

Research Paper

Single grain optical dating of glacial deposits

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Abstract

Determining the age of glacial sediments is difficult for many geochronological methods because of the lack of suitable materials for analysis. Luminescence dating can be applied to the mineral grains making up the glacial sediments. However a major source of uncertainty in previous studies has been whether the mineral grains were exposed to sufficient daylight prior to deposition for the luminescence signal to be reset. Measurements of the optically stimulated luminescence signal from single sand-sized quartz grains offers the potential for explicitly identifying if a sediment contains grains that were not exposed to sufficient daylight to reset their signal. Statistical analysis of the resulting data can then reject those grains to allow the age of the sample to be determined. This study is the first to apply single grain optical dating to glacial sediments, and demonstrates the issues involved by analysis of samples from Chile and Scotland. Ages from 2.4 ± 0.5 to 17.3 ± 1.5 ka are produced. Comparison of the results with independent age control suggests that the ages are reliable. The results also show that the extent of bleaching at deposition varies considerably from one sample to another. For the most incompletely bleached sample, luminescence measurements based on the average of many hundreds or thousands of grains would have overestimated the age of the sample by ~ 60 ka, but the single grain method proposed here was able to reliably date it.

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1. Introduction

Optically stimulated luminescence (OSL) measurements of Quaternary sediments can be used to determine the last exposure of the mineral grains to daylight (Duller, 2004) and are well suited to the analysis of aeolian samples where erosion and transportation of the grains is usually sufficient to fully reset the OSL signal. Recent work has demonstrated that the OSL in such samples is uniformly reset (Bray and Stokes, 2003) and that young ages can be obtained for modern samples (Singarayer et al., 2005). However, sediments associated with glacial activity are more complex for optical dating because it is possible that they were not exposed to sufficient daylight prior to deposition to completely reset the luminescence signal. Luminescence measurements of modern glacial sediments (Gemmell, 1999; Rhodes and Pownall, 1994)

generally found that the luminescence signals had not been completely reset. These residual signals would create large uncertainties in any age estimates for older samples. In spite of the difficulties encountered in the study of modern sediments, many authors have attempted to date glacial sediments using luminescence (Owen et al., 1997; Mangerud et al., 2001; Kamp et al., 2004).

Very few depositional environments are uniform in the extent to which luminescence signals are reset. Thus instead of generalising that all glacial sediments are incompletely bleached, a preferable approach would be to assess the extent to which each sample that was measured had had its luminescence signal reset at deposition. Duller et al. (1995) studied glacial sediments from Scotland and attempted such an approach by using the distribution of D_e values obtained from single aliquot measurements of feldspars. This allowed them to identify some samples that had not been adequately reset at deposition, and this was confirmed by the age overestimates that they obtained for these samples when compared with independent age control. For instance, a glaciofluvial sand from the Mains

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of Cardno (MC) gave a single aliquot infrared stimulated luminescence (IRSL) age of 108 ± 13 ka, yet was known to be associated with the deglaciation of this area which occurred between 15 and 20 ka. From the Burn of Bigholm (BBH) a glaciofluvial deposit gave an IRSL age of 21.3 ± 4.6 ka, but was bracketed by ^{14}C ages indicating a calibrated age of between 11.0 and 13.3 ka. Plotting the D_e obtained from an aliquot as a function of the signal intensity showed a positive correlation, indicating that the optical age was an overestimate. However the data could not be used to obtain the correct age.

In the last decade, protocols (Murray and Wintle, 2000) and equipment (Duller et al., 1999) have been developed that make it feasible to measure the equivalent dose (D_e) of single mineral grains. Such measurements can infer

whether different grains had their luminescence signal reset to different extents at deposition, and statistical models applied to attempt to obtain the correct age. Such single grain measurements have been applied to fluvial (Thomas et al., 2005), marine (Olley et al., 2004) and archaeological (Roberts et al., 1999; Jacobs et al., 2003; Jacobs et al., in press) sediments where there is the potential for grains to have had their OSL signal reset at deposition to different extents. However this paper is the first attempt to use these methods for glacial sediments. This paper assesses the potential for using single grain luminescence measurements of quartz from glacial sediments from Chile to provide an absolute chronology, and it then reports the application of these new methods to the two samples from Scotland described above.

