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Anomalous luminescence of subglacial sediment at Haut Glacier d'Arolla, Switzerland – a consequence of resetting at the glacier bed?

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SWIFT, D.A., SANDERSON, D.C.W., NIENOW, P.W., BINGHAM, R.G. AND COCHRANE, I.C.: Anomalous luminescence of subglacial sediment at Haut Glacier d'Arolla, Switzerland – a consequence of resetting at the glacier bed?

Luminescence has the potential to elucidate glacial geomorphic processes because primary glacial sediment sources and transport pathways are associated with contrasting degrees of exposure to light. Most notably, sediment entrained from extraglacial sources should be at least partially reset, whereas sediment produced by glacial erosion of subglacial bedrock should retain substantial luminescence commensurate with a geological irradiation history. We set out to test the validity of this assumption at Haut Glacier d'Arolla, Switzerland using sediment sampled extraglacially and from the glacier bed. Contrary to our expectations, the subglacial samples exhibited natural signals that were substantially lower than those of other sample groups, and further (albeit limited) analyses have indicated no obvious differences in sample group luminescence characteristics or behaviour that could account for this observation. For glaciological reasons, we can eliminate both the possibility that the subglacial sediment has been extraglacially-reset or exposed *in situ* to heat or light. We therefore advocate investigation of possible resetting processes related to subglacial crushing and grinding, and speculate that such processes, if more generally present, may enable the dating of subglacially-deposited tills using luminescence-based techniques.

Keywords: Subglacial sediment, sediment transport, sediment tracing, geomechanical resetting, optically stimulated luminescence, thermoluminescence.

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Luminescence properties of sedimentary deposits have the potential to further understanding of complex geomorphic systems and processes by elucidating their sediment sources and transport pathways. Firstly, luminescence behaviour could be exploited in situations where quantifiable differences in sensitivity, fading or bleaching characteristics, for example, are produced by mineralogically distinct sediment sources or transport pathways characterised by contrasting bleaching-dosing histories. Secondly, residual dose could be exploited where sediment sources or transport pathways are associated with varying degrees of luminescence accumulation or resetting. The latter approach should be particularly applicable to glaciated catchments, where exposure to daylight should result in extraglacial sources being substantially bleached, whilst sediment eroded from bedrock beneath many metres of glacier ice should carry substantial luminescence commensurate with a purely geological irradiation history (cf. Fuchs & Owen 2008).

Minerals generate luminescence because structural defects trap ‘free’ electrons produced by naturally occurring ionising radiation. Resetting of luminescence systems requires such trapped electrons to be released under stimulation in natural or laboratory settings. Relaxation processes can include recombination at luminescence centres, where a proportion of the energy that is liberated is released as light (Aitken 1985, 1998). Resetting is widely considered to be dominated by the effects of heat and light (Wintle & Huntley 1979; Liritzis, 2000), making luminescence a useful tool for dating (cf. Lian & Roberts 2006) or process tracing (e.g. Rink *et al.* 1999; Bateman *et al.* 2007) in geology and geomorphology. Potential as a process tracer in the glacial environment has been demonstrated by Gemmell (1994, 1997), who attributed the substantial residual dose of proglacial stream suspended sediment to the entrainment of sediment from mainly subglacial sources. Resetting of residual dose at the glacier bed as a result of subglacial grinding and crushing has been proposed (e.g. Morozov, 1968; Dreimanis *et al.* 1978; Singhvi *et al.* 1994), but the efficacy of such 'geomechanical resetting' remains controversial (Toyoda *et al.* 2000).

We set out to examine whether residual dose could be used to elucidate the sources of sediment evacuated by the subglacial drainage system at Haut Glacier d'Arolla, Switzerland (Fig. 1). Firstly, extraglacial and subglacial sediments representing inputs to and outputs from the drainage system were sampled under night-time conditions; extraglacial sediment was sampled at the glacier margin and from glacial streams, whilst subglacial sediment was sampled *in situ* from beneath ~100 m of glacier ice, utilising boreholes drilled through the ice to the glacier bed (see Fig. 1 for drill site location). For reasons given below, residual dose was initially characterised using simple polymineral screening measurements, with full single-aliquot regenerative (i.e. SAR) procedures being undertaken on a subset of samples only. We show that, rather than exhibiting substantial equivalent dose commensurate with a geological irradiation history, the luminescence of the subglacial sample group was substantially reset relative to that of the other major sediment types. Possible reasons for these surprising observations are explored.

Field area and sampling method

Haut Glacier d'Arolla (Fig. 1A) is a classic alpine glacier at which sediment transport is dominated by the subglacial drainage system (Sharp *et al.* 1993; Swift *et al.* 2002). This system accesses a thin layer of deformable sediment at the ice-bed interface that is produced by erosion of the underlying bedrock (Hubbard *et al.* 1995; Harbor *et al.* 1997; Fischer & Hubbard, 1999). The majority of the annual sediment load is evacuated by hydraulically efficient subglacial channels that evolve in spring and summer (Nienow *et al.* 1998; Swift *et al.* 2002) and in which sediment transport is limited only by the rate of sediment supply (Swift *et al.* 2005; cf. Alley *et al.* 1997). Nevertheless, a portion of the sediment transported by subglacial channels is entrained in extraglacial streams, such as those fed by western-facing cirque glaciers below the Bouquetins ridge (Fig. 1b; Swift *et al.* 2005). Runoff from glacial sources causes sediment evacuation from the ice-bed interface to peak shortly after midday; however, runoff from the Bouquetins cirques continues into the evening. The catchment geology is complex, consisting of amphibolites, granites and gabbros that represent various stages of the Alpine Orogeny (Fig. 1C).

Sediments sampled at night in August 2000 comprised seven samples from the base of two ~100 m-deep glacial boreholes and 16 extraglacial samples: seven samples from marginal streams; three surface samples from marginal moraine; and six samples from two proglacial streams that emerge from the eastern portion of the subglacial drainage system (Fig. 1A, B). Stream samples comprised suspended sediment obtained by immersing an opaque sample bottle into a well-mixed section of the flow; moraine samples were scraped into opaque 35-mm film canisters from exposed sediment surfaces. Borehole sampling was undertaken using a water sampler modified from the design of Blake & Clarke (1991) (see Tranter *et al.* 2002). The boreholes had been drilled in mid-July using a hot-water drill (ambient drill-tip water temperature ~50°C) and were sampled ~30 days later, after subglacial instrumentation – which had been deployed at the time of drilling – had been removed. The sampler was shaken vigorously at the base of each borehole prior to closure of the sampler *in situ*; samples were protected from light and were stored and transported in opaque polypropylene bottles.

Drilling and sampling methods do not indicate potential for significant contamination of borehole samples by optically-reset sediment. There is potential to release reset sediment from glacier ice during drilling; however, because debris causes problems during drilling, boreholes were located away from supraglacial and englacial debris accumulations, and, other than the highly conspicuous eastern medial moraine (Fig. 1), no significant debris structures are known to exist in the vicinity of the drill site (see Goodsell *et al.* 2005). Supraglacial and/or englacial streams are another potential source of reset sediment; however, supraglacial runoff is characterised by extremely low sediment concentrations, and boreholes do not act as a focus for runoff from wide areas of the glacier surface. Furthermore, as the basal sediment layer in the vicinity of the drill-site is up to 10 cm thick (Hubbard *et al.* 1995; Harbor *et al.* 1997; Fischer & Hubbard 1999), the potential for contamination by reset sediment would have been further reduced by thorough mixing of the basal sediment layer both during drilling and by vigorous shaking of the Nielsen sampler at the base of each borehole when sampling.

