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Investigations into the Potential Effects of Pedoturbation on Luminescence Dating

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Abstract

Much effort has been focussed on understanding the luminescence properties of natural minerals to achieve a reliable, accurate and precise dating technique. However, some field related aspects, such as the influence or effect of post-depositional disturbance on luminescence dates, are as yet under explored. In the case of pedoturbation, depending on its intensity, the rate of sedimentation and unit thicknesses, potentially the whole sedimentary record at a site can be affected. This may lead to distorted OSL chronologies and erroneous sediment burial ages.

Pedoturbation can result in sediment mixing and/or exhumation that affect luminescence both at the bulk and single grain level. Effects of these two principle processes on luminescence ages are examined using standard multigrain and single grain protocols. High resolution sampling of surface gopher mounds was used to determine the efficiency of bio-exhumation in resetting luminescence signal. Results show this is an inefficient mechanism for onsite sediment bleaching. The effects on luminescence signal of bio-mixing were explored by comparing a sample collected from within a krotovina (infilled burrow) to an adjacent undisturbed sample. Results show the difficulties in identifying pedoturbated samples at the single aliquot level and the possible inaccuracies in using the lowest palaeodose values to calculate OSL ages. Where pedoturbation of samples is suspected, use of probability plots of palaeodoses data is recommended. From these plots it is proposed that only data falling within a normal distribution centred on the peak probability be used to calculated OSL ages and to mitigate problems arising from pedoturbation.

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1. Why worry about Pedoturbation?

Pedoturbation refers to the post-depositional disturbance of sedimentary deposits and soils either through mixing or exhumation. It is a global near surface phenomenon caused by numerous processes (e.g. Wood and Johnson, 1978; Johnson and Watson-Stegner, 1990). Perhaps the most prevalent of these, and one focussed on by this paper, are disturbances by flora and fauna (bioturbation). This operates at a variety of scales ranging from the movement of individual grains to the creation of small-scale landforms such as mima mounds (earth mounds commonly 20-30 m in diameter and up to 2 m high; Butler 1995) that comprise tens to hundreds of cubic meters of sediment. Studies of sediment moved by the northern pocket gopher (*Thomomys talpoides*) for example indicate the scale of this activity may be as much as 3-4 mm ha^{-1} (Thorn, 1978). Implications for alteration of the Quaternary sedimentary record are multiple. Pedoturbation may obliterate pre-existing stratification, create features that mimic it (e.g. stone zones), or result in trace fossils, e.g. krotovina (Fig. 1; Johnson et al., 1987). Field identification of pedoturbated sediments from a sedimentological perspective is often difficult. Sandy deposits, are highly prone to pedoturbation and it may be difficult to distinguish deposits generated by pedoturbation from the pristine Quaternary sedimentary deposits (e.g. Leigh, 2001). Whilst the effects of pedoturbation on OSL ages may be small, recent advances in the quoted precision of OSL ages (< 4%) makes it timely to investigate its effects.

2. Pedoturbation: some theoretical effects

The effects of pedoturbation can be evaluated from two different perspectives. Firstly how variations in the extent of pedoturbation and the dynamics (i.e. sedimentation rate) of the depositional environment may affect the sedimentary record. Secondly, how the exhumation and mixing processes of pedoturbation may modify depositional palaeodoses and age estimates as determined by optically stimulated luminescence (OSL).

2.1 Depositional dynamics

Sedimentation rates may influence the depth and duration of pedoturbation and thereby the effects on OSL age estimates.

