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First luminescence-depth profiles from boulders from moraine deposits: insights into glaciation chronology and transport dynamics in Malta Valley, Austria

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Abstract

In this study, we investigate the potential of rock surfaces to provide luminescence burial ages for boulders from moraine deposits. We sampled four boulders from a terminal moraine at the Malta Valley, Austria, all deposited ~2 m below the present ground surface, and measured the IRSL signal as a function of depth into the boulder surfaces. It is clear from these profiles that all four boulders were exposed to at least some daylight prior to final deposition, and in one boulder, there is evidence for multiple exposure/burial events. The profiles show that the luminescence signal at the surface of two boulders must have been completely zeroed before burial. The burial doses derived from these two well-reset surfaces can thus be safely used to calculate burial ages, which may be the same as the depositional age of the terminal moraine. The IRSL signals from both boulders seem to suffer from anomalous fading with g-values of up to 15 % decade⁻¹. The younger fading-corrected age of ~14 ka is in agreement with the deposition of the terminal moraine and coincides with the assumed Gschnitz stadial, while the older age of ~39 ka most likely represents an earlier event during which this boulder was exposed to light.

Our results suggest that there is a high probability of sampling light-exposed and even well-bleached boulders from moraine deposits. We thus conclude that rock surface luminescence dating offers the possibility of obtaining reliable ages for moraine deposition. Even boulders which are partially bleached and thus not suitable for dating can provide insight into transportation pathways as well as depositional processes in glacial environments leading to a better understanding of the dynamics of glaciers.

Keywords: Rock surface luminescence dating, Burial dating, Moraine, European Alps, Gschnitz

1. Introduction

Our knowledge of the extent of past glaciations in various parts of the world is often entirely based on stratigraphic correlations of glacial landforms (e.g. Ellwanger et al., 2011; Grosswald, 1998; Lee et al., 2012; Mangerud et al., 2011). However, many of these correlations lack the numerical chronological framework vital to constrain the timing of glacial advances and retreats. Commonly used dating methods (e.g. radiocarbon, cosmogenic nuclides) can be unreliable when applied to moraine deposits. Radiocarbon (^{14}C) dating depends on organic carbon, which is usually scarce or non-existent, can suffer from contamination, and in any case dates the deposits indirectly with an upper age limit of ~45 ka. Cosmogenic nuclide (CN) dating (most commonly using cosmogenic ^{10}Be) is often the only available method, but it too can be compromised by inherited CN content arising from prior exposure or by post-depositional displacement of the boulder; both of these can lead to a large scatter in the data, especially in older deposits (>20 ka) (Applegate et al., 2012, 2010; Heyman, 2014; Heyman et al., 2011; Putkonen and O'Neal, 2006; Putkonen and Swanson, 2003).

More recently, a new luminescence dating technique has been proposed, based on the resetting of luminescence signals with depth into rock surfaces (e.g. Chapot et al., 2012; Freiesleben et al., 2015; Jenkins et al., 2018; Sohbati, 2015; Sohbati et al., 2011). One of the basic assumptions in conventional luminescence dating is that the sedimentary grains are sufficiently exposed to light, so that the latent luminescence signal is completely reset prior to burial; this assumption cannot be readily tested for individual grains. The great advantage of luminescence rock surface dating is that the extent of resetting is recorded within the rock. Thus, luminescence signals associated with distinct events can be identified and measured. This not only allows us to reliably determine the deposition age of a rock surface, by extracting the signal acquired since burial, but under certain circumstances, to also identify multiple burial and exposure events in the history of a single clast (e.g. Freiesleben et al., 2015; Sohbati et al., 2012a, 2015). In the context of glacial environments, this information can also provide insight into the transportation and depositional processes of moraine boulders, e.g. what fraction of moraine boulders are plucked from bedrock and transported

beneath the ice and so never exposed to daylight; such knowledge is almost impossible to obtain by any other existing methods. This makes data from each boulder valuable, irrespective of whether or not it is suitable for dating.

In this study, we evaluate the potential of rock surface burial dating (i.e. dating the time since burial of a rock surface) for moraine deposits. Glacial environments are known to be difficult to date using conventional luminescence dating of sediment grains due to incomplete bleaching and often poor quartz luminescence sensitivity (e.g. Fuchs and Owen, 2008). In this respect, luminescence-depth profiles in rocks have a big advantage as they allow us to make a statement about how far the bleaching front penetrated into the rock prior to burial and to what depth the luminescence signal was completely zeroed. Furthermore, CN dating assumes that the most effective erosional process of glaciers is subglacial and therefore most boulders found in moraine deposits are deposited without previous exposure to cosmic rays and consequently to daylight (e.g. Balco, 2011); this assumption is testable using luminescence rock surface dating. Here we address these issues and assumptions in dating glacial landforms by examining luminescence-depth profiles in small boulders taken directly from within a terminal moraine in order to investigate the daylight exposure history of the boulders (e.g. whether light exposed, and if so, how many exposure/burial events). A secondary aim is to evaluate the applicability of the technique to date moraine deposits.