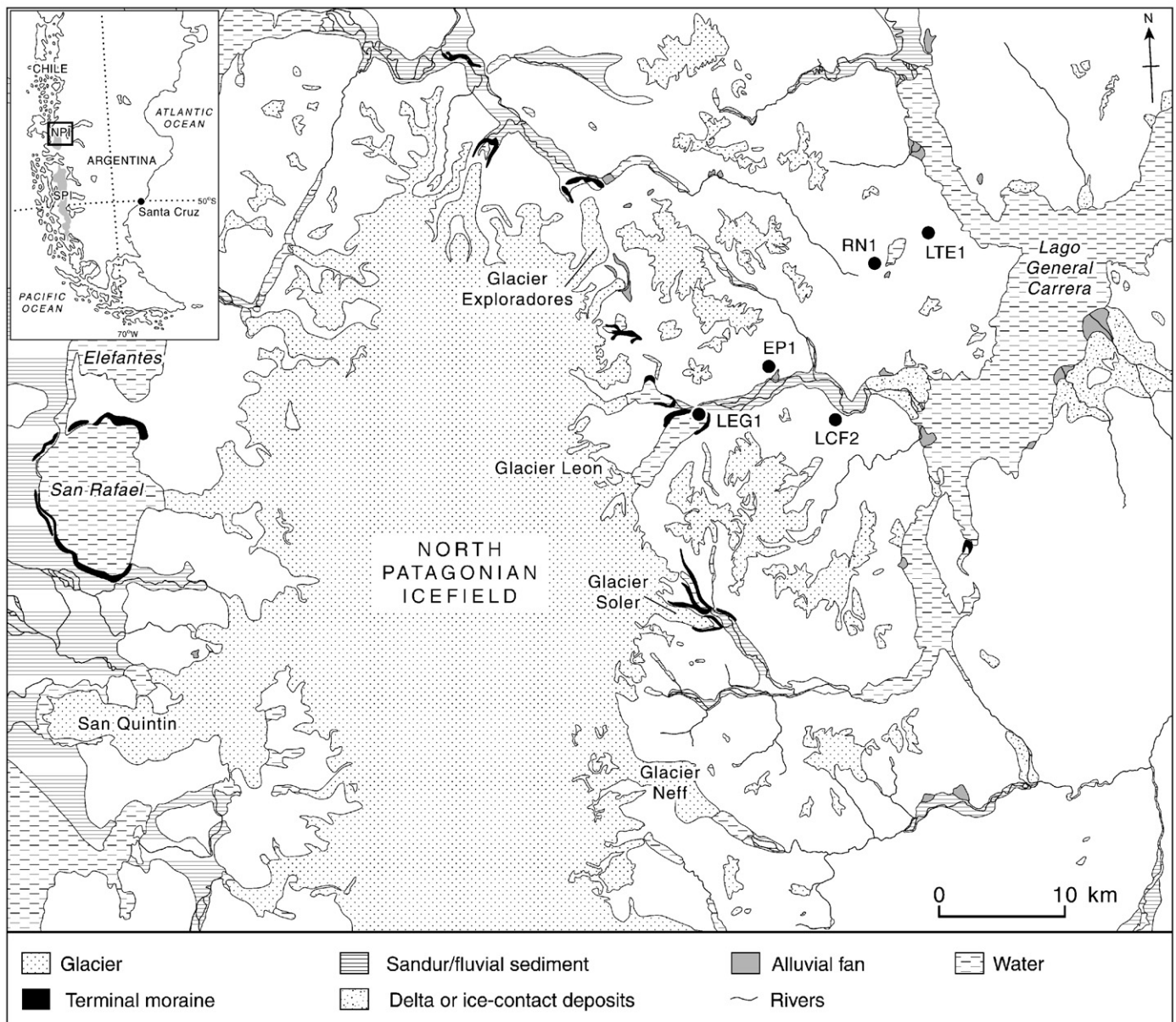


Fig. 1. Map of the North Patagonian Icefield (NPI) in southern Chile (adapted from Glasser et al., 2005). Samples for OSL dating (Aber79/RN1, LTE1, LEG1/4, EP1 and LCF2) were collected from the Exploradores and Leones valleys.

2. Sites

The impetus for this paper is ongoing research into the Late Quaternary history of ice cover over the southern Andes (Glasser et al., 2004). An important requirement of this work was the determination of an accurate chronology for the glacial deposits left by previous ice cover. The North Patagonian Icefield (NPI) lies between 46°S and 48°S in southern Chile (Fig. 1). Together with the larger South Patagonian Icefield, it represents the vestige of a larger ice sheet which covered the southern Andes during the last glaciation. To the northeast of the NPI are the Exploradores and Leones valleys, both of which have glaciers at their western ends that are fed by the main icefield, and which contain a wide range of glacial sediments recording the deglaciation of the area (Glasser et al., 2004).

Two samples (Aber79/RN1 and LTE1) for luminescence dating were collected from ice-contact glaciofluvial deposits along the margins of the Exploradores valley and four samples (Aber79/LEG1, LEG4, EP1 and LCF2) from similar depositional contexts in the Leones valley (Fig. 1). Morainic sediments were avoided since it was thought that these were less likely to have been exposed to daylight at deposition.

Some independent age control was provided by cosmogenic radionuclide dating of boulders on moraines in the Exploradores and Leones valleys. In the Exploradores valley, two boulders on a moraine found between samples RN1 and LTE1 gave ^{10}Be ages of 10.5 ± 0.8 and 11.4 ± 0.9 ka (Glasser et al., 2006). In the Leones valley, boulders from the moraine associated with samples LEG1 and LEG4 were also dated using ^{10}Be . In this case the samples were too young to produce accurate dates, but the analyses indicated that they were less than ~ 3 ka.

3. Equipment and methods

Samples for OSL measurements were collected in plastic or metal tubes and transported back to the laboratory avoiding exposure to daylight. Quartz grains (180–211 μm in diameter) were separated from the sediment by treating it with HCl and H_2O_2 to remove carbonates and organics, dry sieving, density separation ($2.62 < \rho < 2.70 \text{ g cm}^{-3}$) using solutions of sodium polytungstate, and etching in 40% hydrofluoric (HF) acid for 45 min. Recovery of quartz was very variable from one sample to another. For sample LTE1 less than 0.1% by weight of the initial sample was recovered as sand-sized quartz. For the other samples the recovery varied from $\sim 0.5\%$ to 2%.

