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SEDIMENTARY HISTORY AND THE INTERPRETATION OF LATE QUATERNARY DUNE RECORDS: EXAMPLES FROM THE TIRARI DESERT, AUSTRALIA AND THE KALAHARI, SOUTH AFRICA[1]

HISTORIA SEDIMENTARIA E INTERPRETACIÓN DEL REGISTRO DE DUNAS DEL CUATERNARIO TARDÍO: EJEMPLOS DEL DESIERTO DE TIRARI, AUSTRALIA Y DEL KALAHARI, SUDÁFRICA

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Stabilized sand deposits from arid regions are often used as palaeoenvironmental proxies for past periods of enhanced aeolian activity. Although widespread use of optically stimulated luminescence (OSL) dating techniques has opened up the possibility of systematic analyses of dune building chronologies, palaeoenvironmental histories cannot be reconstructed from chronological data alone. The reconstruction of regional palaeoenvironmental histories should consider all available evidence - stratigraphic, sedimentological and micromorphological, and chronological. This paper highlights potential issues with the interpretation of dune records in the context of stratigraphic preservation, using examples from the Tirari Desert in Australia and the Kalahari Desert in southern Africa.

Sedimentological characterisation of linear dunes in the Tirari Desert demonstrates that reworking of underlying dune sediments and buried soils is common, thereby calling into question simplistic interpretations of dune formation involving sequential deposition and pedogenesis. This case study highlights the limitation of the augering technique, although useful information can be gained nonetheless. Three OSL age estimates confirm the presence of at least two Holocene dune building episodes, but cannot constrain the timing of the onset of dune building. Higher frequency sampling and micromorphological analyses may further elucidate the palaeoenvironmental history of individual dunes.

In the Southwestern Kalahari, interdune sediments have been described as the least sensitive part of the aeolian landscape, thus offering the potential for longer records of aeolian deposition. This is found not to be the case at Witpan, where interdune sands are extensively mixed and probably younger than the linear dune cores. The lunette at Witpan records numerous short-lived and rapid deflationary events from the nearby pan (*playa*). These are considered to reflect changes in sediment source rather than pedogenesis. These examples highlight the value of combining micromorphological, sedimentological and chronological studies for palaeoenvironmental reconstruction.

Key words: Interdunes, linear dunes, luminescence dating, lunettes, Quaternary, Tirari Desert, Kalahari Desert.

Depósitos consolidados de arena se utilizan a menudo en las regiones áridas como archivos paleoambientales de períodos de mayor actividad eólica. Aunque se ha generalizado el uso de las técnicas de datación por luminiscencia ópticamente estimulada (OSL), que ha abierto la posibilidad de análisis sistemáticos de la formación de dunas, la historia paleoambiental no puede ser reconstruida sólo a partir de datos cronológicos. Para reconstrucciones paleoambientales regionales se deben examinar todas las pruebas disponibles –estatigráficas, sedimentológicas y micromorfológicas– y cronológicas. Este artículo pone de relieve los posibles problemas que se pueden encontrar en la interpretación de registro de dunas, dependiente de las condiciones de preservación estatigráfica, a partir de ejemplos del desierto de Tirari en Australia y el desierto de Kalahari en Sudáfrica.

La caracterización de los sedimentos de las dunas lineales en el desierto de Tirari demuestra que las transformaciones en la estructura de sedimentación de las dunas y suelos enterrados es muy común, por lo que pone en tela de juicio la interpretación simplista de la formación de dunas con base en la deposición secuencial y pedogénesis. Este estudio de caso pone de manifiesto que aunque limitada la técnica de barrenado, la información adquirida puede ser útil. Tres estimaciones de edad por OSL confirman la presencia de al menos dos episodios de formación de dunas en el Holoceno, pero no puede limitar el tiempo de la aparición de la formación de las mismas. Un número mayor de muestras y análisis micromorfológicos futuros podrán ayudar a dilucidar aún más la historia paleoambiental de las dunas.

En el suroeste del Kalahari, los sedimentos interdunas se han descrito como los menos sensibles del paisaje eólico, ofreciendo así la posibilidad de registros de deposición eólica de larga data. Este no es el caso de Witpan, donde las arenas interdunas están altamente mezcladas y posiblemente son más jóvenes que los núcleos de dunas lineales. La luneta de Witpan registra cortos y rápidos eventos de deflación de la playa cercana. Éstos se consideran como reflejos de los cambios en la sedimentología de origen de la luneta y no debido a procesos de pedogénesis. Estos ejemplos destacan el valor de combinar estudios micromorfológicos, sedimentológicos y cronológicos para la reconstrucción paleoambiental.

***Palabras claves**: interdunas, dunas lineales, fechados por luminiscencia, lunetas, Cuaternario, desierto de Tirari, desierto de Kalahari.*

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Dunefields are a major landscape component of the southern hemisphere deserts, and recent advances in dating techniques, in particular optically stimulated luminescence (OSL) dating, have enabled more systematic exploration of the palaeoenvironmental evolution of these regions. However, palaeoenvironmental histories can rarely be constructed from chronological data alone, particularly in dynamic environments such as dunefields where reworking is common. In such environments, stratigraphy and sediment characteristics, including micromorphology, are crucial for interpreting desert dune records.

Stabilised dunefields enable investigation of past periods of enhanced dune accumulation, particularly since the advent of OSL dating of dune sands, and the dunefields of central Australia and southern Africa have featured prominently (e.g. Fitzsimmons et al. 2007a; Telfer and Thomas 2007; Stokes et al. 1997; Thomas and Shaw 2002). These regions are in many ways analogous; both are mid-continental regions characterized by low-relief landscapes dominated by linear dunes, and both suffer a paucity of palaeoenvironmental proxy archives. In both regions, dune building events have typically been used to infer periods of aridity (Bowler 1976; Fitzsimmons et al. 2007a; Stokes et al. 1997; Wasson 1983a), although interpreting the palaeoclimatic signal is not straightforward (Telfer and Thomas 2007). In some stabilised dunefields, dunes preserve buried soils; in such cases, stratigraphy provides a useful tool for reconstructing palaeoenvironmental histories (Fitzsimmons et al. 2007a). However, dynamic landforms such as desert dunes seem to produce inherently incomplete records, and evidence of hiatuses may not be obvious from either the chronology or preserved stratigraphy. Truncation and reworking are common processes in dune evolution, and appear to vary between individual sites (Telfer and Thomas 2006, 2007) and along dune lengths (Fitzsimmons 2007a; Telfer and Thomas 2006). As a consequence, environmental histories must be considered carefully, and in the context of all available evidence.

