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Novel insights into the post-IR IRSL$_{200}$ signal bleachability of single-grain K-feldspars in fluvial modern analogues from the Southern Central Andes, Chile

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Abstract.

Post-infrared infrared stimulated luminescence (post-IR IRSL) signals from potassium feldspars are gaining prominence in both luminescence dating and luminescence-based sediment tracing techniques. To enhance the accuracy and reliability of these applications, it is essential to develop a comprehensive understanding of how post-IR IRSL signals undergo bleaching. While previous studies have explored post-IR IRSL bleachability using multi-grain approaches, a systematic single-grain investigation on modern analogues has not been conducted. In this study, we examined the bleaching behaviour of the post-IR IRSL$_{200}$ signal at the single-grain level in eleven modern floodplain samples from the tectonically active Southern Central Andes. Our study demonstrated considerable variation in the mean residual doses observed following two days of laboratory solar simulator bleaching across the sample set. This variability was evident not only between different samples but also among individual grains within the same sample. Thus, we evaluated the influence of bleaching duration, grain-specific geochemical composition, catchment-scale lithological variability, and the size of the natural dose on both laboratory-measured residual doses and remnant doses. Our laboratory bleaching experiments showed consistent post-IR IRSL$_{200}$ signal behaviour across four different samples, reaching a plateau based on normalised luminescence signal after two days of exposure to solar simulator light. While individual grains exhibited a wide range of bleaching rates, this variability did not account for the spread in residual dose values. Notably, extended light exposure reduced variability in signal intensity, underscoring its role in dose homogenisation. Geochemical analysis of major oxides showed no significant correlation with either residual dose magnitude or bleaching rate, suggesting that mineral composition (including K-concentration) does not influence bleaching efficiency at the individual grain level. Furthermore, bleaching behaviour remained consistent across samples regardless of catchment lithology, with no discernible relationship between lithological units and remnant or residual dose values. Most importantly, we identified a strong positive exponential correlation ($R^2 = 0.86$) between residual dose and natural remnant dose, revealing dose-dependent bleaching efficiency and the presence of a unbleachable component at the time of deposition. By integrating insights on bleachability with the information on the unbleachable component and remnant doses derived from modern analogues, we highlight the limitations of correcting palaeodoses by directly using remanent doses and evaluate three context-sensitive correction strategies. Finally, we discuss how residual dose and the unbleachable component can be leveraged to more reliably identify well-bleached grains, enhancing the accuracy of luminescence-based sediment tracing applications.

1 Introduction

Over the past decades, optically stimulated luminescence (OSL), infrared stimulated luminescence (IRSL), and post-infrared infrared stimulated luminescence (post-IR IRSL) dating have been used extensively in Quaternary research to develop

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chronologies across diverse environmental settings (Wallinga, 2002; Jain et al., 2004; Bateman et al., 2008; Rittenour, 2008; Reimann et al., 2011, 2012; Chamberlain et al., 2017; Brill et al.,2018; Bonnet et al., 2019). One of the essential preconditions of these dating techniques is the pre-burial bleaching event, which resets the luminescence signal accumulated in the mineral grains after burial due to their exposure to external radiation in the surrounding sediments, incoming cosmic radiation (Preusser et al., 2008), and varying contributions from internal radiation (Zhao et al., 2005). However, incomplete or partial resetting of the previously accumulated luminescence signal has been frequently reported, especially in fluvial and glacio-fluvial settings (Wallinga 2002; King et al., 2013; Bonnet et al., 2019), creating a major source of uncertainty in age estimates. While incomplete bleaching poses a significant challenge for luminescence dating, it offers valuable opportunities for luminescence-based sediment tracing of geomorphic processes (Bonnet et al., 2019; Chamberlain and Wallinga, 2019; Rhodes and Leathard, 2022; Guyez et al., 2022, 2023; de Boer et al., 2024).