A single grain luminescence system based around a 10 mW Nd:YVO₄ laser emitting at 532 nm was used for measurement of the quartz (Duller et al., 1999), and the resulting OSL was detected by an EMI 9235QA photomultiplier filtered by 7.5 mm of Hoya U-340 glass. The power density of the laser when focussed onto an individual grain is approximately 50 W cm^{-2} , and the

duration of stimulation was 1 s. A $^{90}\text{Sr}/^{90}\text{Y}$ beta source delivering 2.8 Gy/min to the grains was used for irradiation. The purified quartz was mounted on specially designed holders so that the luminescence signal from each grain could be measured (see Fig. 6 in Duller, 2004), and between 1000 and 3000 grains of each sample were measured. The single aliquot regenerative (SAR) dose procedure was used to determine their equivalent dose (D_e), with a preheat of 220 °C for 10 s and a cutheat of 160 °C. As well as the regeneration measurements necessary for the SAR procedure, additional measurements were made on each grain to assess (i) its ability to recycle a given regeneration dose and (ii) the effect upon the OSL signal of exposing the grain to infrared stimulation. Duller (2003) suggested that this latter procedure could help to identify grains whose luminescence signal did not originate from quartz.

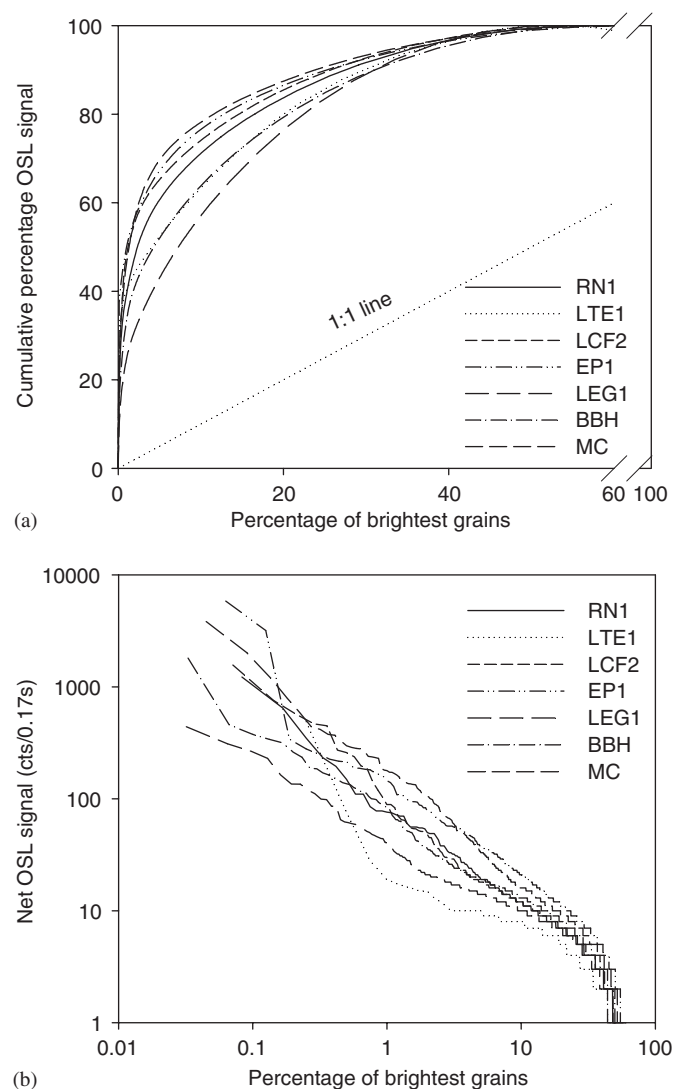


Fig. 2. The variation in OSL signal from individual quartz grains following an 8.3 Gy irradiation and a cutheat to 160 °C. The net OSL signal from each grain in a sample has been ranked from brightest to dimmest. The data are plotted as (a) a cumulative light sum plot and (b) as the absolute brightness of each grain.

4. Luminescence analysis of quartz from Chile

The intensity of the OSL signal emitted from single quartz grains is highly variable. As part of the SAR procedure, all grains in this study were given a test dose of 8.3 Gy. One means of comparing the brightness of the quartz from different samples is to rank the net OSL signal (the first 0.17 s of optical stimulation minus the last 0.17 s of stimulation) from each grain from brightest to dimmest. The resulting data can be displayed both in relative terms as a cumulative light sum (Fig. 2a) and absolutely (Fig. 2b).

Plots such as Fig. 2a have previously been published by Duller et al. (2000) and Jacobs et al. (2003). The samples studied here behave in a manner similar to previously published datasets, with the majority of the total OSL signal originating in a small (<10%) proportion of the grains. However, it is notable that more than 40% of the grains do contribute to the OSL signal, whereas in previous data sets it was rare for this figure to be more than 20%. One reason for this is that there are very few bright grains in this data set (Fig. 2b), thus making the relative contribution from dim grains more important. Two

samples, LTE1 and LEG1, are dimmer than the others, and for these samples it was difficult to obtain sufficient bright grains to generate D_e values. Low sensitivity of the OSL signal from quartz extracted from sediment close to glaciers has also been reported for Himalayan samples (Rhodes, 2000).