This paper highlights potential issues with the interpretation of stratigraphic, sedimentological and chronological evidence in the context of dune formation and palaeoenvironmental reconstruction. We present two individual case studies from the dunes of the Tirari Desert of Australia and the Kalahari Desert of southern Africa which illustrate the importance of considering stratigraphy in tandem with the chronological data, and also highlight some difficulties in interpreting dune formation on the basis of sediment mixing, reworking and incomplete preservation.

Linear Dunes and Lunettes

Linear dunes are considered most likely to have formed under broadly multi-directional wind regimes, although several models for individual dune formation have been proposed. Wind-rift accretion models suggest a predominantly lateral movement of sand from interdune swales to form linear ridges (Hollands et al. 2006), under the influence of localised winds that may be detached from regional wind patterns and affected by existing dune morphology. Alternative theories invoke sand movement primarily longitudinal to the dune axis, resulting in net elongation (Tsoar 1983; Tsoar et al. 2004). As with the wind-rift mechanisms, modification of local winds may result from interaction with the linear form of the dune, promoting parallel wind flow (Tsoar 1983). Either model results in vertical accretion of sediment over time (Tsoar et al. 2004). However, subsequent removal of deposited sediment by reworking may affect stratigraphic preservation (Munyikwa 2005a). This may be influenced by sediment supply (Kocurek 1998), and it is likely that individual aeolian units record the latter phases of depositional episodes (Nanson et al. 1992).

Hiatuses between dune-building events may be sufficiently humid and stable to cause pedogenesis (Bowler and Magee 1978). Desert dune soils are characterised by increased concentrations of translocated clay which forms coatings (cutans) surrounding sand grains, as well as pedogenic carbonates and gypsum (Wasson 1983b). Clays are reorganised and physically illuviated down the stratigraphic column (Schaetzl 2001), whilst carbonates and gypsum are mobilised in solution and precipitated as a result of the reaction between meteoric water and calcium carbonate and sulphate ions in the sediment (Brewer 1976). Cutans can be used to provide information relating to pedogenesis and reworking, as described in Fitzsimmons et al. (2007b). Intact clay cutans represent evidence of illuviation and therefore soil development. Reworking of palaeosols by subsequent aeolian activity often abrades cutans without completely removing them. Observations of cutans and the extent of their preservation therefore indicate the relative roles of pedogenesis and reworking of sediment. Palaeosols can be used as stratigraphic markers, defining the upper limits of a particular dune unit and forming subsequent to periods of enhanced aeolian activity. This model has been used to interpret dune chronologies in Australian contexts (e.g. Fitzsimmons et al. 2007a; 2007b; Lomax et al. 2003), although it is less useful in African dunefields due to the scarcity of palaeosols (Telfer and Thomas 2007), as will be discussed in this paper.

Lunette dunes, also found both in Australian and southern African dunefields, are crescentic dunes found downwind of pan (*playa*) basins. They are formed from material which may be deflated from the pan surface, or transported during inundated phases by wave action (Bowler 1973, 1983), or may show more complex sediment source pathways (Telfer and Thomas 2006). They have been used for as palaeoenvironmental proxies of dune accumulation (e.g. Marker and Holmes 1995; Lawson and Thomas 2002). At Witpan in southern Africa, the presence of numerous distinct stratigraphic markers within the lunette stands in sharp contrast to the almost structureless linear dune sands surrounding the lunette, and these were investigated with a similar rationale to the Australian linear dune palaeosols.

Tirari Desert, Australia: Sedimentological and Stratigraphic Evidence for Reworking

The Tirari Desert is a linear dunefield in southeastern central Australia (Figure 1), a region which is currently the driest part of the continent. It is bounded to the west, east and north by the large *playa* Lake Eyre, the Sturt Stony Desert and Warburton Creek respectively. Several ephemeral creeks cut through the Tirari Desert and flow towards

