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Bleaching of quartz OSL signals under natural and laboratory light conditions

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Abstract

Resetting or bleaching of the luminescence signal is a fundamental factor in luminescence dating. It must occur in nature during the event or process to be dated for an accurate age, but if it happens during sample processing in the laboratory it destroys the sample for dating purposes. In this study, we look into bleaching of quartz optically stimulated luminescence by light in nature and in the laboratory. Unsieved quartz-rich extracts and 180–250 μm quartz grains with known doses were exposed to outdoor light and laboratory light sources, respectively, and the change in dose with exposure time was measured. The outdoor conditions included direct sunlight, diffuse light from a cloud-covered sky and weak twilight, while indoor light sources were white fluorescent light, light from a computer screen and red darkroom light. Complete resetting took place only in daylight and was faster during sunny than cloudy conditions, and with bleaching rates that changed with exposure time. For all other light sources, including the darkroom lights, bleaching occurred to various degrees but was not complete after the longest exposure, which ranged from 15 min to 24 hours. The results show that some bleaching occurs even by low-intensity light with a limited spectrum. This implies that care should be taken in the laboratory not to expose samples to any light unnecessarily, but at the same time gives hope for bleaching in nature even in settings with limited or variable light conditions.

Keywords: quartz OSL, luminescence signals, resetting

1. Introduction

In luminescence dating, bleaching (zeroing, resetting) of the luminescence signal is a fundamental factor. To get an accurate luminescence age, the sediment must be effectively bleached at the time of deposition but it must not be bleached during field sampling or sample processing in the laboratory. Bleaching of the luminescence signal is mainly dependent on light intensity, light spectrum and duration of exposure (Spooner, 1994; Singarayer et al., 2005). Material properties such as grain size, grain coating and mineralogy may also influence bleaching efficiency (Jain et al., 2003; Sohbati et al., 2017). For sediments in nature, these characteristics are largely controlled by location and depositional environment, e.g. elevation of the sun, cloudiness, sediment transport process, sediment provenance, water turbidity and sedimentation rate.

In settings with limited or variable light exposure, sediments may not be sufficiently exposed to completely reset the luminescence signal at the time of deposition, resulting in incomplete bleaching and unwanted apparent age overestimation in luminescence dating. To quantify this effect, many studies have looked into bleaching in nature and the problem of incomplete bleaching, e.g. by investigating modern or known-age samples (e.g., Stokes et al., 2001; Alexanderson & Murray, 2012; King et al., 2013) or by analysing luminescence signals or dose distributions (e.g., Galbraith et al., 1999; Bailey, 2000; Singarayer et al., 2005). We thus now have a general knowledge of bleaching potential in various depositional environments (e.g., Jain et al., 2004; Fuchs & Owen, 2008), but also know that residual doses (apparent age overestimations) may vary greatly between sites and samples.

However, fewer studies have looked into the bleaching process and how fast bleaching takes place under various conditions. The approaches of the studies that have been

Lab.no	Site	Genesis	Age (ka)	Dose (Gy)	Preheat/ Cutheat (°C)	Out-door	In-door	Reference
13017	Starmoen, SE Norway	aeolian dune	10.0 ± 0.5	33.5 ± 0.7	260/240		x	Alexanderson & Henriksen (2015)
13028	Skattungheden, C Sweden	aeolian dune	10.7 ± 0.5	36.4 ± 0.6	220/200	x		Alexanderson & Bernhardson (2016)
13039	Orsa, C Sweden	glacifluvial delta	11.9 ± 0.6	47.9 ± 1.1	220/200	x	x	Alexanderson & Bernhardson (2016)
15001	Höllviken, S Sweden	beach sand	4.7 ± 0.3	4.9 ± 0.1	180/160	x		Alexanderson, unpublished data
15096	Zaskale, S Poland	fluvial terrace	19 ± 1.1	27.0 ± 0.7	260/220		x	Olszak, unpublished data

Table 1. Sample information.

made range from controlled (laboratory) to natural conditions for both sediments and illumination, and both 'dry' and underwater settings (e.g., Godfrey-Smith et al., 1988; Berger, 1990; Sommerville, 2003; Sanderson et al., 2007).

As important as full resetting is at the time of deposition, as important it is to avoid light exposure during processing of luminescence dating samples since any exposure would result in apparent age underestimation. Most luminescence laboratories use low-intensity darkroom light to minimise the risk of light exposure, and samples are normally exposed to such darkroom lights during preparation. However, in many laboratories there are also other, brighter light sources (e.g. white light, computer screens) that are not normally on but to which the samples could accidentally be exposed and which may have a large bleaching effect.

In this study, we will examine the bleaching process by exposing samples with known doses to various light conditions, both outdoors and indoors, and measure the change in dose with exposure duration. The light sources are selected to represent common natural conditions (outdoors) and typical laboratory light sources (indoors). We will determine the rate of bleaching of the quartz OSL signal and any residual dose for the different light sources (experimental set-ups), and the implications for bleaching in nature and for laboratory handling will be discussed.

2. Sample descriptions

Samples previously analysed (fully dated) at the Lund Luminescence Laboratory were used for these experiments. The samples were chosen to represent different sediment types (aeolian, (glaci)fluvial and beach) from different areas (Sweden, Norway, Poland), see Table 1. All samples were known to have good luminescence characteristics, including a fairly strong signal dominated by a fast component, and to have a limited spread in equivalent dose (Alexanderson & Henriksen, 2015; Alexanderson & Bernhardson, 2016; Olszak, unpublished data).