Another potential source of reset sediment is turbid water that down-borehole video has shown to enter boreholes from small englacial channels (e.g. Copland *et al.* 1997). However, such channels appear to be rare at Haut Glacier d’Arolla; the best example to have been observed during borehole-survey was the result of turbid water, comprised of sediment disturbed from the glacier bed, being forced into an englacial channel during drilling (Copland *et al.* 1997). Furthermore, Copland et al. (1997) concluded that the majority of borehole turbidity appeared to be generated by basal water flow through or above unconsolidated basal sediment at the ice-bed interface. Stone & Clarke (1996) have also reported borehole-observations from temperate glaciers during the melt season that show frequent mobilisation of basal sediment at the ice-bed interface.

Sample preparation and initial screening results

Simple preparation techniques and a simple polymineral single-aliquot multiple-stimulation screening approach (Table 1) were used for all samples on account of the small volume of subglacial sediment acquired using the borehole sampling technique. The samples were prepared by settling in water before washing in a 10% HCl solution for 30 minutes to remove carbonate minerals; no reaction with the HCl solution was observed, and because the samples were devoid of organic material, no further pre-treatments were undertaken. Mineralogical and grain size characteristics (the latter estimated to be 10–100 μm) were later checked for consistency using an FEI Quanta SEM. All luminescence measurements were made from small quantities of sample dispensed onto 0.25 mm-thick 1 cm-diameter stainless steel discs using a Risø DA15 luminescence reader equipped with a bialkali photomultiplier (ET9235QB) and 9 mm Hoya U340 filter to detect near-UV radiation. Although polymineral luminescence was anticipated to be dominated by feldspar emission, and therefore to exhibit fading (cf. Krbetschek *et al.* 1997), the same multiple-stimulation procedure was used for all measurements.

The multiple-stimulation screening procedure (Table 1) was applied to two discs per sample and comprised sequential measurement of: (i) Infra-Red-Stimulated Luminescence (IRSL) (60 s stimulation at 60°C with an 830 nm laser diode delivering approximately 240 mW cm^{-2} to the sample); (ii) post-IR blue Optically Stimulated Luminescence (OSL) (30 s stimulation at 125°C with GaN diodes at 470 nm delivering approximately 30 mW cm^{-2} to the sample); and (iii) Thermally-stimulated Luminescence (TL) (ambient to 500°C at 5°C s^{-1} with a second heating to enable background-subtraction). Background-corrected luminescence signals were then extracted from raw IRSL and OSL shine-down and TL glow-curves as shown in Fig. 2 and used to estimate the Residual Dose (D_r) using the simplest form of the single-aliquot regenerative-dose protocol,

$$\text{palaeodose} = \frac{L_n}{T_1} \times \frac{T_2}{L_r} \times \text{regenerative dose,} \qquad (1)$$

where L_n, T_1, L_r and T_2 are the background-corrected natural signal, a subsequent test-dose signal, a regenerative dose signal, and its associated test-dose signal, respectively (Table 1; cf. Galbraith 2002). Similar multiple-stimulation procedures have been used in diverse luminescence profiling studies to provide robust diagnoses of sediment transportation and depositional processes (e.g. Sanderson *et al.* 2003, 2007; Burbidge *et al.* 2007; Sanderson & Murphy 2010).

Fig. 3 shows that initial D_r estimates reproduced well and covered several orders of magnitude between the major sample groups, exceeding that which could reasonably be expected to have arisen from methodological problems and uncertainties. Notably, although regenerated signals (L_r) were uniformly intense (typically around 10^4 counts for all sample groups), subglacial samples yielded low-intensity natural signals (L_n in Table 1) compared to those in other sample groups (e.g. sample 1277, Fig. 2). Consequently, the subglacial sample group demonstrated substantially lower residual dose than any of the other sample groups, regardless of stimulation method (Table 2). A small number of samples exhibited weak or non-existent natural signals (see caption to Fig. 3), but largely in the case of post-

IR OSL, which can be attributed to the dominance of emissions from feldspar minerals (predominantly feldspar mineralogy was confirmed by SEM analyses).

Further investigation of luminescence characteristics

The surprising results and subsequent discussions with peers inspired us to undertake additional work to assess whether unexpectedly low subglacial residual dose could be readily explained by: (1) differences in luminescence behaviour between the subglacial and extraglacial samples; or (2) rogue luminescence behaviour that could cause the subglacial samples to have apparent lower residual doses.

Dose response

Uncertainties regarding residual dose estimates using the initial screening procedure and the luminescence behaviour of different sample groups were investigated by applying single-aliquot regenerative-dose (SAR) procedures to six key samples (including two subglacial samples). The procedure employed the same polymineral multiple-stimulation procedure (Table 1) with the addition of a range of regenerative doses (from 10 to 1000 Gy) and recuperation and recycling steps; further, the procedure was applied to eight discs per sample, which, following initial data appraisal, enabled mean values to be calculated for each regeneration point belonging to each sample. SAR residual dose estimates were obtained and compared with the initial screening estimates, bearing in mind the potential timing and role of known sensitivity changes (e.g. Wallinga *et al.* 2000, 2001; Blair *et al.* 2005).

SAR curves (Fig. 4) were supra-linear but all samples demonstrated good SAR characteristics (Table 3) and similar SAR behaviour, although subglacial TL exhibited higher sensitivity than other samples to doses in excess of 100 Gy (Fig. 4C). Recycling and recuperation values for all samples were mostly good (Table 4), with recycling ratios typically within the range 0.9–1.1 at ±1σ, and only two OSL recuperation values being >5% (subglacial samples 1277 and 1285). Given the polymineral nature of the samples, the SAR characteristics were therefore as good as could be anticipated and SAR D_e estimates were well-constrained (Table 4) and within saturation limits (cf. Fig. 4). SAR D_e estimates also compared well with the initial residual dose estimates (Table 4).

Shape of the decay curve

Consideration was given to whether natural and regenerated signals of certain sample groups exhibited different decay properties that might invalidate SAR approaches. LM-OSL (e.g. Thomas *et al.* 2006) was rejected because changes in decay properties can also arise from differences in sample mineralogy and/or the number of bleaching-dosing cycles to which sediment has been exposed (e.g. Bailey *et al.* 2003; Lukas *et al.* 2007), and our limited experience of applying to feldspar systems indicated that the complex overlapping signal distributions obtained would be extremely difficult to deconvolve. A standard signal analysis approach (cf. Bailey *et al.* 2003) that used existing data sets was therefore employed, comprising analysis of IRSL and OSL signal-decay plots and D_e(t) plots. The latter were produced using sensitivity-corrected IRSL and OSL signals from successive integration intervals of the raw shine-down curves (Fig. 5).

Signal-decay plots (Fig. 6) demonstrated no significant differences in the form of natural and regenerated signals for individual samples, and no obvious differences between sample groups; post-IR OSL is characterised by slow decay, indicating that this signal is likely to be dominated by feldspar (or quartz without a fast component). D_e(t) plots for IRSL signals were either flat or showed a slight decline, whereas the OSL D_e(t) plots tended to show some increase (Fig. 7). For quartz minerals, it has been suggested that a rise of D_e with integration time occurs in partially-reset samples as a result of better resetting of the fast component relative to the slower components (e.g. Bailey *et al.* 2003). For feldspar minerals, such components have not been identified, and dependency of residual dose on integration period may have other causes (e.g. signal stability). OSL D_e(t) plots are therefore consistent with resetting of naturally-acquired luminescence signals, but, given our limited knowledge of feldspar signals, no inferences can be made other than that there are no clear differences between the sample groups.