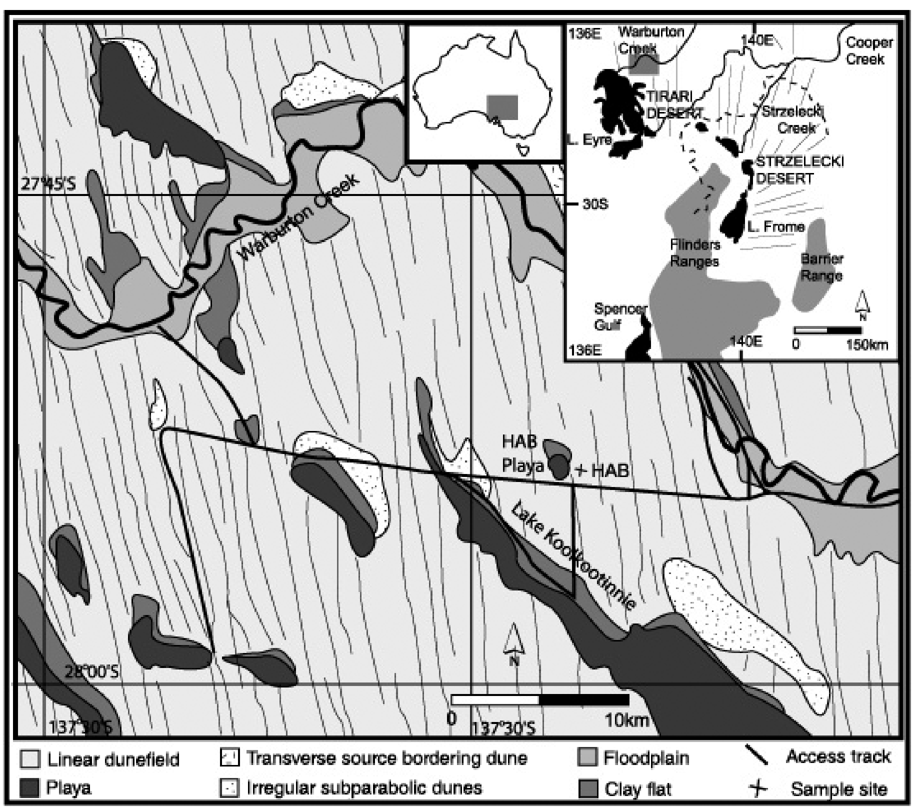

Figure 1. Map of the northern Tirari Desert dunefield, showing the north-trending linear dunes, Warburton Creek and elongate *playas*.

Mapa de dunas en el norte del desierto de Tirari, mostrando las dunas lineares, el río Warburton y las playas alargadas.

Lake Eyre. Ancestral palaeochannels, alluvial plains and floodplains of these creeks form the substrate beneath the linear dunes (Fitzsimmons 2007b). In places, elongated playas, such as Lake Koolkootinnie (Figure 1), have developed along palaeodrainage lines (Tedford and Wells 1990).

Although this region lies within the most arid part of Australia, the linear dunes of the Tirari Desert often preserve composite stratigraphies of several units, bounded by unconformities indicated by palaeosols (Fitzsimmons et al. 2007a). However, the arid climate of this region suggests that the depositional histories of these dunes may be more complicated than the simple sequential model of formation involving deposition followed by pedogenesis. The possibility of removal of part or all of the individual units and associated palaeosols must be considered (Munyikwa 2005a). This region therefore provides an opportunity to investigate the sedimentary history of a linear dune, using the combined tools of stratigraphy, OSL dating, sedimentology and micromorphology.

HAB site

The HAB site is a linear dune located approximately 11 km west of the Warburton Creek and 1 km east of a small playa in the northern Tirari Desert (Figure 1). It lies in an area of closely spaced, north-south oriented linear dunes (Figure 2a). There are few points of convergence between the dunes in this area; linear dunes continue parallel to one another for tens of kilometres. This separation suggests minimal morphologic interaction between the dunes, possibly due to greater sediment supply through time relative to other parts of the Australian desert dunefields (Fitzsimmons 2007b). The likely independent formation of this dune makes this a useful site for assessing the extent of preservation of dune sedimentary history.

The HAB site lies on a palaeo-alluvial plain substrate. Dune sediment is dominated by quartz and is grey in colour, associated with the occurrence of gypsum. Gypsum is also common in the underlying fluvial sediment as an induration material (Tedford et al. 1986). The HAB dune formed after the cessation of fluvial activity and associated alluvial sediment deposition in the area.

The dune comprises two crests, rising 5.0 m and 6.4 m above the substrate to the east and west respectively (Figure 2b). The eastern crest was augered for sampling. Gypseous substrate material was encountered at 5.4 m depth, indicating that the substrate slopes westward beneath the dune, but is not planar (Figure 2b). This suggests that linear dunes can develop on uneven surfaces. The extent to which this slope is related to the playa 1 km to the west, which occupies a low point in the topography, or is a local effect, cannot be ascertained from the cross sectional data.

Sampling and laboratory methods

The dune sediments were sampled by augering to 5.9 m depth from the eastern crest. A marked change from sandy aeolian to grey, gypseous material was observed at 5.4 m, indicating the transition between dune and substrate sediments. Sediment texture and colour, general grain size and sorting, were observed at 0.2 m intervals down the auger hole. Four non-oriented samples were taken for thin section microscopy at depths of 0.7 m, 2.9 m, 4.5 m and 5.8 m.

Three samples were taken for OSL dating at depths of 1.7 m, 3.1 m and 4.1 m. These were sampled and processed in the laboratory using the methods detailed in Fitzsimmons et al. (2007a). OSL samples were measured using the Single Aliquot Regenerative (SAR) dose protocol of Murray and Wintle (2000, 2003). This has successfully produced reliable ages in Australian aeolian contexts (Banerjee et al. 2003; Fitzsimmons et al. 2007a; 2007b; Lomax et al. 2003). Equivalent dose and dose rate data for the three samples are published in Fitzsimmons et al. (2007a).

The lowermost sample (K0503), taken from 4.1 m depth, produced an age of 10.7 ± 0.7 ka. The middle sample, taken at 3.1 m depth, produced an age of 6.6 ± 0.4 ka. This sample may lie within a palaeosol as shown in Figure 2c, and therefore may have been subject to post-depositional mixing and resetting of the luminescence signal, as discussed in Bateman et al. (2003). However, there was no evidence from the palaeodose distributions from the 12 aliquots analysed to suggest that mixing occurred within the sample. This indicates either that the sample was taken from undisturbed material in the lowermost part of the palaeosol, or that the palaeosol was weakly developed and did not experience substantial pedoturbation. The palaeosol is discussed further in the following section. The uppermost sample, at 1.7 m, produced an age of

