture and, thus, it has been impossible to come up with any representative reconstruction for the Late Pleistocene climate for the region.

4. Results

This study has re-interpreted the luminescence data taking, the morphogenetic history of the dunes into account. When the Kalahari linear dunes are treated as having developed under bi-directional wind regime, results suggest that the region experienced dry conditions during the periods 48 41, 36 23, 17-10 ka. The lack of environmental markers makes it difficult to speculate on the nature of the environment that prevailed during the intervening periods.

If the dune sequences are assumed to have evolved under a helical roll vortices environment on the other hand, it appears as if the environmental changes that occurred within the region were very localized. Data from the eastern part of the study area indicate that arid conditions prevailed during the periods 115-95, 46-41, 26-20 ka (Stokes et al, 1997; Munyikwa et al., 2000). Reconstructions from the southern part show aeolian mobilization of dune sands at 27 23 and 17 10 ka (Thomas et al., 1997) whilst results from the northern sector shows dune building activity during the periods at 32 27, 16 13, 10 8 and 5 - 4 ka ago (O'Connor and Thomas 1999).

5. Conclusions

The results of the re-evaluation of the Kalahari luminescence data indicates that assessment of the morphogenetic aspects of linear dune formation should constitute an important facet of paleoenvironmental studies that seek to reconstruct past environments using data acquired from linear dune sequences. Current practices have paid little attention to dune development models when interpreting luminescence dating results and these results illustrate that different results may be arrived at, depending on the manner in which the dune sequences are thought to have evolved. Dune sequences that evolve under bi-directional wind influence retain distinctly different information from that retained in dune sequences which develop under the influence of helical roll vortices.

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