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Quaternary Geochronology 2 (2007) 57–64

QUATERNARY GEOCHRONOLOGY

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Research paper

Detecting post-depositional sediment disturbance in sandy deposits using optical luminescence

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Received 31 March 2006; accepted 1 May 2006
Available online 13 June 2006

Abstract

Post-depositional mixing or exhumation is common in surficial sediments, yet may be unobservable from field evidence. However, any disturbance may have significant consquences in terms of establishing a reliable luminescence age determination. Optically stimulated luminescence (OSL) measurements, particularly measurements at the single grain level, can be used to gain an insight into both contemporary and past post-depositional processes.

This paper examines sites from Texas and Florida (USA) with independent chronological control to demonstrate the potential effects of varying degrees of bioturbation on OSL. Results show that contemporary soil forming processes clearly impact on the palaeodose (D_e) replicate distributions which are measured in order to derive an OSL age. Significant levels of scatter and apparently zero dose grains are observed in the upper-most sediments; declining with depth from the surface. D_e replicates from undisturbed and fully bleached sediments are unskewed, show low overdispersion (OD) and comparable single grain and single aliquot OSL ages. Bioturbated sediments, however, may show highly skewed multi-model D_e distributions with higher OD values, zero dose grains at depth, and significant diffences between single grain and single aliquot results. True burial ages may be derived from minimally bioturbated sediments through the application of statistical analysis such as finite mixture modelling to isolate D_e components. However, for significantly bioturbated sediments, the latter approach, even at the single grain level, produces inaccurate ages. In such cases we argue that additional evidence (both dating and contexual) may be required to identify with confidence the burial D_e population.

Keywords: Bioturbation; Single grain; Optically stimulated luminescence dating

1. Introduction

The underlying principle of optically stimulated luminescence (OSL) dating is that sediments collected for dating have remained undisturbed since their burial. This assumption is not valid if, subsequent to deposition, sediments are disturbed. Bioturbation refers to the post-depositional translocation, either vertically or laterally of sediments and soils either through mixing or exhumation by flora and fauna (Balek, 2002). The depth and intensity to which bioturbation affects sediments is dependant on net sedimentation rates, duration and type of bioturbation (Bateman et al., 2003; Bateman et al., 2006).

Of particular concern are near surface unconsolidated sandy deposits which are highly prone to bioturbation, yet are often most suited and accessible for OSL sampling. Bioturbation may result in trace fossils, e.g. krotovina or root casts (Johnson et al., 1987), whilst clearly discernable bedding structures are a good indicator that bioturbation has been minimal. However in the OSL sampling context, many sand units freshly exposed or viewed only from augering appear structureless. Additionally, as bedding forms as a consequence of a range of variables a lack of

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1871-1014/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quageo.2006.05.004

bedding may or may not be a good indicator as to whether post-despositional disturbance has occurred. Thus in a worse case scenario bioturbated geologically ancient sediments may be easily confused with pristine Quaternary deposits (Leigh, 2001; Frederick et al., 2002).

The mixing and exhumation of grains during bioturbation may bring together grains with very different palaeodoses (D_e). Bioturbated sediments may exhibit multi-modal D_e distributions but unlike poorly bleached sediments this distribution may have modes both higher and lower than the D_e distribution associated with the true burial age. Bioturbation has been cited for apparently erroneous ages or unaccountable D_e distributions, especially positively skewed ones (Feathers 2003; Forrest et al., 2003; Sanderson et al., 2001). Evidence that bioturbation is the causal mechanism is limited, although Bateman et al. (2003) demonstrated that gopher mounds show multi-modal D_e distributions and that observable shifts in mean D_e were apparent in a filled burrow.

This paper, presents new single grain (SG) OSL data from sites in Florida and Texas (USA) which are thought to have undergone varying degrees of bioturbation and for which there is independent age control. We outline parameters which may indicate bioturbation and apply a finite mixture model to see whether the D_e population associated with burial can be successfully extracted for OSL age determination. This compliments and extends the single aliquot (SA) data of Bateman et al. (2006).

2. Methodology

Samples were prepared for coarse grained quartz OSL under subdued red lighting following Bateman and Catt (1996). As the OSL signal measured with SA is an average of c. 1500 grains the true distribution of D_e values within a sample may be masked. This is of particular significance in heterogeneously dosed samples (e.g. bioturbated) in which grains with a low or zero D_e signal will be particularly biased against (Duller, 2004). Measurement of the accumulated dose at the SG level obviates this problem.