Bleaching of the luminescence signal in various environmental settings is primarily influenced by external geomorphic and environmental factors, which determine the duration of sunlight exposure required for bleaching (King et al., 2014; Reimann et al., 2015; Brill et al., 2018; Chamberlain and Wallinga, 2019). However, it is well known that the rate and degree of bleaching are also impacted by the choice of minerals and the type of luminescence signal used. For instance, K-feldspar IRSL and post-IR IRSL signals are especially susceptible to incomplete bleaching, as exposure to daylight resets their luminescence signal more slowly than the quartz OSL signal (Godfrey-Smith et al., 1988; Thomsen et al., 2008; Buylaert et al., 2012; Kars et al., 2014; Reimann et al., 2015; Zhang et al., 2023). Therefore, improving the use of K-feldspars for luminescence dating and luminescence-based sediment tracing in complex geomorphic contexts requires a detailed and quantitative understanding of the bleachability of the K-feldspar luminescence signals, particularly the post-IR IRSL signals.

Previous studies based on multi-grain measurements have demonstrated that certain post-IR IRSL signals can be effectively bleached, resulting in residual doses, i.e., the luminescence signal remaining after controlled laboratory or natural bleaching, typically below 2 Gy (Reimann et al., 2011; Reimann and Tsukamoto, 2012). However, other investigations have reported a broader range of residual doses, reaching up to ~40 Gy following laboratory bleaching (Stevens et al., 2011; Thiel et al., 2011; Alexanderson and Murray, 2012; Buylaert et al., 2012; Lowick et al., 2012; Sohbati et al., 2012; Kars et al., 2014; Yi et al., 2016). Notably, these residual doses have been found to positively correlate with the corresponding natural burial doses, suggesting that incomplete bleaching is often inherited from the depositional history (Sohbati et al., 2012; Buylaert et al., 2012; Kars et al., 2014; Yi et al., 2016). In addition, several studies have identified an unbleachable signal component in post-IR IRSL measurements, which complicates signal resetting and dose interpretation (Yi et al., 2016; Brill et al., 2018; Zhang et al., 2023). Further complexity arises from the investigations of modern analogues (i.e., present-day depositional environments used as references for past depositional environments), which highlight the occurrence of remnant doses, defined as the natural luminescence signal remaining at the time of deposition and burial (Kars et al., 2014). These remnant doses can be substantial, with values reaching up to ~50 Gy (Thomsen et al., 2008; Buylaert et al., 2009; Madsen et al., 2011; Alexanderson and Murray, 2012; Buylaert et al., 2012; Murray et al., 2012), raising major concerns regarding bleaching efficiency across a variety of modern depositional settings.

Moreover, single-grain luminescence studies have highlighted considerable inter-grain variability in bleaching behaviour, leading to substantial differences in residual dose estimates (Smedley et al., 2015; Choi et al., 2024). For example, Smedley et al. (2015), working with aeolian and glaciofluvial samples, reported grain-to-grain variability in laboratory bleaching rates, resulting in variable residual dose estimates. However, they found no clear relationship between post-IR IRSL bleaching rates and the equivalent dose (D_e) values. In a more recent study, Choi et al. (2024) exposed two soil samples to natural sunlight for controlled durations and observed variable post-IR IRSL residual doses across individual grains. Their findings revealed a positive correlation between both D_e and residual dose with the recuperation dose, a signal component measured during Single-Aliquot Regenerative dose (SAR) protocols. This suggests that the recuperation dose may serve as a useful proxy for assessing grain-specific bleachability, potentially enabling the identification of well-bleached grains within

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heterogeneously bleached samples. Additionally, considering the chemically complex nature of feldspars, further challenges may stem from grain-to-grain variations in K-concentration within K-feldspar grains, primarily affecting the internal dose rate. Although recent investigations (Buylaert et al., 2018; Smedley et al., 2019; Maßon et al., 2024) observed no relationship between internal K-concentration and either D_e estimates or luminescence signal intensity, it remains unclear whether K-concentration influences single-grain bleaching rates and consequently residual doses.

