Aberystwyth University

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Sohbati, Reza; Murray, Andrew S.; Chapot, Melissa S.; Jain, Mayank; Pederson, Joel

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Optically stimulated luminescence (OSL) as a chronometer for surface exposure dating

Reza Sohbati,[1,2] Andrew S. Murray,[1] Melissa S. Chapot,[3,4] Mayank Jain,[2]
and Joel Pederson[3]

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[1] We pioneer a technique of surface-exposure dating based upon the characteristic form of an optically stimulated luminescence (OSL) bleaching profile beneath a rock surface; this evolves as a function of depth and time. As a field illustration of this new method, the maximum age of a premier example of Barrier Canyon Style (BCS) rock art in Canyonlands National Park, Utah, USA, is constrained. The natural OSL signal from quartz grains is measured from the surface to a depth of >10 mm in three different rock samples of the Jurassic Navajo Sandstone. Two samples are from talus with unknown daylight exposure histories; one of these samples was exposed at the time of sampling and one was buried and no longer light exposed. A third sample is known to have been first exposed 80 years ago and was still exposed at the time of sampling. First, the OSL-depth profile of the known-age sample is modeled to estimate material-dependent and environmental parameters. These parameters are then used to fit the model to the corresponding data for the samples of unknown exposure history. From these fits we calculate that the buried sample was light exposed for ∼700 years before burial and that the unburied sample has been exposed for ∼120 years. The shielded surface of the buried talus sample is decorated with rock art; this rock fell from the adjacent Great Gallery panel. Related research using conventional OSL dating suggests that this rockfall event occurred ∼900 years ago, and so we deduce that the rock art must have been created between ∼1600 and 900 years ago. Our results are the first credible estimates of exposure ages based on luminescence bleaching profiles. The strength of this novel OSL method is its ability to establish both ongoing and prior exposure times, at decadal to millennial timescales or perhaps longer (depending on the environmental dose rate) even for material subsequently buried. This has considerable potential in many archeological, geological and geo-hazard applications.

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1. Introduction

[2] Cosmogenic nuclide (CN) and optically stimulated luminescence (OSL) dating are two well-established complimentary methods in Quaternary dating; they can be used to determine the age of different geological and archeological features. In general CN dating estimates the length of time that a rock has been exposed at or near the earth's surface, while OSL dating is used to determine the time elapsed since sedimentary grains were last exposed to daylight (i.e., the burial age). However, there is at least one other way in which luminescence signal can be used to give chronological information: *Polikreti et al.* [2002, 2003] suggested the possibility of using luminescence to estimate the length of time a rock surface was exposed to daylight. While looking for a method to determine the authenticity of marble artifacts of disputed age, they investigated the daylight bleaching of the thermoluminescence (TL) signal with depth in several samples and proposed a model to describe the dependence of TL intensity with depth on exposure time and depth; unfortunately they were unable to quantify this exposure time reliably. In general OSL signals bleach faster than TL signals (because they are, by definition, light sensitive) and, in contrast to OSL, TL signals have some significant unbleachable component. Thus daylight bleaching of the OSL signal will penetrate further into a rock surface than the corresponding TL bleaching process, and the residual surface signal will be

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[1] Nordic Laboratory for Luminescence Dating, Department of Geoscience, Aarhus University, Aarhus, Denmark.

[2] Center for Nuclear Technologies, Technical University of Denmark, Roskilde, Denmark.

[3] Department of Geology, Utah State University, Logan, Utah, USA.

[4] Now at Institute of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, UK.

Corresponding author: R. Sohbati, Nordic Laboratory for Luminescence Dating, Department of Geoscience, Aarhus University, DTU Risø Campus, DK-4000 Aarhus, Denmark. (resih@dtu.dk)

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very much smaller. These characteristics make it likely that OSL is a more suitable signal for luminescence exposure dating than TL. Here we show that OSL can be used quantitatively to estimate the exposure time of a rock surface. Based on this we are able to constrain the age of an example of Native American rock art from the Canyonlands National Park, Utah, USA.

[3] Luminescence is the light emitted from many crystalline materials during heating (TL) or optical stimulation (OSL); it arises from the release of stored energy accumulated, in the form of trapped charge, through the action of ionizing radiation. In luminescence measurements, this heating or optical stimulation is carried out under controlled laboratory condition so that the emitted light can be measured. In solid rock, the latent luminescence has accumulated in response to the amount of natural ionizing radiation (mainly from radioactive isotopes in the ^{232}Th, ^{238}U series and ^{40}K) absorbed since rock formation. Heating or exposure to daylight, removes the latent luminescence acquired previously in a so-called bleaching or resetting process. In a rock surface continuously exposed to daylight, this resetting will penetrate deeper into the surface with time.

[4] *Sohbati et al.* [2011] studied the depth dependence of the bleaching of the infrared stimulated luminescence (IRSL) signal from granitic rocks. Using some simplifying assumptions, they presented a model of this dependence and showed it to be a good descriptor of the remaining luminescence in their naturally exposed samples. However, they were unable to determine realistic estimates of some of the parameters in the model from first principles, and they did not have any sample of known exposure history with which to calibrate their model.