To measure sample D_e's, grains were mounted in 300 μm pits with 100 pits per 9.6 mm stainless steel aliquot. A Risø TL DA-15 SG 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 values were determined using a SA regenerative (SAR) protocol (Murray and Wintle, 2000) with an experimentally derived preheat of 200 °C for 10 s prior to each OSL measurement. 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 ensure more than 40 SG D_e values for each sample. Grains which exhibited no naturally acquired dose but which had good SAR growth curves generating D_e values of zero or within errors of zero (zero dose grains) were retained and are discussed below.

Dose rates were determined in the field using an EG&G Micronomad NaI field γ-spectrometer for the Texas sites but the Florida sites were below reliable detection limits so were analysed using inductively coupled plasma mass spectrometry (Table S1). Where sand units were less than 30 cm thick, adjacent sediments were also analysed and their γ dose contribution modelled using data from Aitken (1998). Conversion from elemental concentrations to effective dose rate followed that of Aitken (1998). Attenuation for moisture used estimates based on the modern contents and the cosmic dose contribution was calculated as per Prescott and Hutton (1994).

As bioturbated samples could contain both anomalously low and high D_e values the minimum age model of Galbraith et al. (1999), widely used for partially bleached samples (Olley et al., 2004), is inappropriate. Instead, the finite mixture model was used (Galbraith et al., 1999; Roberts et al., 2000) with the D_e mode with the highest probability selected for age calculation purposes. Ages are quoted in years from sampling (2004) with one sigma confidence intervals (Table S1).

A number of parameters were used to help identify bioturbation in the samples. Mixing/exhumation associated with bioturbation should increase the degree of inter-grain scatter and lead to an hetrogeneous D_e distribution non-normally distributed around a sample mean (Bateman et al., 2003). However, D_e hetrogenaity can come from a variety of sources. Due to the contexts and location of all sites used in this study partial bleaching of sediments prior to deposition can be discounted. An IR depletion ratio (Duller, 2003) and recycling ratio within the SAR protocol was employed with all measurments to, respectively, prevent the inclusion of contaminate feldspar grains and to monitor performance of sensititivity corrections. Whilst beta hetrogenaity cannot be ruled out, the uniformity of measured dose rates within sites (Table S1) is used to infer that *within* site changes in D_e replicate scatter should not be from this source. As such, we believe SG D_e distributions for these samples can be used to evaluate bioturbation. To quantify the degree of dose heterogeneity overdispersion (OD) values, the estimate of variance beyond which can be accounted for by the measurement uncertainty of every grain (Galbraith et al., 1999), were calculated. To quantify whether high D_e or low D_e tails existed a skewness parameter was also calculated (Eq. S1) with values close to zero indicating a normal D_e distribution. Where both SA and SG data was available, a ratio of the two was calculated as a bioturbated sample should have a significantly different mean D_e due to the averaging effects of the SA approach masking hetrogeneity. Finally, percentage of zero dose D_e grains were also calculated. Whilst such grains may reflect sensitization during the initial (and uncorrected) natural OSL measurement in the SAR protocol, examination of trends in concentration with depth may indicate that some sediment now found at depth was recently exhumed and then mixed down profile.

3. Sampling sites

The four sites chosen for this study are all from localities with evidence for differing degrees of bioturbation. The Avon Park Air Force base in Florida is on an extensive sand mantle formed in the Tertiary/Quaternary as part of a barrier dune complex. The Texan sites are also found on a regional sand mantle from the Tertiary period formed as part of a fluvial system. For both regions, the sand is superficial, unconsolidated and the climate conducive to good sunlight exposure (resetting) of sand grains should they be moved. All sampling for OSL used 5 cm diameter opaque PVC tubes driven into freshly exposed verticle sections apart from at the Rena Branch site where more detailed work and intensive sampling of the modern soil required the use of 1 cm diameter tubes.

At the Ebersbach midden site, two OSL samples were collected from two discrete lake-shore ridges located next to Lake Arbuckle in the Avon Park Air Force base, central Florida (Frederick et al., 2005). These beach ridges are thought to have formed as the result of storm floods associated with hurricanes reworking the underlying Tertiary/Quaternary marine sands found through out the rest of Avon Park. The <3 m high ridges, contained thin horizontally bedded horizons of organic material and sand. Sharp boundaries between units existed and SA OSL and calibrated radiocarbon ages were in close agreement (Fig. 1a; Bateman et al., 2006). This site is thus considered a pristine depositional site.