4.1. Dose response and sensitivity change

Figs. 3a and b show the SAR growth curves obtained from two grains (grain number 74 and 47) of sample RN1. The equivalent dose (D_e) obtained from each grain is similar (~20 Gy). Rhodes (2000) found that thermal transfer may be a significant problem with glacial sediments, but for these samples the L_x/T_x ratio obtained following a zero regeneration dose, was always found to be less than 8% of the natural signal, and normally much smaller than this. Shown as an inset on the diagram of each growth curve is the response of the grain to the test dose (8.3 Gy) through the SAR sequence. The data are normalised to the response obtained from the first measurement of the test dose for each grain (T_n). Previously published plots

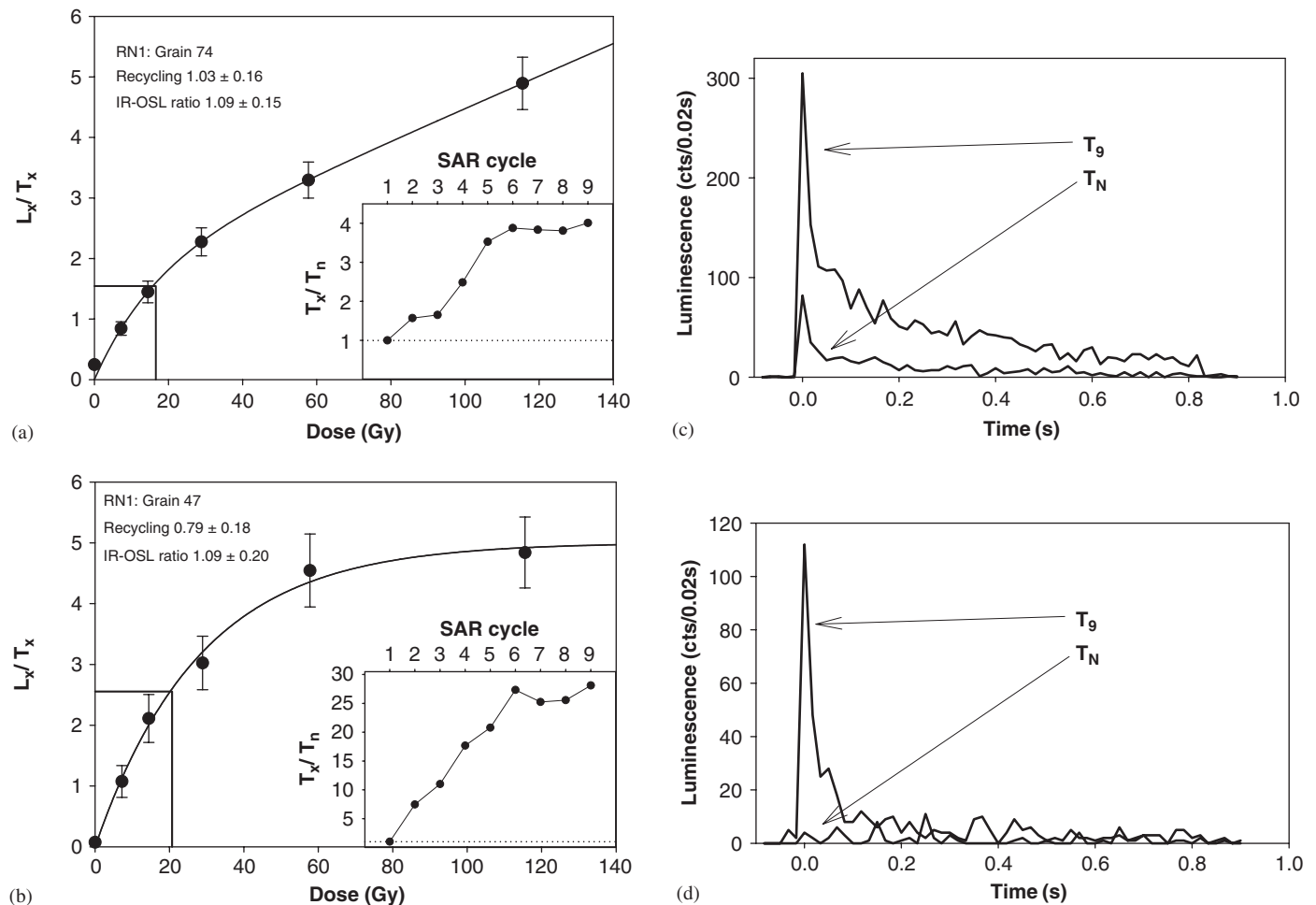


Fig. 3. (a,b) OSL growth curves for two single grains from sample Aber79/RN1. Shown as an inset in each diagram is the change in the ratio of T_x/T_n through the SAR sequence. (c,d) The OSL signals from the same grains as shown in (a) and (b). For each grain the OSL signal following the test dose (8.3 Gy) after the measurement of the natural (T_n) and after measurement of the final regeneration dose (T_9) are shown.

of T_x/T_n for aeolian sediments show changes in sensitivity of up to a factor of 3 during the SAR sequence (Armitage et al., 2000; Jacobs et al., 2003). Grain 74 shows a change by a factor of 4 (Fig. 3a), still within the range previously reported. However, grain 47 increases in sensitivity by a factor of 28 (Fig. 3b). In spite of these dramatic changes in sensitivity, the recycling ratios for the two grains are consistent with 1.00 ± 0.10 within errors (1.03 ± 0.16 and 0.79 ± 0.18), implying that the test dose measurement is correcting for these changes appropriately.