3. Experimental procedures

3.1. Sample preparation

To make the experiments as realistic as possible, the samples were prepared differently for the outdoor and indoor experiments, respectively. For the outdoor experiments, the sample should be as close to its original state as possible, but still allow us to measure a signal dominated by quartz. Untreated and unexposed sediment was therefore only put through density separation with heavy liquid (LST Fastfloat, 2.62 g/cm^3) to extract a quartz-rich fraction. The sediment thus largely retains its original (quartz) grain-size distribution but has lost most signal-contaminating feldspar grains ($\sim$ 50 % for samples 13028, 13039 and $\sim$ 5 % for 15001).

Although samples at all stages of preparation could be exposed to light indoors during preparation and measurement, we here chose to analyse fully processed samples. For the indoor experiments, we therefore used 180–250 µm quartz grains that had been extracted for previous dating analyses but had not been used. These samples had been through full preparation including wet sieving, density separation (at 2.62 g/cm^3) and chemistry (10 % HCl for 15 min, 10 % H_2O_2 for 15 min, 40 % HF for 60 min and 10 % HCl for 40 min). For more details see e.g. Alexanderson & Bernhardson (2016).

3.2. Outdoor experiments

The outdoor experiments took place in Lund, S Sweden (55.71° N, 13.20° E, ca. 67 m a.s.l.); experiments O-1 and O-2 outside the Department of Geology, Lund University and experiment O-3 in a residential quarter in Lund. Three experiments with different light conditions were carried out (Lindvall, 2017), as described below. Large (8 mm) aliquots of quartz grains were placed in shallow metal containers with lids and exposed to light by taking off the lids for set times. Three aliquots per exposure duration were used. Due to technical problems, the field spectrometer could not be used for the outdoor experiments and light intensities are based on modelled data from SMHI (2017) and no spectral distributions are available.

Experiment O-1 was done on a cloudy day (April 10, 2017, at 3–4 pm). The sky was almost completely covered by grey, medium-high level clouds. In addition, the experiment was carried out in the shadow of a building to avoid exposure to direct sunlight through occasional holes in the cloud cover. The global irradiance in Lund was during that afternoon declining from ca. 400 to ca. 260 W/m^2 (SMHI, 2017) but as the samples were placed in shadow they would only have been effected by diffuse light ($<$ 200–300 W/m^2), dominated by longer wavelengths. Samples were exposed for 5 s, 10 s, 30 s, 1 min, 2 min, 5 min, 10 min, 30 min and 1 hour.

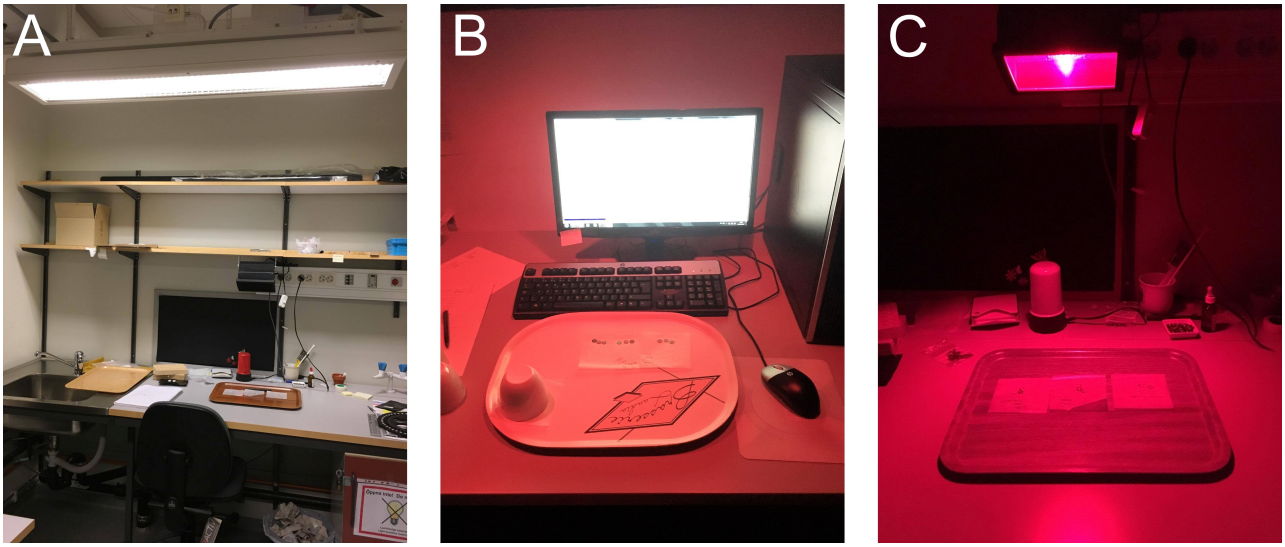

Figure 1. Indoor experiments. A. In experiment I-1, the samples were exposed to light from a fluorescent tube for 10 s to 15 min. B. In experiment I-3, samples were placed in front of a computer screen for 10 s to 15 min. C. In experiment I-4, the samples were exposed to red, darkroom light for 24 hours.

Experiment O-2 took place on a sunny day (April 11, 2017, at 1–2 pm) with only a few clouds in the sky. The global irradiance in Lund was then 650 W/m^2, of which ca. 410 W/m^2 was direct irradiance (SMHI, 2017). Samples were exposed to direct sunlight for the same durations as in experiment O-1.

