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Preserving the palaeoenvironmental record in Drylands: Bioturbation and its significance for luminescence-derived chronologies.

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Abstract

Luminescence (OSL) dating has revolutionised the understanding of Late Pleistocene dryland activity. However, one of the key assumptions for this sort of palaeoenvironmental work is that sedimentary sequences have been *preserved intact,* enabling their use as proxy indicators of past changes. This relies on stabilisation or burial soon after deposition and a mechanism to prevent any subsequent re-mobilisation. As well as a dating technique OSL, especially at the single grain level, can be used to gain an insight into post-depositional processes that may distort or invalidate the palaeoenvironmental record of geological sediment sequences. This paper explores the possible impact of bioturbation (the movement of sediment by flora and fauna) on luminescence derived chronologies from Quaternary sedimentary deposits in Texas and Florida (USA) which have both independent radiocarbon chronologies and archaeological evidence. These sites clearly illustrate the ability of bioturbation to rejuvenate ancient weathered sandy bedrock and/or to alter depositional stratigraphies through the processes of exhumation and sub-surface mixing of sediment. The use of multiple OSL replicate measurements is advocated as a strategy for checking for bioturbated sediment. Where significant OSL heterogeneity is found, caution should be taken with the derived OSL ages and further measurements at the single grain level are recommended. Observations from the linear dunes of the Kalahari show them to have no bedding structure and to have OSL heterogeneity similar to that shown from the bioturbated Texan and Florida sites. The Kalahari linear dunes could have therefore undergone hitherto undetected post-depositional sediment disturbance which would have implications for the established OSL chronology for the region.

KEYWORDS: bioturbation, luminescence dating, Florida, Texas, Kalahari

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1. Introduction

Drylands are known to be particularly sensitive to shifts in climate. Whilst often largely devoid of organic material, sediments laid down as geomorphic responses to climatic shifts have formed the basis for a large and ever growing body of research into past environments both in the Pleistocene and further back into the Geological record (e.g. Thomas and Shaw, 2002; Biswas, 2005). Underpinning this research is a conceptual framework (Figure 1) which is reliant on two key assumptions. Firstly that dryland areas have not only experienced past climatic shifts but that they respond to such shifts in a predictable and

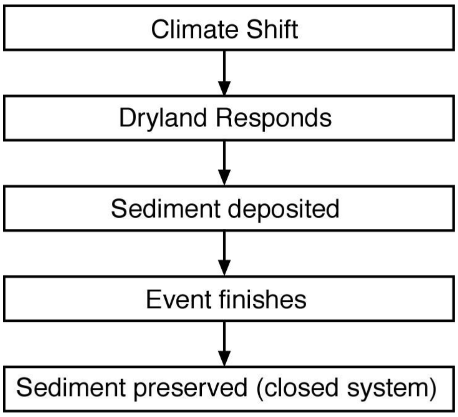

Figure 1 A conceptual model for utilizing the palaeoenvironment proxy record contained in dryland sediments.

characteristic manner, producing identifiable and characteristic sedimentary deposits. Work from dunes of the Kalahari has shown this to be the case, with dunes responding to major climatic shifts such as the last glacial maximum (*ca.* 21ka) (e.g. Thomas et al., 2003; Bateman et al., 2003a). Secondly, these sedimentary deposits are preserved, pristine and uncontaminated, in a closed system such that on examination today their characteristics and age can be reliably determined and appropriate palaeoenvironmental and palaeoclimatic inferences made. Setting aside issues relating to equifinality and sediment interpretation there are two main pitfalls within this framework. Firstly, the preservation of sediments in the Geological record is complex. As Kocurek (1998) showed in his conceptual model, the amount of sediment deposited and preserved in an aeolian environment is highly dependent not only on climate but on sediment production, supply, transport competence, erosion and stabilisation. Thus for any given climatic cycle (e.g. cold-warm-cold) only a small percentage of sediments that were deposited may survive and be preserved into the next cycle. Secondly, few sediments are preserved in a truly closed environment and they may be subject to post-depositional disturbance. Post-depositional disturbance ranges from groundwater flowing through sediments and subtly altering their chemical composition, to physical distortion due to changes in loading or vertical/lateral stresses, through to significant alterations in association with pedogenesis. As Figure 2 illustrates, dunes can be composed of

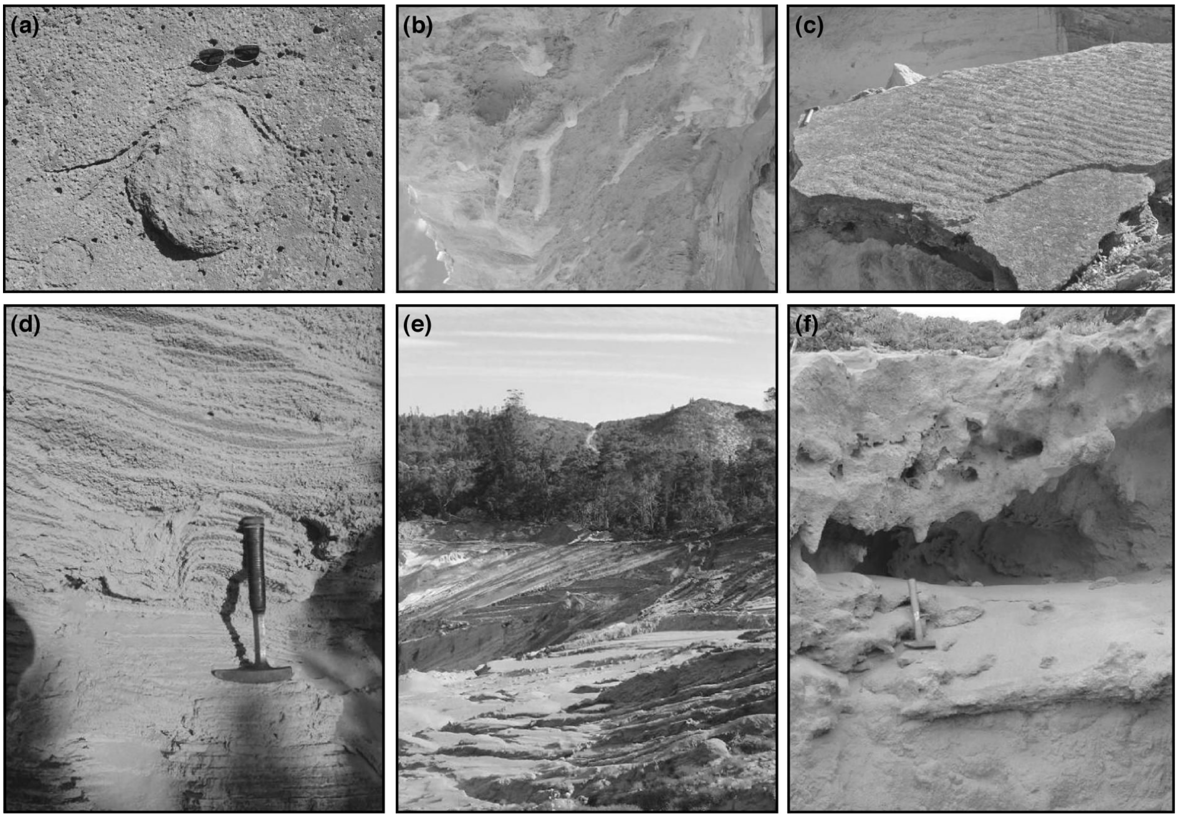

Figure 2 Mid-Late Pleistocene aeolianites from the Western Cape, South Africa where pristine sedimentary structures and post-depositional disturbance have been preserved. (a) elephant foot print cast (note also preserved push up ridge at front of print) (b) Rhizome casts associated with a palaeosol (c) wind ripples preserved within finely bedded aeolianite (d) slump structure within dune forset beds (e) large-scale preserved dune forsets (f) Mole rat tunnels preserved beneath a palaeosol (viewed from underside of an overhang).

