Constraining the age of rock art by dating a rockfall event using sediment and rock-surface luminescence dating techniques

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\section*{A R T I C L E  I N F O}

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\section*{A B S T R A C T}

Optically stimulated luminescence (OSL) is used to determine the age of a rockfall event that removed part of the pictograph figures at the Great Gallery rock art panel in Canyonlands National Park, Utah, USA. Analyses from the outer millimeter of the buried surface of a rockfall boulder and quartz grains from the underlying sediment both provide consistent ages that also agree with an AMS radiocarbon age of a cottonwood leaf found immediately between the clast and underlying sediment. Measurement of the OSL signals as a function of depth into the surface of the boulder clearly shows that there is no detectable increase in the OSL signal to a depth of at least 3 mm suggesting that the OSL signal was fully reset to this depth before burial. Consistent OSL and radiocarbon ages for this rockfall event provide a minimum age of ~900 a for the Great Gallery, which is the type locality of Barrier Canyon Style rock art with a controversial and unknown origin.

\section*{1. Introduction}

Rockfalls are one of the most common geomorphic processes in high relief regions, and they are a key part of the erosion and evolution of landscapes with escarpments and cliffs. Rockfalls are also a significant geohazard for people who live, travel, and work in very steep terrain (Chiessi et al., 2010; Lan et al., 2010; Santi et al., 2009). Additionally, some rockfalls have important crosscutting stratigraphic relations with culturally or geologically significant features. As with many geohazards, efforts have been undertaken to determine the frequencies and magnitudes of events as well as to establish correlations with major triggers such as climatic, topographic, biologic, and geologic factors (intense storms, earthquakes, etc.) (Chiessi et al., 2010; Perret et al., 2006; Schneuwly and Stoffel, 2008; Stoffel et al., 2005). Despite this, determination of the age and rates of rockfall events remains difficult due to complications in established chronologic methods.

Two of the most established rockfall dating techniques, dendrochronology and lichenometry, are indirect measurements requiring the presence of specific species of organisms (Lang et al., 1999). Dendrochronology is a useful method for dating rockfall events that occur in forested regions as it may be used to provide both spatial and temporal data (Perret et al., 2006; Schneuwly and Stoffel, 2008; Stoffel et al., 2005). However, this method is only applicable for rockfall events that have removed a portion of a forest stand or where sizeable rock fragments injure trees sufficiently to leave scars distinguishable from other growth disturbances (Stoffel and Perret, 2006). Lichenometric techniques are applicable only to certain species of lichens and are based on the relationship between lichen size and surface age in a specific environment; this relationship is dependent on climate conditions, lithology, and exposure (Bajgier-Kowalska, 2008; Winchester and Chaujar, 2002). In order to use lichenometry to date a rockfall, lichen must be present and the regional relationship between diameter size and surface age must be determined either by measurements of growth rate over several years or measuring lichens on surfaces of known age (Jomelli et al., 2007).

Cosmogenic exposure dating, on the other hand, is able to directly date the exposed surface of fallen boulders (Matmon et al., 2005) but is highly reliant upon assumptions of the exposure history of a sample (Heyman et al., 2011). For example, Matmon et al. (2005) discovered that cosmogenic nuclide production rates are sensitive to shielding and vary spatially over short distances. In order to compensate for this, Matmon et al. (2005) turned to external constraints from field relations and optically stimulated
luminescence (OSL) dating in order to reduce this variability and obtain ages in agreement with radiocarbon ages. While cosmogenic radiation is part of the environmental dose rate used in OSL dating, the amount of radiation from cosmogenic sources is small compared to the contribution of radioactive nuclides in the surrounding sediment, thereby reducing any errors due to variations in cosmogenic radiation calculations.