[5] In this study, we investigate the applicability of this model of light penetration and the resulting resetting of the luminescence signal with depth and time using the natural OSL signal from quartz grains. Our results are used to constrain the age of the archeologically significant Barrier Canyon Style (BCS) rock art. Three bedrock samples of Jurassic Navajo Sandstone were collected from our study locality in Canyonlands National Park. The first sample was initially exposed during road cutting 80 years ago and was still exposed at the time of sampling. The luminescence from quartz grains extracted from this sample was measured as a function of depth from the exposed surface. The resulting luminescence profile from the known-age sample was modeled to estimate the time and spectrum-averaged product of the regional daylight flux and photoionisation cross section. The other two samples are from talus of unknown daylight exposure histories; one of these samples was exposed at the time of sampling and one was buried, and no longer light exposed. The parameters derived using the first (known-age) sample are used to fit the light exposure model to the OSL-depth data for the samples of unknown exposure history. From these fits we calculate exposure ages.

[6] This approach provides, for the first time, credible estimates of exposure times based on luminescence, of both an ongoing exposure and a "fossil" exposure episode.

2. Bleaching With Depth Model

[7] In related work we have shown that, following the suggestion of *Polikreti et al.* [2002, 2003], a double exponential function of exposure time and depth can be used to describe the penetration of light in naturally exposed granite cobbles [*Sohbati et al.*, 2011]. The simplified form of this function is:

$$L = L_0 e^{-\overline{\sigma\varphi_0} t e^{-\mu x}} \tag{1}$$

where L_0 is the maximum luminescence signal intensity at saturation (assumed to be constant at all depths prior to bleaching), L is the luminescence remaining at depth x (mm) after an exposure time t (s), σ (cm^2) is the photoionisation cross section and φ_0 (cm^{-2} s^{-1}) is the photon flux at the surface of the rock ($\overline{\sigma\varphi_0}$ (s^{-1}) is thus the effective decay rate of the luminescence at the rock surface when it is exposed to a particular daylight spectrum) and μ (mm^{-1}) is the attenuation coefficient as the light penetrates the rock. This model makes the simplifying assumption that the daylight spectrum does not change shape significantly with depth into the rock; as a result, the attenuation factor μ can be treated as a constant. This assumption is discussed further in section 7.

[8] When a rock surface is first exposed to daylight the charge population (and so the latent luminescence signal) trapped in its constituent minerals (e.g., quartz and feldspar) starts to decrease. This charge had accumulated due to previous exposure to natural ionizing radiation. The saturation level of a luminescence dose-response curve for quartz is typically less than 200 Gy [*Wintle and Murray*, 2006], which means for typical quartz dose rates of 1 to 1.5 Gy ka^{-1} it will take 100–200 ka to reach saturation. Thus it is very likely that in most bedrock samples the radiation exposure time was sufficient for the trapped charge population to saturate. According to equation (1), as the surface is exposed to light for longer periods, the latent luminescence signal is reduced farther into the rock. This means that in a sample which has been exposed to light for a prolonged period (decades to millennia), the remaining luminescence will be zero (fully bleached) at the surface and then increase, initially exponentially, before approaching saturation at a depth where charge detrapping due to light penetration is negligible compared to the rate of charge trapping due to the environmental dose rate [*Polikreti et al.*, 2002; *Laskaris and Liritzis*, 2011; *Sohbati et al.*, 2011, 2012]. This depth depends on the opacity of the rock and the daylight spectrum, which is a function of the geographical coordinates, weather condition and local shadowing effects. However, several authors have shown that a few minutes [*Habermann et al.*, 2000] to a few hours [*Vafiadou et al.*, 2007; *Sohbati et al.*, 2011] of daylight exposure is enough to bleach the outer 2 mm surface of granitic rocks. Figure 1 illustrates the evolution of such residual luminescence curves with exposure time.

[9] *Sohbati et al.* [2012] further developed this model by including an environmental dose rate term and demonstrated its applicability to the OSL signals from quartzite cobbles. This allowed them to detect two exposure events prior to two burial periods in the history of a single cobble [*Sohbati et al.*, 2012]. However, an accurate estimation of exposure time

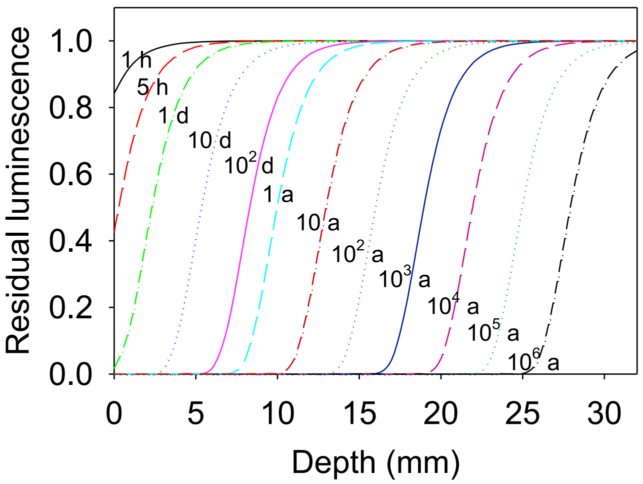

Figure 1. Profile of residual luminescence in a rock after a given exposure time, as predicted by the model. The longer the exposure time, the farther into the rock is the luminescence signal reset. These curves are based on parameters reported for granitic rocks from Denmark by *Sohbati et al.* [2011].

was again impossible because of the difficulty of calculating the spectrum-weighted photoionisation cross section σ (cm^2) as a function of depth. In the present study we have chosen the alternative approach, of measuring the term $\overline{\sigma\varphi_0}$ appropriate to the site and host rock type by fitting equation (1) to data from a road-cut sample (HS-OSL-29) using the known exposure time, *t*, of 80 years.