2. Materials and methods

2.1. Samples from the Malta Valley terminal moraine

The terminal moraine sampled for this study is located in the Malta Valley, southern Austria (Fig. 1). The upper part of the valley extends to the Tauern Window, where gneisses from the sub-penninic Venediger nappe are exposed (Pestal et al., 2006). These gneisses are most likely the source of the rocks deposited in the valley by glaciers (Reitner, 2005). No direct numerical dating is available for this terminal moraine, but according to the published map of the Geological Survey of Austria (Pestal et al., 2006) it is associated with the Gschnitz stadial (Reitner, 2005) at about ~15 - 16 ka (Federici et al., 2012; Ivy-Ochs et al., 2006a, 2006b; Ravazzi et al., 2014; Reitner et al., 2016). Boulders from within the moraine were taken from the upper part (~2 m below the present ground surface) of the terminal moraine (46.955 °N, 13.493 °E, 4678 m NN) in a natural outcrop incised by the Malta River (Fig. 1). The boulders were completely covered before excavation. After cutting back the section, exposed boulder surfaces were spray-painted black; to avoid additional light exposure, the whole boulder was

then wrapped in an opaque bag as it was released from the surrounding sediment. A sample of the surrounding matrix was also collected for dose rate measurements. After unpacking of the samples under subdued orange light in the laboratory all boulders could be identified as fine foliated gneisses. The gneisses are not highly metamorphic and have a mineralogical composition resembling that of granites. Following Benn and Ballantyne (1994), boulder MAL-01 (210 mm × 140 mm × 80 mm) can be classified as a rod, MAL-03 (210 mm × 140 mm × 100 mm) is between rod and slab and MAL-05 (240 mm × 220 mm × 90 mm) is a slab. All three boulders are well rounded. MAL-02 (110 mm × 100 mm × 90 mm) is of spherical shape, but very angular.

2.2. Laboratory work

Following Sohbaty et al. (2011), boulders were drilled using a diamond-tipped, water-cooled core drill with a resulting core diameter of ~10 mm. The cores were sliced in 1.5 mm increments, using a water-cooled low-speed wafering saw with a diamond-coated blade. The blade was 0.3 mm thick, resulting in slices ~1.2 mm thick. Some of the surface slices were treated using 10% HF for 40 min. and 10% HCl for 20 min. to remove any coatings or weathering by-products that could affect the signal. No difference was observed between the luminescence signals from chemically treated and untreated surface slices. No chemical treatment was applied to the inner slices.

The infrared stimulated luminescence (IRSL) signal was measured using a Risø luminescence reader model TL/OSL DA 20, equipped with Schott BG-39/Corning 7-59 blue filter combination following a single-aliquot regenerative-dose (SAR) protocol (Table 1). The reader was calibrated using quartz rock slices sensitised and irradiated in the same way as calibration quartz used for normal calibration (Hansen et al., 2018, 2015). The IRSL signal was measured at 50 °C with a preheat temperature of 250 °C for 100 s (Wallinga et al., 2000). A high temperature IR stimulation at 290 °C at the end of each cycle was also employed to minimize a possible signal transfer to the next cycle (Murray and Wintle, 2003).

3. Luminescence measurements

3.1. Profile and dose measurement

For cores longer than 20 mm, the natural sensitivity-corrected signal (L_n/T_n) of each slice was first measured to construct the luminescence-depth profile, using a test dose of ~106 Gy or ~47 Gy (Table 1). The equivalent doses (D_e) of all surface slices (depth <1.5 mm) were also

measured by constructing dose-response curves for individual slices using SAR. In addition, a saturation dose of ~ 4 kGy was given to 6 inner slices from each boulder using a ^{60}Co gamma source and measured using the same test dose as for the natural signal, to establish the sensitivity-corrected signal corresponding to laboratory dose saturation in our samples ($L_{\text{Sat}}/T_{\text{Sat}}$).

