Quantifying bleaching for zero-age fluvial sediment: A Bayesian approach

Alastair C. Cunningham a, b, *, Mary Evans b, Jasper Knight c

a Centre for Archaeological Science, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, Australia
b School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa
c School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, Johannesburg, South Africa

HIGHLIGHTS

- We sampled modern river sediment from low-flow and flood elevations.
- The unbleached OSL dose was measured.
- Bayesian methods can estimate the proportion of well-bleached grains.
- Low-flow sediments are well bleached; flood deposits are poorly bleached.

ABSTRACT

Luminescence dating of sediment requires the sand grains to have been exposed to sunlight prior to their most recent burial. Under fluvial transport, the amount of sunlight exposure may not always be sufficient to reset the luminescence signal, a phenomenon known as 'partial bleaching'. The extent of bleaching is dependent on a combination of geomorphic, sedimentological and fluvial processes. If bleaching can be quantified, and the relationship with these processes understood, it could potentially be used as a new environmental proxy for changes in the dynamics of river systems. Here, we use a recently developed statistical model to evaluate the extent of bleaching, by inferring the proportion of well-bleached grains in the small-aliquot population. We sampled low-flow and flood deposits at a single site on the River Sabie, South Africa. We show that the low-flow sediment is almost perfectly bleached (>80% of grains well bleached), while sediment at flood elevations is partially bleached (20–70% of grains well bleached). The degree of bleaching may show a relationship with flood magnitude as defined by elevation above normal river level, and we speculate on the causes of variability in bleaching between flood samples.

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1. Introduction

Optically Stimulated Luminescence (OSL) dating is most useful in settings where other dating methods are inapplicable, and one such setting is for relatively young (<2000 year old) fluvial sand. OSL methods estimate the radiation dose absorbed by sand grains during burial, but the utility of OSL dating rests on the bleaching of the luminescence signal by sunlight prior to burial of the grains. Under fluvial transport the light intensity may not be sufficient to fully reset the OSL signal; the measured OSL signal then derives from not only the burial dose of interest, but also any previous deposition cycle(s), leading to an overestimate of the burial dose and age. This poor-bleaching effect is most noticeable for young samples, because the burial dose may be very small compared to the poorly bleached 'remnant' dose.

Several complementary research lines have been pursued in an effort to overcome the problem of partial bleaching and to produce reliable ages for fluvial sediments. These research approaches include instrumental development (e.g. Bøtter-Jensen et al., 2000), protocol improvements (e.g. Ballarini et al., 2007), signal analysis (e.g. Cunningham and Wallinga, 2010), and statistical models of the De distribution (e.g. Galbraith et al., 1999). This study pursues a more empirical theme, which has sought to measure how the OSL
bleaching varies in nature in relation to the depositional context of sampled sediments. For example, bleaching could be influenced by the distance grains have travelled within the catchment (Stokes et al., 2001; Jain et al., 2004; Alexanderson and Murray, 2012); or in glacio-fluvial streams, the location within the braid bar (King et al., 2014). Usually, samples are taken from modern sedimentary settings that can be considered to have ‘zero age’, referring to a burial age of zero-years within the limits of our detection. Any sediment less than ~10 years old would qualify. Zero-age samples permit a simple estimate of bleaching, because any $D_0$ that is measured can be assigned to the remnant dose. For samples of unknown age, however, estimating the degree of bleaching is more difficult, because it is dependent on an accurate assessment of the burial dose. Nevertheless, a bleaching statistic would be very useful. Besides telling us whether an OSL age is believable, it could quantify these effects in different environmental settings, then bleaching statistics could be used as a palaeoenvironmental proxy.

We took a set of samples from a single location (at 25°01′10″S, 31°10′30″E) on the Sabie River in Mpumalanga Province, South Africa (Fig. 1a). The sampling site is located downstream of the town of Hazyview and represents a transitional middle-reach zone, lying between the bedrock highland and alluvial lowveled portions of the river.