Here we introduce two different approaches to using OSL to date a rockfall event. These approaches are applicable to a broader set of environments than dendrochronology and lichenometry, and yet avoid many of the challenges of cosmogenic exposure dating. They can also be used to calibrate lichenometry in a given region so that it can be applied to dating other rock surfaces. In this study, these two approaches are applied to a rockfall event that removed parts of Barrier Canyon Style (BCS) rock art figures at the BCS type section, the Great Gallery, in southeastern Utah. This rock art style is indigenous to the central Colorado Plateau of the American Southwest and is characterized by elongate anthropomorphic figures with rounded, sloping torsos produced through a combination of wall preparation, rock pecking, and application of multiple pigments (Schaafsm, 1971; Tipps, 1994). The age of BCS art remains unknown and controversial despite attempts to radiocarbon date accessory brush fibers in the mineral-based pigment (Watchman, 2003) and stylistic comparisons to other rock art and figurines (Manning, 1990; Schaafsm, 1971; Tipps, 1994). Current hypotheses of the age of BCS rock art range from about 8000 a (Coulam and Schroedl, 1996) to as late as 400 a (Manning, 1990), Schaafsm (1971) observed that individual panels are relatively consistent in techniques and style suggesting that each was painted by a single individual. Therefore, by determining the age of a rockfall event associated with the destruction of a single figure, we provide a minimum age for the creation of the Great Gallery rock art panel and by extension, BCS rock art.

2. Luminescence background and approach

Optically stimulated luminescence provides a numerical age estimate of the last exposure to daylight of minerals such as quartz and feldspar. Upon burial, exposure to natural ambient radioactivity and, to a lesser degree, cosmogenic radiation (together making up the environmental dose rate) creates free charge in crystal lattices at a rate proportional to the energy absorbed from the radiation. Some of this charge then becomes trapped at crystal lattice defects of various energy levels. In the laboratory, charges trapped in these meta-stable energy level defects are released by light stimulation, enabling them to return to their original valence state by recombining at luminescence centres in the crystal lattice. Thus light stimulation produces a luminescence signal whose intensity is related to the number of trapped charges, and simultaneously empties the lattice defects, re-setting the luminescence signal. The total luminescence signal generated by the release of the trapped charge held in the naturally irradiated mineral grains and the laboratory radiation dose required to regenerate a luminescence signal of the same intensity (the equivalent dose) are measured in the laboratory. The time since last exposure to daylight of the mineral grains can then be calculated by dividing the equivalent dose by the environmental dose rate.

One approach to dating a rockfall using OSL is to analyze the top layer of sediment grains directly underlying a fallen rock, assuming that at least some of the grains in this surface layer would have been exposed to sufficient daylight to fully reset the trapped-charge population (Bush and Feathers, 2003) prior to being covered by the talus clast. Another approach is to date the shielded, basal surface of a talus clast itself. As with the dating of the underlying sediment, it must be shown that the rock surface was sufficiently exposed to light to remove any prior trapped-charge population, and so reset the latent luminescence signal to zero (Sohbati et al., 2011, 2012). This light exposure could have occurred either while the rock was part of the original cliff-face or during movement to the burial location; although the speed of rockfall events makes it less likely that the necessary light exposure could occur during transport. In this study, the presence of preserved pigment on the underside of a fallen talus boulder is one line of evidence that the buried rock surface was previously exposed on the canyon wall and therefore received prolonged light exposure, probably sufficient to remove the existing luminescence signal prior to the burial event.

OSL techniques have been developed predominantly for quartz and feldspar minerals, and so these should be the target minerals in any sampled rockfall talus. Sedimentary lithologies with ample quartz are likely to be especially suitable as research has shown quartz grains to be more sensitive to dose when they have experienced multiple cycles of burial and light exposure (e.g. Li, 2002; Pietsch et al., 2008; Preusser et al., 2006; Sawakuchi et al., 2011). Although feldspar analyses have been less commonly applied in dating studies due to anomalous fading of the luminescence signal, recent studies have reported methodologies that overcome this problem (Thiel et al., 2011; Thomsen et al., 2008; Buylaert et al., 2012). In addition to selecting a rock of suitable composition, samples should be taken from rocks that are unlikely to have moved since the event of interest so as to rule out multiple light exposures.