3. Site Description, Sample Selection and Preparation

[10] Our study site lies within the Horseshoe Canyon Unit of Canyonlands National Park in Utah. The locality is known for its narrow slot canyons formed in the Navajo Sandstone; alcoves in these canyons contain ancient rock art. At our site a series of preserved fluvial terraces and other geomorphic relations constrain the burial and exposure of an alcove that hosts the Great Gallery, the type locality for BCS rock art [*Jackson*, 2010]. The age of the BCS rock art in the Great Gallery is controversial despite attempts to directly date it using radiocarbon [e.g., *Watchman*, 2003; *Tipps*, 1994; *Manning*, 1990; *Schaafsma*, 1971]. Proposed ages range from ~8000 years [*Coulam and Schroedl*, 1996] to as young as 400 years [*Manning*, 1990]. An OSL age of ~900 years has been determined recently for a rockfall event that removed some of the rock art, providing a minimum age [*Chapot et al.*, 2012]. The Navajo Sandstone itself is a well sorted, very fine- to fine-grained rock that is only moderately cemented with calcite, trace silica and interstitial clay. It is a feldspathic quartz arenite interpreted as having been deposited almost entirely by aeolian processes [*Sanderson*, 1974; *Huntoon et al.*, 1982].

[11] As a part of an investigation into the age of the Great Gallery rock art, *Chapot et al.* [2012] collected two rock samples for OSL dating; both of these samples are used in this study. One sample (HS-OSL-25) was taken from the buried surface of a pigmented talus boulder that had previously been exposed to light as a part of the alcove panel. The second sample (HS-OSL-28) was a clast collected ~4 m away in essentially the same landscape position within the alcove, but from another fallen boulder in an eroded slope of latest Pleistocene-Holocene deposits; this clast was presumed to have been exposed to light for a significant number of years [*Chapot et al.*, 2012]. This neighboring clast was used as a modern bleached analogue of the buried surface of sample HS-OSL-25 before it fell from the canyon wall and was shielded. Analysis of the outer 1 mm of this modern analogue sample determined that it had been exposed long enough for its residual luminescence signal to be reduced to negligible levels [*Chapot et al.*, 2012]. By assuming that the same bleaching applied to sample HS-OSL-25 from the pigmented talus block before it fell, an age of ~900 years was derived for the rockfall event by convntional OSL dating of the quartz grains extracted from the outer 1 mm surface of the buried boulder [*Chapot et al.*, 2012]. However, no information on the daylight exposure history of these samples is available. Our goal is to estimate how long the exhumed modern analogue sample has been exposed to daylight, and especially how long the buried sample with rock art had been exposed to light on the rock wall prior to collapse and burial. In this latter case, by estimating its prior duration of exposure, we gain an estimate of when the rock surface first became available to the prehistoric artist. This is a valuable maximum-age constraint on the rock art.

[12] Key to estimating these exposure durations is the calibration of our model through the use of a sample of the same bedrock with a known exposure history. Sample HS-OSL-29 was collected from Navajo Sandstone that was first exposed to daylight when a narrow oil-exploration road into Horseshoe Canyon was cut in the winter of 1929/1930 ~2 km from the Great Gallery alcove (ranger Gary Cox, personal communication, 2011). All three samples were in positions with east-facing exposure, and we assume that all were exposed to a similar light spectrum and flux. A summary of samples is given in Table 1.

[13] The Navajo Sandstone is very friable, so care was needed to obtain grains from a known depth from the surface. The rock fragments (about 3 cm × 3 cm × 2 cm) were first secured in a block of Plaster of Paris with the original rock surface exposed at the surface of the plaster. This surface was then lightly abraded in 1 mm increments up to a depth of 12 mm (12 subsamples) using a medium coarse (#100) carbide paper (carbide grains were analyzed

Table 1. Summary of the Samples

Sample Name	Description
HS-OSL-25	Buried surface of a pigmented talus boulder that had previously been exposed as a part of the Great Gallery alcove panel
HS-OSL-28	Exposed surface of a boulder on an eroded slope of latest Pleistocene-Holocene deposits within the alcove
HS-OSL-29	Exposed surface of a rock wall at the side of a road-cut in the winter of 1929/1930, 2 km from the Great Gallery alcove