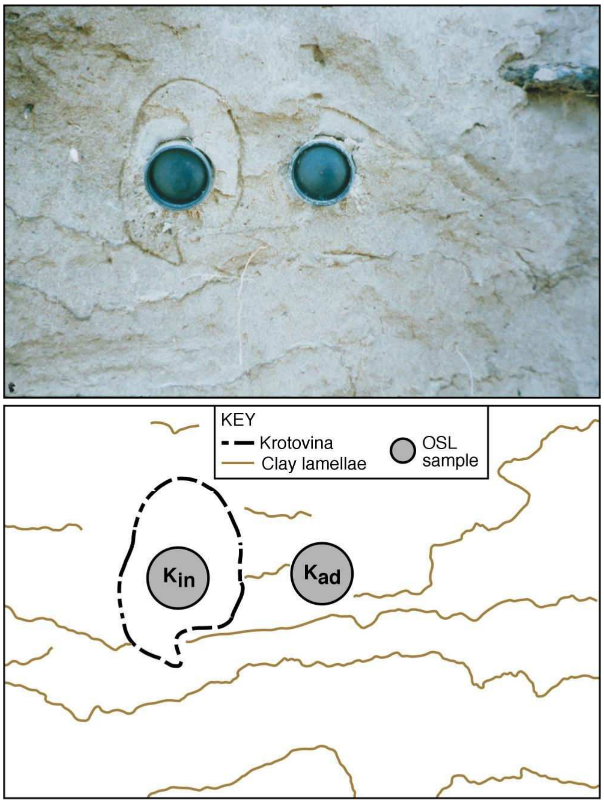

Figure 1: Photograph and line drawing of Krotovina (infilled burrow) with OSL samples within in (K_{in}) and adjacent (K_{ad}) to it as used for experiment B.

The manner of its effect will be determined by three principle factors:-

i) the rate and depth of ongoing or 'normal' pedoturbation

ii) the sedimentation rate (high, low, or negative (i.e. erosion taking place)

iii) the thickness of the sedimentary packages (where 'thick' packages are those significantly thicker than the depth of 'normal' pedoturbation, and/or thin packages are thinner than the 'normal' depth of pedoturbation.

Figure 2 shows a schematic of the effects of pedoturbation on a sedimentary record, taking into account the above factors. This is described more fully below.

Scenario I: Under conditions of episodic deposition of thick sedimentary units followed by periods of quiescence, theoretically only the uppermost portion of each unit will undergo pedoturbation (Fig 2a). In this scenario sediment grains moved up would be progressively exposed to sunlight and the OSL signal bleached away. If intensively sampled, OSL may show a reduction in estimated age compared to true age for any particular unit and artificially low sedimentation rates. However, the pedoturbation can involve the movement up or down, but not bleaching, of both older and younger material, for example downward movement of grains due to roots. In this instance the effect on the OSL ages would be through a degradation of and an overall homogenisation of palaeodose (D_e - the amount of stored dose accumulated since burial). The exact reduction or increase of mean D_e would be dependent on volume % of younger and older material and the extent of mixing.

Scenario II: For low sedimentation rates and thin sedimentary packages, then potentially the *entire* sediment column will be disturbed (Figs 2b & 2c). In this situation, OSL ages will still increase with depth but will be an intermediate age reflecting *both* burial age and magnitude and timing of pedoturbation. If the latter has varied through time then an age reversals can occur on shorter depth scales.

Scenario III: Stable, non-accreting surfaces may be rejuvenated by bioturbation leading to meaningless OSL dates in respect of dating sediment deposition. As pedoturbation intensity decreases with depth, the probability of grains buried at depth reaching the surface and being bleached decreases. Thus single aliquot OSL ages in this scenario should increase with depth as the ratio of exhumed bleached and unbleached grains changes in a pedoturbated profile. The depth variation in OSL age and D_e scatter would reflect the relative intensity/frequency of pedoturbation, not sedimentation deposition age. The different hypothetical scenarios show that the effects of pedoturbation can range from minor (i.e. limited to specific discrete zones within the sedimentary record), to having affected the whole sedimentary record and corresponding OSL ages. This is without considering complications arising from erosive phases that may allow pedoturbation or further pedoturbation of the upper surfaces of newly revealed sediments. The significance of pedoturbation is also a function of sediment antiquity, as the proportion of OSL due to pedoturbation, rather than burial, will decrease through time once pedoturbation stops.