3. Site description and sampling methods

The Great Gallery rock art panel is located in an alcove cut into Jurassic Navajo sandstone (Huntoon et al., 1982) in the Horseshoe Canyon Unit of Canyonlands National Park, southeastern Utah (Fig. 1). Navajo sandstone is a well sorted, very fine to medium-grained, friable, and porous quartz sandstone that is sparsely cemented with calcite and very small amounts of iron oxide (Sanderson, 1974). It is interpreted as having been deposited largely by aeolian processes in an extensive dune field where water played a significant role in the development of sedimentary structures (Sanderson, 1974). A number of talus boulders from past rockfall events rest under the Great Gallery on a strath fluvial terrace with some of the boulders showing evidence of pigment from the overlying rock art (Fig. 2). The sediment underlying the rockfall boulders and atop the strath terrace may be of either alluvial or eolian origin and probably includes not only weathered Navajo material but also material weathered from the Kayenta formation fluvial sandstone which outcrops 1–2 km upstream from the Great Gallery; this formation is the substrate for most of the upper drainage of the canyon (Huntoon et al., 1982).

Samples were collected from a talus boulder with rock art pigment on its buried surface, lying at the immediate base of the rock art panel (Fig. 2). Although it cannot be determined whether the boulder was part of the most recent or oldest rockfall event at the site, the presence of pigment and its location clearly indicate that it was part of a rockfall event that damaged the rock art figure seen in Fig. 2, and therefore must have occurred after the creation of this figure. Sampling was undertaken during a moonless night with the aid of amber-filtered torches. The boulder was lifted and samples collected from both the down-facing, tabular side of the boulder and from the underlying sediment in contact with the rock face. When the boulder was lifted, buried leaves from the tree species dominating the surrounding canyon bottom (Populus fremontii) were discovered pressed against the rock face, and one leaf was analyzed with AMS radiocarbon analyses at Beta Analytic, Inc. (Beta #283086, see Table 3 below) to provide an independent age
control for the rockfall. A portable low-speed electric drill with a cutting blade and a chisel were used to take rectangular block samples of the boulder, and the sediment beneath the rock was carefully scraped from the underlying surface in as thin a layer as possible (<5 mm). The rock sample (HS-OSL-25) was collected from the deepest buried surface that had previously formed part of the cliff surface before the rockfall. The sediment sample (HS-OSL-23) was collected under the boulder in a location that showed no evidence of post-burial disturbance (Fig. 2). In addition, a modern analogue rock sample (HS-OSL-28) was collected to investigate the size of any residual dose (and so apparent residual age) in a rock surface currently exposed to daylight. Although this sample would ideally have been taken from the exposed canyon wall, this was not permitted by the park authorities because of archaeological sensitivity and the potential visibility of sampling scars to future park visitors. Therefore, a modern analogue sample was collected from the currently light-exposed surface of a boulder on an immediately adjacent, latest Pleistocene fill terrace of inter-fingered talus and alluvium. This terrace has been exhumed by recent erosion and lies at the same height within the alcove as the original position of the talus boulder sampled for HS-OSL-25 before the rockfall collapse (Fig. 2). The modern analogue therefore shares the same geometric situation in terms of shielding from sunlight in the canyon; it is also derived from the same bedrock exposure.

The likely amount of daylight exposure varies between the three samples. The rockfall boulder surface was likely exposed for a prolonged period (centuries to millennia) on the canyon wall prior to collapse, but the sediment surface of the strath terrace (preserved under the boulder) was exposed for an unknown but probably shorter period. In addition, the impact of the rockfall may have displaced some proportion of the light-exposed grains on the sediment surface, as the falling boulder imbedded itself in the terrace surface. Then even the grains immediately underlying the fallen boulder may not have received full daylight exposure. The modern analogue sample, although exposed in a similar position to that of the boulder when on the canyon wall, was likely exposed for a shorter duration and has a more complicated exposure history. Nevertheless, we expect it to have been exposed to full sunlight for decades if not centuries. We must also acknowledge that light

Fig. 1. A map of the western United States, showing the location of Horseshoe Canyon and its catchment with respect to the Green River.