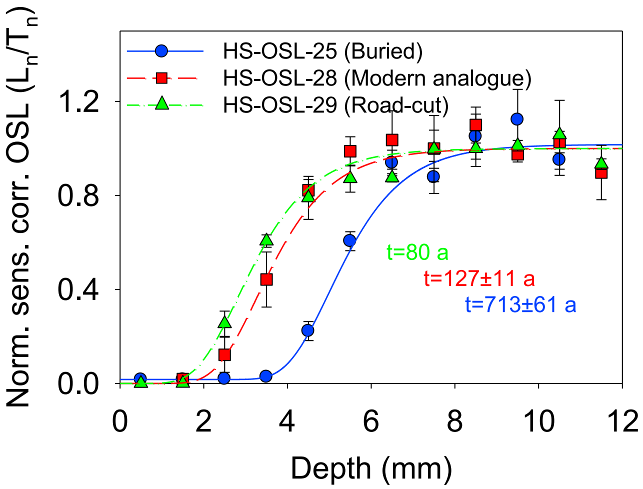

Figure 2. Bleaching with depth model fitted to data points of three samples with different exposure histories. Each data point is an average of at least three aliquots. Error bars represent one standard error. The curves are best fit model calculations assuming common values of $\overline{\sigma\varphi_0}$ and μ for all three samples.

separately and no detectable luminescence sensitivity was observed). The abraded grains of all subsamples were then treated with 30% HCl to dissolve plaster and carbonate, before etching in concentrated (40%) HF for 60 min and a final treatment with 10% HCl for 40 min to remove any precipitated fluorides. The etched grains were then dry sieved to 63–150 μm.

4. Instrumentation

[14] All measurements were made using a Risø TL/OSL reader (model TL-DA 20) with blue light stimulation (λ = 470 nm, ~80 mW cm^{-2}) and photon detection in the UV through a 7.5 mm Hoya U-340 glass filter. Beta irradiations used a ^{90}Sr/^{90}Y calibrated source mounted on the reader [*Bøtter-Jensen et al.*, 2010]. Grains were mounted as large (8 mm diameter) aliquots in a monolayer using silicone oil on 10 mm diameter stainless steel discs. The heating rate was 5°C s^{-1} throughout. All thermal treatments and stimulations at temperatures higher than 200°C were carried out in nitrogen atmosphere and a pause of 10 s was inserted before stimulation to allow all grains to reach the measurement temperature.

5. Measurements and Data Analysis

[15] Feldspar contamination of the OSL signal in the samples was examined using an IR depletion ratio test [*Duller*, 2003]. For a total of 18 aliquots from all the samples described above the average IR depletion ratio was 0.956 ± 0.005 (n = 18). We conclude that the contribution from feldspar to our fast-component quartz OSL signal is negligible. In all three samples, sufficient grains were recovered to make at least three aliquots from each of the 1 mm depth increments, to a depth of >10 mm. For each aliquot, the natural OSL signal (L_n) and the subsequent response (T_n) to a test dose were measured in the first cycle of a single aliquot regenerative (SAR) protocol [*Murray and Wintle*, 2000]. A preheat temperature of 200°C for 10 s and a cut-heat of 180°C were applied prior to natural and test dose measurements, respectively. Optical stimulation was carried out at 125°C for 40 s using blue light. A high temperature blue light stimulation at 280°C was also applied at the end of each SAR cycle to reduce recuperation [*Murray and Wintle*, 2003] (but note that only one cycle was needed for the data of Figures 2 and 3). The test dose was kept constant for all aliquots from a given profile, but varied between 4.5 and 12 Gy from one profile to another. All the signals were dominated by the quartz fast component [*Jain et al.*, 2003; *Singarayer and Bailey*, 2004]. Nevertheless, to minimize any contribution from the more difficult to bleach and more thermally unstable medium and slow components [*Li and Li*, 2006; *Pawley et al.*, 2010], the initial 0.8 s (the first 5 channels) of the signal minus a background integrated over 1.6 s (channels 16–25) was used for calculations. Details on the choice and testing of measurement criteria and the performance of SAR using this material can be found in *Chapot et al.* [2012]; here it is sufficient to point out the observed measured to given dose ratio (the dose recovery ratio) was 1.00 ± 0.03 (n = 12) indicating that our chosen protocol is able to measure a known dose given to a fully bleached sample prior to a typical laboratory thermal treatment in the temperature range of 160 to 260°C. In our case we do not measure dose, but nevertheless this observation serves to confirm that the test dose signal measured after the natural signal is successfully correcting for any sensitivity change that may occur in the first measurement.

[16] If a sample has been exposed for a prolonged period, the luminescence signal should be negligible at the exposed surface. However, *Chapot et al.* [2012] reported a small residual signal at the surface of the modern analogue sample (HS-OSL-28). They showed that this signal arose because of thermal transfer, and thus should be subtracted from the natural signal. Taking this into account, the residual signals were measured following *Chapot et al.* [2012] and