The Burnt Hammock site, also from Avon Park, Florida, came from a structureless, texturally homogeneous, unconsolidated sandy mantle thought to be part of a Tertiary or Early Quaternary barrier dune (Fig. 1b). As there is a lack of sedimentary structures and temporally discreet archaeological horizons appeared to have been 'smeared' (Fig. 1b; Frederick et al., 2005) this site is interpretated as an ancient landsurface which has been rejeuvenated by recent (Holocene to modern) post-depositional disturbance. Data from three OSL samples are presented here.

Both the Cottonwood Springs and Rena Branch sites, located in East Central Texas close to the town of Jewett, were selected for further investigation as previous archaeological excavations have provided independent chronological control in the form of archaeological material and radiocarbon dates (Fields et al., 1991; Fields and Klement, 1995). The Cottonwood Springs site was located near to the summit of a small wooded hill. Here, a 4 m verticle profile revealed 3.5 m of structureless massive sand above a buried Bt soil horizon (Fig. 2 and Fig. S1a). The depostional history of this sand is unclear. Whilst the independant radiocarbon, archaeological and SA OSL evidence (Bateman et al., 2006) suggested that this site was undisturbed the lack of sedimentary bedding may indicate otherwise. A total of seven samples were collected for SG OSL analysis.

The Rena Branch site was situated in a pocket of possible alluvial sand found on a narrow, gently sloping interfluve ridge approximately 10 m above the confluence of Rena Branch and Alligator Creeks. A 3.0 m profile, adjacent to the original archaeological excavation, revealed a sand with no primary bedding structures, infilled burrows (krotavina) and root casts (Fig. 3 and Fig. S1b). It also contained a diffuse buried palaeosol between 0.9 and 1.7 m depth and some weakly developed clay lamellae which increased in thickness towards the base of the sequence where a red clay Bt horizon was encountered. Whilst the krotavina and age reversals in both the radiocarbon and SA OSL ages (Bateman et al., 2006) suggest some bioturbation, the presevation of a buried soil suggests that this site may have not been intensively disturbed. Data from eleven samples is presented.

4. Results

4.1. Modern bioturbation and its effects

In theory, sediment at or just below the surface should undergo maximum mixing and disturbance as this is where animal and plant activity is most intense and soil overturn rates highest (Heimsath et al., 2002). This disturbance should decline in intensity with depth and it was hoped to discern this trend from intensive sampling of the modern soil at the Rena Branch site (Fig. 3 and Fig. S1c, Table S1). For these samples, OD values, from both SA and SG data, show declining D_e scatter from the surface within the modern soil into the underlying sand unit (Fig. 3). Zero dose grains follow a similar pattern (Fig. 3). Whereas SA OD values decline within the soil the uppermost sample at the SG level has a much lower OD due to the large number of zero dose grains in this sample. Skewing values within the modern soil show no discernable trends. Thus OD values and zero dose values may be particularly useful in highlighting samples currently undergoing bioturbation but also in identifying older samples which were once bioturbated.

4.2. "Pristine" versus highly bioturbated sites

The two Florida sites sampled are thought to represent the "end members" in a post-depositional disturbance continuum; that of undisturbed (Ebersbach midden) and completely disturbed (Burnt Hammock). The SG data from the two samples from Ebersbach Midden are highly reproducible and normally distributed with low OD (29% and 32%) and relatively low skewness (1.288 and 1.643; Fig. 1a; Table S1). The mean D_e for both samples is the same irrespective as to whether measured at SG or SA levels (Fig. 1a; Table S1). The SG OSL ages are also corroborated by the independent radiocarbon dates from the sites. Data from the Burnt Hammock site have much higher OD values (51–84%), SG D_e distributions show a significant skewing (1.48–4.07) with a shift of the mean D_e