large-scale and micro-scale sedimentary structures and bedding. These are often particularly well displayed in aeolianite outcrops where recent weathering accentuates the grainsize or compositional differences of these structures. In these well-preserved sequences, evidence for bioturbation (the movement of sediment by flora and fauna) is apparent in the form of footprints, rhizome casts and burrows (Figure 2). Thus where preservation of structure is good enough, there is evidence that bioturbation has been an active process in dune environments.

This paper focuses on bioturbation and how this form of post-depositional disturbance may have a significant impact on dryland palaeoenvironmental records, particularly those derived through luminescence dating of sediments. In this paper we present examples from sites in Texas and Florida (USA), for which both evidence of bioturbation and independent chronologies exist. We assess the potential the significance and magnitude of these processes on luminescence derived chronologies through intensive sampling and consideration of additional sedimentological, geomorphic and archaeological evidence. Through comparison with these independent chronologies, the degree of disturbance from which still reliable ages may be determined is assessed. The implications for luminescence based records of Quaternary environmental change from dryland environments typified by southern Africa's Kalahari desert are discussed, as are sampling and measurement strategies that may enable the detection and reliable dating of disturbed sequences.

2. Bioturbation in drylands

Terrestrial bioturbation is the process whereby particles are translocated vertically and/or laterally within near-surface unconsolidated sedimentary deposits by animals or plants (Balek, 2002; Whitford and Kay, 1999). This may lead to the exhumation of some sediment forming biomantles and may also cause larger objects, through gradual removal of finer surrounding sediment, to be displaced downwards, possibly forming stonelines (e.g. Johnson, 2002, Fig. 6; Brown et al., 2004). In drylands there are many potential sources of disturbance. In terms of insects, these include termites which as well as constructing the impressive and widespread termite mounds, are reported in the Kalahari termites to also burrow to between 1.8-2.4 m (West, 1970 cited in Balek, 2002). At a smaller scale, ant galleries can attain depths of 4 m with colonies of certain species building multiple gallery complexes per year (Tschinkel 2003). Fossorial rodents like meerkats, molerats and gophers bioturbate sediments in the process of creating burrows, mounds and tunnels. Sediment may be moved to the surface as excavation mounds or be moved within the subsurface as old tunnels and chambers are back filled or collapse (which may move younger sediment downwards). In some semi-arid and arid environments excavated material may cover 15-20 % of the land area in which foraging activity occurs, whilst the burrow systems of some species comprise volumes as high as 900 m^3 (Whitford and Kay, 1999 and references therein). In the case of animals such as the Pocket Gopher (Geomyidae) these effects tend to be concentrated in the upper 5-20 cm of a soil, although some species excavate to depths of 1.5 m (Reichman and Seabloom, 2002). The small (c. 1 kg) marsupial *Bettongia penicillata* of Australia can dig as many as 100 *c.*15 cm deep holes per night and is capable of displacing over 4 tonnes of soil annually (Garkaklis et al., 2004). Vegetation, particularly trees, may also disturb sediment both through the growth and decay of root systems and via tree throws. Where the latter is clearly a surficial, tree root growth can extend to great depths in areas with deep water tables.

Bioturbation is thus most intensive within a metre or so of the surface. The primary control on how much of the sedimentary record is exposed to bioturbation is dependant on the periodicity of sediment deposition, i.e. how long sediments are within the upper 1-2 metres, and the depth of sediment deposited within single events. Scenarios of potential bioturbation effects with respect to variable sedimentation rates are outlined in Bateman et al. (2003b, Figure 2). These range from the minor disturbance of a rapidly accreting deposit, to a worst case scenario (in terms of palaeoenvironmental reconstruction) in which bioturbation of a weakly indurated but geologically ancient sand strata could lead to, through exhumation of sediment, a surficial sandy mantle (Figure 3). At this extreme, insects or fossorial rodents may bring deeply buried sediment through a soil via discreet vertical tunnels leaving the latter largely intact but buried by the exhumed material. This falls outside the depositional conceptual framework outlined in Figure 1, with the rejuvenated sandy mantle having no palaeoenvironmental significance despite being indistinguishable in terms of sedimentological attributes (e.g. Phillips, 2004) and mineralogy from a structureless sand-sheet deposited as the result of environmental change.

Efforts have been made to understand the effects of bioturbation in the marine record (both near shore and deep ocean), through ichnofabric analysis of ancient geological near shore strata (e.g. Malpas et al., 2005) and through radionuclide tracers more recent shallow (e.g. Shull 2001) and deep ocean sediments (e.g. Thomson et al., 2000). The effects of terrestrial bioturbation have been highlighted by archaeologists (e.g. Wood and Johnson, 1978; Frolking and Lepper, 2001; Fowler et al., 2004), geographers (e.g. Johnson 2002), soil scientists (e.g. Tyler et al., 2001) and researchers interested in bioturbation and biologically aided slope transport (e.g. Brown et al., 2003; Heimsath 2002; Bunzl 2002; Gabet 2000). However, very little is published about the potential impacts of these processes especially upon luminescence chronologies and the attendant palaeoenvironmental records preserved within dryland sediments. More specifically, the significance of these processes on the derivation of reliable (*depositional age*) luminescence ages, is yet to be investigated.

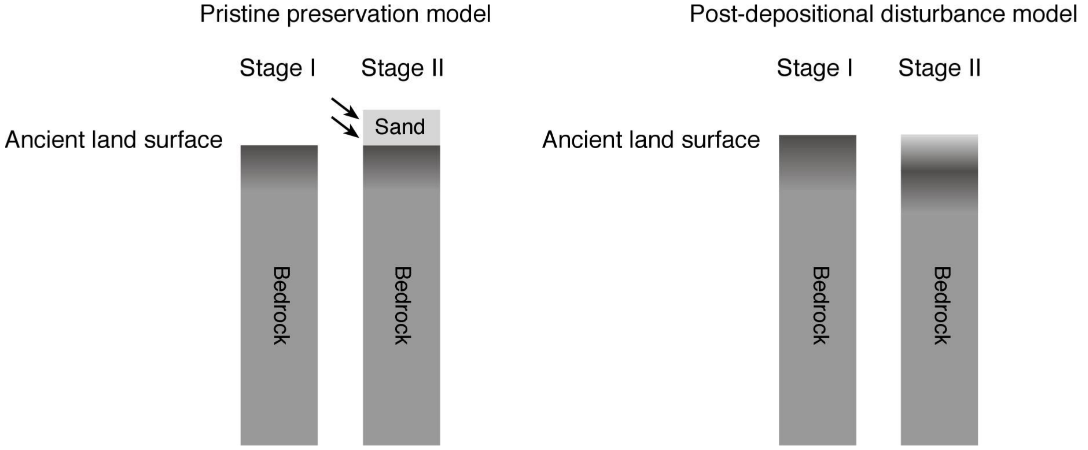

Figure 3 A schematic of a depositional and pedoturbation model in the creation of a sand body on top of a weakly indurated geological sandy strata.