Experiment O-3 was carried out in the late evening of April 19, 2017, starting at 9 pm. The sky was clear with scattered clouds. The light changed from twilight to night during the experiment with global irradiance from $<$ 20 W/m^2 to zero (SMHI, 2017). However, in addition to the natural light, there was also some light from surrounding houses and street lamps; the closest was 10 m away. Samples were exposed for 15 s, 30 s, 1 min, 5 min, 15 min, 30 min, 1 hour and 3 hours.

3.3. Indoor experiments

The indoor experiments were carried out in the Lund Luminescence Laboratory, Lund University, Sweden. Three different light sources typically found in any luminescence laboratory were used in four different set-ups (Stjern, 2017); these are described below. Large (8 mm) aliquots of quartz grains were placed on trays below or in front of the light source and exposed for set times. Outside the set exposure times, aliquots were covered by porcelain or metal containers. Three aliquots per exposure duration were used.

In experiment I-1, samples placed on a bench were exposed to white light from a fluorescent tube hanging from the ceiling directly above (Figure 1A). The light source was 140 cm from the samples and was of the type T5 ECO SAVER HE with 32 W effect (AuraLight, 2014). The light from the source was dominated by wavelengths around 540 and 620 nm with irradiance of 0.06 and 0.08 W/m^2/nm at the bench level, respectively, according to measurements with a spectrometer (ASD FieldSpec FR), corresponding to ca. 2.6 W/m^2 for the measured spectrum. This matches data given in the technical data sheet (AuraLight, 2014). Samples were exposed for 10 s, 30 s, 60 s, 5 min and 15 min.

The same light source was used in experiment I-2, but instead of illumination from above, the light reached the samples through a partly open door. The samples were placed on a bench 80 cm from the door and were exposed for 10 s, 30 s, 60 s and 5 min.

In experiment I-3, samples were placed 30 cm in front of an active computer screen, which mainly showed white (a full window of Risø SequenceEditor) (Figure 1B). The screen was of the type Fujitsu L20T-3 LED with a typical light intensity of 250 cd/m^2 (Fujitsu, 2012), which can be converted to ca. 0.4 W/m^2 at the source. Due to technical problems it was not possible to use the spectrometer to measure the light spectrum and irradiance at the samples' location for this experiment. Instead dominating wave lengths and corresponding spectral irradiance were assumed to be around 460, 530 and 650 nm and 0.01, 0.008 and 0.016 W/sr/m^2/nm, respectively, based on data from another study with a similar screen (Cajochen et al., 2011). Samples were exposed for 10 s, 30 s, 60 s, 5 min and 15 min.

Darkroom light was used in experiment I-4, where samples were placed on a bench 53 cm below a wall-mounted lamp (Figure 1C). The light source was a 15 W tungsten light bulb behind a red transparent glass filter (Fotokemika C-15). The light was too weak to be measured by the spectrometer so no wavelength or irradiance values are available. The samples were exposed for 24 hours.

3.4. Dose measurements and calculations

Dose measurements were carried out in a Risø OSL/TL reader model DA-20 with a ^{90}Sr/^{90}Y beta radiation source by following a single aliquot regeneration (SAR) protocol

(Murray & Wintle, 2000, 2003). Stimulation was by blue light (470 ± 30 nm; $\sim$ 50 mW/cm^2) at 125 °Cfor 40 s, and detection was through a 7 mm U340 glass filter. For sample 15001, post-IR blue stimulation was used due to some remaining feldspar contamination. The same preheat and cutheat temperature settings as in original dating analyses were used (Table 1; Alexanderson & Henriksen, 2015; Alexanderson & Bernhardson, 2016; Olszak, unpublished data). Since the previous analyses had shown that no or very few aliquots were rejected due to poor recycling ratios or high recuperation for the selected samples (ibid.), shortened SAR-protocols with three regenerative doses only were used for some measurements.

Equivalent doses were calculated in Risø Analyst v. 4.31.9, using exponential curve fitting. Aliquots were accepted if test dose error was < 15 %. A few aliquots gave doses much higher ($> +2\sigma$) than the natural dose; these were rejected.

Initial bleaching rates were calculated by linear interpolation between the zero-exposure equivalent dose and the dose measured at the shortest exposure time. Exponential curve fitting was done for the data from experiments O-1, O-2 and I-1, and surface power density dependent bleaching rates were calculated for these three data sets.

4. Results

4.1. Outdoor experiments

The samples that were exposed to daylight (O-1 cloudy, O-2 sunny) were bleached relatively rapidly; after 10 s the dose was 20 % or less of the natural dose (Figure 2, Figure 3). The initial bleaching was more rapid in direct sunlight than under cloud cover with average bleaching rates of 15 %/s and 9 %/s, respectively, for the first 5 s of exposure. After 1–2 min. there was no further change in dose with exposure time and the dose stabilised at 0.7–2.5 Gy (Table 2). This final dose corresponds to 3–7 % of the original dose for the older samples (13028, 13039) and 14–16 % for the younger sample (15001), cf. Table 1.

During the evening-night experiment (O-3), samples initially lost 20–40 % of their natural dose with a rate of 2 %/s for the first 30 s. With further exposure the average dose did not change much (70-80 % of the natural dose), but there was much variability between individual values (Figure 2, Figure 3).

The bleaching related to approximated surface power density (i.e. irradiance $\times$ exposure time) could not be well fitted to a single exponential curve (Figure 3B) as the slope (rate) changes with exposure. The slope is also lower for cloudy conditions than for sunny, and very low for the night experiment. For the initial part of the curves, decay constants were calculated to -4.0 and -0.8 for the sunny and cloudy conditions, respectively.