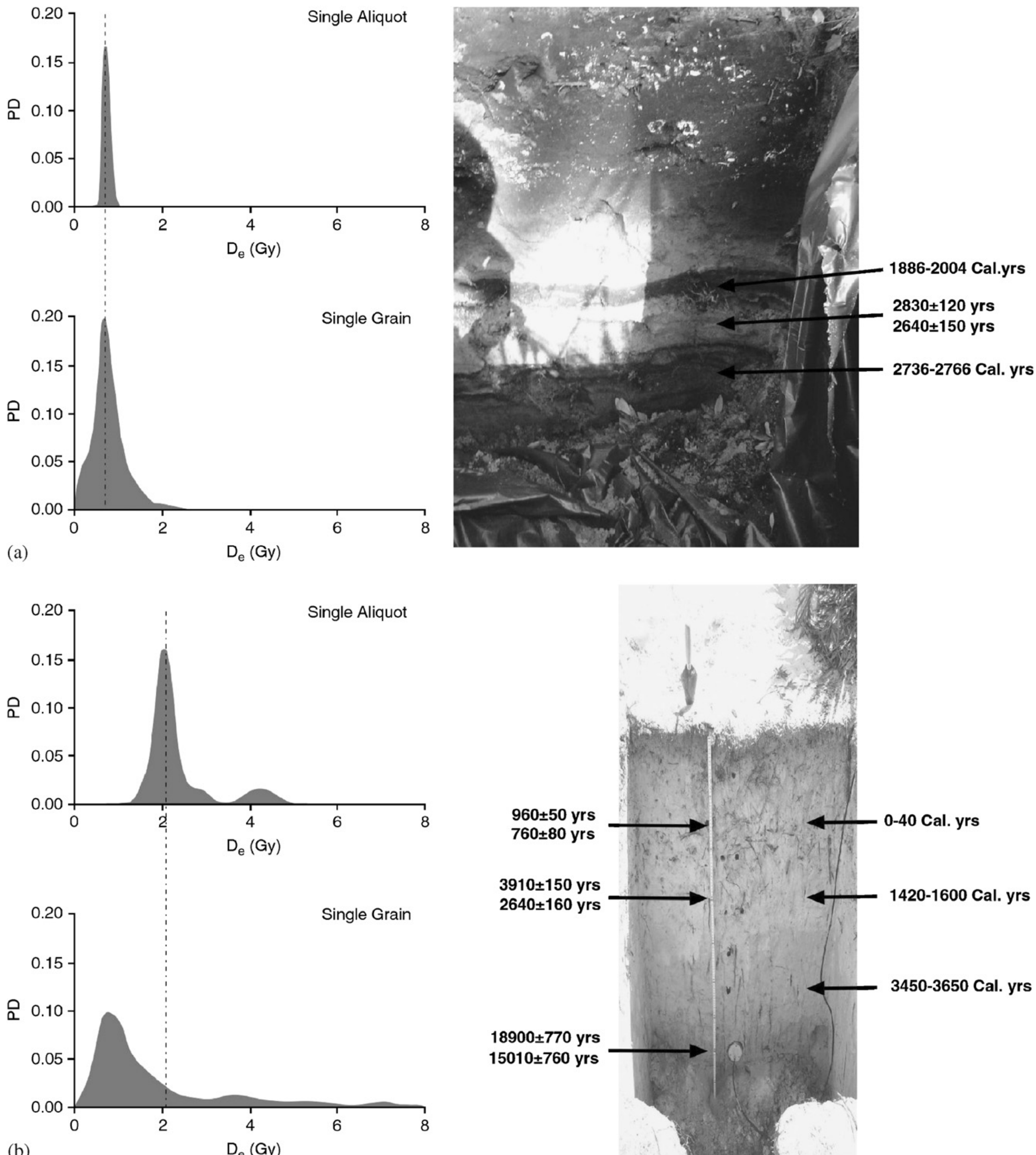

Fig. 1. Ages (both OSL and cal. radiocarbon OSL) and D_e distributions for (a) the undisturbed site of Ebersback Midden, Florida (modified from Bateman et al., 2006) and (b) the disturbed Tertiary/Quaternary site of Burnt Hammock, Florida. Note in all cases upper OSL age is based on single aliquots and lower OSL age based on single grain measurements.

towards lower values (Fig. 1b). There are also significant numbers of zero dose grains in the upper sample (28%). Whilst radiocarbon and OSL ages do increase with depth (Fig. 1b) there is a clear disagreement between the two (Fig. 1b). The use of OD, skew parameters at the SG level combined with monitoring numbers of zero dose grains and differences between SA and SG D_e's, therefore enables the differentiation of clearly bioturbated and clearly undisturbed OSL samples. In the case of the latter, it was not possible to calculate true OSL burial ages which agreed