Table 1
The single- aliquot regenerative dose (SAR) procedure for equivalent dose determination.

<table>
<thead>
<tr>
<th>Step</th>
<th>Sediment sample (HS-OSL-23)</th>
<th>Rock samples (HS-OSL-25, 28)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Give dose</td>
<td>240 °C for 10 s</td>
<td>200 °C for 10 s</td>
</tr>
<tr>
<td>2. Preheat</td>
<td></td>
<td>180 °C for 0 s</td>
</tr>
<tr>
<td>3. Measure OSL</td>
<td>1 s green laser at 125 °C</td>
<td>40 s blue light at 125 °C</td>
</tr>
<tr>
<td>4. Give test dose</td>
<td>12.2 Gy</td>
<td>4.5 Gy</td>
</tr>
<tr>
<td>5. Preheat</td>
<td>160 °C for 0 s</td>
<td></td>
</tr>
<tr>
<td>6. Measure OSL</td>
<td>1 s green laser at 125 °C</td>
<td>40 s blue light at 280 °C</td>
</tr>
<tr>
<td>7. Bleach</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Repeat steps 1–7 for a range of regeneration doses including a zero dose and a repeated regeneration dose.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
penetration into rock surfaces can be affected by weathering, desert varnish, and lichen growth; while penetration into sediment surfaces can be affected by bioturbation. In the case of our samples, the modern canyon wall near the rock art panel has little varnish or lichen growth but the canyon bottom does have plant and animal life that could have disturbed the sediment surface prior to burial. Based on these observations we anticipate that there may be some effect of sediment mixing and/or partial bleaching on the sediment sample, but that this is much less likely in the surface layers of the rock samples.

4. OSL sample preparation and measurement facilities

The sediment sample from under the talus boulder (HS-OSL-23) was prepared for analysis using standard methods for isolating quartz. The sample was wet-sieved to extract 63–150 μm grains and then treated with 10% HCl and sodium hypochlorite to remove carbonate and organic material. Heavy minerals were separated using a 2.7 g/cm² solution of sodium polytungstate. The sample was then given routine HF treatment involving 47% HF for three 30 min sessions in order to dissolve feldspars and remove the surface layer from quartz grains; thereby removing the part of the grain affected by alpha particle irradiation. After HF treatment, samples were treated with 37% HCl for 30 min to remove any fluorides and dry sieved to remove grains <63 μm.

The sandstone rock samples (HS-OSL-25 and HS-OSL-28) were extremely friable, and so care was needed to obtain grains from a known depth from the surface. The rock fragments were secured in a block of plaster with the original rock surface exposed at the surface of the plaster. This surface was then abraded in 1 mm increments using carborundum paper. The friability of the rock samples was such that the abrasion quickly overcame the weak cement and the sand grains were removed intact. To test whether the carborundum grains could contaminate our luminescence signals, grains from the carborundum paper were given a dose of 60 Gy and stimulated with blue LED stimulation (470 nm). No signal was detectable above background. All grains from rock samples were treated with 30% HCl for 24 h to dissolve plaster and carbonate mineral grains. They were then treated with 40% HF for 1 h and 10% HCl for 40 min, and finally the etched grains were dry sieved to 63–150 μm. The possibility of feldspar contamination was tested using a standard IR depletion ratio (Duller, 2003) in which the effect of prior infrared (IR) stimulation on the blue-stimulated signal from the sample is examined. For a total of 12 aliquots from the two rock samples described above the average IR depletion ratio was 0.95 ± 0.01 (n = 12), confirming that any feldspar contribution to the dose estimates from these samples is negligible.