For residual dose and dose recovery tests, six fresh surface slices from each sample later identified as suitable for dating (i.e. MAL-03 and MAL-05) were bleached in the solar simulator (Hönle SOL 2) for three days. Residual dose measurements using three slices from each sample revealed low residuals of 0.4 ± 0.1 Gy (MAL-03) and 0.6 ± 0.2 Gy (MAL-05). The three remaining slices were given a dose of ~ 9.4 Gy. The dose recovery ratios were then calculated by first subtracting the residual doses from the measured doses, and then dividing by the given dose. The derived ratios of 0.93 ± 0.04 ($n = 3$) and 0.97 ± 0.004 ($n = 3$) for MAL-03 and MAL-05, respectively, are indistinguishable from unity, and it is concluded that our SAR protocol is able to measure accurately a known dose given to these samples before any thermal treatment.

3.2. Anomalous fading

The luminescence-depth profiles (Fig. 2) show that the deeper slices are in field saturation and should, therefore, represent the signal of an infinitely old sample. However, the L_n/T_n of these inner slices plot below the saturation level in laboratory dose-response curves (Fig. S1). This observation is in accordance with the well-known instability of the K-feldspar IRSL signal arising from anomalous fading. Therefore, fading measurements were conducted on 12 inner slices of long cores from each sample following Auclair et al. (2003). Before measurement, the slices were bleached in the solar simulator for four hours to erase any latent IRSL signal. The g -value was measured using different delays between irradiation and IRSL measurement, with the longest delay of > 8 weeks after irradiation (Fig. S2).

4. Dose rate

For the measurement of the radionuclide concentrations (^{238}U , ^{226}Ra , ^{232}Th and ^{40}K) within the rocks and in the surrounding sediment, subsamples of the rocks and a sediment sample were pulverized and homogenized. The sediment sample was then ashed at 450°C for 24 h to remove organic matter. To prevent loss of radon and to provide a standard counting geometry, the crushed material was cast in wax in a cup-shaped mould. After storage for more than three weeks to achieve ^{222}Rn equilibrium, the casts were measured with a high-

purity germanium detector for more than one day (cf. Murray et al., 2018, 1987). As mentioned above, only one sediment sample was taken for the dose rate of the surrounding sediment because of the apparently homogeneous nature of the finer material; no bedding or other structures could be detected in the deposits (Fig. 1). Given the rock spacing, the gamma doses from surrounding rocks embedded in the moraine deposits are most likely negligible compared to the dose rates already incorporated into the dose rate calculations. Following Freiesleben et al. (2015) we did not account for the alpha dose rate because the contribution to the total dose rate is negligible; this is also supported by the fact that we could not find any difference between D_e s from untreated surface slices and surface slices etched with HF. As the boulders were surrounded by sediment we modelled the variation of dose rate at the rock/sediment interface following Aitken (1985: Appendix H) (cf. Sohbati et al., 2015). The factors for beta and gamma attenuation (Table 2) were taken from Sohbati et al. (2015). This variation of dose rate with depth was incorporated in the modelling of the depth profiles.

In order to estimate the average feldspar grain size in our samples, we measured the spatial distribution of K, Na, Ca, Al across several slice surfaces from each boulder (Figs. 3, S3) using a Micro X-ray Fluorescence spectrometer with a spot size of $\sim 20\mu\text{m}$ ($\mu\text{-XRF}$, M4 Tornado, Bruker). We used the graphical software ImageJ (Schneider et al., 2012) to convert the possible grains seen in the $\mu\text{-XRF}$ element mapping into ellipsoids and take the mean ferrets to represent grain size range (Table 3); these range between $490 \pm 250\mu\text{m}$ (MAL-01) and $230 \pm 140\mu\text{m}$ (MAL-03). Taking a closer look at the K-distribution in the $\mu\text{-XRF}$ images it can clearly be seen that the larger green areas are not single crystals but apparent aggregations of grains (Figs. 3, S3). We therefore excluded bigger aggregations of grains by choosing a maximum ellipsoid area of 1 mm^2 . In all the samples, except for MAL-01, the K-rich areas in the samples are in sub-millimetre distance from each other. We focus particularly on the K-rich areas, because K-rich feldspars have long been understood to dominate the blue emission band of IRSL from feldspar (Baril and Huntley, 2003; Prescott and Fox, 1993; Sohbati et al., 2013; Thomsen et al., 2018; Tsukamoto et al., 2012). Thomsen et al. (2018) have also recently shown that the blue IRSL emission from granite rock slices mainly originates from K-rich feldspar. K-concentrations obtained from gamma spectrometry in the sampled boulders are mostly low except for MAL-02 (Table 2). We therefore investigated whether the K-rich areas are likely to be made up of K-feldspars with a typical K-content of 10-14 % (it is widely assumed that blue luminescence from feldspars is predominantly from such K-rich feldspar, e.g. Baril and Huntley, 2003; Buylaert et al., 2018;