3. Luminescence Dating and bioturbation

The luminescence dating technique relies on the premise that individual grains of quartz or feldspar act as micro dosimeters. They store trapped charged in proportion to the amount of background ionizing radiation they have been subject to since burial. Every time grains are exposed to sunlight or high temperatures this trapped charge is released thus resetting the ‘timeclock’. An inherent assumption in luminescence age determination is that the sediment has been fully “reset” or ‘bleached’ by exposure to sunlight prior to burial and that no subsequent post-depositional sediment disturbance has occurred. Bioturbation thus has the potential to invalidate the latter but also to cause bleaching unrelated to sediment deposition.

Late Pleistocene aeolian sediments are widely thought to be the best type of sediments which to apply the optically stimulated luminescence (OSL) technique as they tend to be quartz rich, sandy and the transportation of sediment by wind makes exposure to sunlight prior to burial highly likely. Additionally in most dryland environments quartz rich sediments have been subjected to multiple erosion, transport and burial cycles in which the quartz grains have become highly sensitised both in terms of their ability to “store” the ionizing radiation that they are subjected to their response during luminescence measurement.

The application of luminescence dating, however, could add to the confusion in the worst case scenario of a rejuvenated sandy mantle outlined in section 2. As the exhumation during bioturbation would reset the OSL signal, even an OSL derived chronology could show a deceptively reassuring increasing age with depth (reflecting primarily the decreasing intensity of bioturbation with depth). This is where careful examination of replicate OSL data both at the multi- and single grain level is essential. In principle, sand grains from an unmixed sample buried at the same time in the same location should have stored the same palaeodose (D_e) from which a luminescence age can be calculated. High replicate reproducibility is expected with the D_e values forming a single normal (highly peaked) distribution around the mean (Fig. 4a). If not all grains are reset prior to burial or bioturbation has occurred then such a distribution is unlikely (see Bateman et al., 2003b, Fig. 3). Poorly reset samples would lead to a high D_e tail in the distribution from grains carrying an antecedent D_e signal unrelated to the final burial event. Bioturbation could affect D_e distributions by exhuming some grains and causing them to be reset, producing a low D_e tail. Further, sub-surface mixing may cause grains from differently age sediments to be mixed together causing either a multi-modal D_e distribution (e.g. Sanderson et al., 2001, Forrest et al., 2003) or a very low broad D_e distribution. If either have occurred intensive sampling down profile may also reveal age reversals.

OSL measurements can be made at the single aliquot level and, due to recent technical advances, down at the single grain level. As the OSL signal

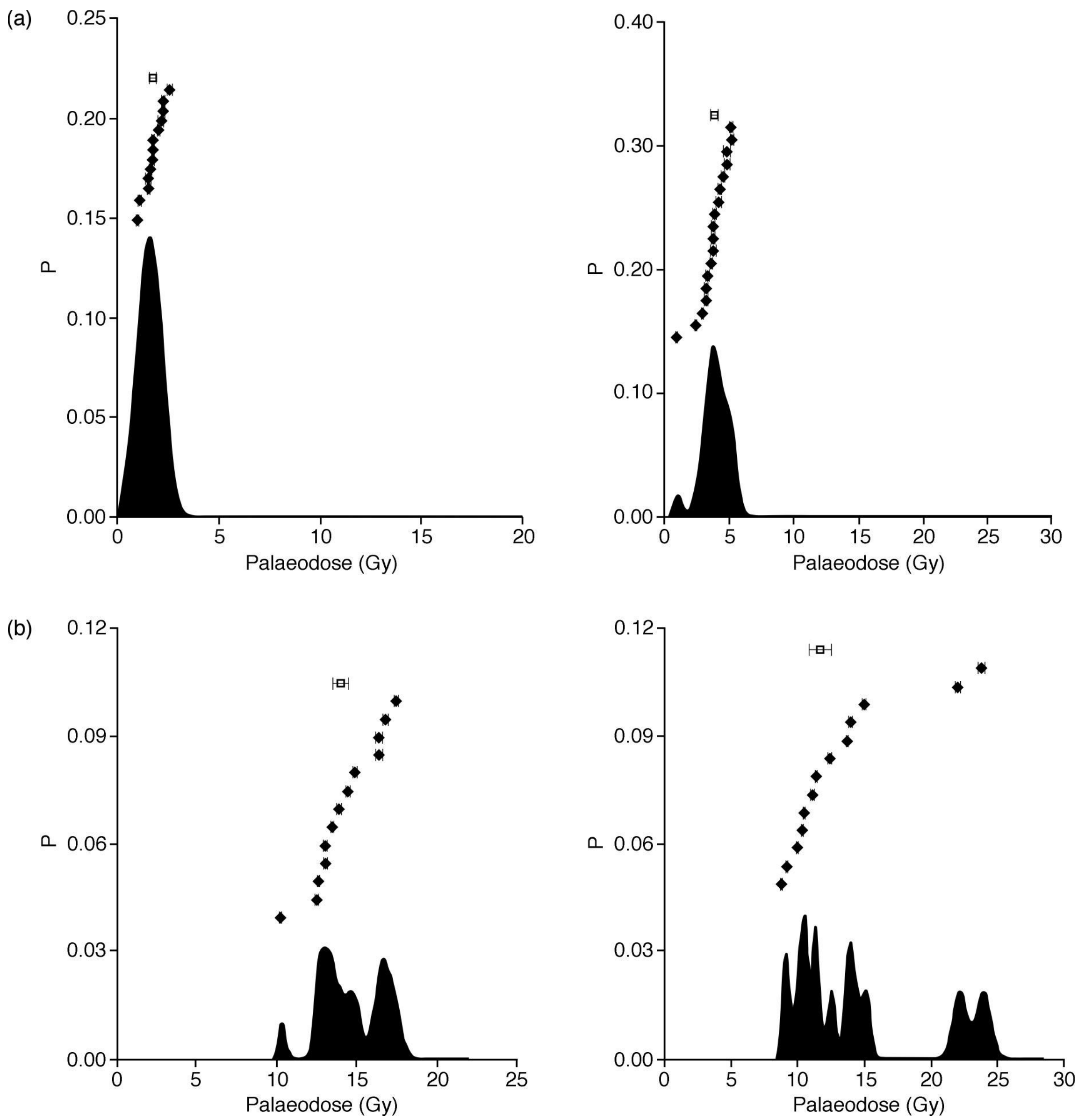

Figure 4 Examples of multiple OSL D_e replicates from (a) typical pristine dune samples (b) linear dunes at the Tsodilo Hills, Botswana (Thomas et al. 2003). D_e measurements and associated errors (closed squares) and sample mean and error (open squares) are shown.

measured with a standard aliquot is an average of *c.* 2000 grains the true distribution of D_e values within a sample may be masked as an average light signal is produced. This is of great significance in heterogeneously dosed samples (e.g. bioturbated) in which grains with a low or zero D_e signal will be particularly biased against. Measurement of the accumulated dose from *individual* grains obviates this problem and is now possible as a routine measurement with modern luminescence measurement machines. It is thus possible to assess the full range of accumulated dose within a sedimentary deposit. Both approaches were used in this study.