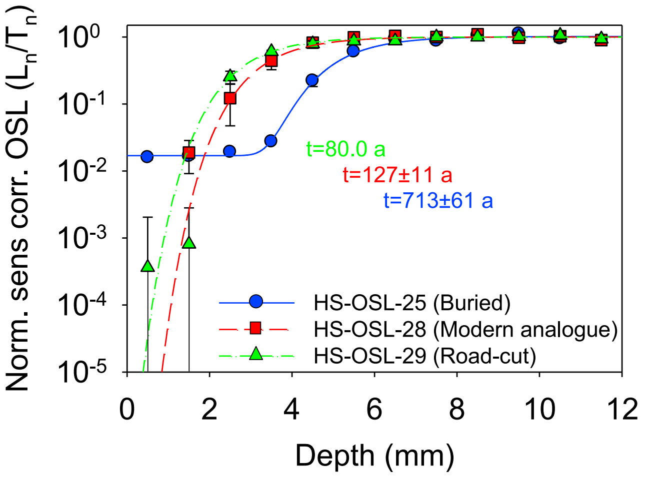

Figure 3. The same data as presented in Figure 2, but with L_n/T_n axis on a logarithmic scale. The finite signal built up in sample HS-OSL-25 during burial can be clearly seen.

subtracted from the sensitivity-corrected natural signals at all depths for each of the three samples. The resulting values were then normalized to the saturation level found deep within the clast, using the average light level found in the deepest four 1 mm subsamples (8.5–11.5 mm) as the saturating level.

6. Results

[17] Figure 2 shows the sensitivity-corrected natural OSL signals (L_n/T_n) (after thermal transfer subtraction and normalization to the signal in saturation) plotted against depth for all samples. The grains are derived from 1 mm thick layers, and the depth of the mid-point of each layer is assumed to apply to all the grains from that layer. The measurements were carried out on multigrain aliquots, and so the measured OSL signal represents the average residual luminescence at a particular depth. All the data points follow the general trends expected from the model (compare with Figure 1). In the modern analogue (HS-OSL-28) and road-cut (HS-OSL-29) samples exposed to light at the time of sampling, the luminescence signal is, as expected, negligible at the surface; it then increases smoothly with depth until it saturates at a depth of ~7 mm. A similar trend is observed for the buried sample (HS-OSL-25). However, unlike the exposed samples, it has a finite signal near the surface which remains almost constant to a depth of ~3 mm and then starts to increase with depth until it saturates at a depth of ~8 mm. This is more clearly illustrated when the same data are presented on a logarithmic scale (Figure 3). This near-surface signal has built up in the sample as a result of exposure to natural radiation during burial after the rockfall event. Since it remains constant to a greater depth into the rock than in the exposed samples, we deduce that, before burial, the buried rock face was exposed to daylight for a longer period than the currently exposed samples.

6.1. Model Fitting

[18] By quantifying the length of time this sample was exposed on the canyon wall, we hope to add a maximum age constraint to the BCS rock art. To this end, equation (1) was first fitted to the road-cut sample (HS-OSL-29; of known 80 year exposure time) to acquire the best estimate of the effective bleaching rate at the surface, $\overline{\sigma\varphi_0}$. This fitting gives a value of $6.8(\pm 0.6) \times 10^{-9}$ s^{-1} for $\overline{\sigma\varphi_0}$. It was then assumed that: (i) the effective photoionisation cross section, σ, and the light attenuation coefficient, μ, are the same for all samples, and (ii) the daylight flux at the earth's surface φ_0 is regionally uniform, and is thus similar at the two sampling locations (although it is possible that local shadowing effects will alter the spectral shape somewhat). Nevertheless, the road-cut fitted value of $\overline{\sigma\varphi_0}$ is assumed to apply to all three samples.

[19] Since all three samples are assumed to have the same light attenuation characteristics, the best estimate of the light attenuation coefficient μ should be obtained by fitting all three data sets simultaneously. To allow this, the buried data set must be modified to remove the signal acquired during burial (because equation (1) forces the light signal to zero at the surface). This was achieved simply by subtracting the average constant surface signal (average of the three values from the surface 3 mm) accumulated during burial from all the other points in this profile. This distorts the shape of the profile very slightly, but the effect is well within the uncertainties of the individual data points at depths >4 mm. Then all three data sets were fitted simultaneously with μ as a shared parameter to give 1.01 ± 0.02 (mm^{-1}) as the best estimate for the light attenuation coefficient, μ. The results of this fitting process are shown for the road-cut sample HS-OSL-29 and the modern analogue sample HS-OSL-28 in Figures 2 and 3 as a dash-dot line passing through the triangles (road-cut) and as a dashed line through the squares (modern analogue); it can be seen that the model represents these observations well.

[20] Equation (1) was then modified by adding a constant C to represent the extra luminescence signal resulting from the burial dose, and the original data of sample HS-OSL-25 were fitted with $\overline{\sigma\varphi_0}$ and μ as fixed parameters. This fit is also shown in Figures 2 and 3, as a solid line passing through the circles (buried sample); again the model provides a good representation of the observations. The estimated exposure times, t, are also derived from the fitting process: the modern analogue HS-OSL-28 appears to have been exposed to daylight for ~125 years, whereas the buried rock art sample HS-OSL-25 was exposed for ~700 years before it detached from the cliff face during a rockfall event and was buried.