4.2. Indoor experiments

In both experiments with fluorescent light (I-1, I-2), doses were reduced to $\sim$ 90 % of the natural dose after 10 s of exposure (Figure 4), corresponding to initial bleaching rates of 0.1–1.8 %/s. In the experiment with light from directly above, further bleaching to $\sim$ 50 % had occurred after 5 min (300 s) and after 15 min (900 s) the doses were $\sim$ 20 % of the natural (Figure 4A, Table 3). When light came through a partly open door, there was no further significant change in dose after 10 s, although there was some variability between samples and aliquots (Figure 4B).

The doses in samples exposed to light from a computer screen (experiment I-3) were reduced to $\sim$ 80 % on average, but with much variability between samples, aliquots and exposure time (Figure 4C). One sample (15096) showed further reduction after 15 min to $\sim$ 40 % of the natural dose.

After 24 hours of exposure to darkroom light (experiment I-4), the doses had been reduced to 32.1 ± 1.2 Gy (13017), 42.1 ± 1.7 Gy (13039) and 21.4 ± 1.8 Gy (15096) (Table 3). This corresponds to 79–97 % of the natural dose remaining, and yields bleaching rates of 0.1–0.9 %/hour.

Due to the lower irradiance for the indoor light sources, the rate of bleaching related to approximated surface power density does not show a very clear pattern, but the shape of the curve for experiment I-1 seems to follow those of the outdoor experiments (Figure 3B) and a decay constant of 0.3 was calculated.

5. Discussion

5.1. Experimental sources of error

Although there is an overall decrease in remaining dose with exposure time, particularly for the daylight experiments, there are some values that break the steady decrease (Figure 2). An example is the 10 s measurement in experiment O-1, where values for all three samples are higher than expected and for two of the samples even higher than the preceding value (Figure 2). Since this appears systematic for all aliquots in all samples for this particular exposure time, we suspect that it is due to something that occurred during the experiment, e.g. an error in the exposure time when opening/closing the containers. Particularly for the very short exposure times and the more intense light sources a small error in timing may have a relatively large effect.

There is also inter-aliquot variability for the different experiments and samples (Figure 2, Figure 4). This variability is largest for the indoor experiments I-2-4 and the night-time outdoor experiment (O-3). For the indoor experiments, particularly I-3 (computer screen), part of the variability could be due to a directional component to the light, which may have yielded slightly different intensities depending on a particular aliquots location. The fluorescent light from above, as well as the daylight, on the other hand provided evenly distributed light to all exposed aliquots, resulting in less variability.

Another factor, which likely explains some of the inter-

Sample	Experiment Exposure (s)	O-1 cloudy Mean dose (Gy)	O-2 sunny Mean dose (Gy)	O-3 night Mean dose (Gy)
13039	0	47.9 ± 1.1	47.9 ± 1.1	47.9 ± 1.1
	5	28.54 ± 0.94	14.3 ± 1.1	
	10	30.8 ± 6.4	6.89 ± 0.80	
	15			28.5 ± 7.5
	30	10.96 ± 0.36	4.2 ± 1.4	35.5 ± 3.9
	60	7.49 ± 0.67	2.72 ± 0.16	42.7 ± 1.5
	120	3.22 ± 0.74	1.96 ± 0.53	
	300	2.04 ± 0.69	0.98 ± 0.32	35.2 ± 1.1
	600	1.93 ± 0.36	2.317 ± 0.091	
	900			37.0 ± 3.4
	1800	1.10 ± 0.55	1.85 ± 0.45	36.5 ± 2.6
	3600	1.45 ± 0.13	2.01 ± 0.40	29.8 ± 2.7
	10800			28.8 ± 9.2
13028	0	36.37 ± 0.64	36.37 ± 0.64	36.37 ± 0.64
	5	21.4 ± 1.2	8.20 ± 0.32	
	10	20.2 ± 1.9	4.67 ± 0.74	
	15			30.3 ± 2.4
	30	7.79 ± 0.74	1.53 ± 0.41	28.6 ± 2.5
	60	4.97 ± 0.46	1.66 ± 0.44	29.4 ± 1.4
	120	3.06 ± 0.21	1.01 ± 0.28	
	300	2.09 ± 0.50	0.830 ± 0.092	30.05 ± 0.85
	600	2.24 ± 0.39	1.28 ± 0.17	
	900			32.2 ± 1.9
	1800	2.52 ± 0.27	2.45 ± 0.12	29.96 ± 0.93
	3600	2.02 ± 0.18	2.47 ± 0.26	36.3 ± 5.8
	10800			30.4 ± 1.6
15001	0	4.92 ± 0.10	4.92 ± 0.10	4.92 ± 0.10
	5	2.07 ± 0.21	1.257 ± 0.012	
	10	2.62 ± 0.19	0.89 ± 0.13	
	15			3.68 ± 0.24
	30	1.270 ± 0.086	0.723 ± 0.094	4.00 ± 0.14
	60	0.71 ± 0.22	0.757 ± 0.084	3.94 ± 0.27
	120	0.850 ± 0.091	0.827 ± 0.052	
	300	0.837 ± 0.020	0.680 ± 0.053	3.73 ± 0.71
	600	0.800 ± 0.017	0.563 ± 0.077	
	900			3.14 ± 0.55
	1800	0.840 ± 0.035	0.89 ± 0.15	3.83 ± 0.87
	3600	0.77 ± 0.19	0.710 ± 0.066	3.47 ± 0.33
	10800			3.5967 ± 0.0033