Measurements were carried out using automated Risø TL/OSL-DA-20 readers. Sediment samples were analyzed using single grain discs and green laser (532 nm, 10 mW/cm²) stimulation from the Risø single grain attachment. However, due to the small grain size of the sample it may be that some holes contained more than one grain. Rock samples were mounted as large (8 mm) monolayer aliquots on 10 mm diameter stainless steel discs using silicone oil and were stimulated with blue LEDs (470 nm, 80 mW/cm²). All light stimulations were carried out after a pause of 5–10 s to allow the grains to reach the measurement temperature. Photon detection was through a 7.5 mm Hoya U-340 glass filter in all cases. Beta irradiations used calibrated 90Sr/90Y sources mounted on the readers. Further details on instrumentation can be found in Bøtter-Jensen et al. (2010). The first 0.8 s of the signal produced minus an early background (1.7–2.5 s) integration intervals were used for the multiple grain aliquots, while the first 0.08 s of the signal minus an early background (0.17–0.25 s) integration intervals were used for the single grain discs to isolate the fast component.

5. Determining measurement conditions

Dose measurements were carried out using a single aliquot regenerative (SAR) protocol based on the procedure of Murray and Wintle (2000, 2003). To determine the appropriate SAR thermal pretreatments, dose recovery pre-heat plateau tests were undertaken using samples HS-OSL-23 and HS-OSL-25 (Fig. 3a). These tests were performed on both samples as their grains have different sources and therefore may have different luminescence properties. The dose recovery test is usually considered the most sensitive laboratory test for the suitability of a SAR protocol. In this measurement a sample is exposed to light to remove any pre-existing light-sensitive trapped-charge population, and then given a known dose. This given dose is then recovered using the SAR protocol, and the ratio of the measured to given dose is calculated. If this ratio lies within some limits (usually ±10%) of unity then it is accepted that the measurement protocol is able to recover a known dose given to a sample before any heat treatment. The 24 aliquots of each sample were bleached twice for 100 s using blue LED light, with a pause of 3 h between light exposures to allow for any charge trapped in shallow refuge traps to return to the OSL trap. Sample HS-OSL-23 was given a dose of 22.1 Gy and HS-OSL-25 was given a dose of 4.5 Gy. The given doses were then measured using the SAR protocol. No significant difference (<10%) was observed up to a preheat temperature of 280 °C for HS-OSL-23 and
220 °C for HS-OSL-25 (Fig. 3). The average measured to given dose ratios up to these temperatures were 0.98 ± 0.05 (n = 18) and 1.00 ± 0.03 (n = 12) for HS-OSL-23 and HS-OSL-25 respectively, confirming that a known laboratory dose can be measured with an acceptable accuracy.

Thermal transfer tests were also undertaken for these samples to determine whether the increase in average measured to given dose ratios with temperature was due to thermal transfer. This test is identical to the dose recovery test described above, except that no initial dose is given, and so the measured dose should also be zero. Any detectable dose is attributed to thermal transfer. The results of this test show a clear trend of increasing thermal transfer with temperature for HS-OSL-25, whereas sample HS-OSL-23 has greater thermal transfer variability with little temperature dependence (Fig. 3b).

Based on these results, sediment and rock samples were analyzed with preheat temperatures of 240 °C and 200 °C (for 10 s), respectively (Table 1). At these temperatures, the samples had thermal transfer doses of 0.63 ± 0.10 Gy (n = 3) for the sediment sample and 0.25 ± 0.12 Gy (n = 3) for the rock samples. All light stimulations were performed at 125 °C. High-temperature blue-light stimulation at 280 °C was also applied at the end of each rock sample cycle to reduce recuperation (Murray and Wintle, 2003). The test dose varied between 4.5 and 12 Gy. All OSL signals were dominated by the fast component (Fig. 4); the early background subtraction employed in data reduction helps to isolate this signal. Recycling ratio and recuperation tests were carried out routinely to examine the reliability of the SAR protocol. Rejection criteria for large aliquot data included recycling ratios >10% from unity and recuperation >10% of the natural signal. For single grain disc measurements, rejection criteria were broadened to >20% from unity for the recycling ratio and a criterion that the test dose signal/noise ratio be >3σ was also applied.