Another difference between the grains is the intensity of the T_n signal, with grain 74 yielding 233 counts in the interval from 0 to 0.17 s (after subtracting the background signal), while grain 47 gives only nine counts after background subtraction (Figs. 3c and d). The impact of this very weak test dose response is that the uncertainty on the value of L_n/T_n is large, and the error on the D_e values for the two grains reflect this (17 ± 3 Gy for grain 74, and 21 ± 36 Gy for grain 47). The increase in sensitivity of grain 47 through the SAR sequence is such that for the last test dose measurement (T_0), the signals from the two grains are within a factor of four of each other (934 and 253 counts).

4.2. Equivalent dose results and statistical analysis

For each sample a minimum of 1000 grains were analysed (Table 1). As has been found previously (Duller et al., 2000; Yoshida et al., 2000; Jacobs et al., 2003), only a

small proportion of the grains that were measured gave a sufficiently bright OSL signal to enable a growth curve to be constructed. For these, further analysis was undertaken to ensure that only those grains whose OSL characteristics are appropriate for SAR were included in later statistical analysis. The criteria used to reject grains have been described previously by Jacobs et al. (2003), and include having a recycling ratio and an IR-OSL depletion ratio that are consistent with a value of 1.00 ± 0.10 within errors. After this rejection process, the number of grains remaining for which a D_e value can be obtained varies markedly from one sample to another. For some samples approximately 5% of grains gave acceptable D_e values (e.g. RN1 and EP1), while for others fewer than 0.5% did so (e.g. LTE1). The very low recovery rate for LTE1 made it impossible to obtain sufficient data for further analysis.

The D_e values obtained for four samples from Chile are shown as radial plots in Figs. 4a–d. In each case the weak OSL signals obtained, and especially the low signal intensities measured from the natural dose and the first test dose, mean that the precision of the individual D_e values are low. In addition, an instrumental uncertainty of 3% on each OSL measurement has been incorporated (Duller et al., 2000; Jacobs et al., 2003) which reduces the precision further. The data have been analysed using the finite mixture model of Galbraith and Green (1990), following the approach described by Rodnight et al. (in press). Typically the data are well fitted with three

Table 1

Number of quartz grains measured for each sample, the number of grains for which valid D_e values could be obtained, analysis of the resulting distributions using the finite mixture model and minimum age model, and the ages obtained using the D_e obtained from application of the finite mixture model

Sample	Number of grains measured	Number of valid D_e values ^a	Finite mixture model				Minimum age model D_e (Gy) ^d
			Number of components 'k'	Percentage of grains in main component	Calculated D_e (Gy) ^b	Age (ka) ^c	
<i>Exploradores valley</i>							
Aber 79/RN1	1200	64 (5.3%)	3	82	16.7 ± 1.0	9.7 ± 0.7	17.1 ± 1.3
Aber 79/LTE1	1000	3 (0.3%)	—	—	—	—	—
<i>Leones valley</i>							
Aber 79/LCF2	1400	21 (1.5%)	2	95	16.7 ± 1.7	7.2 ± 0.8	16.5 ± 2.2
Aber 79/EP1	1600	77 (4.8%)	3	80	15.4 ± 0.8	6.0 ± 0.4	13.8 ± 1.1
Aber 79/LEG1	2900	18 (0.6%)	2	57	6.4 ± 1.2	2.4 ± 0.5	6.2 ± 1.2
Aber 79/LEG4	1700	26 (1.6%)	2	84	6.8 ± 1.8	3.3 ± 0.9	7.5 ± 2.2
<i>Scotland</i>							
Aber 79/BBH	3000	96 (3.2%)	3	84	31.4 ± 0.9	10.8 ± 1.0	21.8 ± 1.8
Aber 79/MC	2200	92 (4.2%)	3	46	33.7 ± 0.8	17.3 ± 1.5	21.3 ± 2.0

^aThe number of grains from which a measurable signal could be detected, and which passed the various rejection criteria described in the text (i.e. recycling ratio, IR-OSL depletion ratio). The number of grains finally used for statistical analysis is expressed as a percentage of the total number of grains measured and given in brackets.

^bThe D_e used for age calculation was determined using the finite mixture model of Galbraith and Green (1990) with 10% overdispersion. The number of components fitted is shown as the value of 'k', as is the percentage of the grains contained within the main component.

^cAges were calculated using the equivalent dose determined using the finite mixture model and the dose rate shown in Table 2.

^dAn overdispersion of 10% is included in each measurement when using the minimum age model to make the results directly comparable with those from the finite mixture model.