Table 2. Equivalent doses measured after exposure to outdoor light. The dose is the mean of three aliquots and the uncertainty represented by the standard error of the mean. Exception is the zero exposure dose, which is based on ca. 24 aliquots (Alexanderson & Bernhardson, 2016; Alexanderson, unpublished data).

aliquot variability, is the inherent variation in (natural) dose as well as sensitivity between aliquots, as shown by the ranges of measured equivalent doses during dating analyses (Alexanderson & Henriksen, 2015; Alexanderson & Bernhardson, 2016; Alexanderson and Olszak, unpublished data). Although these samples were selected based on their limited spread of equivalent doses, occasional outliers still occurred. Such outliers may also explain some of the very high doses

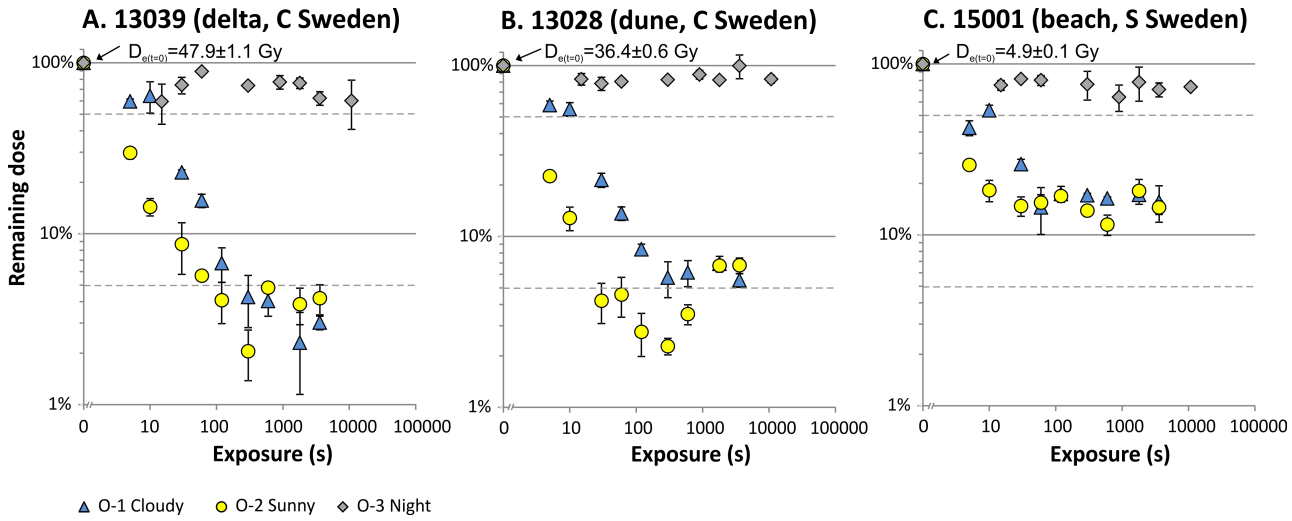

Figure 2. Remaining doses in % of the initial (zero exposure) equivalent dose (D_e) after exposure to outdoor light for the three samples and the three different outdoor experiments. The mean of three aliquots and the standard error of the mean for each exposure is shown. The value of the natural (equivalent) dose for the specific sample is given in each diagram. For values in Gy for the various exposures, see Table 2. A. Sample 13039 from a glacifluvial delta in central Sweden. B. Sample 13028 from an aeolian dune in central Sweden. C. Sample 15001 from Holocene beach sediments in southern Sweden.

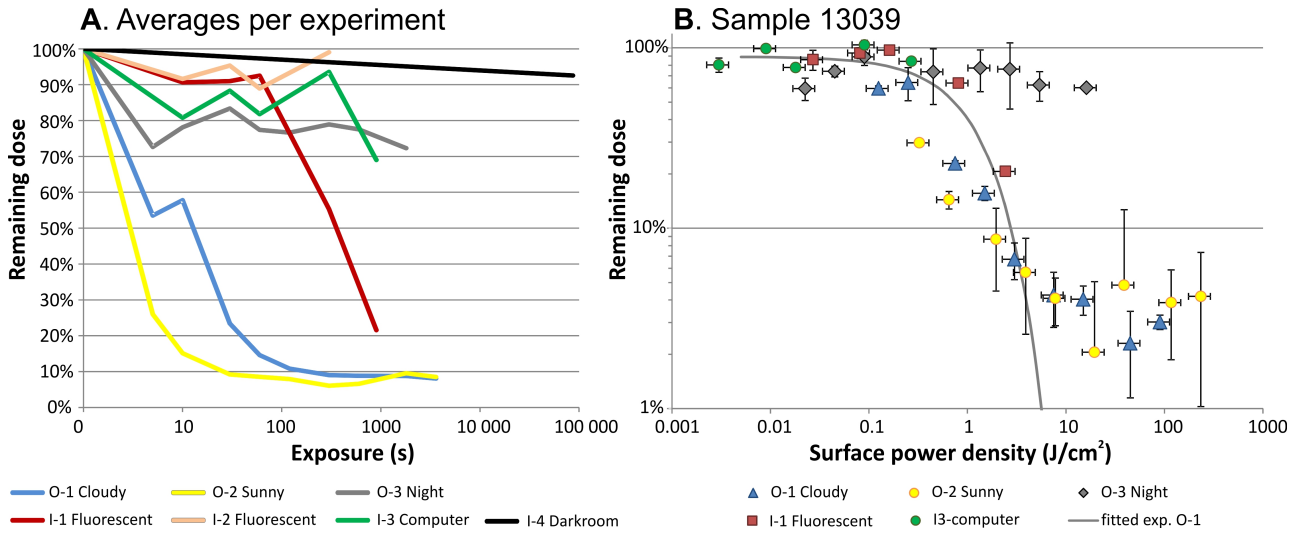

Figure 3. A. Averages of the remaining dose plotted against exposure time for all experiments and samples. B. Remaining doses for sample 13039 plotted against approximated surface power density (irradiance × exposure time) for five of the experiments and a single exponential function fitted to experiment O-1 data. See Table 2, Table 3, Figure 2 and Figure 4 for data points and values.