6. Environmental dose rate

The radionuclide concentrations in samples HS-OSL-23 and HS-OSL-25 were measured using inductively coupled plasma atomic emission spectroscopy (ICP-AES), inductively coupled plasma mass spectrometry (ICP-MS), and high resolution gamma spectrometry (Table 2). For the ICP analyses, fractions of HS-OSL-23 and HS-OSL-25 were pulverized, homogenized and submitted to ALP Chemex for analysis using their ME-MS61 method. This method digests 0.25 g subsamples with perchloric, nitric, hydrofluoric and hydrochloric acids, tops up the residues with dilute hydrochloric acid and analyzes them with ICP-MS. The bulk concentration of K, Rb, U and Th measured during the ICP-MS were converted to gamma and beta dose rates using the conversion factors of Olley et al. (1996). For high resolution gamma spectrometry 250 g subsamples of HS-OSL-23 and HS-OSL-25 were pulverized, homogenized, and heated to 450 °C for 24 h to remove organic matter. The material was then cast in wax to prevent radon loss and to provide a reproducible counting geometry. Samples were stored for three

Fig. 3. a) Regenerative dose preheat-plateau/dose recovery plots for samples HS-OSL-23 and HS-OSL-25. The given dose for sample HS-OSL-23 was 22.1 Gy and the test dose preheat was maintained at 160 °C throughout. The given dose for sample HS-OSL-25 was 4.5 Gy and the test dose preheat was always 20 °C less than the regenerative dose preheat. Each point represents the average and standard error of at least three aliquots. b) Thermal transfer preheat-plateau test for both samples.

Fig. 4. Light stimulation decay curves of typical natural signals from quartz grains extracted from a) the first millimetre of HS-OSL-25 and b) HS-OSL-23.
weeks to allow $^{222}\text{Rn}$ to reach equilibrium with its parent $^{226}\text{Ra}$ before being measured on a high purity germanium detector for 24 h. Details on the gamma spectrometry calibration are given in Murray et al. (1987).

The field moisture content of the sediment was negligibly small at the time of sampling and essentially no moisture or rainfall had occurred in the recent history of the samples due to the desert climate and location in a sheltered alcove. Therefore, burial moisture content was assumed to be $1.0 \pm 0.75\%$ for the boulder and $2.0 \pm 1.5\%$ for the sediment. The cosmic dose rate was calculated based on rockfall boulder thickness and sample site elevation, latitude, and longitude using the method of Prescott and Hutton (1994). This component of the dose rates was also adjusted for 49% local shielding by canyon walls based on azimuth measurements of the horizon taken in the field, similar to measurements made for cosmogenic exposure dating (Dunne et al., 1999). Environmental dose–rates incorporating estimated water-content history, chemistry and cosmic contribution were then determined (Aitken, 1998) (Table 2). The results obtained using ICP analyses are in very good agreement with those from high resolution gamma spectrometry. The dose rate in the sediment sample (HS-OSL-23) is $2.05 \pm 0.08$ Gy/ka, somewhat higher than the dose rate of $1.71 \pm 0.07$ Gy/ka in the rock sample (HS-OSL-25). Since all samples were taken on average within 0.5 mm of the rock/soil interface, and since the dimensions of the rock were similar to the effective range of the relevant gamma radiation, the total dose rate for all samples was taken as $1.88 \pm 0.08$ Gy/ka (Table 2), which is the mean of the rock and sediment dose rate samples.