7. Parameter Sensitivity

[21] It is interesting to investigate whether the parameter values $\overline{\sigma\varphi_0}$ and μ obtained by fitting the model to the known-age road-cut sample are significantly different from the values that can be calculated from first principles. To quantify the value of $\overline{\sigma\varphi_0}$, *Sohbati et al.* [2011] approximated the dependence of photoionisation cross section on wavelength $\sigma(\lambda)$ by extrapolating the data of *Spooner* [1994a] for feldspar to the values up to 10 μm. They also normalized the blackbody spectrum to the annual average amount of solar energy received at the earth's surface in their study region to give the wavelength dependent flux of photons at the earth's surface $\varphi(\lambda, 0)$. Knowing the values of $\sigma(\lambda)$ and $\varphi(\lambda, 0)$, they summed the product over the wavelength range of 300 nm to 10 μm, at intervals of 5 nm, to estimate their $\overline{\sigma\varphi_0}$. However, the exposure time they obtained from their fitting using this estimate was much shorter than what they expected for their samples. Although the exclusion of visible light from the integration wavelength range lengthened the exposure time to some extent, it remained substantially too short.

[22] Following a similar approach, we modified the photoionisation cross section dependence on wavelength to that for quartz (the target mineral in this study) using the data provided by *Spooner* [1994b], and adjusted the photon flux dependence on wavelength to that for the study region (Southwestern Utah) (NASA surface metrology and solar energy. http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi). This calculation gave estimated values for $\overline{\sigma\varphi_0}$ of the order of 10^{-1} and 10^{-6} s^{-1} for the wavelength ranges of 300 nm − 10 μm and 700 nm − 10 μm, respectively. These values are orders of magnitude larger that the value of $\sim 7 \times 10^{-9}$ s^{-1} obtained from the model fit to the known-age road-cut sample.

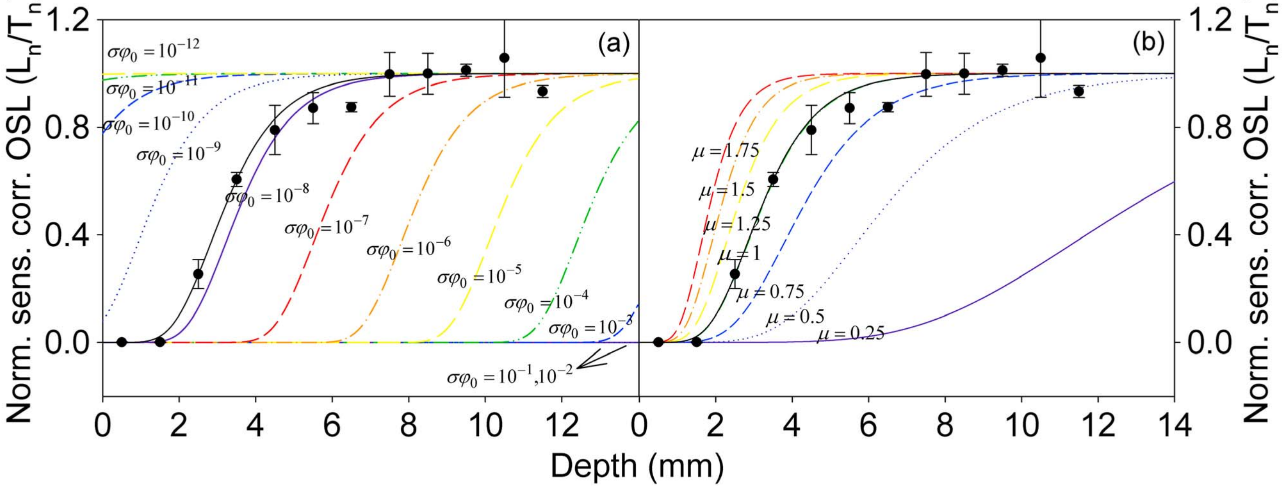

Figure 4. Dependence of the model on the involved parameters (a) $\overline{\sigma\varphi_0}$ and (b) μ. The OSL-depth curves vary significantly with the parameter values. The experimental data measured from the known-age road-cut sample are shown as filled circles for comparison.

[23] Figure 4a shows the dependency of the shape of the OSL-depth curves on the chosen value of $\overline{\sigma\varphi_0}$. It is clear that $\overline{\sigma\varphi_0}$ values of the order of 10^{-1} to 10^{-6} s^{-1} (as derived above) result in curves very different from the measured profile of the road-cut sample. Since the values of σ were based on direct measurements by *Spooner* [1994b] (although with considerable extrapolation), and the incident solar spectrum φ_0 is well known, this discrepancy suggests that the bleaching of the quartz OSL signal with depth into this sandstone must be the result of exposure to much longer wavelengths than those dominating the full solar spectrum. Presumably the effective spectrum lies >700 nm (calculated $\overline{\sigma\varphi_0} < 10^{-6}$ s^{-1}); shorter wavelengths must be completely absorbed very close to the surface of the rock.

[24] Figure 4b presents the dependency of the shape of the OSL-depth curves on the chosen value of the light attenuation parameter μ. All three curves in Figures 2 and 3 were fitted using the same value of μ, although the sensitivity analysis of Figure 4b shows that small deviations in this value produce fits inconsistent with the experimental data from the known-age sample (circles). We thus deduce that it is very likely that the attenuation characteristics of the three rock samples are indeed very similar (as expected).