Stability of the signal

Fading rates were investigated using further aliquots of the six samples previously subjected to SAR analysis (see above). Eight aliquots of each sample were subjected to the same polymineral multiple-stimulation procedure (Table 1); however, the procedure was modified such that four aliquots were stored for 95 days following administration of the regenerative dose, whilst the remaining aliquots were stored prior to administration of the regenerative dose. Measurement of these 'stored' and 'prompt' regenerative doses was then followed by measurement of a 50 Gy test dose, allowing fading to be quantified using the ratio of the sensitivity-corrected 'faded' and 'prompt' signals. The results demonstrate significant fading of regenerated signals (Table 4); nevertheless, fading was generally consistent across all sample groups.

Bleaching characteristics

Uncertainties concerning the bleaching rates of signals in the different sample groups were addressed by bleaching regenerated doses. Bleaching rates of regenerated IRSL, OSL and TL signals were quantified by exposing aliquots of each sample to 'artificial daylight' fluorescent lighting inside a sealed 'lightbox' for periods of 1 and 8 minutes, and to direct sunlight for a period of 1 minute. Furthermore, the precise form of the bleaching curve was investigated by exposing aliquots from two samples (one subglacial and one extraglacial) to 'artificial daylight' for periods of up to 32 minutes. The first approach demonstrated mostly consistent rates of bleaching (Table 5). Exposure to the artificial daylight source did appear to bleach subglacial TL more rapidly than for the other sample types, but this was not observed under exposure to direct sunlight, and may therefore reflect unintended heating of the aliquots as a result of the proximity of the fluorescent lighting, or well-known differences between the spectra of fluorescent lighting and sunlight. Bleaching of regenerated signals (e.g. Fig. 8) exhibited an exponential reduction of signal with exposure time that is typical of geological samples.

Sensitivity change

Residual dose may to some extent reflect sensitivity changes in our samples that cannot be corrected for using normal SAR procedure (e.g. Murray & Wintle 2003). Notably, our multiple-stimulation procedure involves heating aliquots to 500°C prior to administration and measurement of the test dose, which is likely to introduce some sensitivity changes during the first SAR step. Comprehensive dose-recovery tests using a SARA-SAR procedure (as suggested by Wallinga *et al.* 2000) were not possible due to the limited sample material available, and we recommend that additional research be undertaken on the luminescence behaviour of subglacial material from other sites. However, the magnitude of reported effects, which are typically in the range 10–30% (e.g. Wallinga *et al.* 2000; Blair *et al.* 2005, Bateman *et al.* 2010), would be insufficient to account for the observed one to two order of magnitude variation of residual dose between sample groups (Fig. 3, Table 2). Furthermore, there are no reasons to suppose that such effects would lead to different behaviour in the subglacial sample group than in any other.

Discussion

Residual doses of the sample groups and their origin

Unexpectedly low subglacial residual dose dominates residual dose variation in samples obtained at Haut Glacier d'Arolla and is evident even in the difficult-to-reset TL signal (Fig. 3); few extraglacial samples exhibited such low dose, and only in the easy-to-bleach IRSL and OSL signals (Fig. 3A, B). Also notable is the high residual dose exhibited by samples of suspended sediment collected from the proglacial stream, which, given the low residual dose of the subglacial sample group, is not consistent with the expectation that the majority of sediment transported by such streams is entrained at the ice-bed interface (cf. Gemmell 1994, 1997; Swift *et al.* 2005). However, this expectation may not have been valid at the time of sampling because periods of falling discharge are generally associated with the reduced availability of basal sediment (cf. Swift *et al.* 2005), indicating that the majority of sediment in transport may actually have been extraglacial sediment, sourced from fluvial erosion of the slopes below the Bouquetins ridge (Fig. 1A, B).

A number of previous studies have reported anomalous luminescence behaviour of samples from glaciated environments, most notably the poor sensitivity of glacial sediment that arises from poor-intensity signals with weak or absent fast components (e.g. Lukas *et al.* 2007), recuperation of signals after bleaching (e.g. Rhodes & Pownall 1994), or thermal transfer of signals during SAR procedures (e.g. Rhodes & Bailey 1997). Our analyses have shown that such problems do not exist in the case of the samples obtained at Haut Glacier d'Arolla. Furthermore, our analyses indicate consistent luminescence behaviour across all sample groups and indicate nothing that could reasonably account for the observed one to two order of magnitude variation in residual dose between the major sample groups. It follows that we have found no variation in luminescence intensity or behaviour that could be ascribed to differences in sample mineralogy or transport/exposure history (cf. Lukas *et al.* 2007).

There is evidence instead that the luminescence of the sediment types sampled at Haut Glacier d'Arolla reflects natural resetting of geologically-accumulated signals. Firstly, extraglacial sample residual dose, which approaches geological saturation levels (cf. Wintle & Murray 2006), is consistent with only partial resetting, such as that resulting from the reworking of glacially-eroded sediments at or near the ice-margin by debris flows and other mass-movement processes. Secondly, although there are many uncertainties regarding the interpretation of the D_e(t) plots (Fig. 7; see above), rising extraglacial sample OSL D_e(t) is again consistent with partial resetting, whereas subglacial sample OSL D_e(t) is almost flat, which is consistent with total resetting (cf. Bailey *et al.* 2003). Thirdly, the relationship of subglacial sample IRSL, OSL and TL residual dose to that of the other sample groups (Table 2), which indicates substantially lower IRSL and OSL residual dose than for the difficult-to-reset TL signal, is consistent with widely-observed bleaching patterns of natural signals as a result of exposure to heat or light (cf. Table 5).

Assuming subglacial residual dose is indeed a result of natural resetting of near-saturated geological signals, the energy required to have reset such a signal to observed levels can be estimated from rates of bleaching exhibited by regenerated signals when exposed to artificial daylight (Table 5). Knowledge of the signal present in the subglacial bedrock/sediment prior to resetting is also required, but as this is unknown, we substitute this with the mean residual dose exhibited by the other, presumed partially-reset sample groups. By example, the easy-to-bleach subglacial IRSL residual dose is typically 10% of that of the other sample groups (Table 2), which equates to a level of resetting that is produced by approximately 8 minutes of exposure of a regenerated signal to artificial daylight (Table 5). A similar exposure time is arrived at when using the OSL and TL signals (Tables 2, 5). From the irradiance of the artificial source (72.92 W m^{-2}), it follows that the energy required to reset subglacial signals from levels exhibited by the extraglacial sample groups would be ~35 kJ m^{-2}. In terms of exposure to natural light at midday on the glacier surface, when measured irradiance is typically ~1 kW m^{-2}, ~35 kJ m^{-2} equates to an exposure time of ~30 seconds.

The above estimate is a minimum estimate of the energy required to have reset subglacial signals to observed values because: (i) extraglacial samples are believed to have been partially-reset and therefore the actual level of signal present in subglacial bedrock or sediment prior to resetting is likely to have been far greater (SAR growth-curves indicate that it may have been ~1000 Gy; Fig. 4); and (ii) resetting is non-linear (Fig. 8), such that the energy required to reduce the luminescence of a sample by a given proportion increases as trapped electrons are released by the resetting process, such that bleaching rates determined from regenerated signals will be significantly greater than for partially-reset natural signals. Nevertheless, this estimate provides a sound and cautious basis from which to assess possible resetting mechanisms.