Rades et al., 2016). The percentage of the total K-rich area of the slices determined by μ -XRF was calculated from the μ -XRF mapping and assumed to represent the percentage of K-rich areas in the whole rock. This mapping shows that K is evenly distributed in these areas and thus that the K-content in the mapped areas should be similar in concentration. The average K concentration from gamma spectrometry (Table 2) represents the whole K concentration of the rock and so by using the average area and average concentration one can derive the mean K concentration in the K-rich areas. This gives the average K concentration in K-rich areas to be significantly lower than the commonly assumed percentage: 1.6% by weight for MAL-01, 1.7% for MAL-03 and 5% for MAL-05 (Table 3). Only in MAL-02 does the K-concentration approach the usually assumed 12.5% (Table 3). We assume that the areas with high K concentrations are feldspar minerals; given the apparent uniformity of K concentrations in K-rich areas, even if other minerals containing K are present they must have a similar average K content. Dose rates are then calculated using the derived mean grain size for each sample, together with the appropriate calculated K concentrations in K-rich areas.

Results

4.1. Luminescence-depth profiles

Even without modeling, considerable information is available from the luminescence-depth profiles (i.e. L_n/T_n vs. depth, Fig. 2). None of the profiles show disturbances such as have been attributed to opaque minerals by Meyer et al. (2018). This is not surprising as no significant change in lithology could be found in between the slices of the different cores (Figs. 3, S3). All our samples were buried at the time of sampling. Nevertheless, the cores from one surface (see depths 0-3 mm in Fig. 2a) of sample MAL-01 show a signal increase with depth (suggesting prior light exposure), while the core taken from the opposite side of the boulder, shows a similar signal at all depths (depths > 60 mm in Fig. 2a). Four cores of MAL-02 (depth 0-4 mm) show a signal increase with depth for the first two to three slices, followed by a plateau, and then a further gradual increase from about 18 mm to finally reach the saturation level in rock at > 22 mm (second plateau; Fig. 2b). This profile shape is characteristic of that expected from two subsequent exposure/burial events, where the second exposure is shorter than the first (and so leaves some of the signal from the first burial event unbleached). It is also interesting to notice that the profiles have the same depth for the beginning of the first plateau, but the increase of signal leading to the second saturated

plateau starts at slightly different depths in different cores. The core of sample MAL-02 which was taken on the opposite side also shows a decrease of signal at least for the first four slices, but the increase of signal into the depth is not as steep as for the surface of the other side of the boulder. The cores data of sample MAL-03 (Fig. 2c) behave similarly to those from MAL-01 except that, although the two slices nearest the surface have been bleached, daylight has not been able to reset the latent luminescence deeper into this rock surface. For MAL-05 cores could only be recovered from one side due to the brittle nature of the boulder. The L_n/T_n profiles show a very similar exposure history in all three cores of this sample (Fig. 2d).

The profiles were fitted using the Nonlinear Least Square function of R (R Core Team, 2017) and the model from Sohbati et al. (2015):

$$L(x) = \left(\frac{\overbrace{\left(\frac{e^{-t_{e1}\sigma\phi_0 e^{-\mu x}} - 1}{e^{-t_{e2}\sigma\phi_0 e^{-\mu x}} - 1} \right)}^{\text{2nd exposure event}}}{\underbrace{\left(\frac{e^{-t_{e1}\sigma\phi_0 e^{-\mu x}} - 1}{e^{-t_{e2}\sigma\phi_0 e^{-\mu x}} - 1} \right)}_{\text{1st burial event}}} + 1 \right) e^{-\frac{\dot{D}(x)}{D_0} t_{b2}} + 1$$