measured for a few aliquots and that were rejected.

For all experiments, bleaching rates were calculated for the initial part of the decay and by linear interpolation, both of which are simplifications. The dose (signal) decreases exponentially and bleaching rates change with exposure time and with the amount of energy received (surface power density), suggesting the presence of more than one component (cf. Aitken, 1998). However, for the purpose of this study and given the resolution of our data this level of simplification was deemed sufficient.

5.2. Bleaching under natural light

The bleaching rate of our samples in daylight is not as fast as that shown by Godfrey-Smith et al. (1988), where the quartz OSL signal was < 1 % after 10 s of exposure, but is similar to that of other samples from central Sweden (Alexanderson & Bernhardson, 2016) and Scotland (Sommerville, 2003). The difference in bleaching rate may be related to differences in light intensity and spectrum between the studies, or to the characteristics of the quartz (e.g., Jeong & Choi, 2012). In our own dataset, with samples of different depositional and geographic/geologic origin, there is some variation between samples but they generally follow the same

Sample	Experiment Exposure (s)	I-1 fluorescent Mean dose (Gy)	I-2 fluorescent Mean dose (Gy)	I-3 computer Mean dose (Gy)	I-4 darkroom Mean dose (Gy)
13017	0	33.53 ± 0.68	33.53 ± 0.68	33.53 ± 0.68	33.53 ± 0.68
	10	32.4 ± 1.8	27.5 ± 3.0	31.6 ± 6.3	
	30	30.3 ± 2.0	31.1 ± 6.8	29.3 ± 5.2	
	60	31.76 ± 0.39	30.27 ± 0.81	31.2 ± 5.0	
	300	18.3 ± 1.2	33.80 ± 0.40	31.4 ± 2.0	
	900	6.77 ± 0.92		27.7 ± 2.4	
	24 hrs				32.4 ± 1.2
13039	0	47.9 ± 1.1	47.9 ± 1.1	47.9 ± 1.1	47.9 ± 1.1
	10	41.2 ± 5.2	45.0 ± 2.0	38.5 ± 3.5	
	30	44.8 ± 3.1	47.1 ± 3.7	47.4 ± 1.8	
	60	46.5 ± 2.2	48.9 ± 6.4	37.26 ± 0.63	
	300	30.54 ± 0.70	39 ± 11	49.7 ± 3.0	
	900	9.90 ± 0.22		40.4 ± 1.6	
	24 hrs				42.1 ± 1.7
15096	0	27.02 ± 0.72	27.02 ± 0.72	27.02 ± 0.72	27.02 ± 0.72
	10	24.13 ± 0.29	26.68 ± 0.25	18.2 ± 6.0	
	30	24.1 ± 5.4	25.6 ± 3.5	21.2 ± 5.9	
	60	23.1 ± 2.5	20.1 ± 1.5	20.1 ± 5.1	
	300	12.9 ± 1.8	31.3 ± 2.5	22.43 ± 0.43	
	900	6.4 ± 1.4		10.85 ± 0.56	
	24 hrs				21.4 ± 1.8

Table 3. Equivalent doses measured after exposure to indoor light. The dose is the mean of three aliquots and the uncertainty represented by the standard error of the mean. Exception is the zero exposure dose, which is based on ca. 24 aliquots (Alexanderson & Henriksen, 2015; Alexanderson & Bernhardson, 2016; Olszak and Alexanderson, unpublished data).

pattern (Figure 2 - Figure 4) and do not allow us to draw any conclusions on bleaching potential related to sample origin.

Our results show that bleaching is slower with overcast conditions than in sunshine but that the signal (dose) is nevertheless eventually (close to) completely reset after 1–2 min of exposure irrespective of daylight conditions (Figure 2). The intensity of the light was also lower during the cloudy day (< 300 W/m^2) than during the sunny day (ca. 650 W/m^2). The findings are in agreement with previous studies that have shown that bleaching of luminescence signals occurs also by lower intensity light and longer wavelengths such as from diffuse light and underwater light, although it takes longer time (e.g., Godfrey-Smith et al., 1988; Berger, 1990; Sommerville, 2003).