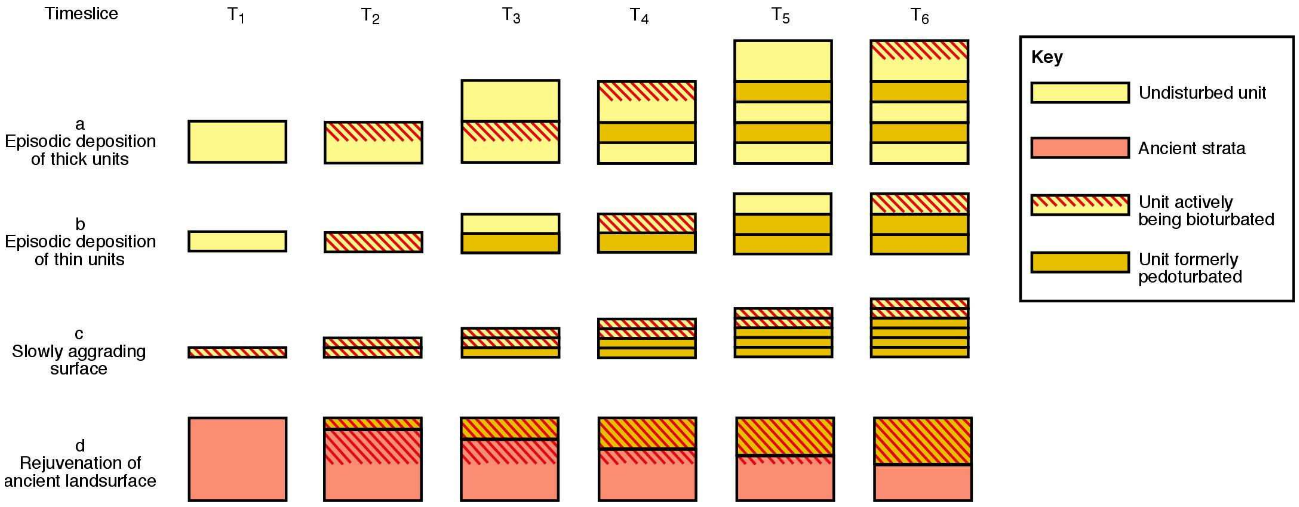

Figure 2: Schematic of potential of pedoturbation to affect sediments throughout stratigraphic column.

2.2 Specific effects of pedoturbation on OSL data

Figures 3a-3f show hypothetical effects of different pedoturbation scenarios on D_e distributions. Implications of pedoturbation on OSL dating are that sediments can be mixed isotropically and/or this should affect D_e reproducibility brought to the surface, resulting in onsite optical bleaching of the luminescence signal. In principle, through enhanced scatter in D_e from individual and otherwise identical grains. If pedoturbation remains a minor component, then mixing in of either older or younger/zeroed sediment into a sample should result in either a positive or negatively skewed D_e distribution (Figs 3a-3d). The affects of this will be more pronounced for D_e distributions derived from single grain than from single aliquot measurements due to the averaging effects on the latter by measuring many grains at once. Where pedoturbation has been prolonged/intense then D_e distributions may remain normal but will become more platykurtic with an increased range of D_e values (Fig. 3e). Alternatively, where discrete episodic phases of pedoturbation introduce exhumed (and optically reset) sediment some time after initial sediment deposition, clearly definable separate D_e distributions may be measurable, of which only one distribution will related to sediment depositional age (Fig. 3f).

In order to investigate these processes and their effect on D_e distributions and OSL ages we performed a series of experiments that were designed to explore both exhumation and mixing by fauna (bioturbation). These experiments used sediment from a well-dated Holocene archaeological site on the sandy uplands of Lee County, Texas, USA (Ricklis, 2001).

3. Experiment A: The effects of exhumation

3.1 Experimental Details

Two gopher mounds formed by the burrowing action of the Plains pocket gopher (*Geomys bursarius*), one less than 24 hours old, the other some weeks old, were sampled by taking a vertical core through the spoil mound into the underlying deposit. In the laboratory, the cores were frozen in liquid nitrogen and sub-sampled by cutting into 1 cm long segments under dark room conditions. All the samples were treated with 10% HCl and 38% H_2O_2 to remove carbonates and organic matter and sieved to a 90-180 μm size fraction. Quartz was extracted from this fraction using sodium polytungstate (density of 2.7 g cm^{-3}), an etch in 48% HF followed by 10% HCl for 60 minutes respectively and finally resieving. Measurements were made in an upgraded Risø TL-DA-12 with stimulation provided by a filtered (Schott GG-420 + SWP interference filter) 150 W Halogen lamp and luminescence detection with a 5 mm thick Hoya-340 filter coupled to a Thorn EMI 9235QA photomultiplier tube. The purity of quartz was checked for possible feldspar contamination at the multigrain level using infra-red stimulated luminescence and none exhibited any significant response above background indicative of feldspar contamination. Each sub-sample underwent a single aliquot regeneration (SAR) protocol using the OSL response to a 2.3 Gy test dose to monitor sensitivity changes (Murray and Wintle, 2000). A