Traditional resetting mechanisms

Subglacial sample residual dose cannot be explained by accidental exposure to light or heat since: (i) light sources present during sampling (i.e. head-torch lights and moon light) cannot have delivered the energy required in the time taken to retrieve and bottle the samples; and (ii) drill-water temperatures during borehole drilling were far below the 200°C preheat used during luminescence measurement (B. Hubbard, pers. comm. 2001). Heat generated by friction between clasts, sediment particles and bedrock during glacier sliding or deformation of basal sediment is also negligible. Consequently, potential resetting mechanisms are limited to: (i) bleaching of sediment *in situ* by light reaching the glacier bed through open boreholes or through glacier ice; (ii) bleaching of sediment in an extraglacial location prior to re-deposition beneath the glacier; (iii) glacier advance over bleached extraglacial sediment; and (iv) resetting *in situ* as a result of a natural process that does not require heat or light.

In situ bleaching is extremely unlikely because it requires unacceptably low attenuation of light, regardless of whether light is transmitted down boreholes or through glacier ice. In the case of borehole transmission, the Lambert–Beer equation (Grum & Becherer 1979) indicates that, given an ice thickness of ~100 m and mean daily solar irradiance of ~0.3 kW m^{-2} (both obtained from field measurements), delivery of 35 kJ m^{-2} to the glacier bed via boreholes that were open for 30 days prior to sampling requires attenuation of light in the borehole to be ≤ 0.12 m^{-1}. Such attenuation rates are unrealistic, given that: (i) typical values for clear water are ~0.2 m^{-1}; (ii) boreholes are normally at least partly water-filled (Hubbard *et al.* 1995); (iii) glacier ice has poor reflective properties; and (iv) boreholes have irregular form and ice-wall texture. Furthermore, flushing of sediment between at the glacier bed (e.g. Hubbard *et al.* 1995; Copland *et al.* 1997) indicates that the sampled sediment is unlikely to have been directly beneath the borehole for 30 days. Similar calculations show that the alternative scenario of bleaching via transmission through ice would require ~268 million years, even when reflection of light at the glacier surface is ignored, and a uniform and generous within-ice attenuation coefficient of 0.8 m^{-1} is assumed (cf. Grenfell & Maykut 1977; Pegau & Zaneveld 2000).

Finally, the possibility of extraglacially-bleached sediment existing beneath the glacier is incompatible with current understanding of subglacial processes. Subglacial re-deposition of extraglacially-bleached sediment is extremely unlikely because sediment transport within subglacial channels, which are occasionally fed by extraglacial streams, is supply-limited (cf. Swift *et al.* 2002, 2005). Sediment can be deposited subglacially when subglacial channels are required to traverse overdeepenings (Alley *et al.* 2003), but the single probable overdeepening at Haut Glacier d'Arolla is not sufficiently deep and does not in any case extend under the drill site (Sharp *et al.* 1993). The alternative scenario of glacier advance over extraglacially-bleached sediment is even more unlikely given the long history of Alpine glacial retreat and the requirement for the overridden sediment to have resisted evacuation by the subglacial drainage system. At Haut Glacier d'Arolla, this system evacuates 2000+ tonnes of sediment per year (Gurnell *et al.* 1992; Swift *et al.* 2002) from a basal sediment layer only ~10 cm thick (Harbor *et al.* 1997), implying spatially-averaged subglacial erosion rates in excess of 1 mm a^{-1}, and a mean basal sediment residence time of only 100 years.

Alternative resetting mechanisms

Calculations of the attenuation of light through ice relate only to absolute intensities of light, whereas it is well-known that shorter-wavelength parts of the spectrum are most attenuated in water (Berger 1990; Bailey *et al.* 2003), resulting in preferential bleaching of feldspar luminescence at water depths beyond those at which effective bleaching of the quartz system can occur, even for turbid water (Sanderson *et al.* 2003, 2007). Since the polymineral aliquots analysed in this study were predominantly composed of feldspar, it is therefore possible that bleaching at the glacier bed could be more effective than anticipated. Without field measurements of the attenuation of different spectra by glacier ice, it is impossible to know just how effective such a resetting mechanism could be. Nevertheless, given that transmission of only a portion of the spectrum would result in a reduction in light intensity, and given that the transmitted wavelengths would still undergo at least some attenuation, such a mechanism remains unlikely.

The absence of plausible resetting mechanisms related to heat or light raises the possibility of more controversial resetting mechanisms. Resetting by subglacial processes has been postulated, particularly the grinding and crushing processes that are responsible for producing and comminuting subglacial debris, because these processes subject individual sediment grains to extremely high stress (cf. Boulton 1974). Various geomechanical resetting mechanisms related to grain stress have been proposed, including: (i) grain fracture, which should result in fewer active luminescence centres that are surrounded by an extended atomic lattice (Toyoda *et al.* 2000); and (ii) the ejection of trapped electrons by stresses imposed on the crystal lattice (Lee & Schwarz 1994) and/or localised frictional heating at grain boundaries (Fukuchi 1989; Lee & Schwarz 1994).

Since our analyses indicate no substantial differences in the sensitivity of subglacial and extraglacial sample groups of a kind that would indicate a reduction in the number of active luminescence centres, our observations are most consistent with resetting of subglacial luminescence via trapped electron ejection, as envisaged by Lee & Schwarz (1994) and Fukuchi (1989). Although rates of subglacial sediment deformation at Haut Glacier d'Arolla have been suggested to be low in comparison to other similar glaciers (Fischer & Hubbard 1999), the combination of a high annual fine sediment evacuation rate (Swift *et al.* 2002) and a relatively thin basal sediment layer (Harbor *et al.* 1997) indicates a potentially highly erosive subglacial environment in which sedimentary particles are subjected to extremely high stresses. Nevertheless, such processes have also been postulated to induce luminescence (Aitken 1985; Toyoda *et al.* 2000; Zöller *et al.* 2009), and their net effects on luminescence signals remain unknown.

Luminescence as a process tracer in glacial systems

Although this study has indicated unexpected luminescence variation at Haut Glacier d'Arolla, the results do indicate that luminescence could elucidate glacial sediment transport pathways. For example, the origin of sediment being evacuated by the subglacial drainage system could be investigated using a simple two-component mixing-model that exploits the contrasting residual dose of extraglacial and subglacial sediments. Nevertheless, uncertainty regarding the nature and efficacy of a subglacial resetting mechanism means that such studies would not be easy to apply without further investigation of the luminescence of glacial erosion products. Further studies of subglacial sediments that have been obtained *in situ* must be paramount (see below), but such samples are logistically difficult to obtain. Further investigation of diurnal variation in the residual dose of sediment evacuated by subglacial drainage systems would also be worthwhile (cf. Gemmell 1994, 1997), but this too is logistically difficult because stream samples are very difficult to obtain under light-free conditions.

Further investigation of a possible subglacial resetting processes might include sampling of a more extensive network of boreholes, since resetting should vary with basal shear stress, which should be highest where the ice is thickest and is moving fastest, and sediment transport distance, which should increase downglacier (provided that not all sediment that is produced by subglacial erosion is at some point evacuated by the subglacial drainage system). Sampling of boreholes over time should also be undertaken to fully eliminate resetting as a result of the transmission of light via boreholes and the contamination of borehole sediment by sediment bleached in englacial and supraglacial locations. The results of such work might enable the identification of other glaciers with subglacial conditions that are conducive to resetting, as well as the identification of

Quaternary sediments that are likely to have experienced transport, and thus resetting, in such environments. Ultimately, such work could enable the dating of subglacially-deposited tills using luminescence-based techniques, as well as the quantification of sediment strain histories and/or residence times in the contemporary subglacial environment.