$\sigma\phi_0$ is the decay rate of the luminescence signal at the boulders surface (ka^{-1}), μ is the light attenuation factor (mm^{-1}) and $\dot{D}(x)$ is the dose rate as a function of depth. This equation includes terms for two exposures (t_{e1} , t_{e2}) and two burials (t_{b1} , t_{b2}); this is the number of events that we observed for MAL-02 in this study. The best-fit parameter values obtained by fitting this equation to a present-day profile can be used in the relevant part of the equation to reconstruct the evolution of the profile retrospectively (cf. Sohbati et al., 2015). The fitting residuals (observed data minus fitted values) show no significant systematic deviations with depth (Fig. S4). To determine the depth at which the boulder surfaces were sufficiently bleached before the last burial, the present-day profile (obtained by fitting to the observed L_n/T_n data) and a modeled profile omitting the final burial event (L_m/T_m) were compared (Fig. 2). The comparison between these profiles shows that the surface slices (depth < 1.5 mm) from two out of four samples (i.e. MAL-03 and MAL-05) were bleached sufficiently to be used for age determination (surface modelled data omitting the final burial event $< 3\%$ of the observed L_n/T_n , Fig. 2; see al Khasawneh et al. 2018). The profile with the yellow triangles of MAL-05 is on the edge of the threshold value, therefore some of the surface slices could have a small residual dose left from the burial before the last exposure and thus lead to a slight overestimation.

4.2. Age calculation

For age calculation, the surfaces of boulders MAL-03 and MAL-05 identified as sufficiently bleached prior to burial were sampled by drilling short cores into the surface and measuring the D_e values from surface slices (depth < 1.5 mm). The D_e from these surfaces are 20 ± 2 Gy ($n = 11$; MAL-03) and 31 ± 2 Gy ($n = 8$; MAL-05). This gives uncorrected IRSL ages of 10.2 ± 1.2 ka and 8.4 ± 0.1 ka, respectively (Table 4). The D_e values for both samples are large compared to the measured residual doses (0.4 ± 0.1 for MAL-03 and 0.6 ± 0.2 for MAL-05), and these values are neglected in the age calculation. The age of the surface of MAL-02 (6.2 ± 0.2 ka, $n = 1$) was also calculated from the surface slice of the only core (yellow triangles; Fig. 2b) that is identified as sufficiently bleached.

4.3. Fading corrected ages

Measurement of fading ($g_{2\text{days}}$; following Auclair et al., 2003) on all the samples gave rates of between 3.9 ± 2.6 % decade⁻¹ ($n=12$; MAL-01) and 15.1 ± 0.9 % decade⁻¹ ($n=12$; MAL-03) (Table 4). A g -value of 15 % decade⁻¹ implies that there should not be any significant natural signal remaining in MAL-03, whereas in fact we observed a D_e of 20 ± 2 Gy; it is deduced that the ' g ' value for this sample is a considerable over-estimate. For MAL-05 ($D_e = 31.4 \pm 1.5$ Gy) the fading rate was 6.8 ± 0.7 % decade⁻¹ ($n=12$) which gives a fading corrected age of 14 ± 2 ka (Huntley and Lamothe, 2001; Kreutzer, 2017). The corrected age for the single surface slice of sample MAL-02 ($D_e = 36.0 \pm 1.2$ Gy) gives 14 ± 1 ka (Table 4).

An alternative approach to fading correction is through a comparison between the natural and laboratory saturated signals (Rhodes, 2015; Sohbaty et al., 2014). In all our samples, the natural (field) saturation level in the deepest part of the profiles is significantly lower than the laboratory saturation level measured from the same slices; this natural signal is presumably in a dynamic equilibrium between signal growth due to dose rate and signal loss due to fading (Fig. S1). This provides a direct measure of the effect of fading for a sample that has been in saturation for a prolonged period (perhaps a few 100s of ka after the rock cooled). It is likely that fading is at its most rapid at high doses (Huntley and Lian, 2006; Kars et al., 2008), and so the ratio between the natural and laboratory saturation levels provides an upper limit to the effect of fading. This natural-to-laboratory saturation (NLS) ratio was derived for each sample by dividing the natural L_n/T_n by the $L_{\text{sat}}/T_{\text{sat}}$ from slices given a laboratory dose of ~ 4 kGy (Table 4). The uncorrected ages were then divided by these ratios to give 18.5 ± 0.4 ka (MAL-02), 39 ± 5 ka (MAL-03) and 14 ± 1 ka (MAL-05).