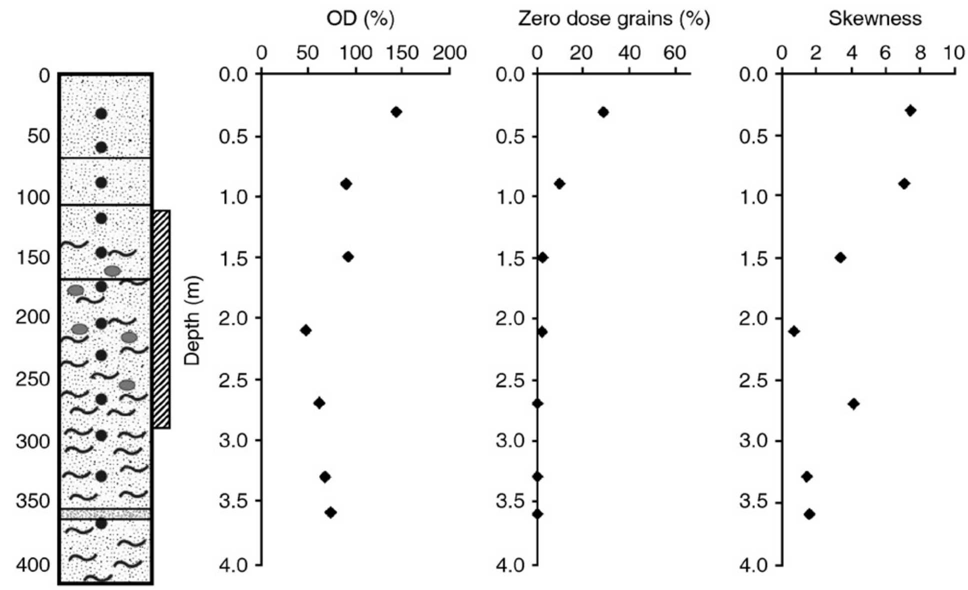

Fig. 2. Single grain OSL data for the Cottonwood Spring site showing low/moderate scatter (OD), zero dose grains limited to the upper 80 cm and less skewed D_e distributions than the Rena Branch site.