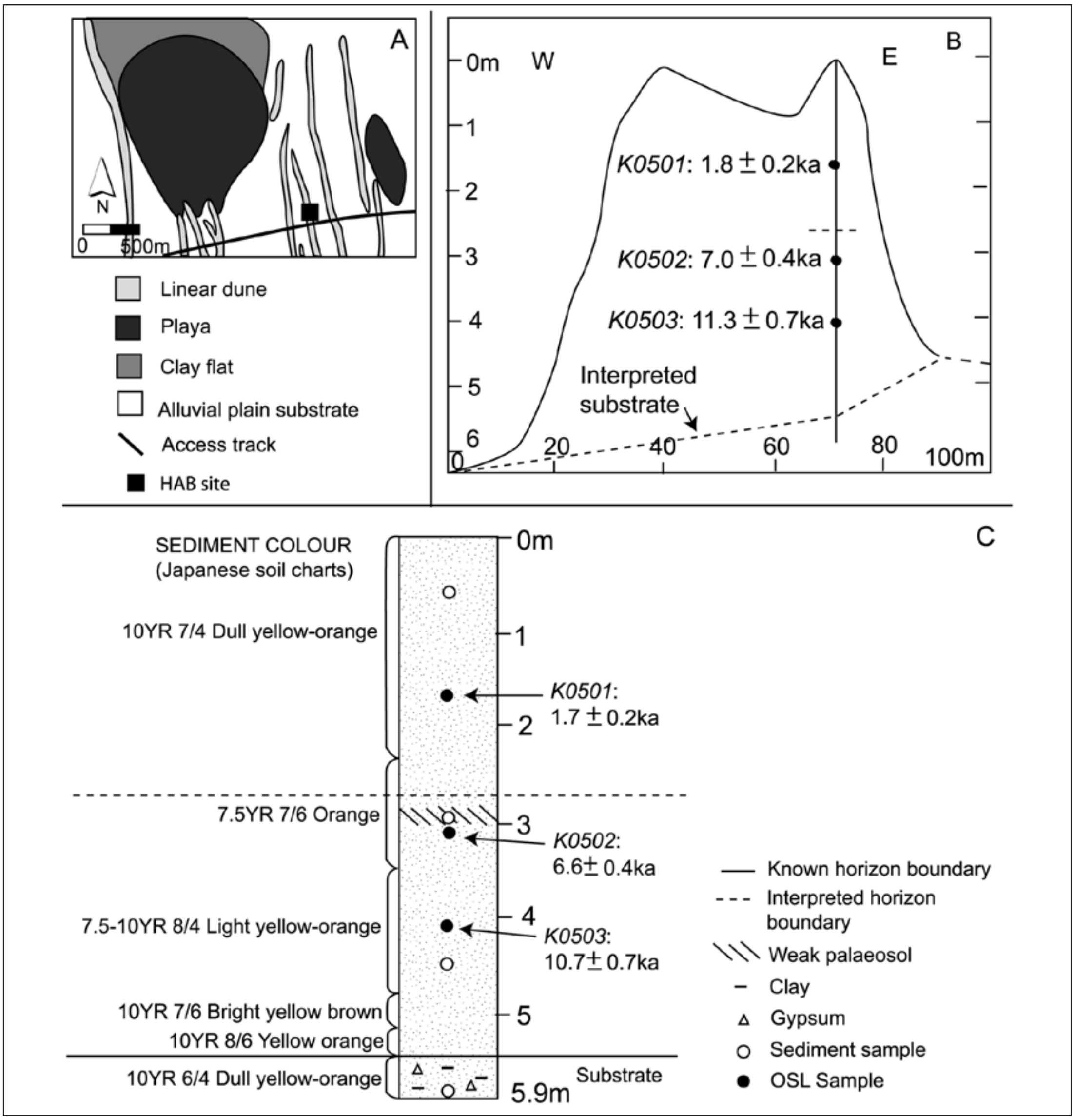

Figure 2. Summary of the HAB site, showing (a) Local geomorphology, (b) Cross-sectional morphology and chronology, and (c) stratigraphic log from auger hole including sediment colour, pedogenic minerals within the substrate and weak palaeosol at ~3m depth.

Resumen del sitio de HAB, mostrando (a) la geomorfología local, (b) la morfología y la cronología de la sección transversal, y (c) el registro estratigráfico, incluyendo color del sedimento, los minerales pedogénicos dentro del substrato, y el suelo antiguo a una profundidad de ~3 m.

1.7 ± 0.2 ka. The age estimates are consistent with stratigraphic position (Figure 2c).

Stratigraphy

The stratigraphy of the HAB site was interpreted from the auger hole, since no stratigraphic exposures were present within the dune. Stratigraphic exposures are rare in the Tirari Desert; as a consequence, augering is often the only practical means of gaining stratigraphic and sedimentological information. The technique is limited in the amount of information that can be obtained, since detailed micromorphologic studies cannot be undertaken using this method, nor can bedding and laminae be observed in the field. By necessity, the stratigraphy of the HAB site was

Table 1. Sedimentological analysis for pedogenesis within HAB dune and underlying substrate.
Análisis sedimentológico para pedogénesis en la duna de HAB y del substrato subyacente.

Sample depth (m)	Cutan description	Mineralogy	Interpretation
0.7	No cutans	Quartz (qtz)+feldspar	Not palaeosol and contains no in situ or inherited soil characteristics
2.9	Rare abraded cutans	Qtz+feldspar+calcite	Weak palaeosol (carbonates) though abraded cutans are probably reworked from different soil
4.5	Abraded cutans	Qtz+feldspar+hematite	Reworked soil material but not palaeosol
5.8 (substrate)	Cutans and matrix	Qtz+feldspar+gypsum+illite	Palaeosol

therefore interpreted on the basis of sedimentary variation down hole.

Field observations of soil colour, taken in combination with dilute hydrochloric acid testing for carbonates, identified no change in colour down hole, nor pedogenic carbonates. Therefore no clear evidence for pedogenesis was identified from field observations using the augering technique.

However, laboratory sedimentological methods were used to identify evidence for reworking and pedogenesis. Micropedological features such as clay cutans were identified by thin-section microscopy. Sediment mineralogy was analysed using X-Ray Diffraction (XRD). The micropedological and petrographic observations are summarised in Table 1.

Possible pedogenesis was identified at 2.9 m depth on the basis of the identification of carbonates by XRD and thin section microscopy. Carbonates were not identified in the field; clearly laboratory techniques provide a greater level of detail for observing and interpreting subtle sedimentological changes. It is possible that the carbonates are contained within abraded cutans and therefore represent reworked material. However the sediment at 4.5 m, which also contains abraded cutans, presumably from reworking of the same source, does not contain carbonate. Therefore the carbonates at 2.9 m are interpreted as pedogenic material. It is important to note that the cutans at 2.9 m are abraded and likely to represent reworked sediment. However, this does not contradict the interpretation of pedogenesis at this depth since the carbonate zone within a soil may occur below that of illuviation (Young and Young 2002). Pedogenesis involving carbonate precipitation appears to be characteristic of Australian desert dunes, and is not observed in African contexts, as discussed later in this paper.