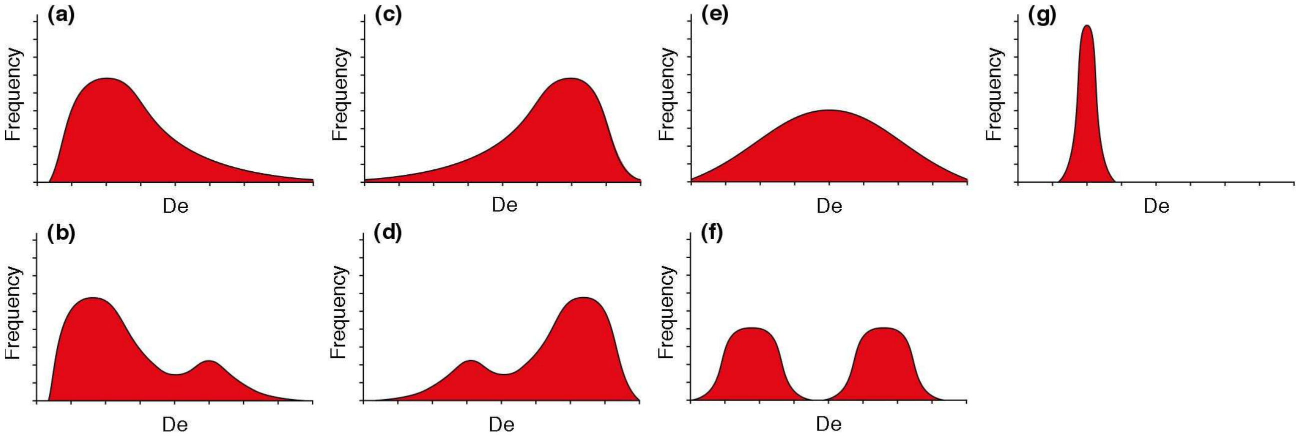

Figure 3: The hypothetical effects of bioturbation on D_e distribution compared to a well bleached undisturbed sample and a poorly bleached undisturbed sample. (A, B) a sample into which younger and exhumed material has been mixed giving rise to a low D_e tail or skewed bimodal distribution. (C, D) a sample into which older material has been mixed giving rise to a high D_e tail or skewed biomodal distribution. (E, F) a sample in which mixing has caused near homogeneity giving a wide range of D_e values with a low frequency at any single value or 2+ definable peaks. (G) undisturbed well bleach sample with a small D_e distribution and high reproducibility. (H) Undisturbed poorly bleached sample with tail of higher D_e values reflecting antecedent OSL signal.

260 °C/10 s preheat prior to each regeneration point measurement and a 160 °C cutheat for the OSL response to the test dose was used. OSL measurements were made at 125 °C with a stimulation time of 80 s to ensure reduction of OSL to <8% of initial OSL, thereby avoiding significant carry over on the next OSL measurement within the SAR protocol. Five regeneration points were measured including a replicate of the first regeneration point which was used to check the sensitivity correction procedure, through calculation of a recycling ratio, was performing adequately. All measurements whose recycling ratio lay outside 1 ± 1 were discarded.

Single grain measurements were made on the Risø TL-DA-15 luminescence reader with a single grain laser stimulation attachment. A focussed 532 nm Nd:YVO_4 laser provided the stimulation to individual grains, whilst luminescence detection was through a U-340 filter coupled to an EMI9235 photomultiplier tube. The individual grains were measured with a SAR protocol identical to that described above. D_e values from grains, (1) with a recycling ratio 1 ± 0.15; (2) good growth with dose; (3) without any feldspar contamination; (4) an error on the D_e <30% were selected. Approximately 2600-2700 grains were measured for each sample to derive a minimum of 50 D_e's which met the above criteria.

For each gopher mound sub-sample 12 single aliquots (limited by amount of material in each sub-sample) were measured and the D_e calculated. In addition, the sub-samples from the top and bottom of the older Gopher mound and from the lowest undisturbed sediment sub-sample were measured at the single grain level.