5. Discussion

5.1. Bleaching of boulders during glacial transport and deposition

The main purpose of this pilot study was to investigate whether boulders from moraine deposits were exposed to daylight prior to their last burial. Two processes may be of interest here: (i) the mechanism providing the boulders/clasts (e.g. plucking from bedrock, uptake from previously deposited sediments with possible extended light exposure, and rockfall on top of the glacier), and (ii) the transport process before final deposition either directly by the ice (subglacial, inglacial, supraglacial) or by glaciofluvial processes (supra-, in-, subglacial and proglacial). Both processes could, in principle, provide opportunities for exposure of boulders to daylight - either by exposure to light in front of the ice before being moved by the forward moving glacier, or by exposure before and/or during the supraglacial and proglacial transport. Profiles from all four boulders in our study show evidence of exposure to daylight of at least one sampled surface. One of the boulders even appears to have recorded two separate exposure/burial events, a first prolonged exposure, followed by a burial, then a second much shorter exposure event, and finally the most recent burial (Fig. 2b). The duration of the last exposure before burial is unknown, because there is no known-age calibration sample available (Sohbati et al., 2012b), but this last exposure only affected the surface slice and at most the outer 3-4 mm of the boulder surface. This exposure may have taken place after the boulders were deposited by supraglacial transport and before they were covered by more material – a process that might take months to years, but probably not decades. It is also interesting that in two of the three samples for which it was possible to measure profiles from opposite surfaces of the boulders, one surface had apparently not been exposed to light. It is difficult to imagine that only one side of a boulder would record a light exposure during supraglacial transport; the latter is much less abrasive than subglacial transport (Boulton, 1978; Lukas et al., 2013 and references therein) and there is bound to be some turning of the boulders. Thus, for a boulder at the surface of the ice, all surfaces are expected to have experienced some daylight exposure, if only through ice. Thus, we interpret the fact that one side of a boulder was not light exposed to indicate that the exposure took place when the boulder was lying on the ground (either before or after ice transport), rather than during transport.

MAL-02 is more complicated because one of the surfaces shows a very long exposure; it is the most angular of the samples and the long exposure is only recorded in one of the surfaces (Fig. 2b). The angularity may be an indicator of supraglacial transport (Benn and Ballantyne,

1994; Boulton, 1996, 1978; Lukas et al., 2013) because subglacial transport leads to more erosion and surface loss (Benn and Ballantyne, 1994; Boulton, 1978; MacGregor et al., 2009). We speculate that this boulder may have been exposed on the valley side for a considerable period, then transported supraglacially to the moraine deposit; it was probably exposed to light to some degree during transport, and one surface was presumably exposed immediately after deposition. The penetration depth due to the long exposure event varies in the different profiles from the same side of the boulder. This could be because of periodic partial cover on the valley side, but perhaps more likely reflects loss of surface as a result of abrasion/chipping during transport.

We have only examined four boulders, and certainly acknowledge that none of these speculations regarding transport can be regarded as firm. Nevertheless, they do serve to illustrate the considerable potential of luminescence to give information on the relative importance of different transport pathways through the glacier, as well as the likely origin of individual boulders. Only the measurement of profiles for a much larger number of boulders and surfaces will show whether morainic boulders can indeed be grouped into those transported supraglacially or sub-glacially, and those sourced from hillslopes, or from bed plucking.

5.2. Fading rate estimation

The signals from slices from deep within the rock, in field (natural) saturation, clearly underestimate those from laboratory saturation doses, presumably because of fading. Using either the standard g-value age correction or the NLS ratio gives same age of ~14 ka for sample MAL-05, which, given the uncertainties, is consistent with published ages for the Gschnitz stadial (Ivy-Ochs et al., 2006a, 2006b). In contrast, the single surface slice of MAL-02 seems to be either younger or older than the Gschnitz, depending on the fading correction method applied. These data suggest that, under the right circumstances, rock surfaces may record moraine emplacement; this is very promising. For MAL-03, correction using the NLS ratio gives an age of 39 ± 5 ka, much older than expected. Correction using a g-value of >15 % decade⁻¹ is not possible; this anomalously high apparent fading rate is clearly unrealistic, given the more limited signal loss observed in the inner part of the rock. It seems likely that MAL-03 was exposed and then buried at ~39 ka, before the final transport event recorded by MAL-05 and possibly MAL-02. In this scenario, MAL-03 was not exposed to significant daylight either during last transport or after emplacement in the moraine. A much larger

number of samples is needed to determine whether this age of ~39 ka reflects a major depositional event in our study area.

6. Conclusions

It seems likely that the luminescence signals from deep within rocks can be used to give an upper limit to the likely effects of fading; in at least one of our samples, the laboratory estimate of fading grossly overestimated these effects. The luminescence-depth profiles measured in this study demonstrate that all of the four boulders sampled from a moraine deposit in the Malta Valley were exposed to light before final burial. These results are very promising; more extensive rock surface dating studies on such deposits are required and, if our results are common, suggest a potential for a robust new method for dating moraines. Luminescence-depth profiles also show a great potential for investigating transport processes in glacial environments.