By contrast, sediments observed at 1.7 m, the depth of the 1.7 ± 0.2 ka sample, exhibit no evidence of pedogenesis. Therefore the boundary between the palaeosol and upper horizon lies somewhere between 2.9 m and 1.7 m, and is indicated by a dashed line in Figure 2c. Pedogenesis must have taken place at some time between approximately 6-2 ka.

It is uncertain whether pedogenesis or depositional hiatuses took place within the HAB dune at other times. At all depths except 0.7 m, both abraded cutans and grains without cutans were observed in thin section, suggesting that deposition was characterised both by reworking of local soil and deposition of fresh material in the form of clean sand grains. It is possible that one or more early episodes of dune activity were separated by hiatuses in deposition and pedogenesis, with the resultant palaeosols completely reworked during subsequent aeolian events (Munyikwa 2005a). Higher frequency sampling, and/or alternative sampling techniques, may resolve this issue. Clearly, dune records must be carefully considered in the context of the stratigraphic, sedimentological and chronological evidence prior to interpretation of palaeoenvironmental history.

Palaeoenvironmental interpretation

The simplest interpretation of the stratigraphic evidence suggests that the HAB dune formed during two episodes of aeolian activity, separated by a hiatus during which conditions were sufficiently humid for pedogenesis. The onset of dune formation may have taken place around 11 ka, with aeolian activity continuing to approximately 7 ka. Shortly after 7 ka, more humid conditions resulted in dune stabilisation and weak pedogenesis.

The nearby playa Lake Eyre was a shallow, perennial lake between approximately 12 ka and 3-4 ka (Magee and Miller 1998). Although the hydrology of Lake Eyre is linked to monsoon patterns further afield (Magee et al. 2004), strengthened monsoonal circulation has also been shown to influence local fluvial systems by the occurrence of more frequent and intense rainfall depressions (Croke et al. 1999). These conditions may have influenced pedogenesis at the HAB site.

Conditions became less stable by 2 ka, as shown by aeolian deposition around that time. Aeolian activity may have initiated earlier, but was not preserved. The lack of cutans of any kind within the sediments of this unit suggests either that this episode of dune activity did not rework the underlying weak palaeosol, or that reworking was sufficiently vigorous to remove all cutans. Since the two lower samples contained reworked sediment from which the cutans were not completely removed, the former argument seems more likely. Aeolian activity was probably characterised by the introduction of fresh sediment to the dune, perhaps from adjacent interdune swales or from an influx of sandy material deposited by inundation of the swales associated with increased fluvial activity in the Warburton Creek. Since the site lies approximately 10 km south of the Warburton Creek, the latter model would require substantial fluvial activity for which there is little evidence from other regional palaeoenvironmental archives at this time. Dune reactivation as a result of increased surface instability under enhanced arid conditions is the more likely scenario. This is supported by the morphology of the dunes in this region, as discussed in Fitzsimmons (2007b).

Linear dune activity associated with increased aridity is also recorded between 4-2 ka in the central Strzelecki Desert approximately 300 km to the east (Lomax et al. 2003), and around 1 ka in the Simpson Desert, approximately 300 km to the north (Nanson et al. 1992). Evidence of multiple sites showing dune activity during the late Holocene indicates that dune reactivation was associated with relative aridification over the last few thousand years.

The palaeoenvironmental history is further complicated by the presence of abraded cutans in the sediments below the 2.9 m palaeosol. The onset of dune formation, and whether the two lower dates correspond to a single or multiple episodes of dune activity, cannot be established. The presence of reworked cutans below the 11 ka sample suggests that the sediment is a reworked palaeosol which has not been preserved in the dune stratigraphy. The linear dune was therefore initiated prior to 11 ka, followed by pedogenesis, and this palaeosol was reworked. Precisely how much earlier cannot be determined, since earlier episodes of dune formation and pedogenesis have been entirely reworked. However, additional chronological studies in the Tirari Desert indicate that dune activity extends to at least 87 ka (Fitzsimmons et al. 2007a).

Dune activity may either have been continuous between 11-7 ka, or there may have been a depositional hiatus. If there was a hiatus, pedogenesis may or may not have occurred, but is not preserved within the stratigraphy. Chronological and sedimentological sampling at more frequent intervals may further elucidate the depositional history.

The stratigraphic ambiguity makes it difficult to reconstruct the precise history of dune formation. Palaeosols preserved within the stratigraphic column provide the most reliable palaeoenvironmental proxy evidence, indicating climatic stability, relative humidity and increased vegetation cover, but the timing of pedogenesis can only be constrained by dating undisturbed dune units which bracket palaeosols.

Southwestern Kalahari: Integrating Chronological Information with Micromorphology

Like the Australian deserts, the Kalahari Desert of southern Africa has been studied for its palaeoenvironmental records (Lancaster 1981; Stokes, Thomas and Washington 1997; Thomas et al. 2000). The Kalahari dunefields extend from Zambia and Zimbabwe in the north and east to Namibia in the west, with the Kalahari's arid core at its southwestern extreme in South Africa and Botswana. The linear dunefields have been identified as essentially relict features, testimony to periods of past aridity (Lancaster 1981; Stokes et al. 1997; Thomas et al. 2000). Recent reviews, however, have urged caution with the interpretation of aeolian chronologies (Munyikwa 2005b; Thomas and Shaw 2002).