A description of the catchment geomorphology and hydrology has been provided by Heritage and Moon (2000) and Heritage et al. (2001), from which we summarise here. The Sabie rises in the Mpumalanga Highlands in NE South Africa, flowing eastwards across the Kruger National Park towards Mozambique. River flow is perennial but subject to discharge extremes: rainfall is strongly seasonal, falling in summer months (Oct–Mar), with more rain in the highlands upstream of the sampling site than in the lowveld/Kruger region. Sampling (June 2013) took place during the dry winter season, when discharge is typically of the order of 4 m$^3$ s$^{-1}$. The upstream bedrock is mostly granite and gneiss, into which a macro-channel is incised. Within this channel the river geomorphology alternates between steeper bedrock-influenced areas in which pool and riffle systems dominate, and less steep alluvial segments characterised by shallow, sandy bars. The flow also varies between single-thread and anastomosing, in both bedrock and alluvial sections.

The sampling site is found in a bedrock-controlled segment; the upstream alluvial segment is constricted by resistant granite bedrock into which diorite dikes have been intruded, marking the beginning of a section of rapids (Fig. 2). Under low flow conditions, the river is contained within a deeply incised canyon (12 m wide, 10 m high); in flood conditions the water flows over an undulating granite platform that rises up to 10 m higher. The site was selected because flood sediment corresponding to different heights of flood inundation could be easily identified and collected from pockets on the granite platform high above normal river level, and a small river beach found at the margin of the low-flow channel could provide equivalent sediment representing low-flow conditions. A schematic representation of the site is shown in Fig. 1b.

We targeted unvegetated, medium to coarse-grained sand at various elevations in an approximate transect perpendicular to the river flow and ascending the bedrock platform. Sediment was collected by pushing small plastic tubes horizontally at about 10 cm depth below the sand surface. The elevation of each sampling point was measured using a Differential Global Positioning System (dGPS), giving vertical precision of a few centimetres. Three samples were taken from the river beach, including one slightly below the waterline at the time of sampling. The samples placed above river level were each taken from a different pocket of sand, occupying an area of 2–3 m$^2$. Based on bulk grain size analysis, these sediments are very similar, comprising medium (8–13%) to coarse sand (34–50%) that is unimodal and moderately well sorted. Mean grain size is in the range 0.542–0.951 mm ($n = 6$).

### 2.2. Measurement details

Sample preparation for OSL dating followed standard procedures for extracting quartz: the sample tubes were emptied under subdued red lighting and the exposed end-portions discarded. After sieving to 180–212 μm, the remainder was treated with HCL, H2O2 and HF, and the quartz extract was further purified by density separation with sodium polytungstate. OSL measurements were performed using a Risø TL/OSL Reader DA–15 (at Wits University) and a DA–12 (Wollongong). Both machines provided optical stimulation by blue LEDs (478 nm) of ~40 mW cm$^{-2}$ constrained by a long-pass filter (GG–420), and detect luminescence with an bialkali EMI 9235QB photomultiplier tube via a single 7.5 mm Hoya U340 detection filter.

No dose-rate or water-content measurements were required for this study. For $D_0$ measurements, the purified quartz grains were affixed to steel discs using silicon spray, over a diameter of 1 mm. For this study, we included a further step of counting the number of grains in each aliquot. This was felt necessary for the new statistical model, and is one of the recommendations arising from the model development (Cunningham et al., 2015). Each measurement sequence contained about 42 aliquots for one sample (~24 h measurement time). After each sequence was completed, we manually counted the number of grains on each disc with the aid of a low-magnification optical microscope. Each $D_0$ estimate is therefore paired with a grain count, typically in the range of 10–25 grains.

The measurement procedure broadly follows the Single Aliquot Regenerative dose (SAR) protocol of Murray and Wintle (2003): A preheat1 temperature of 190 °C for 10 s and preheat2 (cutheat) of 180 °C for 0 s was determined using a ‘thermal-transfer test’, in which the OSL signal is repeatedly measured after progressive heating steps. The TT-test allows the onset temperature of unwanted thermal transfer to be estimated for samples where poor bleaching makes the usual ‘preheat-plateau’ test unsuitable. The OSL was detected for 40 s at 125 °C. A ‘hot bleach’ of 200 °C was...
included at the end of each SAR cycle, to remove residual OSL signals. The OSL signal was collected from the initial 0.20 s of the decay curve, with the subsequent 0.50 s used for the ‘background’, but customised to each reader due to small differences in stimulation power. This ‘early-background’ channel choice maximizes the dominance of the fast OSL component while keeping the signal-to-noise ratio as high as possible (Cunningham and Wallinga, 2010).