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Figure Captions

Fig. 1: a) An excerpt from the geological map *Spittal an der Drau* 1:50.000 (Pestal et al., 2006), showing the location of the sampling site in the Malta Valley. The inset shows the location of the sampling site in the Alps. The terminal moraines associated with the Gschnitz stadial are marked by a red line. The glaciers that transported the moraine flowed from the northwest to the southeast. (a) View alongside the outcrop of moraine deposits in northern direction. The river Malta is to the right > 80 m below the sampling location. The top part of the deposits is of darker colour; this gives a clearly visible boundary between soil and undisturbed deposits. c) Location of MAL-02 in the moraine in the vicinity of a boulder of > 1 m diameter. This large boulder is also visible in the background of picture (a). (d), (e) Boulders MAL-01, MAL-03 and

MAL-05; the newly-exposed surfaces were painted with black spray immediately after excavation.

Fig. 2: Luminescence-depth profiles measured from cores into four boulder samples MAL-01 (a), MAL-02 (b), MAL-03 (c) and MAL-05 (d). The y-axis shows the L_n/T_n data of the individual slices on logarithmic scale. The x-axis represents the depth from the surface along the shortest diameter of the boulder, except for MAL-05, where only one surface was sampled. The first inset with the grey background shows the L_n/T_n for the first five slices in more detail to provide a better view on this part of the profile, which is close to the surface and therefore critical for the assessment of the bleaching front into the rock. The curves in the second, smaller inset (y-axis not on log scale) represent the modelled pre-burial L_m/T_m profiles (M) divided by the profiles fitted to the L_n/T_n data (N) for the depth of the first two slices (3 mm) into the rock surface. These curves are used to determine the extent of bleaching before burial (dotted line: threshold $M/N = 3\%$).

Fig. 3: μ -XRF measurements on slices for one core from samples MAL-03 and MAL-04. Al, Ca, K and Na were measured as main elements in feldspar. These images were used to estimate the average grain size of the feldspar minerals in the boulders. The slices are taken from the same cores and each slice is ~1.2 mm thick.

Fig. S1: Typical dose response and (inset) natural and first regeneration stimulation curves measured from the surface and a deep saturated slice of a core from each boulder.

Fig. S2: Selected plots of the g-value measurements of 12 slices for each boulder carried out after Huntley and Lamothe (2001). Given dose to MAL-02 and MAL-05 was ~47 Gy for and the test dose was ~9 Gy. For MAL-01 and MAL-03 the given test doses were ~105 Gy and ~21 Gy, respectively.

Fig. S3: Micro-XRF measurements on slices for one core from samples MAL-01 and MAL-01. Al, Ca, K and Na were measured as main elements in feldspar. These images were used to estimate the average grain size of the feldspar minerals in the boulders. The slices are taken from the same cores and each slice is ~1.2 mm thick.

Fig. S4: Residuals (observed minus calculated) for the fitted luminescence-depth profiles. Only small systematic error can be observed.

Fig. S5: Histograms of the D_e distribution of the surface slices used for age determination. The standard error (open circles) on the average D_e in each histogram is shown on the secondary (right) y-axis. The slice marked in black for MAL-05 was considered an outlier and is not part of the final equivalent dose calculation.

Table captions:

Table 1: The SAR protocol used in this study

Table 2: Summary of sample codes, radionuclide concentrations and the effective beta and gamma dose rates to surface slices.

Table 3: Percentage of K in grains inferred from the micro-XRF measurements gamma spectrometry

Table 4: Results of quality tests, dose rates and final ages

Table 1. The SAR protocol used in this study

Step	Treatment	Observed
1*	Give dose	
2	Preheat 250 °C for 100s	
3	Stimulation with IR for 200s at 50 °C	L_x (IRSL ₅₀)
4**	Give test dose	
5	Preheat 250 °C for 100s	
6	Stimulation with IR for 200 s at 50 °C	T_x (IRSL ₅₀)
7	Stimulate with IR for 200 s at 290 °C	

* Given doses for the dose response curve measurements for the outermost and deepest slices of individual profiles were at 5.3 Gy, 79 Gy, 106 Gy, 265 Gy, 1058 Gy and 1587 Gy. Given doses for the D_e measurements of MAL-03 were 0 Gy, 5.3 Gy, 11 Gy, 21 Gy with 5.3 Gy as recuperation and 11 Gy, 21 Gy, 42 Gy, 0 Gy with 11 Gy as recycling dose;

** Test dose for the D_e measurements was 5.3 (MAL-03) and 10.6 Gy (MAL-05). For the profiles the test dose was set to 106 Gy except for the measurements of MAL-01 core4 and Mal-02 core 2 where it was ~47 Gy.