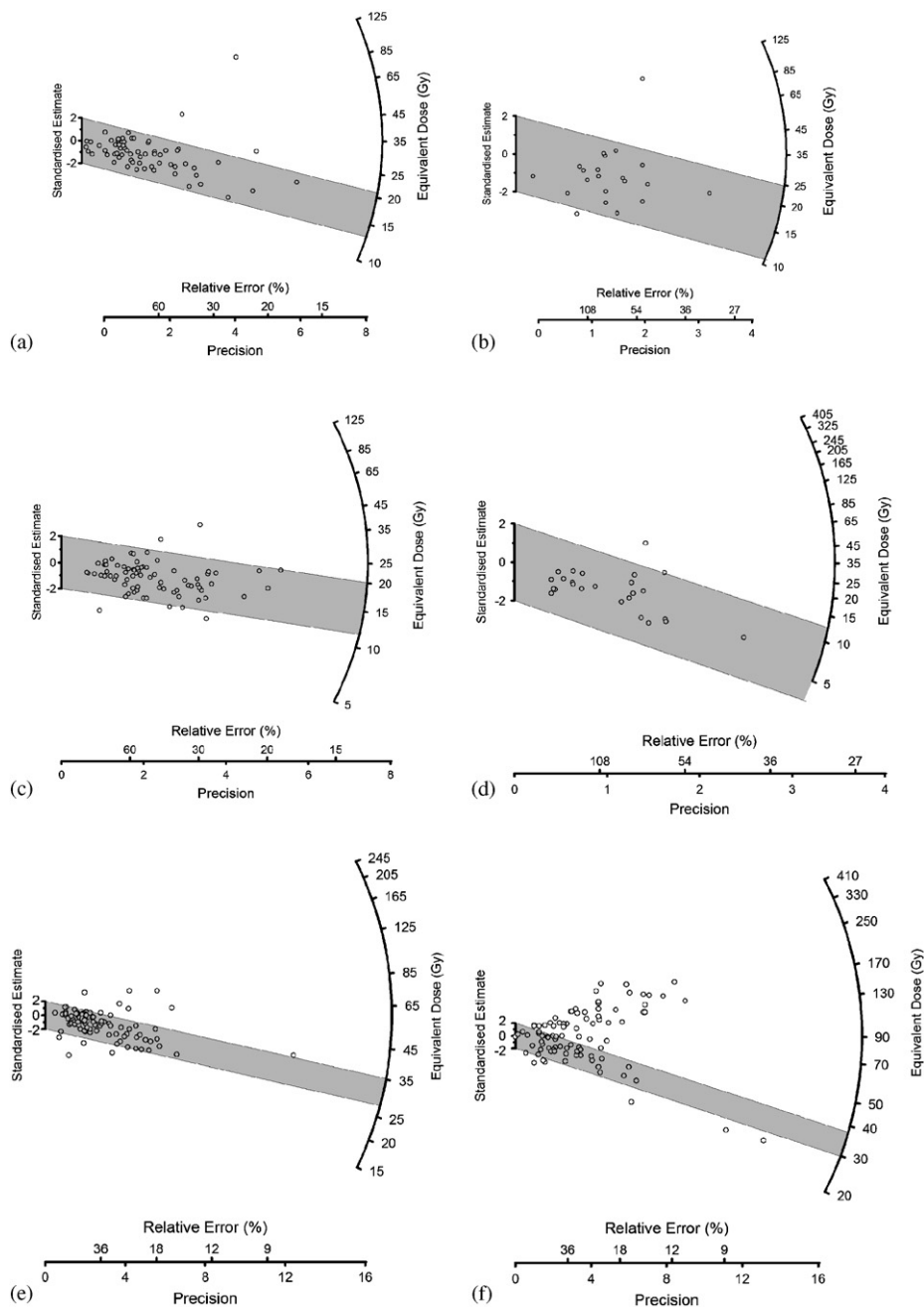


Fig. 4. Radial plots of single grain D_c values from glaciogenic sediments from Chile: (a) RN1, (b) LCF2, (c) EP1 and (d) LEG4. Also shown are radial plots of D_c data from two samples from Scotland, (e) BBH and (f) MC. The grey shading denotes the D_c value obtained from fitting the finite mixture model.

components, and the dose component chosen for age calculation is that with the lowest equivalent dose, but which contains at least 10% of the grains.

Rodnight et al. (in press) found that for the D_c distributions that they obtained from their fluvial samples the minimum age model of Galbraith and Laslett (1993) often gave an underestimate of the correct D_c because of the presence of a few low D_c values, and the use of the finite mixture model is a pragmatic approach for overcoming this problem. For most of the samples studied here, the finite mixture and minimum age model results were very similar

(Table 1), but for the two samples from Scotland (discussed later), the finite mixture model results are significantly lower. Following the work of Rodnight et al. (in press), the finite mixture results have been used here. The D_c calculated for each sample using the finite mixture model is indicated by the shaded grey band in Fig. 4.

The appropriateness of the SAR procedure for analysis of these materials can be assessed by undertaking a dose recovery experiment. Grains of sample RN1 were bleached for 40 s at room temperature using the blue LEDs mounted within the automated reader, left for 10,000 s to remove

charge stored in the 110 °C TL trap, and then bleached again for 40 s. They were then given a dose of 19.3 Gy, and had their D_e measured using the procedure described above. Fifty-five grains gave D_e values that passed the various criteria. Applying the central age model to this data set gave a value of 19.4 ± 1.0 Gy, with 93% of the grains having D_e values that are consistent with this value within two standard deviations (Fig. 5). The ability to recover a known dose, and with limited scatter in the data set, suggests that the SAR procedure is appropriate for this material.