The $D_e$ was evaluated using a linear fit to a single regenerative dose of ~3 Gy. The error term on the $D_e$ assumes Poisson statistics, with an additional 1% uncertainty added to each OSL measurement (Galbraith, 2002). The protocol included a zero and repeated dose point; aliquots were accepted if recuperation was negligible and the recycling ratio was between 0.9 and 1.1.

2.3. The bleaching statistics

In both nature and the laboratory, the unit of interest is the single grain: each grain has a different transport and bleaching history, and it is the smallest volume from which we can realistically measure luminescence. Grains also differ in their luminescence sensitivity per unit dose. To obtain the burial dose, we need to model the single-grain dose distribution, regardless of the number of grains in the aliquot. By necessity, most OSL dating is performed on small aliquots of tens of grains each, and so the observed OSL signal could be derived from many individual grains. The extent of this signal averaging is not just dependent on the aliquot size, but also the single-grain sensitivity distribution; the more highly skewed the distribution, the fewer grains contribute significantly to the signal.

Cunningham et al.’s (2015) age model first specifies the parameters that operate at the single-grain level. Two parameters of the gamma distribution ($a$ and $b$) describe the single-grain sensitivity. Three further parameters describe the equivalent dose: the mean burial dose, $\gamma$; the proportion of well-bleached grains, $p$; and the scale of the remnant dose distribution, $\sigma$. The question that then needs to be solved is what values these parameters must take, given the measured distribution that we observe. This question can be tackled with computational Bayesian statistics, performed in two steps:

1. Estimate the single-grain sensitivity distribution. Both single-grain and multi-grain sensitivity distributions can be approximated with the gamma distribution. Given the number of grains in each aliquot, and the multi-grain sensitivity distribution per
gray (as measured), we estimate the parameters of the single-grain sensitivity distribution.

2. Estimate the dose parameters. This represents the bulk of the computational time. Given the single-grain sensitivity distribution, the number of grains in the aliquots, and the observed multi-grain dose distribution, we estimate the parameters of the single-grain dose distribution.

Model details and code are provided in Cunningham et al. (2015). The key point is that the single-grain dose distribution is estimated even if measurements are made on small aliquots. This is achieved by using extra information in the calculations, viz. the number of grains in the aliquot, and each aliquot’s luminescence sensitivity per gray. The estimates of \( p \) and \( s \) can be used as bleaching statistics. Of these, \( p \) is less sensitive to outliers in the \( D_e \) distribution, so is probably more useful.

It should be noted that these efforts do not become redundant if measurements are made on a single-grain system. Even true single-grain data need to be evaluated with a statistical model. In practice, the grain holes on the Riso single-grain disc may each contain several grains (or none), especially when the grain size is small. ‘Single-grain’ measurements might then be better described as very-small aliquot or micro-hole (Arnold et al., 2012; Berger and Polyak, 2012), and so the computational model would be directly applicable.

3. Results

For each sample the analysis model provides posterior estimates for five parameters. The two sensitivity parameters \( a \) and \( b \) are similar for all sample, averaging 0.04 and 352 respectively. The low value for the shape parameter \( a \) indicates a highly skewed sensitivity distribution (see Cunningham et al., 2015). Example model output for the dose and bleaching parameters is illustrated in Fig. 3.

The burial dose is artificially constrained to lie close to zero for this study (Fig. 3a), allowing more precision in estimating the bleaching parameters \( p \) and \( s \). The posterior estimates of these parameters become the bleaching statistics, when summarised with their mean and standard deviation.