Finally, the results of this study indicate some potential to use the luminescence sensitivity to elucidate sediment transport pathways in a way that is similar to that proposed for residual dose (above). Specifically, SAR measurements (Fig. 4) indicate that the TL saturation of subglacial sediment was markedly higher than for the other sediment types, with that D_e values at 90% of saturation (as indicated by the form of the curves fitted to the SAR measurements) being three times greater than values for other sediment types. However, this feature of the data is not consistent with the anticipated effects of glacial crushing, which might be expected to reduce the saturation point of glacial sediment relative to non-glacial sediment by reducing the number of luminescence centres surrounded by an extended atomic lattice (cf. Lee & Schwarz 1994). Further work is therefore necessary to understand the source of this effect.

Conclusion

This study has shown that the luminescence of subglacial sediment obtained from boreholes drilled to the bed of Haut Glacier d'Arolla through ~100 m of glacier ice appears to have been substantially reset relative to that of extraglacial sediments sampled within the same small catchment. Although further work is required, the results also demonstrate that the observed differences in residual dose cannot readily be explained by differences in the luminescence characteristics or behaviour of the various sample groups. The discussion has further shown that satisfactory process-based explanations related to exposure to heat or light cannot explain observed subglacial sediment residual dose, and we therefore conclude that further work should also investigate alternative resetting processes, including trapped charge ejection as a result of the grinding and crushing that both produces and comminutes sediment in the subglacial environment. Such processes could enable the dating of subglacially-deposited tills using luminescence-based techniques, as well as the quantification of sediment strain histories and/or residence times in the contemporary subglacial environment.

It is hoped that the need for further investigation will be at least partially fulfilled by a recently-started research project that aims to shear sediment with naturally-acquired luminescence under conditions that are representative of the subglacial environment (Swift *et al.* 2010). Nevertheless, further study of subglacial sediment that has been sampled *in situ* is also required if the nature and efficacy of any such subglacial resetting is to be rigorously quantified and constrained. Such studies are necessary to identify contemporary and Quaternary glacial environments that are conducive to the resetting of subglacial sediment and the associated sediments and landforms that may provide evidence of having been glacially-reset.

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FIGURE CAPTIONS

Figure 1. A. Map of Haut Glacier d'Arolla, Switzerland showing sampling locations discussed in the text. The inset key indicates the number of samples obtained at each location (see Supplementary Material for a full sample list). B. Photograph looking SE over the glacier. The approximate location of the drill site, where subglacial sediment was sampled, is indicated by the filled triangle. Surface sediment was sampled from marginal moraine in the upper glacier basin, and stream sediments were obtained from two tributaries of a nearby non-glacier-fed marginal stream and from the eastern subglacial drainage system portal (symbols indicate sampling locations). Glacier-fed extraglacial streams below Bouquetins ridge (numbered 1 to 4) also enter the glacial drainage system and emerge from the eastern drainage portal. C. Distribution of major rock types and sediments in the catchment and surrounding areas (after Tranter *et al.* 2002).

Figure 2. Indicative IRSL and OSL shine-down curves and background-subtracted TL glow-curves measured during read-out of naturally-trapped charge from individual discs prepared from samples 1277 (subglacial sediment), 1280 (portal stream sediment), 1293 (marginal stream sediment) and 1296 (surface sediment). IRSL and OSL signals were calculated by subtracting the underlying background (determined over the last 14.4 s and 7.2 s of observed signal for IRSL and OSL, respectively) from the initial signal (obtained by integration over the first 4.8 s and 2.4 s of observed signal for IRSL and OSL, respectively); TL signals were obtained by integration of the observed signal over the range 300 to 400°C.

Figure 3. Initial Residual Dose (D_r) estimates obtained using the simple polymineral single-aliquot multiple-stimulation screening procedure (see text). Two independent determinations of IRSL, OSL and TL D_r were obtained for each sample (i.e. D_{r1} and D_{r2}) and these are shown on separate axes; error bars reflect photon counting statistics (Galbraith 2002) plus an estimated 2% analytical error (cf. Armitage *et al.* 2006). Subglacial samples are shown as filled triangles; see Fig. 1 for the key to other sample types. D_r values with errors that exceeded ±100%, largely as a

result of very weak L_n signals, were treated with caution; hence, one portal stream sample has been removed from (A) and six samples (including four subglacial sediment samples) have been removed from (B). See Supplementary Material for the full dataset.

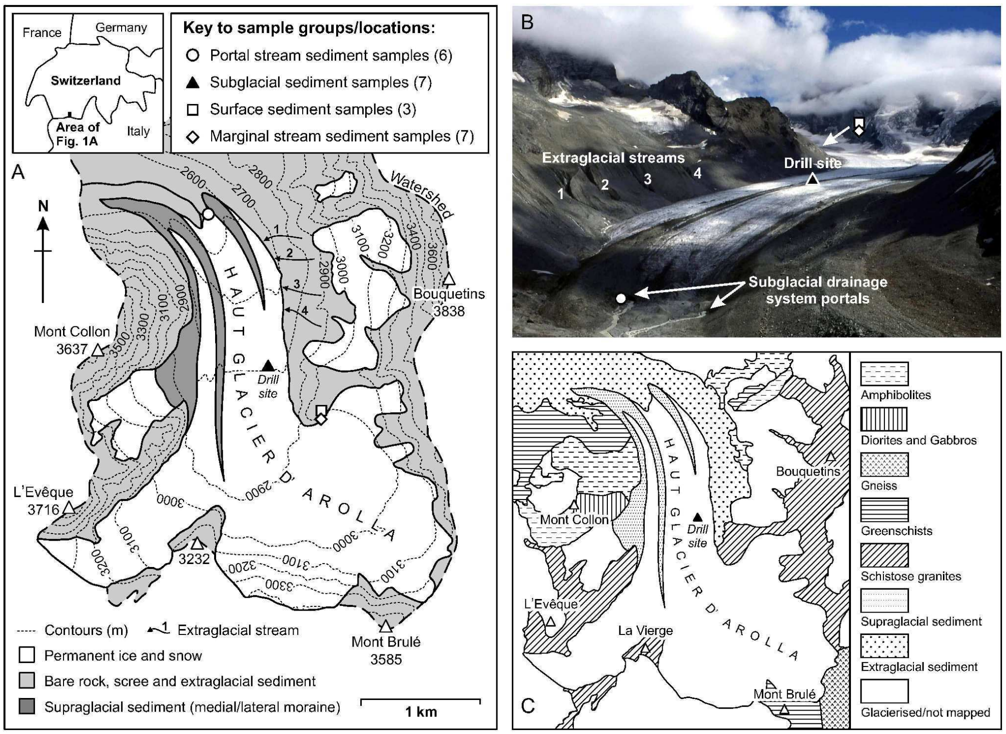
Figure 4. Sensitivity-corrected luminescence growth-curves for various samples using a multiple-stimulation single-aliquot regenerative-dose (SAR) procedure (see text); regeneration points are means of eight aliquots per sample. All plots include a recycling point at 50 Gy; zero dose-point values (not shown) and recycling ratios are summarised in Table 4. Fitted curves are fourth-order polynomials that were also used to calculate the SAR D_e estimates (Table 3); for all curves R^2>0.999 and the standard deviation of the back-transformed residuals is <3%. Key to lines and symbols for all plots is shown in (A); see Fig. 1A for sample key.

Figure 5. Integration intervals (*a*–*f*) used to plot background-corrected IRSL and OSL signal-decay (Fig. 6) and D_e(t) (Fig. 7) (background obtained from interval *x*).