4. Methodology

The samples were prepared for OSL under subdued red lighting following the procedure to extract and clean quartz outlined in Bateman and Catt (1996) and the single aliquot regenerative (modified from Murray and Wintle 2000) approach was used to measure palaeodoses. The purity of the quartz extract was checked using infrared stimulated luminescence and no feldspar contamination was seen. Standard aliquot measurements were conducted using 9.6 mm diameter aluminium disks coated with a monolayer of grains from a sample. Each aliquot thus comprised in the region of 2000 grains which were measured simultaneously. All OSL measurements were carried out using a Risø luminescence reader fitted with a 150 W filtered (GG-420) halogen lamp and OSL was measured through a Hoya-340 filter. The naturally acquired D_e of samples was analysed with a experimentally derived preheat of 200 °C or 180 °C for 10 seconds prior to each OSL measurement in order to remove unstable signal generated by laboratory irradiations. For single grain measurements individual grains were mounted in 300µm pits. The latest generation Risø TL DA-15 single grain laser luminescence reader was used for measurements with a focussed 532 nm $Nd:YVO_4$ laser providing the stimulation and luminescence detected through a U-340 filter. D_e measurement was identical to that of the standard aliquot. As many grains exhibited an OSL signal too low and/or too poorly behaved to be accurately measured, approximately 500-1900 grains were measured in order to derive more than 40 single grain D_e values for each sample.

With both approaches numerous replicate measurements on each sample were made to give an indication of the reproducibility of the D_e measurements. For age calculation purposes aliquots/grains falling outside of two standard deviations of the mean were treated as outliers and excluded (as per Bateman et al., 2003b). The D_e values used in the final age calculation are based on the common age model mean (Galbraith et al., 1999) with ages quoted in years from present (2004) with one sigma confidence intervals. Dose rates for the Texan sites were determined using an EG&G Micronomad field gamma-spectrometer. Similar data from the Florida sites were found to be below the reliable detection limits of the system and therefore sub-samples of sediment were measured using age (e.g. Campbell 1986) and others a Tertiary-Quaternary age (e.g. Scott et al., 2001 and Scott, 2001; p. 21). The whole region is underlain by

Presently the landscape is heavily vegetated either with pine flatwoods, cyprus swamp or oak-palm woodland with the ground-water table seasonally close to the surface over large parts of the landscape. It is therefore an environment in which it is hard to envisage conditions under which sand movement could naturally take place under the prevailing climatic regime. Vegetation clearance by catastrophic events such as fire, which might allow sediment transport, are ineffective as vegetation regrowth occurs within a few weeks under the present climatic regime.

inductively coupled plasma mass spectrometry with conversion from elemental concentrations to effective dose rate following Aitken (1998). Attenuation for moisture used estimates based on the contents of samples when sampled and the cosmic dose contribution was calculated as per Prescott and Hutton (1994).

5. Case studies

We present data from four case studies in the USA, all of which provide independent dating via radiocarbon and archaeological artefact evidence and where sampled intensively for luminescence dating. Two sites from Florida encompass a site with good geomorphic evidence for the recent deposition of a sedimentary feature and secondly, a section through an apparently homogenous sand body. Two sites from Texas are presented to investigate the significance of preserved sedimentary structures and whether such features are diagnostic of an absence of significant bioturbation effects.

5.1 Florida

The central Florida area lies within the Osceola Plain, a nearly flat sandy marine terrace surface that lies about 18-21 m above sea level (White, 1970; Lane et al., 1980). The Lake Wales Ridge is the most prominent topographic feature in central Florida and within the Avon Park Air Force base, the area selected for this case study, the Osceola Plain is interrupted by a smaller broadly north-south trending ridge named Bombing Range Ridge that rises to an elevation of 38-44 m above sea level. The ridges are thought to be relict beach ridges and associated marine sand bars (White, 1970; 119-123; Campbell 1986). The age of these sediment is uncertain, with some sources ascribing a Tertiary carbonate rich strata which, as a consequence of solution, has caused slumping of the sand to form a myriad of irregular and disconnected karstic lakes.

As part of a wider archaeological project, across the Avon Park Air Force range, a large number of pits were dug through the unconsolidated sand on the sandy marine terrace. Here profiles were logged, sediments texturally analysed and archaeological artefacts recovered. Where possible radiocarbon dating was undertaken and the sand was intensively sampled for OSL dating. The data from two of these sites are presented here (Figures 4 and 5; Table 1).

5.1.1 Ebersbach Midden (27° 42' N, 81° 23' W)

Figure 4 shows the Ebersbach Midden site, in which clear geomorphic and sedimentary evidence

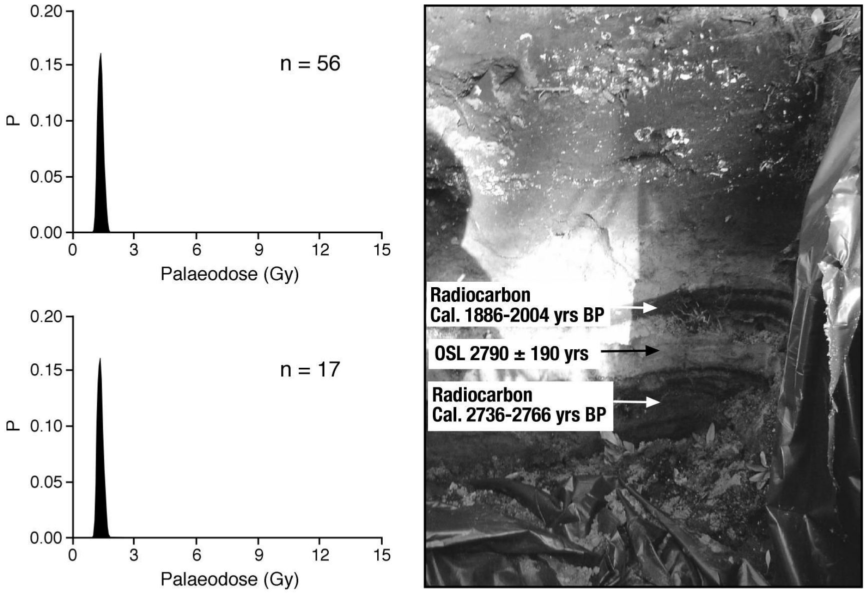

Fig. 5. OSL and radiocarbon chronologies from the Eberbach Midden Site, Avon Park Florida. Also shown as a combined probability plot is the high reproducibility of OSL De replicates; (a) single grain, (b) single aliquot.

indicate sediment transport and deposition took place. At this site two low (<3m) ridges run parallel and adjacent to the shoreline of a lake. These are interpreted as former beach ridges. Test pits demonstrated an interdigitation of organic rich and sandy horizons within the younger ridge. The OSL data from this site reveal three important facts. Firstly, that the OSL age could be independently verified with bracketing calibrated radiocarbon ages. Secondly, in a clearly stratified depositional context, replicated measurements from a single sample showed a high degree of D_e reproducibility for both the standard aliquot single grain measurements. Finally, they also show a normal distribution as theorised in section 3 both at the single grain as anticipated for fully bleached, undisturbed sediments (Duller, 2004).