Collectively, these studies emphasise the complex and grain-specific nature of K-feldspar luminescence signal resetting by natural and artificial sunlight, highlighting the importance of single-grain analyses for accurately capturing variability in both residual and remnant doses. This complexity becomes particularly significant in dynamic depositional settings, where bleaching is highly heterogeneous. In such environments, averaging effects arising from multi-grain measurements can mask the true luminescence signal characteristics of distinct grain populations, including those that are well-bleached, partially bleached, or saturated (e.g., Duller 2008; Bonnet et al., 2019; Guyez et al., 2022, 2023). As a result, meaningful signal distinctions may be obscured, potentially compromising accurate dose estimation and depositional setting interpretation. However, our current understanding of the post-IR IRSL bleaching process under laboratory and natural conditions is largely based on multi-grain measurements (e.g., Lowick et al., 2012; Buylaert et al., 2012; Alexanderson and Murray, 2012; Kars et al., 2014). Existing single-grain studies on this topic are limited in both sample size and the range of depositional settings examined (Smedley et al., 2015; Choi et al., 2024), especially in the context of modern analogues (e.g., Alexanderson and Murray, 2012). Here, we address this research gap through a systematic investigation of laboratory and natural bleaching of single grains from eleven modern fluvial analogues from the Southern Central Andes of Chile (28° S to 38° S), a region characterised by active tectonics (Strecker et al., 2007) and a pronounced climatic gradient (Garreaud et al., 2009). Given the geologic and geomorphic diversity across these catchments, our study aims to: (1) quantify the bleaching characteristics of the post-IR $IRSL_{200}$ signal at the single-grain level; (2) assess the potential influence of bleaching duration, grain-specific geochemical composition, catchment-scale lithological variability and natural D_e on the magnitude of both residual and remnant doses; (3) compare laboratory bleaching with natural bleaching; (4) investigate the use of recuperation dose as a proxy for bleachability and (5) evaluate how knowledge on the degree of bleaching in modern analogues can inform decision-making in dating sedimentary archives and in luminescence-based sediment tracing applications.

2 Materials and methods

2.1 Study area and sampling strategy

The Southern Central Andes (27° S to 38° S) of Chile are characterised by several high peaks (>6000 m), variable volcanic and tectonic activity, as well as a range of climatic conditions influenced by both latitude and altitude. Climate in this region transitions from arid to semi-arid in the northern sectors to a Mediterranean regime in the central-southern areas (Aceituno et al., 2021). This prominent climatic gradient results in a sequence of catchments showing different environmental conditions (e.g., vegetation cover, Fig. 1). In this study, we selected 11 catchments that drain roughly perpendicularly to the Andean Mountain range, with outlets located at the foot of the main Cordillera (Fig. 1a, Table S1). All catchments of the study area show remarkable latitudinal variations in their morphological features resulting from the interaction between volcanic and tectonic processes and climate. The northernmost catchment experiences arid conditions, with a daily average rainfall of less than 0.4 mm (Table S2), while the southernmost catchment, influenced by south-westerly winds, exhibits humid conditions with average rainfall exceeding 4 mm per day (Table S2). The mean normalised difference vegetation index (NDVI) closely follows the rainfall variations, low in the north (0.045) and relatively high in the south (0.281) (Table S2). The Southern Central Andes also features a wide range of slopes, glacier cover, and lithologies (Fig. 1b, Table S1 and S2), making it a natural laboratory for studying Earth's surface processes and for testing the influence of these processes on the bleachability of the luminescence signal in a more diverse and dynamic landscape.

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Samples were collected during a field campaign in 2022, covering a latitudinal stretch of approximately ten degrees (from 28° S to 38° S). Samples were collected by hammering the opaque luminescence sampling tubes into the sediment sections on the modern floodplain (Fig. 2). Eleven samples were collected from eleven catchments (Fig. 1, Table S1). All sampling sites were located at the foot of the main Andean Cordillera to minimise any modulation of erosional signal by downstream storage or reworking and to directly assess the influence of landscape variables on the luminescence signal, as fluvial deposits from these locations provide an optimal record of millennial erosional processes and rates shaping the landscape and supplying sediment to the fluvial network.