3.2 Results

Table 1 and Figure 4 show the results of the single aliquot and single grain D_e data from the fresh and older Gopher mounds. The single aliquot data shows that the gopher mound sediments are not fully bleached by gopher exhumation as all subsamples from the mounds retain a significant fraction of the D_e (>1.7 Gy), which is higher than that of the immediately underlying, undisturbed sediment. As the depth from which the sediment was exhumed and therefore the original D_e is unknown, the degree of bleaching (if any) of the mound sediments cannot be quantified.

Only the uppermost sub-sample in the older gopher mound has a reduced (but not fully zeroed) D_e, probably as a result of exposure to daylight at the surface after gopher exhumation. At the single aliquot level no appreciable increase in scatter around the mean D_e distributions of the samples from the mound was seen when compared to those from the underlying sediment.

The single grain D_e's show an increased range of values, however, the mean D_e values are all within errors of their single aliquot equivalents. The single grain data show the uppermost mound sample had 20% of fully bleached (zero D_e) grains. This compares to 12% of grains being zeroed in the sample from the bottom of the gopher

Table 1: Palaeodose data from vertical samples through two Gopher mounds. Means and one standard deviation errors calculated from all replicate (either aliquots or grains) measured for a given sample.

	Old Gopher Mound	Measurement type	Mean $D_e \pm \sigma$ (Gy)	Min D_e (Gy)	Max D_e (Gy)		Fresh Gopher Mound	Measurement type	Mean $D_e \pm \sigma$ (Gy)	Min D_e (Gy)	Max D_e (Gy)
1	Top of mound	Single Aliquot	2.2 ± 0.34	1.7	2.9	1	Top of Mound	Single Aliquot	1.4 ± 0.40	0.85	2.2
2	Within mound	Single Aliquot	2.7 ± 0.37	2.3	3.4	2	Within mound	Single Aliquot	1.6 ± 0.36	1.1	2.2
3	Within mound	Single Aliquot	2.9 ± 0.27	2.5	3.5	3	Bottom of Mound	Single Aliquot	1.4 ± 0.80	0.54	3.6
4	Bottom of mound	Single Aliquot	3.0 ± 0.39	2.4	4.0	4	Undisturbed sediment	Single Aliquot	0.27 ± 0.35	0.05	1.4
5	Undisturbed sediment	Single Aliquot	0.64 ± 1.0	0.10	3.9	5	Undisturbed sediment	Single Aliquot	0.37 ± 0.28	0.08	0.63
6	Undisturbed sediment	Single Aliquot	0.82 ± 0.47	0.53	2.2	6	Undisturbed sediment	Single Aliquot	0.76 ± 0.32	0.31	1.3
7	Undisturbed sediment	Single Aliquot	0.62 ± 0.17	0.39	1.0	7	Undisturbed sediment	Single Aliquot	2.1 ± 0.95	1.2	4.7
8	Undisturbed sediment	Single Aliquot	0.69 ± 0.08	0.54	0.8	8	Undisturbed sediment	Single Aliquot	1.7 ± 0.61	1.1	3.3
1	Top of mound	Single Grain	2.0 ± 2.4	0.00	10						
4	Bottom of mound	Single Grain	4.5 ± 4.2	0.00	20						
8	Undisturbed sediment	Single Grain	1.4 ± 2.2	0.00	8.0						