5.1.2 Sandy Point Hammock (27° 37’ N, 81° 21’ W)

Ebersbach Midden is, however, the exception in this region and test pits dug elsewhere showed a structureless homogenous sand extending beyond the limits of safe excavation. This same sandsheet, however, yielded archaeological evidence at depths of up to 1.5 m including a population of historical artefacts less than 100 years old with modal depth of burial at 20 cm below the modern surface. OSL dating revealed Holocene and Late Glacial ages which increased in antiquity with depth as would be expected under the laws of superposition. Figure 6 shows data from one such profile, Sandy Point Hammock, which underwent both single grain OSL dating and radiocarbon dating and during excavation produced a ceramic and lithic artefact component. At this locality there is clearly a mismatch between the radiocarbon dates and the OSL ages, which are apparently much older. The data reveal that the two culturally separate (and therefore presumably temporally separate) artefact components, whilst showing clear peaks at certain depths, overlap and are distributed over a wide range of depths. When the single grain D_e replicate OSL data are examined for the upper most sample (25 cm depth) grains which have zero D_e doses are observed, suggesting that they have been recently moved down from the surface. Other samples show poor D_e reproducibility, with a broad distribution of values. Clearly, some samples have a skewed distribution with a number of grains exhibiting very large D_es. There is a clear difference in D_e replicate between all of these and the D_e distribution from Ebersbach Midden which is from a depositional context. Likewise, there is a clear shift in mean D_e

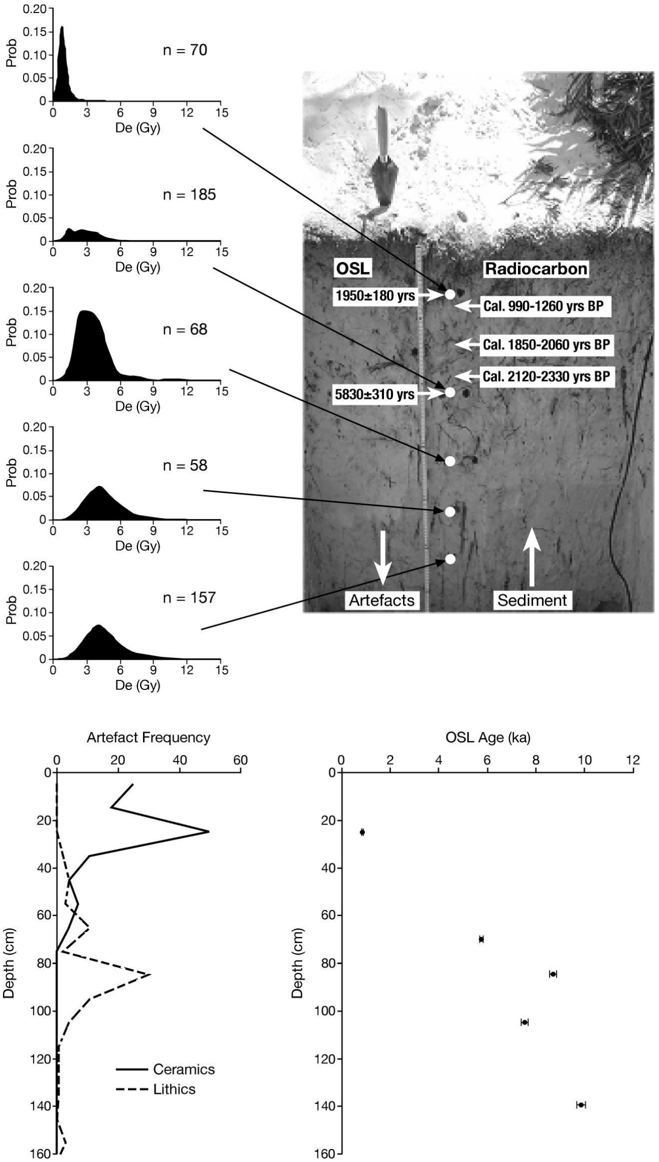

Figure 6 OSL single grain replicate scatter (shown as combined probability plots) and OSL ages compared to radiocarbon dates and archaeological evidence from Sandy Point Hammock, Avon Park Florida.

Table 1. *Summary of OSL data for Florida Sites Ages.*

Sample details		Dosimetry Data							Single Grain Data			
Lab Code	**Depth** (cm)	**U** (PPM)	**Th** (PPM)	**K** (%)	**D_{cosmic}** ($\mu Gy/a^{-1}$)	**n**	**D_e*** (Gy)	**Age (ka)**	**n**	**D_e^*** (Gy)	**Zero De grains (%)**	**Age (ka)**
Sandy Point Hammock												
Shfd04013	25	0.35	0.85	0.03	192 ± 10	19	0.90 ± 0.04	2.51 ± 0.1	70	0.7 ± 0.06	4.2	1.95 ± 0.2
Shfd04012	70	0.57	1.0	0.01	184 ± 9	22	2.88 ± 0.05	7.28 ± 0.3	185	2.33 ± 0.09	0	5.83 ± 0.3
Ebersbach Midden												
Shfd04019	70	0.22	0.3	0.02	191 ± 10	20	0.74 ± 0.04	2.86 ± 0.2	56	0.70 ± 0.06	0	2.56 ± 0.2

† sample concentration less than detection limit for ICP-AES of 0.01%

* Mean D_e derived from common age model after outlier De values remove

values at the single aliquot and single grain D_e level, again indicating large D_e heterogeneity within the sample distribution samples (Duller 2004). The OSL data from Sandy Point Hammock are interpreted as indicating that post-depositional disturbance of the sediment has occurred causing the mixing together of grains previously exhumed with grains of considerably larger D_es derived from the original deposit.