Witpan

Witpan is a 5 km long hourglass-shaped playa with a well developed lunette dune within a linear dunefield (Figure 3a). The playa is incised into Kalahari Group calcretes which form the substrate to the linear and lunette dunes. Thomas et al. (1993) postulated that the currently active sector of the lunette crest, an unusual feature in this region, was driven by sediment recycling. Dating by Thomas et al. (1998) suggested a late Holocene age for the lunette, and this has been confirmed by recent work which has noted considerable spatial and temporal variation under a regime of complex sediment supply (Telfer and Thomas 2006). These observations suggest that rigorous sampling is essential for obtaining a robust understanding of the development of such dunes. A detailed aeolian chronology from the linear dunes at Witpan is discussed in Telfer and Thomas (2007).

During an intensive study of the Witpan area during 2002 and 2004, samples were taken for sedimentological and OSL analysis. Although interdune deposits are not routinely studied as part of surveys of past aeolian activity, four samples were taken from the sandy interdune swales. Interdunes can be depositional or deflationary, and vary in surface topography from bare rock to seasonal inundated lakes (Lancaster 1995). Thomas et al. (2005) consider the interdunes of the Kalahari to be the last element of the dune system to show reactivation. It is this lack of sensitivity that may offer advantages in an environment where it has been shown that landscape sensitivity can readily erase the sedimentary record. "Basal linear dunefield sands" from the southwestern Kalahari were shown by Stokes, Thomas and Shaw (1997) to significantly predate the overlying linear dunes, and were interpreted to represent an intense phase of aeolian activity, reactivating the dunefield to bedrock.

Although palaeosols of the type discussed at the HAB site above have been frequently observed in Australian linear dunes, they are notably absent from dunes observed in southern Africa. However, numerous horizontal laminae occur within the lunette dune at Witpan, and were described by Thomas et al. (1998) as "weakly developed soils" representing "short hiatuses in deposition". These have not previously been considered in detail for the Witpan lunette, and suggest that given the large number of individual horizons and the young age of the lunette, under suitable conditions, pedogenesis within the lunette might occur rapidly. Similar features have been described in Australia (Bowler 1973, 1983; Bowler et al. 2003) and the USA (Schaetzl 2001) but are instead attributed to deflation of clays from playa surfaces rather than palaeosols, which are characterised by both illuviation zones and carbonate precipitation as described in the previous section. Schaetzl (2001) also describes some bands as illuviation fronts due to clay mobility down the stratigraphic column. While palaeosols might indicate distinctive periods of climatic stability, if the laminae at Witpan are analogous to the Australian lunette examples, they may indicate no more than single deflationary events from the playa floor. To this end, intact samples of these laminae were taken from the dune flank for micromorphological analysis.

Interdune profiles

Sampling and laboratory methods

At KAL 04/5, a lightweight hydraulic auger was used to penetrate the Kalahari sands to the calcareous bedrock at 2.3 m. Three OSL samples were taken in light-tight plastic sampling tubes (Figure 3b). At KAL 04/7, bedrock was encountered at 1.4 m, and a single sample was taken for age determination (Figure 3c). Both sites have a sparse covering of grasses (*Schmidtia* and *Stipagrostis* spp.) and shrubs. Care was taken to locate sites apparently undisturbed by roots. As with the HAB samples, no structure was evident from the samples brought to the surface by auger, further illustrating the limitation of this technique. The OSL samples were processed and analysed using similar protocols to those described above for the Australian samples; full details are provided in Telfer and Thomas (2006, 2007).

The interdune deposits, despite reaching the base of the profile, are all Holocene in age, ranging from 1.4-9 ka. The base of the linear dune in between, and apparently overlying the interdune sands, dates from around 75 ka (Telfer and Thomas 2007). The ages at KAL 04/5 are out of stratigraphic sequence, and may be caused by poor resetting of the OSL signal during the initial deposition of interdune deposits, or post-depositional disturbance. Interdunes may be prone to bioturbation, since they are often more vegetated than the dunes, and thus more likely to attract animals. They are also prone to reworking by fluvial activity or ponding that may occur during seasonal or climatic wet phases.

Stratigraphy

One advantage of the OSL SAR protocol is that it yields repeat measurements on different aliquots