8. Discussion

[25] The C value of 0.017 ± 0.001 obtained from the fitting to the rock art sample HS-OSL-25 provides an estimate of the luminescence signal built up in the sample during burial, and thus should provide an estimate of the dose accumulated in the surface grains during burial. To calibrate this signal in terms of dose, the value of C was projected onto a typical dose-response curve from a multiple-grain aliquot of quartz to give an equivalent dose of 1.45 Gy. This is indistinguishable from the burial dose of 1.42 ± 0.07 Gy (corresponding to an age of 760 ± 50 years) obtained using dose-response curves from surface grains extracted from this sample [*Chapot et al.*, 2012].

[26] Any exfoliation of the rock surface and removal of bleached grains from the surface due to weathering and erosion moves the bleaching profile closer to the surface. This means that, in principle, equation (1) estimates a minimum exposure. However, the presence of pigment (<1 mm thick) on the surface immediately adjacent to the sample from the rock art block and varnish (<1 mm thick) on the road-cut sample assure us that exfoliation is not significant, at least for these two samples.

[27] Unfortunately there is no independent age control available to test the reliability of this new method in this study. However, given the textural (grain size and color) similarity of the samples and the conclusion above, that we would be sensitive to any changes in μ from sample to sample, it seems obvious, even without model analysis, that the road-cut and modern analogue have been exposed for similar lengths of time, and that the buried sample must have been exposed for much longer. Clearly it would have been desirable to have had more than one known-age sample for comparison, but nevertheless we think it is very clear that there is a chronological signal recorded in these luminescence profiles, and our quantitative analysis confirms this.

9. Conclusions

[28] This novel OSL application in surface exposure dating is in many ways attractive compared to the more time-consuming and capital-intensive cosmogenic radionuclide dating method, especially for dating events up to few thousand years old. The OSL method can also be used to establish exposure times for buried material, for which the cosmic ray exposure is poorly defined, and it is less sensitive to prior exposure because this can be detected in distortion of the OSL-depth profile, and modeled [*Sohbati et al.*, 2012]. On the other hand, it is likely that some local calibration sample will be necessary to provide an absolute OSL chronology; it is not clear to us that it is practical to derive, from first principles, the site and sample specific estimate of $\overline{\sigma\varphi_0}$ required to provide an exposure age. Such a calibration can

be derived from a local rock of known exposure history, as in the present study, or it may be possible to find samples where one surface was buried at the same time as the opposite surface was exposed. Then conventional OSL dating of the underlying sediment and/or the buried rock face will give an independent age for the exposure event. It may also be possible to derive such a calibration in the laboratory using an appropriate unexposed sample and analogous bleaching conditions. Even in the absence of a calibration bleaching curve, the method can still be used to estimate relative exposure chronologies for similar rock types.

[29] By using a sample of known exposure age, we have been able to quantitatively analyze the way in which the remaining luminescence signal increases with depth into a rock, the surface of which had been previously exposed to daylight. It is particularly exciting that this was possible even using a surface which had been buried for almost 1000 years. As a result of the dating of the rockfall event, we know that the Great Gallery rock art must have been created sometime before 0.8 ka (A.D. 1200) [*Chapot et al.*, 2012]. In terms of constraining the age of the BCS rock art, our exposure age for the buried pigmented boulder, taken together with our estimate of the rockfall/burial age [*Chapot et al.*, 2012] indicates that at least one example of the BCS rock art at the Great Gallery must have been created some time between 900 and 1600 years ago (A.D. $\sim$400 to 1100) during which time the surface of the boulder was part of the cliff-face on the canyon wall. This is the first time that a specific age window has been constrained for the creation of the Great Gallery rock art.

[30] The OSL surface exposure dating method developed here can be used to establish prior exposure times even for subsequently buried material, because any inheritance effects from multiple phases of exposure and burial can be detected in a distortion of the OSL-depth profile, and modeled. The age range of the method is likely to be at least many thousands of years for a continuously exposed surface, although it is more difficult to predict the range and sensitivity for surfaces that have experienced multiple exposure/burial events. We conclude that this method has considerable potential in dating many archeological and geological events such as the construction of megaliths, agricultural land clearance and enclosure, glacial advances and retreats, phases of erosion, and geological processes and hazards such as mass-wasting and fault scarp movement.

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References

Bøtter-Jensen, L., K. J. Thomsen, and M. Jain (2010), Review of optically stimulated luminescence (OSL) instrumental developments for retrospective dosimetry, *Radiat. Meas.*, *45*, 253–257, doi:10.1016/j.radmeas.2009.11.030.

Chapot, M. S., R. Sohbati, A. S. Murray, J. Pederson, and T. Rittenour (2012), Constraining the age of rock art by dating a rock-fall event using single-grain and surface dating luminescence techniques, *Quat. Geochronol.*, doi:10.1016/j.quageo.2012.08.005, in press.

Coulam, N. J., and A. R. Schroedl (1996), Early archaic clay figurines from Cowboy and Walters caves in southeastern Utah, *Kiva*, *61*, 401–412.

Duller, G. A. T. (2003), Distinguishing quartz and feldspar in single grain luminescence measurements, *Radiat. Meas.*, *37*, 161–165, doi:10.1016/S1350-4487(02)00170-1.