Figure 6. Signal-decay plots obtained from IRSL and OSL shine-down curves for various samples: (A) natural IRSL; (B) natural OSL; (C) regenerated IRSL; and (D) regenerated OSL (key to all samples shown in (A)). The plots show sensitivity-corrected luminescence (LX) for successive integration intervals (i.e. $L_X = L_X/T_X$, where *x* is the integration interval) as a proportion of the sensitivity-corrected initial signal (L_A) in interval *a* (integration intervals shown in Fig. 5). Values are means of eight aliquots per sample (except for 1279 in (A) and (B), where values are means of seven determinations). Shine-down curves were measured using the multiple-stimulation approach of Table 1.

Figure 7. $D_e(t)$ plots ($D_e = L_n/L_r \times 50$) obtained from shine-down curves for various samples: (A) and (B) natural IRSL; (C) and (D) natural OSL (key to all samples shown in (A)). Values are means of eight aliquots per sample; integration intervals are shown in Fig. 5.

Figure 8. Resetting of regenerated IRSL signals in sample 1285 (subglacial sediment; filled triangles) and 1296 (surface sediment) as a result of exposure to an artificial daylight source. The graph shows the observed signal after bleaching (L_b) as a proportion of the observed signal with no bleaching (L_u). Symbols are means of two aliquots per sample; errors were calculated as for Fig. 3.



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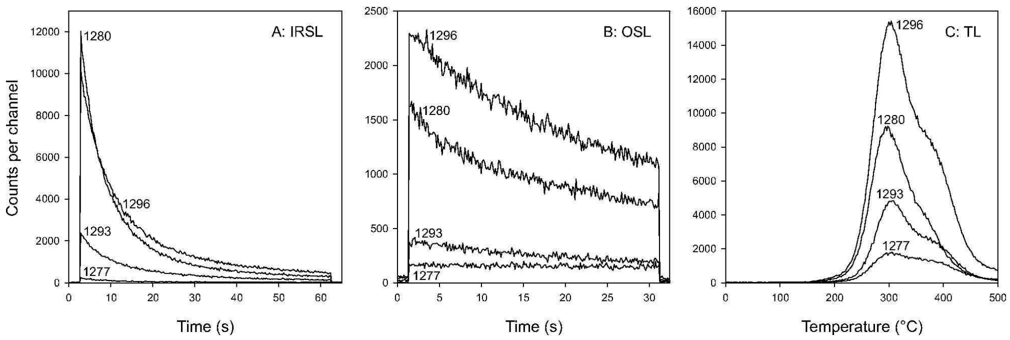

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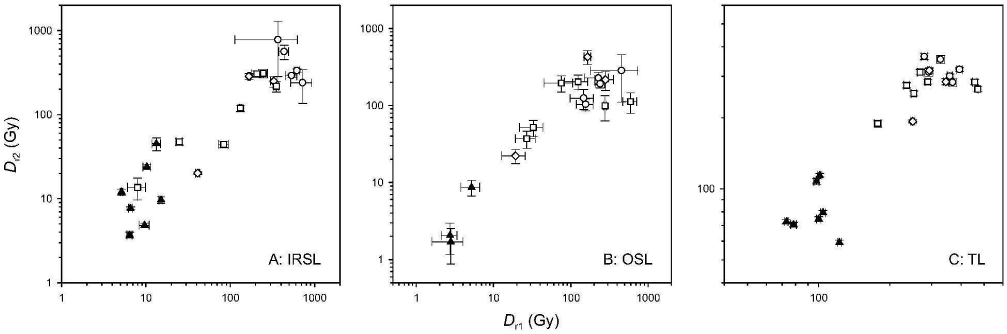

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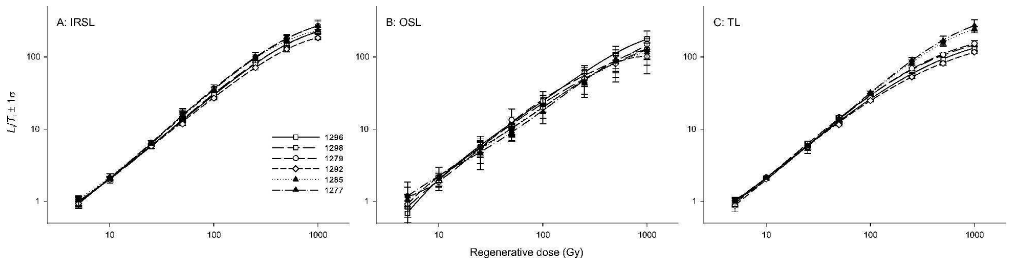

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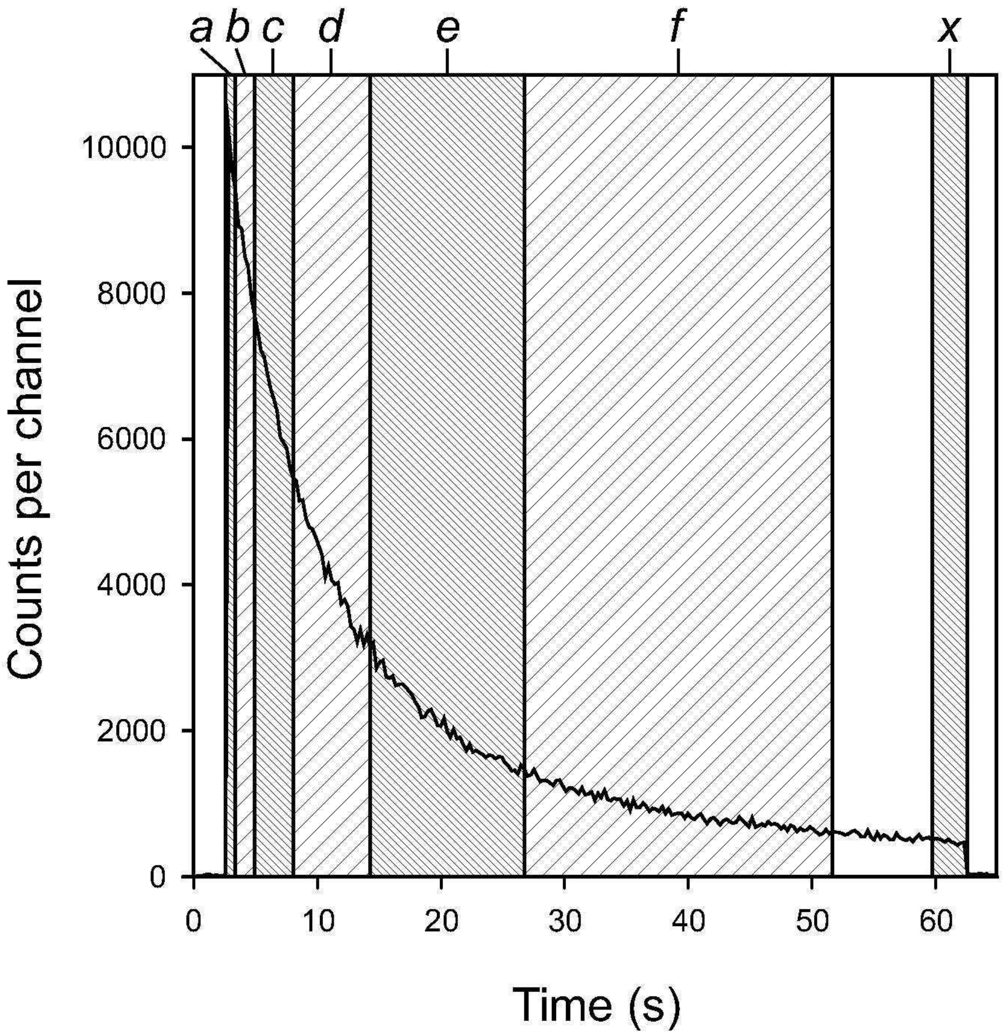