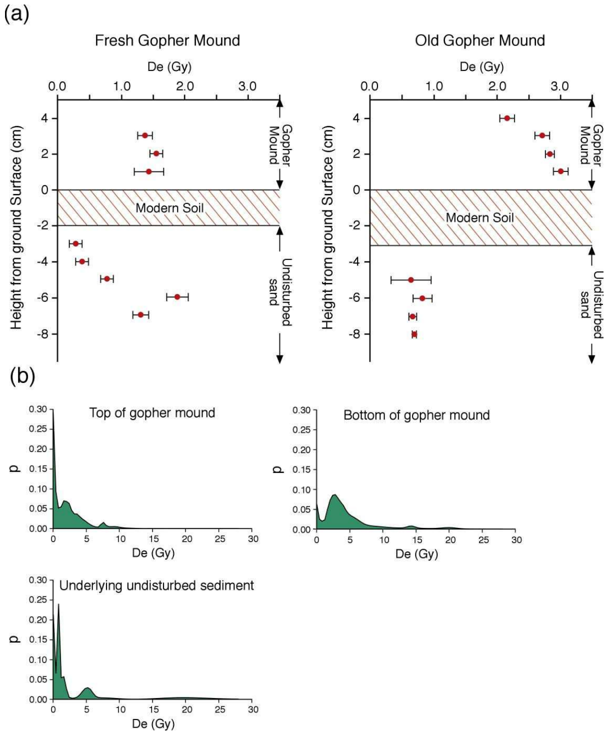

Figure 4: (A) Mean standard aliquot D_e values and standard errors for the sub-samples of the fresh and older gopher mound. (B) D_e distributions from single grain measurements of selected sub samples.

mound and ~31% from the sediment under the modern leaf litter. The inclusion of these zero dose grains is masked at the single aliquot level where *ca.* 5000 grains were measured simultaneously and the OSL signal is dominated by grains with dose. The low number of zero grains at the base of the gopher mound confirms the ineffectively of OSL bleaching during exhumation.

The data from the two mounds suggests that full OSL resetting by gopher exhumation does not occur over a time scale of weeks. Although some grains are brought to the surface and bleached, the bulk of grains retain a significant D_e corresponding to the antiquity of the material exhumed. Sediment directly beneath the modern day soil contains a higher proportion of zeroed grains and a lower fraction of grains with higher palaeodoses. Assuming that the gopher exhumation has been a continuing process, the foregoing suggests that the process of bleaching is occurring after the smearing of exhumed gopher material and/or microscale surface transportation, for example by overland flow or aeolian redistribution.

4. Experiment B: Biomixing

4.1 Experimental Details

To examine the possibilities of discerning the effects of biomixing from OSL data, two samples, one from a krotovina (K_{in}; infilled burrow), and one adjacent to but outside the krotovina (K_{ad}) were collected. The latter was inferred to be in undisturbed sediment based on the fact that laterally extensive undisturbed clay lamellae pass through where the sample was collected (Fig 1). Both the samples were collected from a freshly exposed vertical section using opaque PVC tubing pushed in horizontally and were identically pre-treated and measured using the procedures outlined above. A size fraction of 180-212 μm was selected. Both K_{in} and K_{ad} were analysed at 2 different aliquot sizes, 9.6 mm with approximately 2300 grains and 4 mm with approximately 400 grains, and at the single grain level.

In sedimentology, when undertaking particle size analysis the common practice for comparing distributions is to use numerical descriptions relating to the degree of sorting, skewness and peakedness (kurtosis) of the distribution (Folk and Ward 1957). Such calculations require data to be transformed onto the logarithmic phi scale which is dimensionless

(Krumbein, 1934). In order for similar standardised descriptive terms to be applied to the D_e distributions they were transformed using the expression:-

$$\phi = -\log_2(D_e / D_{e0})$$

where D_{e0} is the origin of the scale set at 1 Gy (Gale and Hoare, 1991).

4.2 Results

Table 2 and Figure 5 show the results from this experiment. Despite the fact that it was expected that only K_{in} had experienced mixing, the mean D_e values (irrespective of number of grains measured) remain within errors of K_{ad}. This may be a reflection on the fact that K_{in} came from a horizontal rather than vertical running burrow in which sediment movements may have mostly been lateral. However, the mean D_e's from K_{in} when compared to K_{ad} are ~4% higher for the 9.6 mm aliquots, ~25% higher for the 4 mm aliquots and ~28% higher for the single grain measurements. Large aliquots mask D_e heterogeneity as the variability and range of D_e values increases as the number of grains measured on an aliquot decreases (e.g. Fig 5b and 5f). This is reflected in the sorting values, which at the single grain level show both samples are poorly sorted (σ_I >1), and at the single aliquot level (9.6 mm aliquots) are well sorted (σ_I <0.49). The D_e distribution also changes from positively/symmetrically skewed (higher D_e values forming tail; SK_I>-0.10) for standard aliquots to negatively skewed (lower D_e values forming tail; SK_I<-0.11) for single grain measurements.

K_{ad} is better sorted and less skewed (either positively or negatively) than K_{in}. Looking in particular at the single grain data it can be seen that the D_e distribution for K_{in} is enlarged with clear peaks of both older (high D_e's) and younger (zero/low D_e's) material incorporated. To an extent any heterogeneity in D_e in larger aliquots is masked especially where the heterogeneity is coming from grains with a significantly lower D_e than the bulk of grains.