5.2 Texas

The underlying geology of much of east-central Texas is composed of weakly consolidated fluvial-deltaic Eocene sandstone (Sellards *et al*., 1932). Overlying this is a superficial unconsolidated sand-sheet of apparently unweathered quartzitic sand up to 4 m in thickness. An often thick argillic soil horizon at depth and/or lag deposit known as the Uvalde Gravel are observed between the two in some places (Fields and Klement, 1995). This sand-sheet has variously been ascribed to the bioturbation and rejuvenation of the underlying Tertiary sandstone (Bruseth and Perttula, 1981; Bruseth and Martin, 2001) or to aeolian, colluvial or alluvial activity (Heinrich, 1986; Thoms et al., 1994; Rogers, 1995). Although the climate is drier than Florida and the landscape a gently rolling dissected upland, present vegetation is dense, forming upland hardwood forests (principally composed of oak, hickory, walnut and holly) and grasslands (characterised by Bermuda grass and Lovegrass; Fields *et al*., 1991). Evidence for sediment transport at present is limited, but unlike the Florida case, there is ample potential energy for slope transport. Within this sandy mantle two previously excavated archaeological sites in the vicinity of the town of Jewett were reopened and sampled for the present study; one completely structureless (Cottonwood Springs) the other with structure in the form of a buried palaeosol (Rena Branch).

5.2.1 Cottonwood Springs (31° 23' N, 96° 13' W)

The Cottonwood Springs site is located on near the summit of a ridge. Here a 4.0 m profile was mechanically excavated directly adjacent to the original archaeological excavation so that new data could be tied to pre-existing archaeological and radiometric data (Fields and Klement 1995). This (and the previous archaeological excavations) revealed a structureless, massive sand body, more than 3.5m thick. This displayed had no evidence of bioturbation (e.g. krotovina) but at depth weakly developed clay lamellae were observed terminating in a red clay Bt horizon with an uneven upper boundary. The primary cultural zone occurred at approximately 1.2-3.2 m below the ground surface. Cultural remains are relatively frequent, and included burned rock concentrations, chipped stone dart and arrow points and one flexed human burial. The remains indicate occupation during the Late Archaic and Early Woodland periods (approximately 4000 to 1800 years B.P.; Fields and Klement, 1995). Also within this zone there was a scattered gravel component.

This site offered the opportunity to explore whether the lack of depositional bedding structure was proof that extensive bioturbation, sufficient to homogenise the sand, had occurred. A total of 10 samples were collected for OSL and multiple measurements were made at the single aliquot level (Figure 7). As exemplified in the selected probability plots, the D_e replicates for all samples were dominated by a broadly well-defined normally distributed peak. In some samples there was a small but appreciable number of aliquots which yielded higher D_e values leading to some skewing, but these were clearly distinct from the main population of data. In plotting the relative standard error (RSD) down the profile (Fig 7) it is apparent that once below the present surface, scatter is uniformly low (average RSD excluding first sample = 27%). The scatter suggests a small amount of disturbance in the form of older sediment moving up profile. One or two replicates also showed low D_e values indicating limited downward mixing of sediment (see the probability plot for sample 3 in Figure 7). If the latter are excluded as outliers (> two standard deviations from the mean) then the lowest

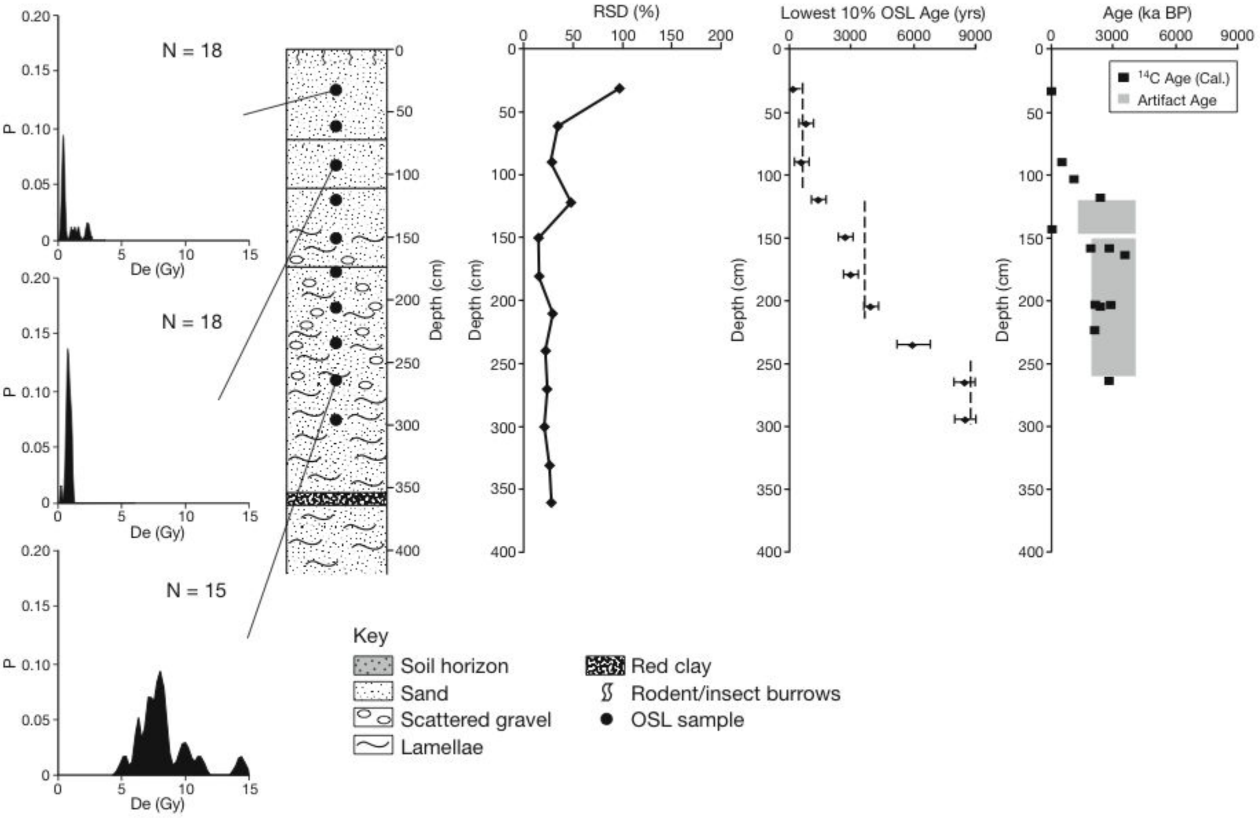

Figure 7 Single aliquot OSL replicate scatter (shown as combined probability plots), D_e relative standard deviation (RSD) as a function of depth and OSL ages compared to radiocarbon and archaeological chronologies for Cottonwood site, Lee County, Texas.

D_e values represent those aliquots whose D_e values closest related to depositional age. For consistency with the other Texan case study, only the lowest 10% of D_e replicate values were selected for age calculation purposes to try factor out older bioturbated material. For this site this made little difference to the ages compared to those based on the average D_e value. The OSL ages from Cottonwood springs show not only an increase in antiquity with depth (without reversals) but fall into groups showing pulses of similar age sediment (Figure 7). This is what would be expected with high intensity sampling of a naturally deposited sedimentary body. When the OSL ages are compared to the independent radiocarbon and artefactual chronologies form this site, there is good agreement between all three. Thus, despite no bedding structure and anthropogenic disturbance, minimal bioturbation has affected the samples. The sand appears depositional and a good chronology can be derived from OSL.