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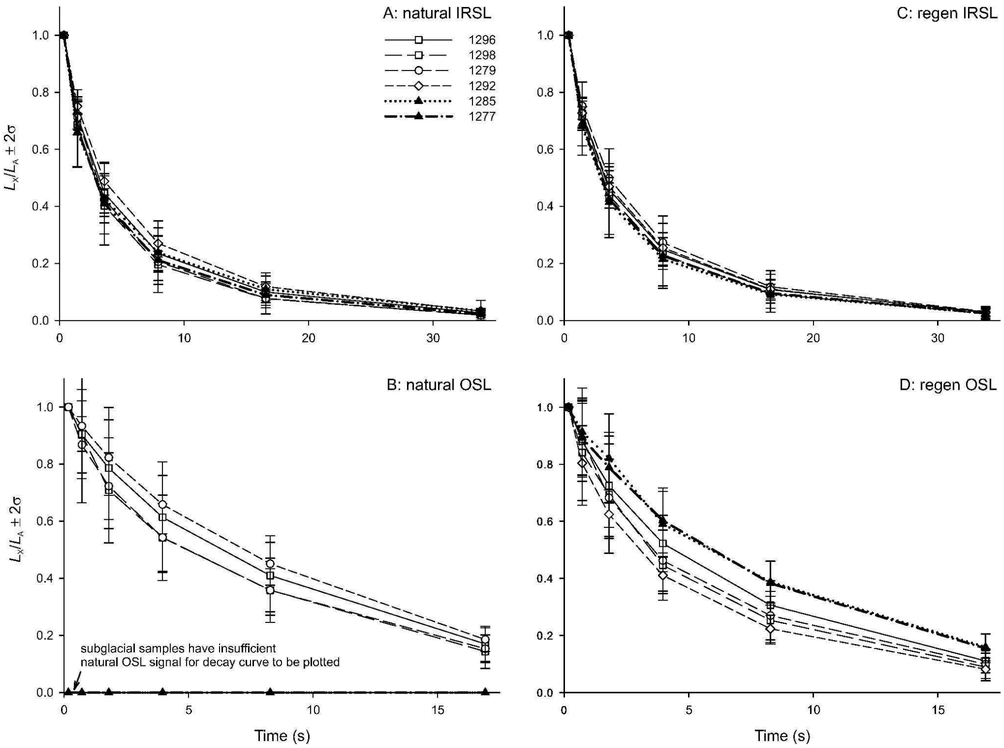

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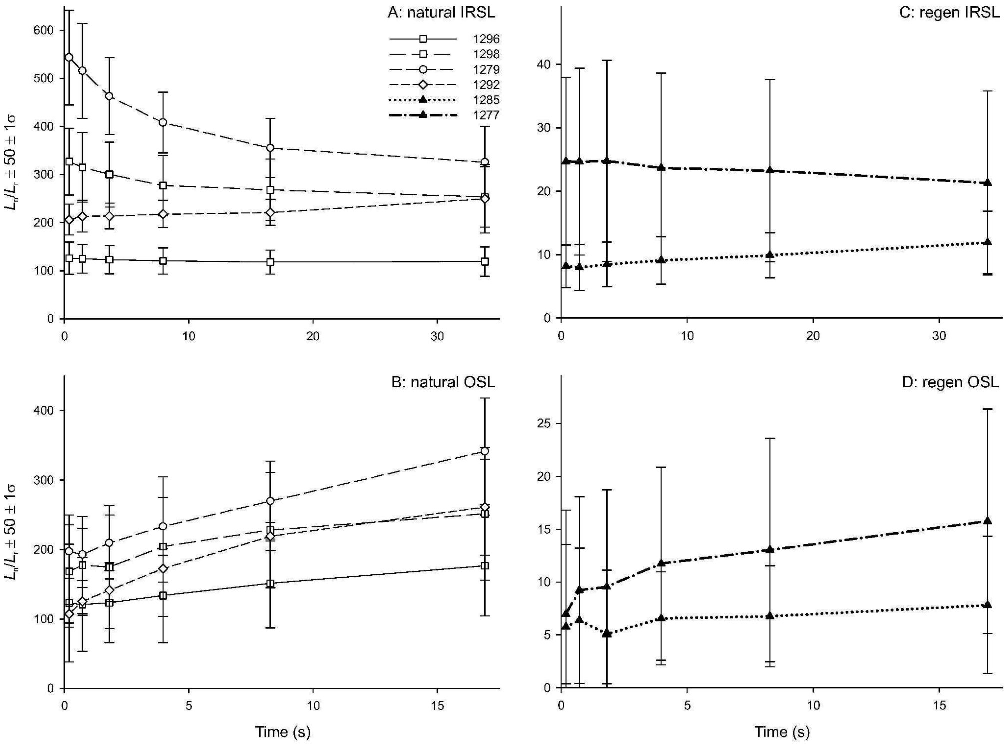

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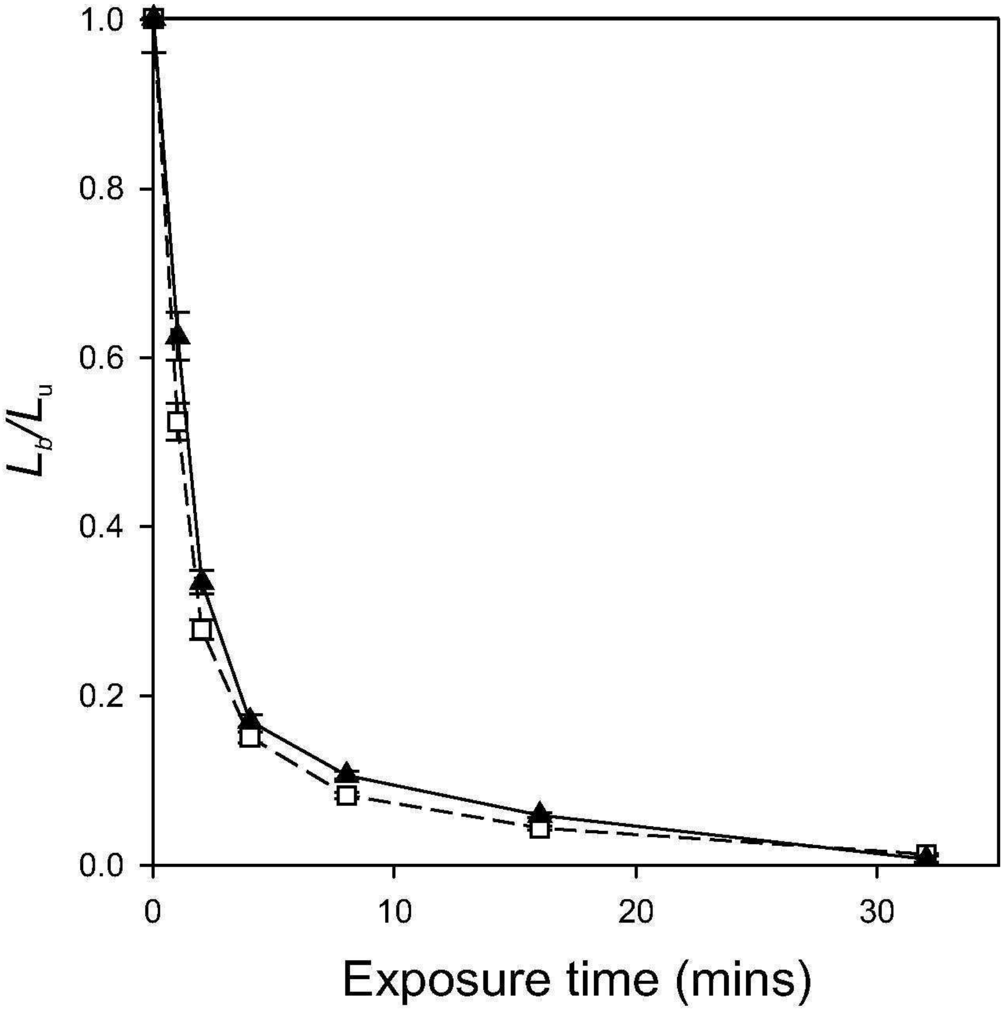