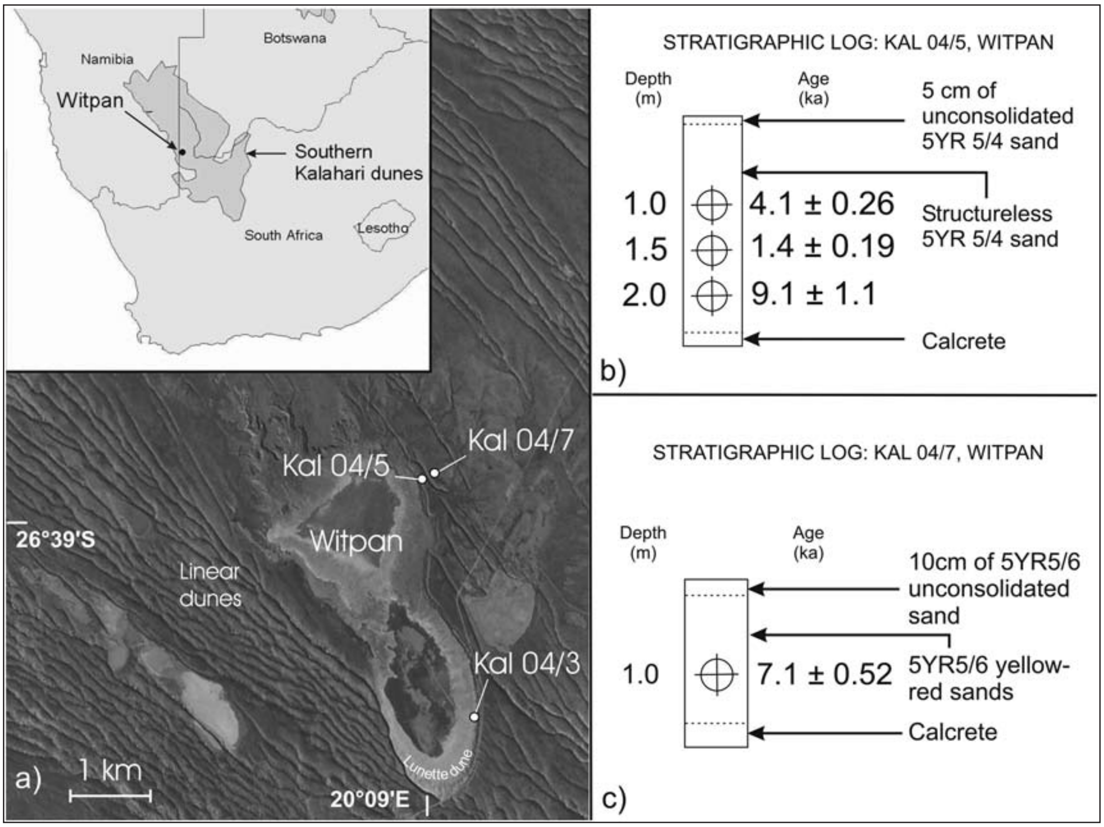

Figure 3. (a) Location of Witpan within the southern dunefield of the Kalahari, and the location of sample sites referred to in the text, stratigraphy and chronologies from interdune profiles, (b) KAL 04/5 and (c) KAL 04/7.
(a) Localización de Witpan dentro de las dunas meridionales del Kalahari, y localización de los sitios de la muestra mencionados en el texto, la estratigrafía y cronología de los perfiles entre las dunas, (b) KAL 04/5 y (c) KAL 04/7.

of the same sample. The dose distributions of these measurements can be used to infer something of the depositional and post-depositional history of the unit being measured. A sample, well-zeroed at deposition and not having undergone post-depositional mixing, should result in a leptokurtic Gaussian fit. However, the lower two samples from KAL 04/5 show strongly bimodal dose distributions, similar to the pedoturbated samples of Bateman et al. (2003), thus implying that near equal post-depositional mixing of two units with different palaeodoses has taken place.

Much of the attention of the OSL community has been focused on methods of describing non-Gaussian dose distributions (e.g. Li 1994; Olley et al. 1999) and obtaining a single palaeodose estimate from them (e.g. Galbraith et al. 1999). However, the focus has generally been on poorly bleached samples, rather than mixtures of well bleached sediments. Although sheetwash and intermittent fluvial processes during storms may result in poorly bleached sediments, aeolian quartz in the Kalahari is assumed to be well bleached due to the nature of aeolian transport, in which sand-sized grains are transported close to the surface (Bagnold 1941) with extended exposure to light.

The interdune sediments at KAL 04/5-2 and KAL 04/5-3 are therefore more likely to comprise well bleached material which has undergone exposure and reworking by vegetation and burrowing animals. The dose distributions of KAL 04/7-1 and KAL 04/5-1 suggest minimal post-depositional mixing, but do not exclude the possibility of the luminescence signal being entirely reset by Holocene bioturbation. Although there is no evidence of mixing at KAL 04/7, the age inversion in KAL 04/5 undermines confidence in the veracity of the single age taken from KAL 04/7.

It may be significant that aliquots with a very high dose (i.e. suggesting pre-Holocene antiquity) are entirely absent from the repeated measurements of even the deepest interdune samples. Even extensively bioturbated samples tend to preserve a luminescence signal from the older components (Bateman et al. 2003). The absence of pre-Holocene aliquots suggests that this component was never present in significant quantities. It may thus be possible to interpret the lower ages as a mixture of Holocene components.

Lunette samples

Sampling and laboratory methods

The lunette at Witpan has been described in detail in Thomas et al. (1993; 1998) and Telfer and Thomas (2006). Figure 4 shows KAL 04/3, with three of the "palaeosols" visible as dark bands. These horizons are darker, finer grained and more resistant to erosion. OSL samples taken from this exposure yielded effectively contemporaneous ages of 2.4 ± 0.1ka, 2.5 ± 0.1ka and 2.4 ± 0.1 ka (Telfer and Thomas 2006). A Kubeïna tin was used to collect each undisturbed sample for micromorphological analyses and thin section preparation.

Stratigraphy

If these horizons are indeed evidence of weak soil development, and therefore humid intervals, then clays in these units would be expected to show evidence of illuviation and cutan development, as discussed in the previous section. However, thin section microscopy shows no evidence of cutan development. The lateral banding is apparently due to a well developed fine groundmass in between porphyritic quartz and calcite grains. The groundmass shows no preferential alignment. There are no grain coatings, other than the reddish-brown iron staining typical of Kalahari quartz, which contrasts with the abraded cutans commonly observed in the Australian sediment examples. The statistically indistinguishable ages suggest that the exposure shown in Figure 4 was deposited over a short time period (perhaps no more than 200 years), and argue against the development of three separate palaeosols. These units more likely represent separate, short-lived deflation events from the pan floor