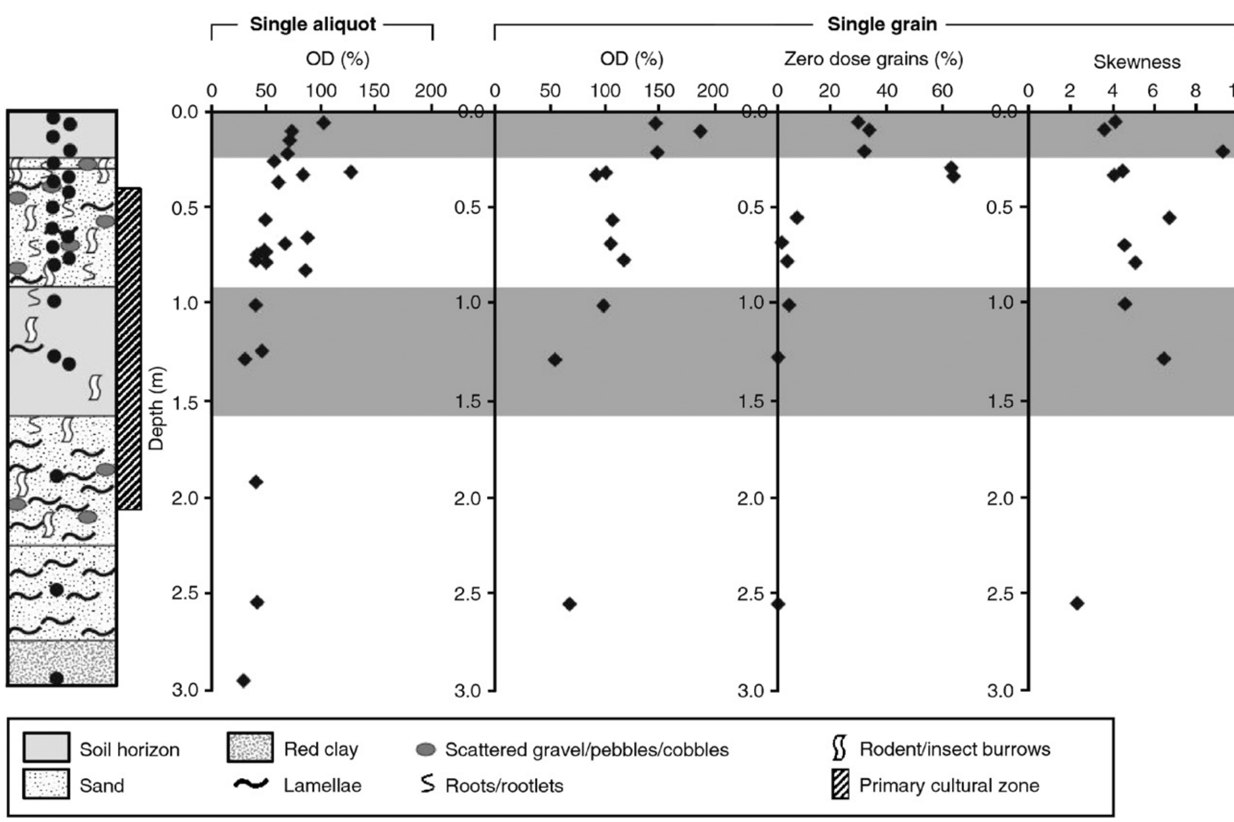

Fig. 3. Stratigraphy and OSL data for the Rena Branch site showing high scatter (OD), large numbers of zero dose grains down profile and strongly skewed D_e distributions. Data for single aliquot OD calculations taken from Bateman et al. (2006).

with independent chronology. Rather the calculated OSL ages appear to be artefacts of bioturbation (both exhumation and near surface mixing) instead of normal geological sedimentation.

4.3. *Identification of partially bioturbated sites*

Previous SA work on the Texas sites suggests that one has evidence that it has undergone a degree of bioturbation

(Rena Branch) whilst the situation at the other (Cottonwood Springs) is less clear (Bateman et al., 2006). SG D_e values from Cottonwood Springs, show a single peaked distribution with a small number of high D_e's (Fig. S2). In contrast the D_e distributions for Rena Branch are broader, or multi-modal (Fig. S3), with more zero D_e grains (Figs. 2 and 3). Comparison of mean D_es made at the SA and SG level (Fig. 4) shows a limited shift at Cottonwood Springs. If the upper sample at 50 cm is excluded on the grounds of being very close to the modern soil, all SA D_e's are within 20% of their SG counterparts. Even similarly excluding samples from the upper 50 cm, results from Rena Branch show marked changes in mean D_e derived from the SA as opposed to SG measurements. A similar contrast is shown in the down profile OD, skewness and zero grain data (Figs. 2 and 3), with the values being much higher for Rena Branch compared to Cottonwood Springs. OD and skewness are particularly high at Rena Branch both in the modern soil and the underlying sand unit, which contained infilled burrows. At both sites the upper samples have significant numbers of zero dose grains indicating that there they have been in recent contact with the ground surface.

On the basis of the scatter, skewness and shift in D_e between SA and SG the Cottonwood Springs site appears to have undergone a degree of disturbance especially in the uppermost sediments. That the new SG OSL ages presented here are in broadly accordance with the independent radiocarbon chronology and archaeological evidence (Fig. 5a) indicates this disturbance has been limited, with the bulk of sediment still primarily reflecting the burial age signal. As such the finite mixture model is able to distinguish the D_e relating to the true burial age. The new SG OSL ages for the Rena Branch site (Fig. 5b), show reversals with depth and are consistently older than both the radiocarbon and archaeological chronologies. Thus despite retaining evidence of former soils, using the

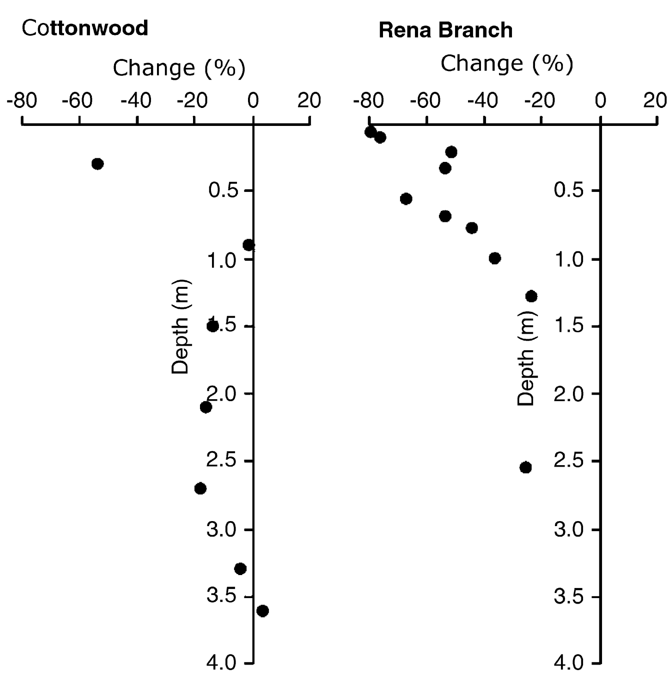

Fig. 4. Comparison of mean D_es derived from both single grain and standard aliquot measurements with data for latter taken from Bateman et al. (2006). Note uppermost sample from Cottonwood and uppermost three samples from Rena branch are thought to relate to modern soils.