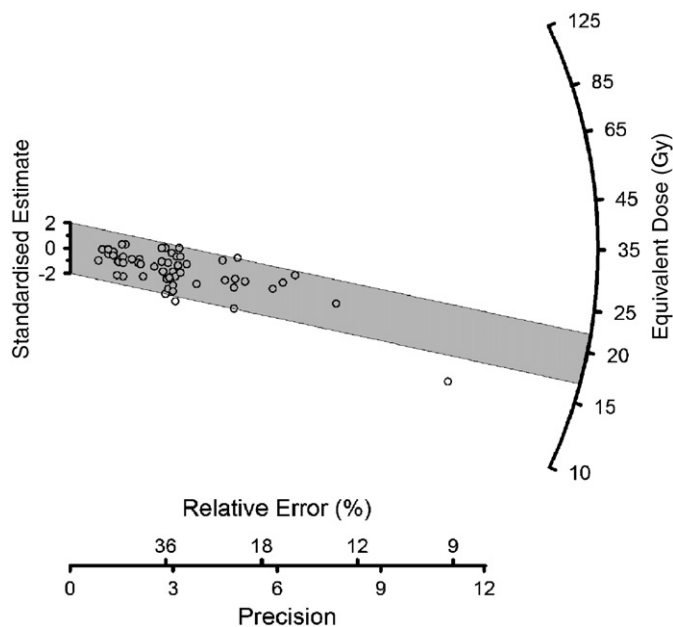


Fig. 5. D_e values for 55 single grains of sample RN1. For this dose recovery experiment, the grains had been bleached and given a known laboratory dose of 19.3 Gy. The grey shading denotes the known laboratory dose.

5. Assessing optical ages for glacial samples

5.1. Chile

The D_e calculated for each sample using the finite mixture model is shown in Table 1, and the data used to calculate the dose rate received by the samples during burial is shown in Table 2. There are two tests of the credibility of these ages, one based on comparison with the cosmogenic radionuclide ages on boulders from moraines, and the other is relative age control on the samples collected from the Leones valley. In the Exploradores valley an OSL age could be obtained only from sample RN1. This sample is from an ice-contact glaciofluvial landform on the northern margin of the valley and can only have formed when ice from the NPI extended at least this far down valley. The age of 9.7 ± 0.7 ka is consistent with the two ^{10}Be ages of 10.5 ± 0.8 and 11.4 ± 0.9 ka obtained from boulders on the moraine 5 km downvalley (Glasser et al., 2006).

In the Leones valley, the cosmogenic radionuclide data are of more limited use. ^{10}Be measurements on boulders from the moraine associated with the OSL samples LEG1 and LEG4 were only able to show that the moraine was young, and that the age was probably less than ~ 3 ka. OSL measurements on LEG1 and LEG4 yielded only a small number of grains for analysis (18 and 26, respectively), but the ages obtained (2.4 ± 0.5 and 3.3 ± 0.9 ka) are again consistent with the cosmogenic data. The samples LCF2, EP1, and LEG1 and 4 form a sequence along the Leones valley providing relative age control. These samples should form a chronosequence from older to younger ages, and indeed the ages in Table 1 show this pattern.

Thus single grain optical dating of glacial sediments from Chile is consistent with the available ^{10}Be cosmogenic nuclide dating results and the expected chronostratigraphic

Table 2
Dose rate data, including U, Th and K concentrations and calculated dose rate during burial

Sample	Depth (m)	U (ppm) ^a	Th (ppm) ^a	K (%) ^a	Dose rate (Gy/ka) ^b
<i>Exploradores valley</i>					
Aber79/RN1	0.7	1.99 ± 0.23	6.68 ± 0.77	0.82 ± 0.06	1.73 ± 0.08
Aber79/LTE1	0.7	3.32 ± 0.49	14.03 ± 1.64	3.00 ± 0.12	4.29 ± 0.19
<i>Leones valley</i>					
Aber79/LCF2	2.5	2.40 ± 0.21	6.35 ± 0.70	1.49 ± 0.05	2.31 ± 0.10
Aber79/EP1	0.6	2.82 ± 0.34	11.28 ± 1.10	1.26 ± 0.08	2.57 ± 0.11
Aber79/LEG1	1.5	2.22 ± 0.26	7.17 ± 0.86	1.87 ± 0.06	2.66 ± 0.11
Aber79/LEG4	0.6	1.35 ± 0.18	4.97 ± 0.59	1.50 ± 0.05	2.05 ± 0.09
<i>Scotland</i>					
Aber79/BBH	1.0				2.90 ± 0.26
Aber79/MC	2.7				1.95 ± 0.16

^aDose rates were measured using a combination of thick source alpha counting and GM-beta counting of finely milled samples. The U and Th concentrations were derived from counting the number of pairs during alpha counting, and the potassium was calculated by combining the alpha counting and beta counting results.

^bDose rate to the samples was calculated using a water content of $10 \pm 5\%$, and also includes the cosmic dose rate. For samples 79/BBH and 79/MC a combination of field gamma measurements and GM-beta counting were used. The dose rate data were taken from Duller et al. (1995) where further information is given.

control. This contrasts with the multiple grain luminescence data obtained by Duller et al. (1995) for some of their samples from Scotland. The next section applies this new single grain approach to these sediments.

5.2. Scotland

The earlier work by Duller et al. (1995) on glacial sediments from Scotland was undertaken using potassium-rich feldspars, making measurements on aliquots containing approximately 1000 grains each. Archived material from this earlier study with a density between 2.62 and 2.70 g cm⁻³ was etched in 40% HF and the resultant quartz was measured using the same procedure as described above for the samples from Chile. Measurement of 3000 grains of sample BBH and 2200 grains of MC yielded 96 and 92 D_e values (Table 1); that is 3.2% and 4.2% of the grains gave acceptable D_e values, similar to the proportions observed in samples from Chile. The variability in the production of OSL from grains of these two samples also matched that observed from samples from Chile (Fig. 2).

The sample from the BBH had previously given a multiple grain IRSL age of 21.3 ± 4.6 ka. The quartz single grain D_e values show some scatter, but a dominant component (84% of grains) is identified by the finite mixture model (Fig. 4e). This gives an age of 10.8 ± 1.0 ka which is consistent with the age control (11.0–13.3 ka) provided by a series of four calibrated radiocarbon ages (Duller et al., 1995).