5. Discussion

The exhumation experiment shows that OSL ages on bioturbated sediment may only be dating when smearing down after exhumation occurred. In an extreme scenario, if material is being exhumed and bleached by gopher activity on an otherwise stable land surface, OSL ages (that in this case measure only the time elapsed since bioturbation) could erroneously be used to infer original sedimentation ages and rates with all the attendant implications in terms of palaeoenvironmental reconstructions.

In both experiments the samples, even those at depth, have grains with zero D_e values. The inclusion of younger/zeroed material within samples could not be detected at the single aliquot level and were only measurable at the individual grain level.

Theoretically the effect of a small proportion of zeroed/younger grains will be to make the mean D_e from a single aliquot an under-estimate of true D_e as they contribute little/no signal to the naturally acquired OSL signal but do contribute to any regenerated OSL signals within a SAR protocol. Possibly this is occurring for the sample from within the krotovina. The inclusion of zero dosed grains could be due to mixing in of surface sand grains within samples. A recent study indicated movement of sand grains from greater than 1 m to the surface due to creep processes that included bioturbation as an active part of the process (Heimsath et al., 2002). Whereas some of the variation in De values seen within samples could be attributed to other variables not considered as part of this study e.g.

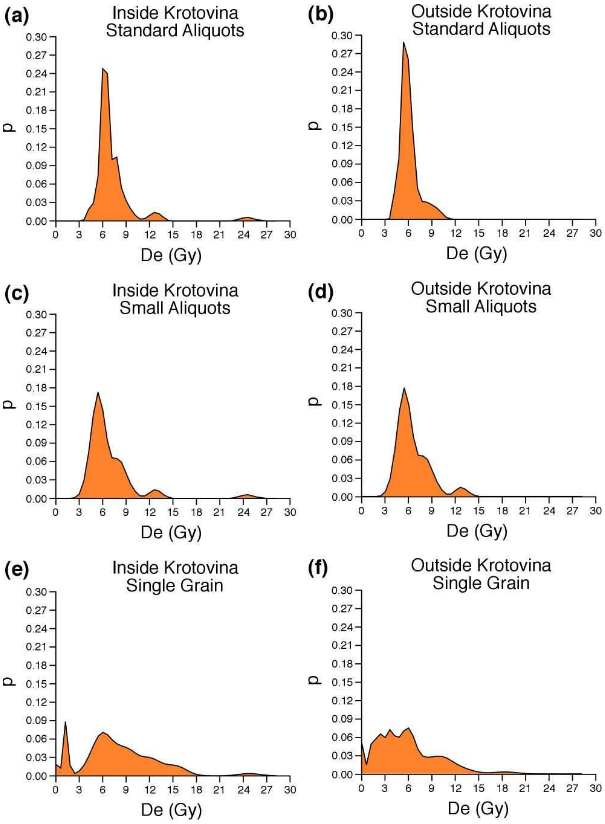

Figure 5: D_e distributions for the samples from within and outside the krotovina burrow plotted as a probability function with a bin size based on the median D_e error of 0.6 Gy.

Table 2: Palaeodose Data for data within (K_{in}) and adjacent to (K_{ad}) the krotovina. Both samples were measured as single aliquot (standard = 9.6 mm, small = 4 mm) and at the single grain level. Age estimates used the dose rate as calculated from in situ field gamma spectrometry (See Ricklis, 2001 for details).