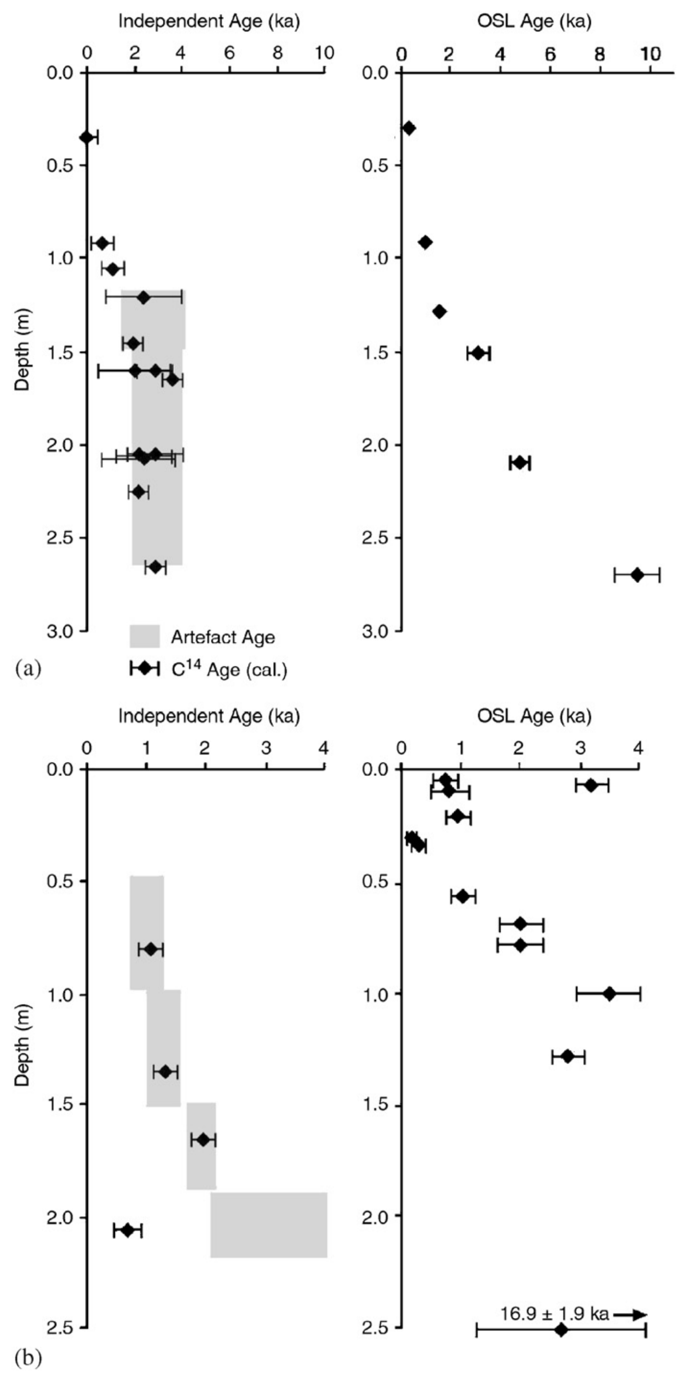

Fig. 5. Holocene single grain OSL ages compared to independantly acquired radiocarbon and archaeological artefact ages for (a) Cottonwood Springs and, (b) Rena Branch. Note broad agreement between all three chronologies for Cottonwood Springs but OSL age reversals and disagreement between the three chronologies for Rena Branch.

same criteria as for Cottonwood Springs, this site appears to be very disturbed. Simple application of the finite mixture model to extract the D_e relating to burial from all the D_e replicates is inappropriate.

Plotting the parameters from the four sites shows clear clustering interpreted as indicative of the relative degree of bioturbation (Fig. 6). The shaded boxes generally encompass the three "levels" of bioturbation identified at these sites. The undisturbed samples (Eberbach Midden and some Cottonwood) are considered as having zero dose grains $<5\%$, a skew <2 and an SG vs. SA shift of $<10\%$. For slightly disturbed samples (Cottonwood) zero dose grains are $<10\%$, skewing is <4 and the SG vs. SA shift is between 5% and 25%. Data falling above these values (Burnt Hammock and Rena Branch) are considered as highly disturbed and unlikely to produce accurate burial ages. More data from both well-established pristine and disturbed sites are needed to firmly determine whether these values are sensible and can be used routinely to define the level of bioturbation at sites with no independent chronology or evidence of disturbance. Additionally, Figs. 6a and b can be used to give information on the mode of disturbance. Burnt Hammock clearly plots in a different space showing disturbance at this site, unlike the Rena Branch site, which is not dominated by exhumation of grains but mixing of older sediments up profile.