In Fig. 4, the bleaching statistics are plotted against sample elevation above river level. The most useful bleaching statistic is \( p \) (the proportion of well-bleached grains), which shows a clear relationship with sample elevation (Fig. 4a). \( s \) is less useful, because it is sensitive to outliers and also to the value of \( p \) (because if fewer grains are subject to the residual dose, there is more uncertainty in the size of that dose: Fig. 4b). Fig. 4c shows the median \( D_e \), which gives an independent indication of the bleaching for these zero-age samples. For samples 3 & 6, we repeated the measurements and analysis to check the reproducibility of the method. Fresh aliquots were prepared and measured, then analysed separately to those samples’ original data.

4. Discussion

4.1. Quality control

There are two internal checks on the validity of the results. The first comes from the repeat points, which correspond well with the original estimates of \( p \). This indicates that the between-sample variability in \( p \) is not caused by random errors in either the model or the \( D_e \) distribution. The number of aliquots per sample was therefore sufficient for a reasonable estimate of \( p \). The second quality control comes from the median \( D_e \) (Fig. 4c). Because these are zero-age samples, the median \( D_e \) provides a simple estimate of the residual dose, and is less sensitive to outliers than the mean. The inverse relationship between \( p \) and median \( D_e \) is a good indication that the model results are meaningful. In fact, the median \( D_e \) is less reproducible than \( p \), because it is still somewhat sensitive to outliers. In the model, outlying datapoints are absorbed by \( s \), leaving \( p \) as the most informative statistic.

Fig. 2. Photos of the study site on the Sabie River, South Africa. (a) Incised canyon and rapids looking upstream from the sampling site. (b) The view downstream from the granite platform. (c) Composite photo looking downstream. The river beach is in the foreground, and the first elevated pocket of sediment is mid-left of the photo, ~2 m above the beach.
4.2. Interpretation

Fig. 4a shows that the best-bleached samples are found on the river beach, deposited during low-flow. For the three samples taken below 1 m elevation, the estimated well-bleached fraction is greater than 80%. This result makes sense considering likely conditions of transport and deposition. At low-flow grains are transported in shallow water, and the low discharge means water is clear enough for good light penetration. Low discharge also means that grains are transported slowly, with opportunities for reworking on bars and banks. On the river beach, gradual accumulation allows grains to be exposed to daylight on the surface, with grains also subject to local reworking by river transport. In contrast, the samples from flood-water elevations are poorly bleached, with the estimated proportion of well-bleached grains varying between 20% and 80%. During high discharge the river is turbid, and grains are eroded and transported quickly. The average water depth during transport will also be greater (by ~6 m in this case), and high rate of sedimentation at the site of deposition may effectively bury the grains instantly.

We feel that the difference in bleaching between flood and low-flow sediment is a conclusive result, supported by a straightforward explanation. Beyond that, there are further interpretations of the data that are less clear cut, but potentially valid and worthy of further investigation. Firstly, within the flood-water samples there may be a relationship between the sampling elevation and the degree of bleaching. This is most apparent in the median $D_e$ (Fig. 4c), albeit on a log scale. The uncertainties in $p$ make any trend
difficult to pick out. However, the sample at 2 m has particularly low $\sigma$; this may be a manifestation of the acknowledged difficulty in distinguishing between low $\sigma$ and high $p$ (Cunningham et al., 2015), which would mean that $p$ for this sample is underestimated. Further measurements may help resolve this. If the trend is confirmed, it would suggest that the light conditions during transport play the crucial role in bleaching, with poorest bleaching during high-discharge floods.

The second point of note is the variability of $p$ and median $D_s$ amongst the flood samples above 3 m elevation. Given the internal quality control described above, we can be confident these differences are not due to measurement or analytical error. It could be due to random, very localised differences between samples, such that if we had re-sampled one location immediately adjacent to the original, we would get different results. For example, many sediment pockets on the bedrock surface (Fig. 1b) are internally organised, with finer sediments in the middle and coarser sediments on the outside. Otherwise, there is a genuine environmental factor causing the differences: they could be deposited by different floods, or more likely, different phases of the same flood. This interpretation is supported by the two worst-bleached samples, located at similar elevation (5–6 m) but from different pockets of sediments. We could hypothesise that the highest discharge removes all sediment from the pockets, and grains only accumulate in pockets close to the surface just before they are isolated from the river flow, in slack-water pools. As the floodwater recedes over a number of days, each pocket would accumulate sediment during a relatively short period, which could be during day or night. Under this hypothesis, the variable bleaching of the flood sediment is due to the light conditions at the point of deposition, plus variations in flow properties during sediment transport such as water turbidity.