7. Equivalent dose results

Equivalent doses from the rock samples (HS-OSL-25, 28) were calculated using the central age model of Galbraith et al. (1999). The resulting OSL age represents the average age of quartz grains within the first millimeter. The equivalent dose from the 1st mm of the rock sample HS-OSL-25 (Fig. 5b) is $1.67 \pm 0.07$ Gy ($n = 21$) with an over-dispersion value of $15.9 \pm 0.3\%$. However, the equivalent dose measured for the 1st mm of the modern rock surface sample, HS-OSL-28 is $0.18 \pm 0.04$ Gy ($n = 6$) with an over-dispersion of $40.4 \pm 17.3\%$. As the equivalent dose of the modern analogue sample is not consistent with zero, a small residual signal may also be present in sample HS-OSL-25. The origins of this residual dose are discussed in the next section.

Sediment sample HS-OSL-23 had 284 out of 1600 single-grain measurements that met the acceptance criteria, a recovery of 18% (Fig. 5a). A minimum age model was used for this sample with the intention of isolating the signal from those surface grains that had been completely bleached prior to burial by the rockfall clast. The dose distribution was analyzed using an unlogged three parameter minimum age model (Galbraith et al., 1999; Arnold et al., 2009) with an over-dispersion value of 40%. Although higher than would normally be expected for a well bleached sample, this value was selected from the over-dispersion value of the modern analogue sample used in this study and takes into account potential thermal transfer variability in quartz grains from different geologic sources. An equivalent dose of $1.53 \pm 0.11$ Gy was obtained from the analysis. The interpretation of the results of this model involves several implicit but untestable assumptions — in particular that the uncertainties (both random and systematic) on single grain dose estimates are in themselves accurate, and that incomplete bleaching is the dominant source of dispersion in the dose distribution. The significant spread in $D_E$ values (up to $\sim 50$ Gy; see Fig. 5a) supports the hypothesis that the sediment layer sampled was mixed and/or partially bleached. At least in part this may have resulted from the impact of the rockfall event and because the sampling method employed for the unconsolidated material was unable to isolate only the uppermost (presumably best bleached) grains.

8. Is daylight bleaching complete?

It is important to consider whether the residual dose measured in the 1st mm of the modern rock surface sample (HS-OSL-28) is the result of partial bleaching of the quartz fast component, or whether it is an unbleachable residual signal (i.e. thermal transfer). Because the laboratory measurements of thermal transfer (see
Section 5) are similar to, or larger than, the observed surface dose in the modern analogue sample HS-OSL-28 (0.18 ± 0.04 Gy), it is highly probable that this minor residual dose originated entirely from thermal transfer.

Further evidence against partial bleaching is available from the measurements of the OSL signals as a function of depth into the rock surface of sample HS-OSL-25 (Sohbati et al., in press). Fig. 6 (simplified from their Fig. 2) shows clearly that there is no detectable increase in the OSL signal to a depth of at least 3 mm into the surface. This observation strongly suggests that the OSL signal was fully reset to this depth before burial. The modern analogue, on the other hand, was apparently not reset to the same depth; the OSL signal for that sample increases more rapidly with depth, reflecting the expected shorter light exposure (see Section 3 above). Nevertheless the surface layer does appear to be fully reset. Sohbati et al. (in press) have used the differences in light penetration in these two samples, and a third sample of known light exposure history, to discuss the length of time for which these rock surfaces were exposed to daylight. In the case of the older sample, they suggest that it had been exposed for ~700 a before breaking off from the canyon wall and subsequent burial.

Assuming that the apparent surface dose in the modern analogue sample HS-OSL-28 arises mainly from thermal transfer, it is likely that a similar signal is present in the measured equivalent dose of the 1σ mm of sample HS-OSL-25, and potentially also the sediment sample HS-OSL-23. If the measured residual dose of 0.18 ± 0.04 Gy is subtracted from the equivalent doses before age calculation, age estimates of 720 ± 70 a for HS-OSL-23 (sediment) and 790 ± 50 a for HS-OSL-25 (rock surface) are calculated, whereas if no correction for thermal transfer is made, age estimates of 815 ± 70 a for HS-OSL-23 (sediment) and 890 ± 50 a for HS-OSL-25 (rock surface) are determined (Table 3).