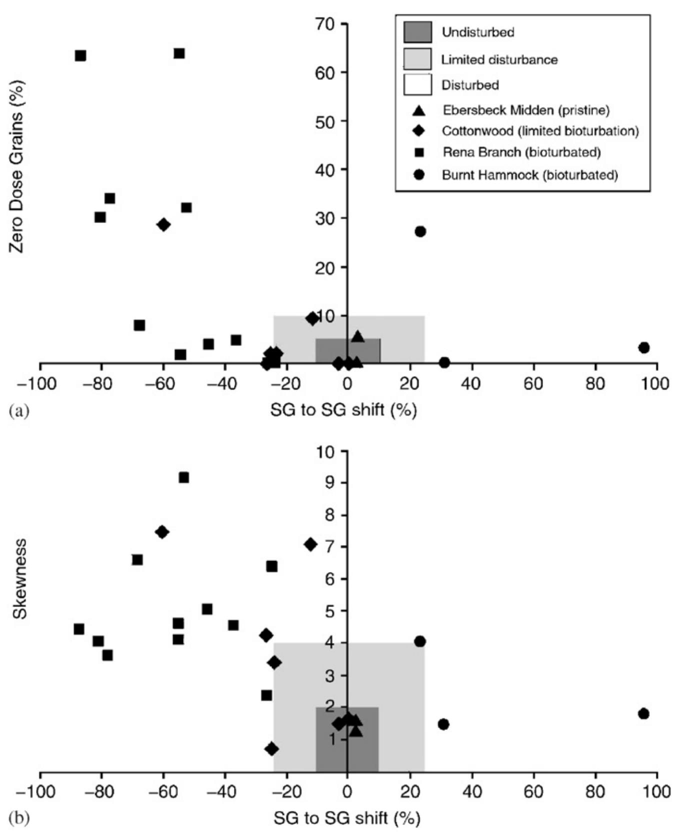

Fig. 6. Bioturbation plots for sites ranging from undisturbed to heavily bioturbated. Plotted are the shift in D_e between single aliquot and single grain measurements plotted against (a) zero dose grains and (b) skewness the distribution of D_e replicates.

5. Conclusions

This study has shown that in modern soil profiles replicate D_e scatter and numbers of zero dose grains are consistent with evidence for active bioturbation. Disturbed sites can still display increasing ages with depth and even some stratigraphy (e.g. the buried soil at Rena Branch) but high OD, D_e skewness, trends in zero dose grains and discrepancies between mean D_e when analysed at both the SA to SG levels appear good indicators of post-depositional disturbance. Such measurements are recommended for the evaluation of samples from sites with an unknown disturbance history. Depending on the magnitude of the disturbance it may or may not be possible to isolate the true burial age. Where disturbance has been limited, as with the Cottonwood Springs site, and a clearly dominant D_e peak still exists in probability plots, true burial ages can still be obtained using the finite mixture model to isolate the D_e population related to burial. For more disturbed sites, e.g. Rena Branch, bioturbation may have mixed and exhumed sediments to such a degree that such an approach is not possible. Generating skewness and OD data for SA OSL analysis alone may only be sufficient to detect samples which have undergone significant disturbance. Use of smaller aliquots, e.g. 2 mm, although giving much less information than SG measurements, may be a way to avoid time-consuming SG measurements but this needs further work to test. Given the potentially random nature of bioturbation within a given sedimentary horizon, better evaluation of any problems present at a site can be made through multiple OSL sampling both within sediment units and down profile. Where disturbance is indicated this should be verified using other chronological and contextual information.

Acknowledgements

Work in Avon Park, Florida was initiated by Duane Peter as part of a Geomarine Inc. project funded by the United States Air Force. Work in Texas was by kind permission of Northwestern Resources Co. with the assistance from Nelle Frisbie, Joel Truart and Ross Fields. Paul Coles is thanked for cartographic assistance. This work was carried out in part with a NERC studentship Grant (NER/S/A/2002/12053) to Claire Boulter.

Editorial handling by: R. Roberts

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.quageo.2006.05.004.

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