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Table 1: Multiple-stimulation procedure used for initial screening

Step[1]	Treatment	Observed[2]
1	Preheat (220°C for 30s)	–
2	Stimulate IRSL (60s at 60°C)	L_n^{IRSL}
3	Stimulate OSL (30s at 125°C)	L_n^{OSL}
4	Stimulate TL (ambient to 500°C at 5°C s^{-1})	L_n^{TL}
5	Stimulate TL (ambient to 500°C at 5°C s^{-1})[3]	–
6	Give test dose, D_T (5 Gy)	–
7	Preheat (220°C for 30s)	–
8	Stimulate IRSL (60s at 60°C)	T_n^{IRSL}
9	Stimulate OSL (30s at 125°C)	T_n^{OSL}
10	Stimulate TL (ambient to 500°C at 5°C s^{-1})	T_n^{TL}
11	Stimulate TL (ambient to 500°C at 5°C s^{-1})[3]	–

[1] Steps 1–11 repeated following a 50 Gy regenerative dose.

[2] Observed signals obtained from raw stimulation curves (see Fig. 2).

[3] Second heating for TL background subtraction.

Table 2: Comparison of D_r exhibited by each of the sample groups

	IRSL		OSL		TL	
Description	D_r[1]	D_{rs}/D_{rx}[2]	D_r[1]	D_{rs}/D_{rx}[2]	D_r[1]	D_{rs}/D_{rx}[2]
Subglacial sediment	12±8.4	–	2.8±2.0	–	90±13	–
Portal stream sediment	512±77	0.02	292±208	0.01	329±19	0.27
Marginal stream sediment	151±120	0.08	131±121	0.02	287±66	0.31
Surface sediment	182±135	0.07	189±147	0.02	281±52	0.32

[1] Values are means of the D_r estimates shown in Fig. 3; errors are ±1σ.

[2] Mean subglacial D_r (i.e. D_{rs}) as a fraction of mean D_r of the other sample types (i.e. D_{rx}).

Table 3: D_r (i.e. initial screening approach) and SAR D_e for various samples

		D_r^1			D_e^2		
Sample	Description	IRSL	OSL	TL	IRSL	OSL	TL
1277	Subglacial sediment	22±13	8.7±8.4	116±67	28±0.1	6±0.2	102±1.0
1285	Subglacial sediment	7.0±2.1	3.5±4.6	70±13	11±0.1	3±0.1	68±0.8
1279	Portal stream sediment	513±94†	245±91†	325±44	453±4.7	224±6.0	397±3.4
1292	Marginal stream sediment	208±42	136±33	291±23	202±2.4	135±1.2	475±10
1296	Surface sediment	138±63†	77±53†	294±61	126±0.1	75±2.4	360±3.7
1298	Surface sediment	294±95†	161±93	325±65	260±2.0	157±2.6	400±4.5

[1] Values are means of eight aliquots per sample (unless indicated by †); errors are ±1σ.

[2] D_e interpolated from the corresponding SAR growth curve (Fig. 4) using the mean sensitivity-corrected natural signal (L_n/T_n; n=8); ±1σ error has been estimated from the standard error of the regression curve.

†Values are means of seven aliquots per sample, owing to measurement faults.

Table 4: SAR recycling, recuperation and fading characteristics for various samples

	Mean recycling ratio[2,3]			Mean recuperated signal (% of *N*)[2,4]			Signal remaining after 95 days[5]		
Sample[1]	IRSL	OSL	TL	IRSL	OSL	TL	IRSL	OSL	TL
1277	0.86±0.13	1.09±0.19	0.97±0.05	0.52±0.88	9.23±8.16	0.10±0.08	0.62±0.11	0.47±0.16	0.58±0.08
1285	0.89±0.07	0.86±0.11	0.94±0.05	1.78±1.64	24.5±23.9	0.12±0.08	0.57±0.20	0.51±0.11	0.58±0.10
1279	0.92±0.06	1.24±0.44	0.89±0.07	0.02±0.03	0.17±0.26	0.02±0.01	0.60±0.07	0.70±0.20	0.74±0.09
1292	0.85±0.08	1.08±0.31	0.84±0.03	0.04±0.03	0.30±0.24	0.03±0.03	0.70±0.08	0.75±0.05	0.89±0.03
1296	0.94±0.07	1.07±0.15	0.92±0.05	0.03±0.03	0.23±0.16	0.05±0.06	0.58±0.06	0.61±0.12	0.73±0.16
1298	0.95±0.08	1.02±0.28	0.94±0.05	0.04±0.04	0.70±1.07	0.03±0.03	0.70±0.06	0.68±0.14	0.79±0.08

[1] See Table 3 for sample descriptions.

[2] Values are means of eight aliquots per sample; errors are ±1σ.

[3] Recycling ratio obtained from the sensitivity-corrected regenerative signals R_1 and R_9 (see text).

[4] The sensitivity-corrected regenerated signal R_2 (zero dose; see text) is expressed as a % of the sensitivity-corrected natural signal (L_n/T_n).

[5] Ratio of the mean sensitivity-corrected regenerated signal in four stored discs to the mean prompt signal in four control discs ±1σ.

Table 5: Remaining dose after various periods of exposure to different light sources, as a fraction of the 50 Gy original dose

	IRSL		OSL		TL	
	1 min	8 mins	1 min	8 mins	1 min	8 mins
Artificial daylight[1,2]*:*						
Subglacial samples	0.62±0.06	0.10±0.02	0.80±0.09	0.15±0.04	0.29±0.02	0.22±0.02
Proglacial stream samples	0.64±0.13	0.14±0.01	0.53±0.19	0.14±0.03	0.62±0.09	0.26±0.03
Marginal stream samples	0.65±0.12	0.13±0.02	0.69±0.10	0.13±0.05	0.64±0.09	0.26±0.02
Surface sediment samples	0.61±0.17	0.14±0.03	0.66±0.18	0.18±0.07	0.69±0.06	0.30±0.05
Direct sunlight[1,3]*:*						
Subglacial samples	0.05±0.03	–	0.07±0.04	–	0.66±0.03	–
Proglacial stream samples	0.06±0.02	–	0.08±0.08	–	0.59±0.04	–
Marginal stream samples	0.05±0.02	–	0.06±0.04	–	0.56±0.04	–
Surface sediment samples	0.05±0.02	–	0.03±0.05	–	0.60±0.05	–

[1] Remaining dose calculated as L_i/L_u, where L_i is the observed signal after exposure and L_u is the observed signal with no exposure; values are means for each sample group (the number of samples in each group is shown in Fig. 1A); errors are ±1σ.

[2] Irradiance measured using a Molectron PR500 pyroelectric radiometer was approximately 73 W m^{-2}.

[3] Undertaken at East Kilbride on 7th March 2005 at midday GMT; measured energy flux was approximately 1 kW m^{-2}.