Habermann, J., T. Schilles, R. Kalchgruber, and G. A. Wagner (2000), Steps towards surface dating using luminescence, *Radiat. Meas.*, *32*, 847–851, doi:10.1016/S1350-4487(00)00066-4.

Huntoon, P. W., G. G. Billingsley, and W. J. Breed (1982), Geologic map of Canyonlands National Park and vicinity, Utah, Canyonlands Natl. Hist. Assoc., Moab, Utah.

Jackson, M. S. (2010), Bracketing the age of the Great Gallery rock art panel in Horseshoe Canyon, Utah by OSL dating of associated alluvial terraces, undergraduate honors thesis, 53 pp., Utah State Univ., Logan.

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

Laskaris, N., and I. Liritzis (2011), A new mathematical approximation of daylight attenuation in rocks for surface luminescence dating, *J. Lumin.*, *131*, 1874–1884, doi:10.1016/j.jlumin.2011.04.052.

Li, B., and S.-H. Li (2006), Comparison of D_e estimates using the fast component and the medium component of quartz OSL, *Radiat. Meas.*, *41*, 125–136, doi:10.1016/j.radmeas.2005.06.037.

Manning, S. J. (1990), Barrier Canyon Style pictographs of the Colorado Plateau. Part one: Hypothesis and evidence for the existence of post circa A.D. 1300 Panels, *Utah Archaeol.*, *3*(1), 43–84.

Murray, A. S., and A. G. Wintle (2000), Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol, *Radiat. Meas.*, *32*, 57–73, doi:10.1016/S1350-4487(99)00253-X.

Murray, A. S., and A. G. Wintle (2003), The single aliquot regenerative dose protocol: Potential for improvements in reliability, *Radiat. Meas.*, *37*, 377–381, doi:10.1016/S1350-4487(03)00053-2.

Pawley, S. M., P. Toms, S. J. Armitage, and J. Rose (2010), Quartz luminescence dating of Anglian Stage (MIS 12) fluvial sediments: Comparison of SAR age estimates to the terrace chronology of the Middle Thames valley, UK, *Quat. Geochronol.*, *5*, 569–582, doi:10.1016/j.quageo.2009.09.013.

Polikreti, K., C. T. Michael, and Y. Maniatis (2002), Authenticating marble sculpture with thermoluminescence, *Ancient TL*, *20*, 11–18.

Polikreti, K., C. T. Michael, and Y. Maniatis (2003), Thermoluminescence characteristics of marble and dating of freshly excavated marble objects, *Radiat. Meas.*, *37*, 87–94, doi:10.1016/S1350-4487(02)00088-4.

Sanderson, I. D. (1974), Sedimentary structures and their environmental significance in the Navajo Sandstone, San Rafael Swell, Utah, *Brigham Young Univ. Geol. Stud., Part 1*, *21*, 215–245.

Schaafsma, P. (1971), *The Rock Art of Utah: A Study From the Donald Scott Collection*, Harvard Univ., Cambridge, Mass.

Singarayer, J. S., and R. M. Bailey (2004), Component-resolved bleaching spectra of quartz optically stimulated luminescence: Preliminary results and implications for dating, *Radiat. Measure.*, *38*, 111–118.

Sohbati, R., A. S. Murray, M. Jain, J.-P. Buylaert, and K. J. Thomsen (2011), Investigating the resetting of OSL signals in rock surfaces, *Geochronometria*, *38*, 249–258, doi:10.2478/s13386-011-0029-2.

Sohbati, R., A. S. Murray, J.-P. Buylaert, N. A. C. Almeida, and P. P. Cunha (2012), Optically stimulated luminescence (OSL) dating of quartzite cobbles from the Tapada do Montinho archaeological site (east-central Portugal), *Boreas*, *41*, 452–462, doi:10.1111/j.1502-3885.2012.00249.x.

Spooner, N. A. (1994a), The anomalous fading of infrared-stimulated luminescence from feldspars, *Radiat. Meas.*, *23*, 625–632, doi:10.1016/1350-4487(94)90111-2.

Spooner, N. A. (1994b), On the optical dating signal from quartz, *Radiat. Meas.*, *23*, 593–600, doi:10.1016/1350-4487(94)90105-8.

Tipps, B. (1994), Barrier Canyon rock art dating, in *Canyonlands: The Archeology of Horseshoe Canyon*, pp. 35–46, Canyonlands Natl. Park, Natl. Park Serv., Moab, Utah.

Vafiadou, A., A. S. Murray, and I. Liritzis (2007), Optically stimulated luminescence (OSL) dating investigations of rock and underlying soil from three case studies, *J. Archaeol. Sci.*, *34*(10), 1659–1669, doi:10.1016/j.jas.2006.12.004.

Watchman, A. (2003), Dating Barrier Canyon style rock art, Great Gallery, Horseshoe Canyon, Canyonlands National Park, report, 13 pp., Canyonlands Natl. Park, Natl. Park Serv., Moab, Utah.

Wintle, A. G., and A. S. Murray (2006), A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols, *Radiat. Measure.*, *41*, 369–391.