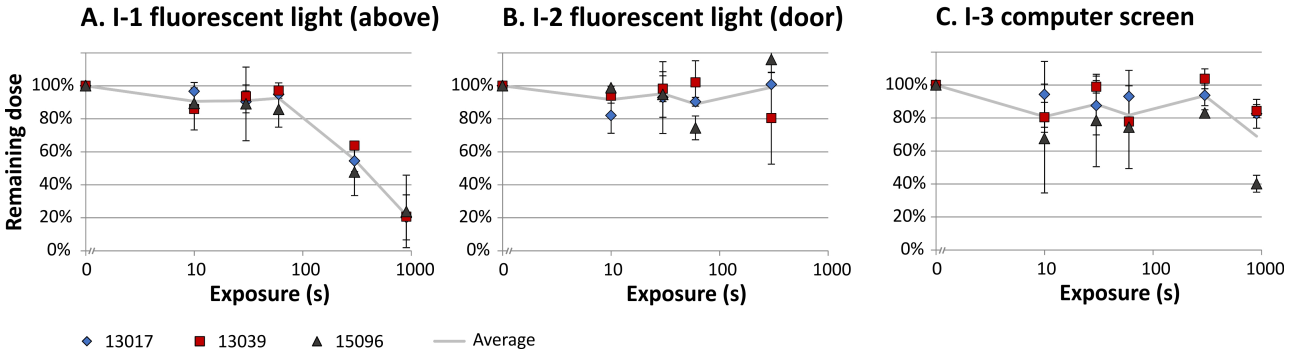

Figure 4. Remaining doses in % of the initial (zero exposure) equivalent dose (D_e) after exposure to indoor light for the three samples and experiments I-1, I-2 and I-3. The mean of three aliquots and the standard error of the mean is shown. For values in Gy for the various exposures, see Table 2. A. Experiment I-1 where samples were exposed to fluorescent light from above. B. Experiment I-2 where samples were exposed to fluorescent light coming through a partly open door. C. Experiment I-3 where samples were placed in front of a computer screen.

The remaining dose after 1 hour exposure to daylight is at face value not consistent with zero within error (0.7–2.5 Gy; Table 2). However, for sample 15001, there is no peak in the OSL signal remaining after 1 min exposure and the residual dose value is an artefact of the background noise; this sample has been completely reset. In contrast, for the two other samples (13028, 13039), there is still a small peak in the OSL signal showing that some signal is there even after 1 hour (3600 s) exposure to daylight. This could be due to a small thermal transfer effect, as shown by Alexanderson & Bernhardson (2016) for samples from the same area. A residual dose of this size – similar to that of some modern fluvial sediments (e.g., Jain et al., 2003) – would likely give rise to some apparent age overestimation for very young (low-dose) samples, while it is insignificant for older (higher-dose) samples.

During night time there was only moderate bleaching of the OSL signal (ca. 20 % on average), and only a slow, or no, continued reduction of dose with exposure time (Figure 2). The intensity of the natural light, and any nearby artificial light, was clearly not strong enough to completely reset the signal, and any sedimentary material that would have been deposited under such conditions would have suffered from incomplete bleaching. Our data are thus in line with the observations of Gemmell (1999), who noted that infrared stimulated luminescence (IRSL) signals and doses were much higher in fine-grained glacifluvial sediments transported during the night than in those transported during the day.

5.3. Bleaching during laboratory work

Our observations show that initially the light from the computer screen is the most efficient of the three artificial light sources in bleaching the OSL signal, but with longer exposure the fluorescent light from above bleaches more (Figure 4) and the shape of the decay is similar to that from the outdoor, daytime experiments (Figure 3B). An explanation may be that the light from the computer screen is dominated by somewhat shorter wavelengths than the fluorescent light, and should thus bleach quicker since shorter (higher energy) wavelengths are more efficient in bleaching the luminescence signal than longer wavelengths (Spooner, 1994), but since we unfortunately do not have accurate data on intensity (irradiance) for the computer screen we cannot draw any conclusions about this.

However, the bleaching from either light source did not occur as fast or as extensively as expected: the signal was not reset completely even after the longest exposure time (15 min). Compared to the daylight experiments, where the signal was reset completely, the artificial light has much lower intensity (< 0.4 W/m^2) and emits in fewer wavelengths, which would lead to slower bleaching rates (Spooner, 1994). Still, from a laboratory risk assessment point of view, there is an effect even after a short exposure (< 10 s) and precautions to avoid accidental white light exposure during sample preparation and measurement must be taken.

Ideally, the laboratory lights required for safe working in a luminescence laboratory should not have any effect on the luminescence signal. However, although the Lund Luminescence Laboratory, like most other luminescence laboratories, uses low-intensity red-orange lights to minimize any unintentional bleaching, these lights do have an effect on the luminescence signal (Figure 3, Table 3). The bleaching rate is slow (0.1–0.5 %/h) but after 24 hours the dose has been reduced by up to 21 %.

It is rare that samples are exposed to darkroom lights for this long, so in practice the risk is fairly small. Nevertheless, samples should not be exposed to the red light unnecessarily. If lengthier exposures are required, a change in light source may be useful. As recently shown by Sohbati et al. (2017), low-intensity, orange LEDs have a small effect on the samples and provide better visibility for laboratory staff than red light from light bulbs with filters.

6. Conclusions

- Samples of quartz-rich extracts from unsieved and unexposed samples exposed to daylight are rapidly reset; after 10 s the dose was 20 % or less of the natural dose. The bleaching rate was slower during cloudy than sunny conditions, likely related to differences in light intensity and spectrum.
- Samples exposed to evening-night light showed some reduction in dose (up to 4 %), but remaining doses varied between aliquots and exposure time but with on average a stable or slightly decreasing dose with exposure time.
- Red darkroom light in the laboratory does cause some bleaching of the luminescence signal in 180–250 μm quartz grains during long exposures. Doses were reduced by 3–21 % after a 24-hour exposure.
- White fluorescent light and bright light from computer screens bleaches samples by up to 20 % within less than 10 s, but then require longer exposures to reduce the luminescence signal further.
- The bleaching rates change with exposure time as well as with surface power density for those experiments for which such data were available, and the curves do not fit with a single exponential function. This suggests that more than one OSL component is present.