Table 2: Summary of sample codes, radionuclide concentrations and the effective beta and gamma dose rates to surface slices.

Sample ID	$^{226}\text{Ra}^*$	^{232}Th	^{40}K	Beta dose rate**	Gamma dose rate***
	(Bq kg ⁻¹)	(Bq kg ⁻¹)	(Bq kg ⁻¹)	(Gy ka ⁻¹)	(Gy ka ⁻¹)
MAL-01	6.66 ± 0.45	3.04 ± 0.38	98.7 ± 6.7	0.87 ± 0.17	0.847 ± 0.091
MAL-02	114.4 ± 1.9	44.1 ± 1.2	1135 ± 31	4.90 ± 0.35	1.882 ± 0.081
MAL-03	6.05 ± 0.41	4.37 ± 0.36	160 ± 8	0.90 ± 0.16	0.877 ± 0.088
MAL-05	36.6 ± 1.1	29.73 ± 0.90	671 ± 21	2.46 ± 0.13	1.331 ± 0.072
Sediment	53.1 ± 1.2	60.3 ± 1.1	598 ± 18	-	-

* Cosmic dose rate is calculated to be 0.17 Gy for all the samples after Prescott and Hutton (1994). For the sediment sample a water content of 10% was assumed. Beta and gamma attenuation coefficients are assumed to be 1.89 mm⁻¹ and 0.015 mm⁻¹, respectively after Sohbati et al. (2015). We assumed equilibrium in the ^{238}U decay chain for all the samples. For the sediment sample we assumed a 20 ± 10% loss of ^{222}Rn .

** Integrated over the depth between 0 and 1.5 mm into the rock surface (surface slice) calculated with the internal dose rate presented in Table 3. This effective dose rate includes the dose rate coming from the surrounding sediment.

*** Integrated over the depth between 0 and 1.5 mm into the rock surface (surface slice). This effective dose rate already includes the dose rate coming from the surrounding sediment.

Table 3: Percentage of K in grains inferred from the micro-XRF measurements gamma spectrometry

Sample ID	% K-rich area in micro-XRF image [%]	K-feldspar abundance in the rock assuming 12.5% K content in K-feldspar grains* [%]	Concentration of K in K- feldspar grains** [wt%]	Mean ferret of mineral grains [$\mu\text{m} + \text{SD}$]	Internal dose rate [Gy ka^{-1}]
MAL-01	17.8	2.27	1.59	490 $\pm$ 250	0.23 $\pm$ 0.08
MAL-02	28.9	28.7	12.41	420 $\pm$ 220	1.48 $\pm$ 0.05
MAL-03	30.1	4.05	1.68	230 $\pm$ 140	0.12 $\pm$ 0.04
MAL-05	44.5	16.97	4.77	250 $\pm$ 190	0.38 $\pm$ 0.04

* Calculated using the gamma-spectrometry results for ^{40}K from Table 2.

** Calculated using the ratio of mapped K-feldspar abundance and the assumed abundance of 12.5%.

Table 4: Results of quality tests, dose rates and final ages

Sample ID	Residual Dose (Gy)	Dose recovery (-)	Fading-rate (%decade ⁻¹)	n (g-value measurement)	Natur. sat / Lab. sat	Total Dose rate** (Gy)	D _e (Gy)	n (D _e measurement)	Age (uncorrected) (Ka)	Age (corrected)* (Ka)	Age (corrected)*** (Ka)
MAL-01	-	-	3.9 ± 2.6	12	0.36	1.884 ± 0.089	-	0	-	-	-
MAL-02	-	-	9.17 ± 0.49	12	0.34	6.95 ± 0.22	36.0 ± 1.2	1	(6.21 ± 0.20)	13.7 ± 1.1	(18.49 ± 0.37)
MAL-03	0.30 ± 0.04	0.93	15.1 ± 0.87	12	0.26	1.949 ± 0.086	20.1 ± 1.8	11	10.2 ± 1.2	-	39.1 ± 4.6
MAL-05	0.41 ± 0.01	0.97	6.8 ± 0.74	12	0.59	3.959 ± 0.082	31.4 ± 1.5	8	8.38 ± 0.71	14.1 ± 1.7	14.2 ± 1.2

* integrated over the depth between 0 and 1.5 mm into the rock surface (surface slice);** fading correction (Kreutzer 2017) after Huntley and Lamothe (2001); *** NLS ratio correction;

Fig. 2

Highlights:

- First luminescence depth profiles from alpine glacial boulders
- Records of several burial and exposure events are identified in moraine boulders