The AMS radiocarbon analysis of the P. fremontii leaf pinned between the talus boulder and underlying sediment has an age of 970 ± 40 14C a BP which calibrates to 870/80 a for HS-OSL-23 (sediment) and 890 ± 50 a for HS-OSL-25 (rock surface) are calculated, whereas if no correction for thermal transfer is made, age estimates of 815 ± 70 a for HS-OSL-23 (sediment) and 890 ± 50 a for HS-OSL-25 (rock surface) are determined (Table 3).

The AMS radiocarbon analysis of the P. fremontii leaf pinned between the talus boulder and underlying sediment has an age of 970 ± 40 14C a BP which calibrates to 870 ± 80 cal BP (Beta #283086, Table 3). For purposes of comparing the radiocarbon age with the luminescence ages, it is necessary to add the time difference between the radiocarbon datum (1950) and the year of sampling/measurement for the luminescence samples (2010): this provides a calibrated age of 930 ± 80 a before 2010. Although the age of the leaf provides a maximum age for the rockfall event, the fragility of the leaf makes it unlikely that it is more than a few years older than the rockfall. The AMS radiocarbon age agrees with the luminescence ages within 2σ error regardless of whether the thermal transfer dose is subtracted. Luminescence ages determined without accounting for thermal transfer are in better agreement with the radiocarbon age and the true luminescence age may be somewhere between the two sets of values discussed above.

9. Conclusions

It has been shown that OSL dating can determine the age of rockfall events by dating the concealed surface of either a fallen rock fragment or the underlying sediment. This is the first time that both such materials have been dated at the same location, and the consistency between our results is very encouraging. The rock surface age is probably the most reliable of the two approaches, as a proportion of the underlying sediment may not have the same age as the event (most probably because the rock buried itself in the sediment surface to some degree when it fell) and because signal-depth analyses can provide evidence of whether the rock surface was completely bleached prior to burial. This is not possible for the unconsolidated underlying sediment sample, and as a result a statistical model was required to extract the burial dose. This involved considerable extra measurement effort, and more importantly it also included the extra assumptions necessary to apply the model (see Section 7).

In comparison to other methods for dating rockfalls, OSL surface dating is applicable in a significantly greater variety of environments than dendrochronology or lichenometry; OSL can be used in any setting where quartz or feldspar grains are first exposed to daylight and then become shielded from light, regardless of climate or surrounding ecosystem. Cosmogenic exposure dating also targets quartz and dates the rockfall event instead of associated biological activity, but the problems associated with shielding of cosmogenic radiation (e.g., canyon walls, vegetation, snow) are significantly more of an influence on the age determination than for OSL dating where cosmogenic radiation is a small fraction of the total environmental dose rate. Furthermore, OSL surface dating has the potential to date the exposure period before burial in addition to the time since burial (Sohbati et al., 2011, 2012, in press).

In this study, we determine a minimum age of ~900 a (A.D. 1100) for the creation of a figure of the Great Gallery rock art panel. Schaafsma (1971) hypothesized that this panel was created by a single individual; if so, this result rules out the hypothesis that the rock art is younger than the Fremont culture (Manning, 1990), which has a distinctly different and well-characterized rock art style (Schaafsma, 1971). Rather, our result supports other hypotheses that suggest the art is an older precursor to Fremont rock art (Coulam and Schroedl, 1996; Schaafsma, 1971). Rock art is notoriously difficult to date, and although the precise age of BCS rock art remains uncertain, the minimum constraint provided here gives additional guidance to a mystery that has resisted successful analysis for generations.

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