4.3. Context and implications

We sampled river sediments that correspond to different flood stages (based on sample elevation relative to the present river level). Even if these sediments were transported and deposited during the same single flood event, variations in flow properties such as water depth, sediment concentration within the water column and turbidity/turbulence might exert control on bleaching history. Thus, a single flood event may result in a wide range of bleaching responses. Highly localised differences in bleaching have also been found in modern glacio-fluvial sediment. King et al. (2014) found that residual doses were smaller in braid-bar sides and tails, and larger in the braid-bar heads; this localised variability was found to exceed that due to distance from the glacier. King et al. (2014) also found bleaching to be better in low-flow sediment compared to flood sediment. Given the dependence on flow regime and local depositional setting, it seems debatable whether downstream transport distance would be as significant as previously suggested (e.g. Stokes et al., 2001; Jain et al., 2004). For rivers in semi-arid regions, it has been presumed that episodic transport of sediment during high discharge does not allow the bleaching to occur (Porat et al., 2001; Gray and Mahan, 2015). Our data provides partial support for this view. Flood deposits are indeed more poorly bleached than low-flow deposits, although at least some grains are well bleached in all the samples studied here.

Further comparison with previous research is complicated by sample-size considerations. This study measured the bleaching in relation to a single variable – floodwater magnitude (or alternatively, low-flow versus floodwater deposits). Other variables that might influence bleaching were kept constant between samples, such as distance downstream, grain size, sample age, depositional setting, and source material. The number of samples (10) was sufficient because the effect size is relatively large; fewer samples may not have produced a conclusive result. It may be possible to detect the influence of more than one variable on the degree of bleaching, but then the number of samples must increase dramatically (e.g. 46 samples used by Cunningham et al., 2015). By contrast, previous studies have attempted to assess two or more variables using only a handful of samples. Murray et al. (1995) and Porat et al. (2001) used six and ten modern fluvial samples respectively, varying sample location and depositional setting; Hu et al. (2010) used 10 modern samples, varying transport mode and distance downstream; Weckwerth et al. (2013) and Jaiswal et al. (2009) used four samples of unknown age; Schielein and Lomax (2013) used 8 samples and multiple variables.

4.4. Bayesian computational methods

This study has continued the gradual exploration of Bayesian statistics for luminescence dating. Although Zink (2013) focused on the age equation, most applications have concerned between-sample chronological modelling (e.g. Rhodes et al., 2003; Clark-Balzan et al., 2012; Cunningham and Wallinga, 2012). For such models, the stratigraphic order of the samples is introduced as new information, then used to constrain the burial age. But the same principle can be applied more broadly. Suppose we knew from the depositional setting that $<50\%$ of grains would be well bleached. In a Bayesian model that information (specified in a prior) could increase the precision in the posteriors of other parameters, including the burial dose. In the same way, any information we might have on beta heterogeneity, or water-content variation over time, could be folded into the model to improve the OSL age. These latter two sources of uncertainty are usually not considered in dating calculations; in future, Bayesian models could account for them fully.

5. Conclusions

We have shown a clear difference in the bleaching characteristics between river low-flow and flood sediments, reflecting differences in water depth, turbidity, speed of transport and deposition rate. We further hypothesise that variation in bleaching amongst flood sediments reflects flood magnitude, and the day-night cycle of variations in bleaching intensity as the flood wanes. The bleaching statistic is shown to be meaningful and reproducible. The surprisingly clear results should spur further research on the bleaching of modern fluvial sediment, with the ultimate aim of using a bleaching statistic as a useful palaeoenvironmental proxy.

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