5.2.2 Rena Branch (31° 27’ N 96° 7’ W)

The Rena Branch site is situated on a narrow, sloping interfluve ridge approximately 10.5 metres above the confluence of Rena Branch and Alligator Creek. At this locality a pocket of sand has been deposited in an erosional feature in the underlying Tertiary sandy bedrock. A 3.0 m profile was excavated adjacent to the original archaeological excavation so that new data could be tied to the pre-existing archaeological and radiometric data. This again revealed a sand unit with no primary bedding structures but it importantly it did contain a clearly defined buried palaeosol between 0.9 – 1.7 m depth, suggesting that total bioturbation and homogenisation of sediment had not occurred. Archaeological artefacts were comparatively sparse towards the base of the exposure, but increased in frequency towards the surface, with the primary cultural zone associated with the palaeosol occurring at 0.7 - 2.0 m below the ground surface. The cultural assemblage was composed of scattered burned rocks, stone tools and occasional ceramic fragments, and is interpreted as non-intensive occupation during the late Archaic (c. 4000-2200 years BP), followed by increased occupational intensity throughout the Woodland and Prehistoric periods (c. 2200-200 years BP). In addition, there was a marked historic (late nineteenth to early twentieth century) component, peaking at 0.3 – 0.45 m below ground surface, reflecting the presence of a farmstead on the site during this period.

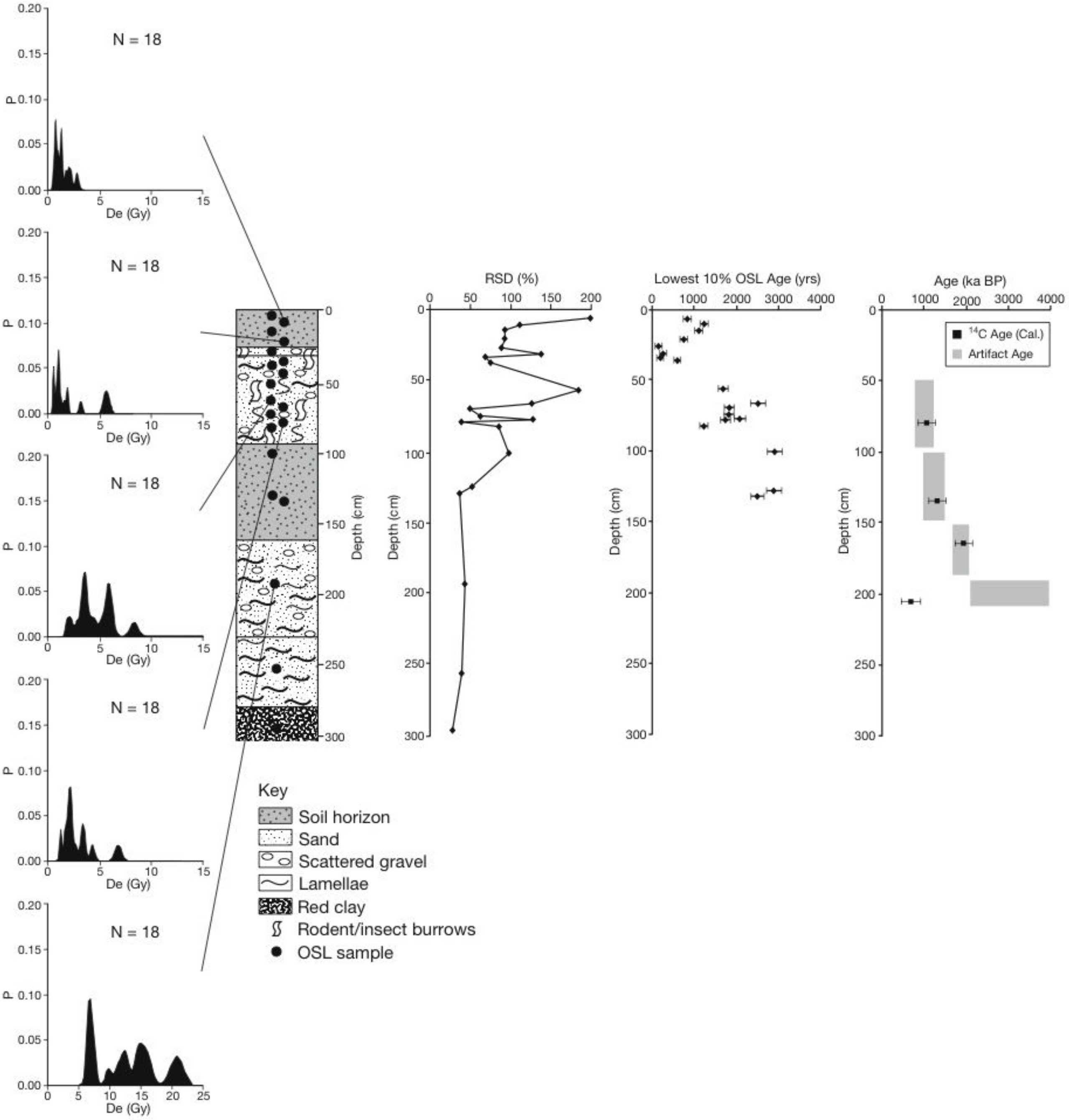

Figure 8 Single aliquot OSL replicate scatter (shown as combined probability plots), relative standard deviation (RSD) as a function of depth and OSL ages compared to radiocarbon and archaeological chronologies for Rena Branch site, Freestone County, Texas. Note the scale change for lowest probability plot.

In the sand unit above the palaeosol some signs of disturbance were noted, including rodent and insect burrows, root casts and limited surface disturbance caused by agricultural practices during the historic period (Fields *et al*., 1991). As with the Cottonwood Springs site the lower part of the profile contained some weakly developed clay lamellae which increased in thickness towards the base of the sequence where a red clay Bt horizon was encountered.

This site offered the opportunity to explore a site which, based on stratigraphic evidence, had undergone some bioturbation whilst still retaining some stratigraphic integrity. A total of 20 samples were collected for OSL dating and multiple replicate measurements were made at the single aliquot level (Fig 8). The D_e replicates for all samples showed multi-modal distributions and poor reproducibility. From these data it is impossible to identify modal D_e values that may relate to sediment deposition and for most samples there is no single dominant D_e peak. In most samples there was an appreciable skewing with a high D_e tail interpreted as sub-surface mixing of older material up the profile. In plotting RSD down the profile it is apparent that both the current soil (mean RSD = 125%) and upper sand unit (mean RSD = 97%) have appreciable scatter and even further down profile the palaeosol (mean RSD = 80%) and underlying sand unit (mean RSD = 41%) still have considerable scatter. Two main conclusions can be drawn from this. Firstly that where there are active soil processes currently occurring, the OSL technique, even at the single aliquot level, is capable of detecting D_e scatter associated with sediment mixing and exhumation. Secondly, this also holds true where there is sedimentary evidence of bioturbation. As with the Cottonwood Springs site, if it is assumed that the aliquots giving the lowest D_e values had more grains unaffected by mixing then ages calculated using the lowest 10% of D_e replicate data should be closest to burial age. When this is done the OSL ages from this site fail to show any consistent increase in antiquity with depth and samples collected within centimetres of each other display statistically significant age reversals. When the OSL ages are compared to the independent radiocarbon and artefactual chronologies from this site there is very poor agreement, with the OSL over-estimating ages at all depths. The large scatter and poor reproducibility of samples from this site are interpreted as indicating that the whole site been adversely affected by bioturbation. This has varied in intensity down profile, detrimentally disturbing the upper profile most. This may reflect Historic land clearance activities, which created habitats more favourable to fossorial rodents than existed under primeval forest cover. The cause of this bioturbation must be attributed, at least in part, to fossorial rodents as krotavina were found in the upper part of the profile. Thus, whilst the site has retained some vestige of structure with the buried palaeosol, an OSL based chronology would be highly erroneous.