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References

Aitken, M.J. *An Introduction to Optical Dating*. Oxford University Press, 1998.

Alexanderson, H. and Bernhardson, M. *OSL dating and luminescence characteristics of aeolian deposits and their source material, Dalarna, central Sweden*. Boreas, 45: 876–893, 2016.

Alexanderson, H. and Henriksen, M. *A short-lived aeolian event during the Early Holocene in southeastern Norway*. Quaternary Geochronology, 30: 175–180, 2015.

Alexanderson, H. and Murray, A.S. *Luminescence signals from modern sediments in a glaciated bay, NW Svalbard*. Quaternary Geochronology, 10: 250–256, 2012.

AuraLight. *Technical Data Sheet T5 ECO SAVER HE.*, 2014.

Bailey, R.M. *The interpretation of quartz optically stimulated luminescence equivalent dose versus time plots*. Radiation Measurements, 32(2): 129–140, 2000.

Berger, G.W. *Effectiveness of natural zeroing of the thermoluminescence in sediments*. Journal of Geophysical Research: Solid Earth, 95(B8): 12375–12397, 1990.

Cajochen, C., Frey, S., Anders, D., Späti, J., Bues, M., Pross, A., Mager, R., Wirz-Justice, A., and Stefani, O. *Evening exposure to a light-emitting diodes (LED)-backlit computer screen affects circadian physiology and cognitive performance*. Journal of Applied Physiology, 110(5): 1432–1438, 2011.

Fuchs, M. and Owen, L.A. *Luminescence dating of glacial and associated sediments: review, recommendations and future directions*. Boreas, 37(4): 636–659, 2008.

Fujitsu. *Data Sheet Fujitsu Display L20T-3 LED Display*, 2012.

Galbraith, R F., Roberts, R.G., Laslett, G.M., Yoshida, H., and Olley, J.M. *Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia. Part I: experimental design and statistical models*. Archaeometry, 41(2): 339–364, 1999.

Gemmell, A.M.D. *IRSL from fine-grained glacifluvial sediment*. Quaternary Science Reviews, 18(2): 207–215, 1999.

Godfrey-Smith, D.I., Huntley, D.J., and Chen, W.-H. *Optical dating studies of quartz and feldspar sediment extracts*. Quaternary Science Reviews, 7: 373–380, 1988.

Jain, M., Murray, A.S., and Bøtter-Jensen, L. *Characterisation of blue-light stimulated luminescence components in different quartz samples: implications for dose measurement*. Radiation Measurements, 37(4-5): 441–449, 2003.

Jain, M., Murray, A.S., and Bøtter-Jensen, L. *Optically stimulated luminescence dating: How significant is incomplete light exposure in fluvial environments?* Quaternaire, 15: 143–157, 2004.

Jeong, G.Y. and Choi, J.-H. *Variations in quartz OSL components with lithology, weathering and transportation*. Quaternary Geochronology, 10: 320–326, 2012.

King, G.E., Robinson, R.A.J., and Finch, A.A. *Apparent OSL ages of modern deposits from Fåbergstølsdalen, Norway: implications for sampling glacial sediments*. Journal of Quaternary Science, 28(7): 673–682, 2013.

Lindvall, A. *Hur snabbt påverkas och nollställs luminiscenssignaler under naturliga ljusförhållanden?* BSc. thesis, 501, Department of Geology, Lund University, Lund, 2017. URL http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8916161&fileOId=8916170.

Murray, A.S. and Wintle, A.G. *Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol*. Radiation Measurements, 32(1): 57–73, 2000.

Murray, A.S. and Wintle, A.G. *The single aliquot regenerative dose protocol: potential for improvements in reliability*. Radiation Measurements, 37(4-5): 377–381, 2003.

Sanderson, D.C.W., Bishop, P., Stark, M., Alexander, S., and Penny, D. *Luminescence dating of canal sediments from Angkor Borei, Mekong Delta, Southern Cambodia*. Quaternary Geochronology, 2(1): 322–329, 2007.

Singarayer, J.S., Bailey, R.M., Ward, S., and Stokes, S. *Assessing the completeness of optical resetting of quartz OSL in the natural environment*. Radiation Measurements, 40(1): 13–25, 2005.

SMHI. *STRÅNG data*, 2017.

Sohbati, R., Murray, A., Lindvold, L., Buylaert, J.-P., and Jain, M. *Optimization of laboratory illumination in optical dating*. Quaternary Geochronology, 39: 105–111, 2017.

Sommerville, A.A. *Luminescence dating of wind blown sands from archaeological sites in northern Scotland*. Phd thesis, College of Science and Engineering, University of Glasgow, 2003. URL http://theses.gla.ac.uk/id/eprint/2934.

Spooner, N.A. *On the optical dating signal from quartz*. Radiation Measurements, 23(2): 593–600, 1994.

Stjern, R. *Hur påverkas luminiscenssignaler från kvarts av ljusexponering under laboratorieförhållanden?* BSc. thesis, 519, Department of Geology, Lund University, Lund, 2017. URL http://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=8916682&fileOId=8916718.

Stokes, S., Bray, H.E., and Blum, M.D. *Optical resetting in large drainage basins: tests of zeroing assumptions using single-aliquot procedures*. Quaternary Science Reviews, 20(5): 879–885, 2001.

Reviewer

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