Sample MC from the Mains of Cardno had previously given an IRSL age of 108 ± 13 ka which overestimated the known age of 15–20 ka by at least a factor of five. Growth

curves from different quartz grains show a large variation in D_e . In addition to those grains with D_e values of several tens of grey (Fig. 6a), there are also grains with much larger D_e values (Figs. 6b and c). The radial plot of the quartz single grain data (Fig. 4f) shows that it contains grains with D_e values that range from ~ 30 to ~ 400 Gy, explaining why the multiple grain aliquots overestimated the correct age so dramatically. Fitting the quartz data with the finite mixture model separates the lower dose population, giving a D_e of 33.7 ± 0.8 Gy and an age of 17.3 ± 1.5 ka.

The single grain quartz approach used in this study is more successful than the previous multiple grain IRSL data in identifying incompletely bleached sediments and obtaining accurate D_e values for age determination. What would have been the effect of making OSL measurements on these quartz extracts using multiple grain aliquots instead of single grains? The individual luminescence signals from each grain can be mathematically combined to simulate the OSL signal that would have been obtained had all the grains from a sample been measured on a single aliquot. This synthetic aliquot approach has been described previously by Jacobs et al. (2003) where they combined together all 100 grains from each single grain holder. In the current study, all the grains from a sample were combined. For sample BBH (3000 grains) this gave a D_e of 39.2 ± 3.6 Gy, about 20% larger than that obtained using single grains (31.4 ± 0.9 Gy). For MC (2200 grains) the synthetic aliquot D_e was 172 ± 16 Gy (Fig. 6d). In both cases the growth curves obtained give no indication of the complex mixture that is represented, and both recycling ratios and the IR-OSL ratio are within errors of unity. These synthetic aliquot experiments demonstrate the

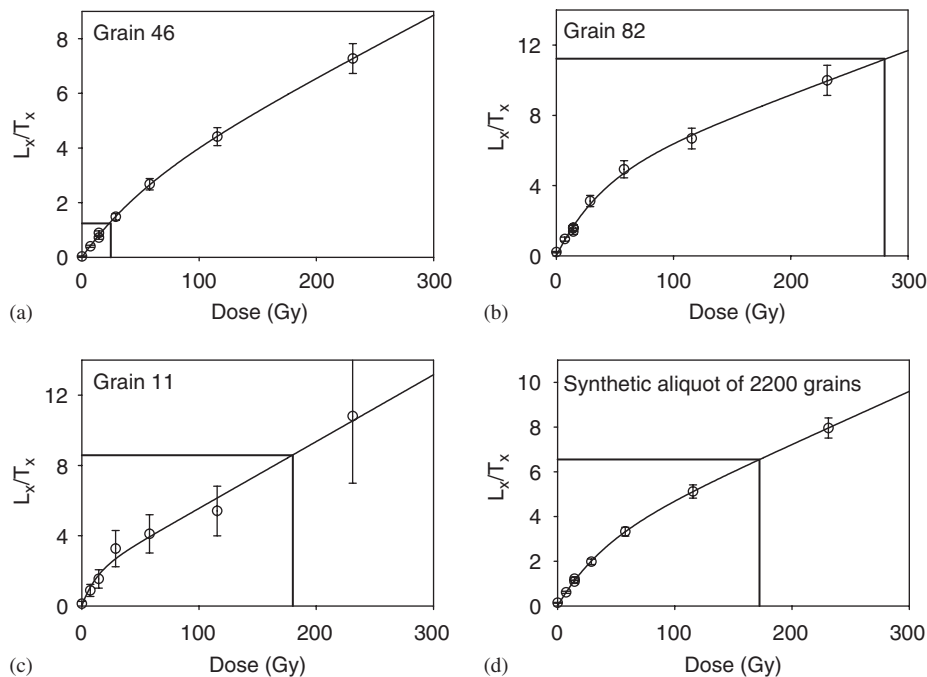


Fig. 6. (a, b, c) Growth curves for sample MC from Mains of Cardno from three individual quartz grains. (d) The growth curve generated by summing the OSL signals from all 2200 grains of MC that were measured.

potential for significantly overestimating the D_e if multiple grain aliquots are measured.

6. Conclusions

Single grain OSL measurements on quartz from glacial samples are challenging because of the low sensitivity that is commonly encountered. However it is only by making such measurements that it is possible to detect whether a sample was relatively well bleached at deposition. Many of the samples from Chile, and sample BBH from Scotland, appear to have been surprisingly well bleached at deposition. In part this can be attributed to careful sampling of glaciofluvial sediments which are the most likely to be exposed to daylight at deposition. However, sample MC contains a significant proportion of very poorly bleached grains. Combining together the OSL signals from all the single quartz grains that were measured for this sample to make a single synthetic aliquot gave a D_e of 172 Gy, which would have resulted in an age more than 60 ka too old. Previous multiple grain IRSL measurements on feldspars also gave an age that was more than 80 ka too old.

Thus although OSL ages of glacial materials based on measurements using multiple grains on each aliquot may be correct, one can only be confident of the age determined when additional single grain measurements are made to investigate the completeness of bleaching at deposition. Comparison with independent ages based on cosmogenic ^{10}Be , ^{14}C on organic material, and relative age control support the accuracy of these single grain optical ages.

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