Sample Details		D_e Data						Descriptive data on D_e Distribution			Age Estimates	
Sample	**Size**	**N**	**Min (Gy)**	**Max (Gy)**	**Range (Gy)**	**Mean (Gy)**	**Normally Distributed (Gy)**	**Sorting (σ_I) (phi)**	**Kurtosis (K_G) (phi)**	**Skewness (SK_I) (phi)**	**Mean (ka)**	**Normally distributed (ka)**
K_{in}	Standard	32	4.21	7.86	3.65	6.37 ± 0.81	6.29 ± 0.22	0.36	1.22	0.19	2.5 ± 0.40	2.5 ± 0.26
	Small	43	3.93	24.44	20.52	6.91 ± 3.31	5.41 ± 0.15	0.51	1.11	0.11	2.8 ± 1.3	2.2 ± 0.22
	Single	49	0.00	24.71	24.71	7.97 ± 4.73	5.76 ± 0.15	1.16	1.58	-0.33	3.2 ± 1.9	2.3 ± 0.23
K_{ad}	Standard	31	4.24	9.64	5.40	6.13 ± 1.22	5.72 ± 0.40	0.27	0.99	0.07	2.4 ± 0.54	2.3 ± 0.27
	Small	42	2.58	8.97	6.39	5.16 ± 1.31	4.94 ± 0.63	0.48	1.08	0.08	2.1 ± 0.56	2.0 ± 0.31
	Single	50	0.00	18.32	18.32	5.77 ± 3.74	5.61 ± 0.58	1.52	1.54	-0.38	2.3 ± 1.5	2.2 ± 0.32

microdosimetry, zero dosed grains can only be due to recent bleaching. That mixing, bringing grains down from the surface, occurring even in the 'undisturbed' samples is a significant cause of this variability is supported by all the samples used in the study also containing some grains with much higher D_e values.

No diagnostic scatter in D_e values was observed by which pedoturbated samples could be distinguished. Whilst distributions such as Fig 3A or Fig 4B could be equally attributable to partial bleaching of sediment prior to burial (e.g. Olley et al. 1999) the authors content that incorporation of minor amounts of zero/low D_e's can only be attributable to post-depositional disturbance. Selection of the appropriate D_e values therefore is critical to distinguish between those affected by bioturbation and those reflecting true absorbed dose since sedimentation. The above results indicate that the use of the minimum or a subset of the lowest D_e values (e.g. Olley et al., 1999; Fuchs and Lang, 2001) is not appropriate in cases where younger material has been mixed in. If it is assumed that undisturbed and well-bleached samples have normally distributed D_e populations (as per Fig 2g) then using only the normally distributed data centred on the highest probability peak as shown in Fig 5 should produce D_e values closer to the true burial age. To do this a second probability curve was overlain on and scaled to the krotovina data as plotted in Fig 5. This second curve was adjusted so that the peak position (mean) and width (error) matched that of the peak of the highest probability displayed in the original data. From this second probability curve a D_e, termed a normally distributed D_e, and associated error was calculated (Tab. 2, Column 8). Use of this peak assumes the amount of material bio-mixed in is small, i.e. the maximum peak probability reflects burial age, which should remain valid unless scenarios Fig 2e or 2f are encountered. The calculated normally distributed D_e values show the biggest changes for K_{in} and overall a decrease in variability within and between the 2 samples can be seen, as would be expected if the effects of gopher mixing were being mitigated. The resultant calculated ages are more consistent, irrespective of number of grains measured and are in line with samples from the same stratigraphic horizon elsewhere on the site which had independent corroboration from archaeological artefacts (Ricklis, 2001).

6. Conclusions

A number of conclusions can be drawn from the work presented here:-

- OSL dates can be significantly influenced by pedoturbation.
- Bio-exhumation can be important if exhumed material is preserved without smearing down due to rapid sedimentation or where it causes apparent rejuvenation of otherwise stable deposits. Even where microscale redistribution of surface sediments does cause OSL resetting the question remains as to whether dating of these microscale events after exhumation reflects overall site/landscape depositional history.
- Poorly sorted negatively skewed D_e distributions, as calculated by descriptive statistics, may be indicative of bio-mixing in younger material and such samples should be treated with caution and analysed at the single grain level.
- Incorporation of older material by bio-mixing may be discerned even at the standard aliquot level and can be excluded provided sufficient replicates have been measured to adequately quantify the D_e distribution. Younger contamination is only apparent at the single grain level.
- Adoption of calculating the D_e value by fitting a normal distribution curve to only the data where there is the highest frequency of replicates

producing similar D_e values mitigates contamination problems.

As far as the authors are aware this is the first attempt at examining the influence of pedoturbation on OSL and further work is clearly needed to fully explore its effects. In particular to explore whether it is possible to differentiate between a pedoturbated but essentially geomorphically stable surface from a bioturbated but geomorphically active environment, i.e. between scenario Fig1d and scenarios Fig 1a-c. Use of sites with other independent chronological information against which to test the OSL results will be critical for this.

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