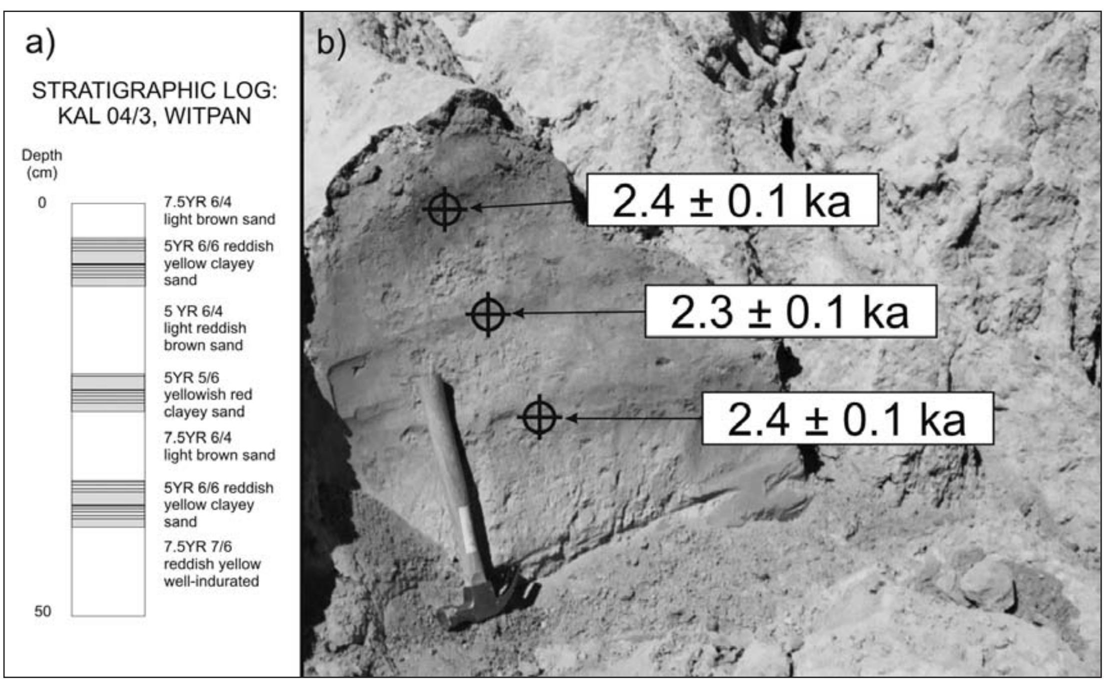

Figure 4. At Kal 04/3, in the northern (i.e. *playa*-facing) flank of the lunette, an exposure was cleaned for sampling for luminescence and micromorphology sampling. Dates from Telfer and Thomas (2006).
En Kal 04/3, en el flanco norte de la luneta, una exposición fue limpiada para obtener muestras para análisis de luminiscencia y micromorfología. Cronología de Telfer y Thomas (2006).

during conditions more conducive to the deflation of clays and silts.

Palaeoenvironmental interpretation

The combined chronological, stratigraphic and micromorphological data presented here yield valuable information about local palaeoenvironmental conditions. The age of the interdune sands cannot readily be interpreted due to the complex luminescence signal due to poor bleaching or post-depositional mixing. However, the deposits are unlikely to predate the Holocene, unlike the older linear dune cores. The dunes at Witpan do not appear to be stacked on top of earlier sediments forming the basal sands of Stokes, Thomas and Shaw (1997). It is considered more likely that the interdunes were weathered to bedrock during the early Holocene or coinciding with the end of the period of enhanced aeolian activity identified from southwestern Kalahari dune records at c. 9-16 ka (Stokes et al. 1997; Telfer and Thomas 2007). The linear dunes were not completely reworked over this period. It is interesting to note that, by contrast, the HAB dune in Australia may have been completely reworked from an older dune in the Holocene. This is inferred from the presence of abraded cutans in the basal sediments, and OSL dating of older dune cores in the region which suggest that aeolian activity took place at various times throughout at least the last 87 ka (Fitzsimmons et al. 2007a). Clearly, regional palaeoenvironmental histories should not only consider all available evidence from individual sites, but should involve a more widespread sampling strategy.

The interdunes at Witpan do not represent a viable archive of palaeoenvironmental information. Further work, including detailed stratigraphic studies, is required to understand their depositional significance and investigate the reasons for the poor dating results. This further highlights the need to explore more than one site in detail.

The laminar horizons evident in the stratigraphy of the indurated lunette at Witpan have previously been described as palaeosols which may infer periods of sediment stability (Thomas et al. 1998). This raises the possibility of their palaeoenvironmental significance. Lawson and Thomas (2002) suggested that the horizons could form as weakly developed palaeosols during depositional hiatuses. However, the lack of palaeosol characteristics suggests that these horizons are depositional in nature, and are more likely due to changes in sediment source (Telfer and Thomas 2006). The clay-rich lunette sediments may nevertheless yield palaeoenvironmental evidence of deflation from a playa with fluctuating near-surface water table levels (Bowler 1973, 1983).

Conclusions

Arid landscapes provide important palaeoenvironmental archives. Desert dunefields are a major component of arid landscapes, and as such have the potential to provide valuable information relating to the history of sediment transport and aridity. However, desert landforms such as dunes and interdunes are inherently dynamic features, and this presents challenges for the interpretation of aeolian records. It is therefore important to understand the issues involved with the preservation and interpretation of such records.

This paper demonstrates the importance of using all available evidence in the interpretation of dunefield archives. In the case of the HAB site in the Tirari Desert of Australia, field observations did not identify sedimentological variation or pedogenesis, however micromorphological and XRD analyses highlighted a possible soil horizon at 2.9 m depth. The timing of this pedogenesis was able to be constrained by OSL dating to between 6-2 ka. Dune building and pedogenesis was compared with other palaeoenvironmental archives from the region. However, the extensive evidence for reworking suggests that despite the information gained from these analyses, the palaeoenvironmental history is more complex and requires not only higher frequency sampling at the site, but also additional sampling across the region. Investigations conducted into the stratigraphy and chronology at Witpan in the southwestern Kalahari also highlight the complexities for arid zone palaeoenvironmental reconstruction posed by the reworking of aeolian sediments. Basal interdune sands have been suggested to be the least sensitive element of linear dune landscapes, thereby offering the potential to extend the aeolian record. However, at this location, bioturbation has extensively disturbed the interdune sands. The interdunes are most likely to be Holocene deposits, suggesting aeolian reworking to bedrock at a time when adjacent linear dune cores were still preserved. Extension of the aeolian record may be better addressed through studies of the linear dune cores. Laminar bedding structures within the lunette at Witpan, previously interpreted as palaeosols, are suggested instead to reflect changes in sediment source rather than climatically-induced pedogenesis.

Incomplete records are common across the southern hemisphere dunefields. The two case studies presented here highlight potential issues with the interpretation of stratigraphic, sedimentological and chronological evidence in the context of dune formation and palaeoenvironmental reconstruction. In so doing, we advise that caution must be taken in reconstructing palaeoenvironmental history from desert dune records, and that the complexity in interpreting desert dune records is not limited to a single region, with the issue extending across the southern hemisphere and beyond.

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