6. Discussion

The data from the four case studies spans the range of bioturbation impacts on sediment preservation. The Ebersbach Midden site shows pristine, unimpacted sediment with OSL data normally distributed and highly reproducible. Whereas the Sandy Point Hammock site illustrates that under present-day Floridian conditions, whilst depositionally stable, the surface sediment is being overturned and mixed to a depth of more than 1.5 m. In the course of this, archaeological artefacts have been preferentially moved downward and sediment moved upward (illustrated by the high D_e skewing of the OSL replicate data). The most likely agent for this disturbance is treethrows and insects – in this case ants. Tschinkel (2003) showed that ant colonies in Florida can excavate nests down to 4.0 m from the surface, up to twice a year. He also observed that ants backfill chambers with material removed when excavating lower chambers, thereby causing a net upward movement of sand grains within a profile. Sandy Point Hammock therefore represents the worst case scenario in terms of the reliable application of OSL dating, in that bioturbation is rejuvenating ancient sediments.

Critical to understanding the possible breadth of the bioturbation problem in dryland contexts is whether a lack of sedimentary structure in a dune should be taken as a possible indication of bioturbation and potentially problematic OSL dates. The data from the two Texan case studies suggest that absence of structure cannot necessarily be interpreted as indicating bioturbated sediment. The data from the Cottonwood Springs site shows that despite its lack of structure this site has not undergone significant bioturbation and that an absolute and reliable chronology can be obtained in this context. In contrast the Rena Branch site, despite having some stratigraphic structure, has been sufficiently post-depositionally disturbed to invalidate any efforts to obtain single aliquot OSL dates from this site. Further work looking at the single grain measurements for both these sites is ongoing (Bateman et al. 2007).

These case studies have obvious implications for palaeoenvironmental work carried out in dryland environments; for example the relict dune systems of southern Africa's Kalahari deserts (e.g., Stokes et al., 1997, Thomas et al., 2000, Thomas and Shaw, 2002). Unlike our case studies, reliable independent chronologies are typically not available to test such a hypothesis. However, pertinent observations regarding the sedimentology and structure of these dunes, as well as examples of detailed single aliquot measurements can be made. Large swathes of the Kalahari are covered in small-medium scale linear dunes which range in height above interdunes up to ca. 25m (e.g. Lancaster, 1981). Some of these are degraded whilst others have semi-active crests during periods of short-term drought. Where pits have been hand-dug into these geomorphic features they display no obvious internal structure. This contrasts with the larger-scale linear dunes of the Namib Desert. Here visual inspection and ground penetrating radar have found extensive and clearly discernable bedding structures which formed during dune construction (Bristow et al., 2000). Whilst bedding is attributed to a range of variables (e.g. grain orientation, packing, particle size sorting), the lack of structure within Kalahari linear dunes is not an artefact of sediment size as there is sufficient size variability for differential beds to be picked out if they existed (Bateman et al., 2003a, Fig 3). Likewise it is not an artefact of observations limited entirely to freshly exposed soil pits, as the extensive sections through the Kalahari sands at the Mamatwan manganese mine are completely devoid of sedimentary structures (Bateman et al., 2003a). One possible explanation for this lack of structure is that it has been lost through post-depositional disturbance, i.e. the sediments are bioturbated.

Further evidence for such a conclusion comes from the OSL data from the region. Figure 8 exemplifies replicate D_e values, measured on single aliquots, from Kalahari desert linear dunes at Tsodilo Hills, Botswana. Instead of having high reproducibility and a normal distribution which would be expected from a dune, these samples show a wide variety of D_e values with a multi-modal distribution. In light of the low probability of incomplete bleaching on deposition in this environment, this poor reproducibility may be explained if sediments of different ages have been mixed together after they were buried. The primary mechanism, if this is correct, is that the sediments have been bioturbated. This has huge potential implications for the existing regional OSL framework that has been established for the Kalahari (e.g. Thomas et al., 2000, Thomas et al., 2003) and may explain some of the difficulties of integrating the aeolian record with other sources of proxy data in this region.

7. Summary and Conclusions

In the case studies presented from sandy environments in Texas and Florida, by undertaking detailed sampling and multi-replicates of single samples, it has been demonstrated that whilst the effects of bioturbation on luminescence chronologies can be potentially severe, modern OSL techniques are able to detect post-depositional disturbance. The case studies serve to show that ancient sandy surfaces can be seemingly covered with surficial sediments that on face value produce statigraphically consistent ages. However, in reality these young OSL dates have little relationship to burial age and more to do with the type and intensity of bioturbation which has rejuvenated a more ancient strata. The case studies demonstrate that a lack of sedimentary structure in sandy drylands environments can not be taken as diagnostic of bioturbation and nor does the presence of stratigraphy preclude the possibility that the sediments have been disturbed. In dryland contexts, by sampling geomorphic features like dunes the likelihood of accidentally dating rejuvenated ancient surfaces is avoided. However, careful thought should be given to the potential impact that former climatic regimes may have had in changing the intensity of vegetation and faunal disturbance both spatially and in terms of the depth within the sedimentary record.

As such we argue that when establishing an OSL chronology in dryland setting with no independent age control it is critical to undertake intensive down profile sampling, preferably in conjunction with mapping of subsurface stratigraphy by for example ground penetrating radar and to produce multiple D_e replicates. This allows the careful scrutiny of D_e scatter and skewness and also the identification of age reversals in order to pick out problematic samples/sites. In terms of bioturbation, where OSL D_e replicates have a high reproducibility and are normal distributed OSL ages appear to agree with independent ages. Thus, similar data generated in a dryland setting can be treated with some confidence. However, where replicates have significant numbers of zero age grains at depth, poor reproducibility, are skewed or have broad D_e distributions, these samples may have been mixed and/or exhumed post-depositionally. Our case studies suggest that the D_e distributions from the Kalahari dunes shown in Fig 9 may have been bioturbated. In the Kalahari (and other drylands) it is extremely difficult to undertake an initial assessment of the possible impact of bioturbation to sediments and its affect on OSL dates due primarily to the paucity of alternative reliable chronometric control. Therefore, in addition to the above OSL strategies, efforts must be made to make the most of sedimentological, geological and geomorphological expertise when sampling in order to avoid locations and sedimentary units in which post-depositional disturbance is more likely.

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