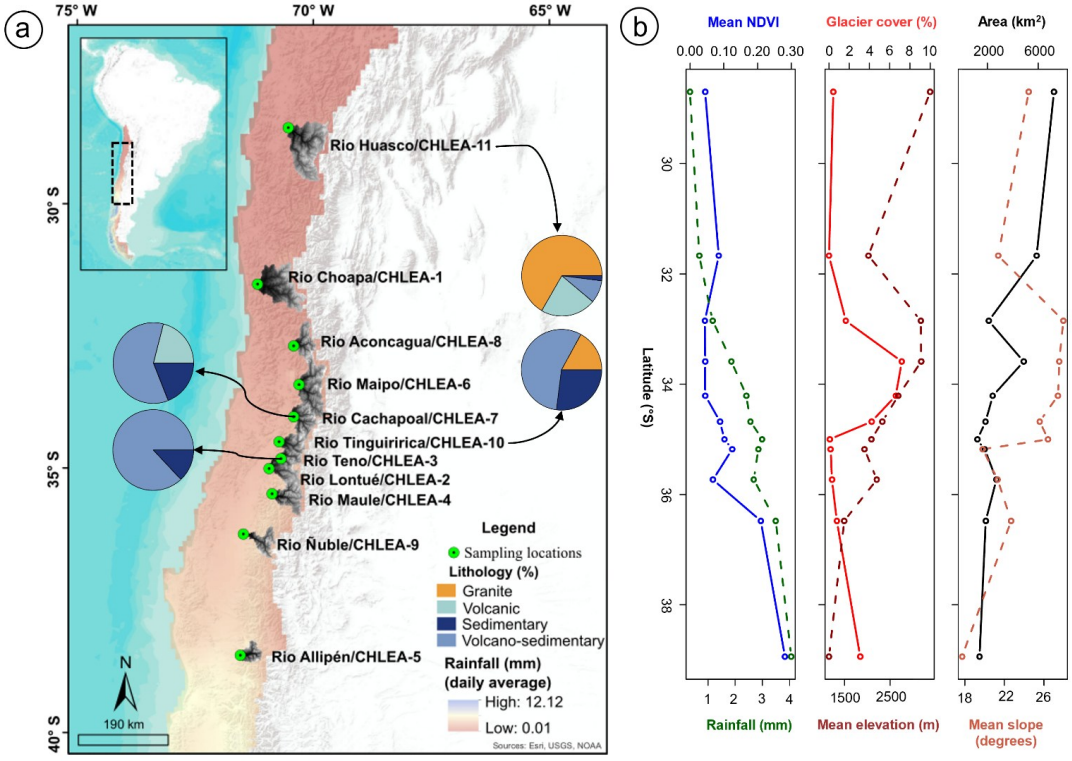

Figure 1: (a) Map of the study area displaying the eleven catchments considered in this study. A 30 m resolution digital elevation model has been used to delineate catchments, considering sampling locations as outlets. Each catchment highlights the river name and corresponding sample ID, with green points marking the sampling locations. The daily average rainfall (mm) map [GPM_3IMERGDF v06] (Huffman et al., 2023) shows a precipitation gradient from north to south. Pie charts depict the lithological composition of four catchments (Table S1) from which samples were selected for the bleaching experiment. Base map sources: Esri, USGS, and NOAA. (b) spatial variations in catchment properties along a north to south trend (with the latitudinal distribution of catchments). Analysed catchment properties include mean normalised difference vegetation index (NDVI), daily average rainfall (mm), glacier cover (%), mean elevation (m), total catchment area (km²), and mean slope (degrees). Details of all these parameters are provided in Table S2.

2.2 Sample preparation

Samples were prepared under subdued red-light conditions at the Cologne Luminescence Laboratory (CLL, University of Cologne). Hydrochloric acid (HCl, 10%) and hydrogen peroxide (H_2O_2, 10%) were used to remove carbonates and organic material, respectively. Sodium oxalate ($Na_2C_2O_4$, 0.01 N) was used to disperse the sediment particles. After chemical treatment, the samples were sieved to obtain the 200–250 µm grain size fraction. This sieved fraction was used to extract K-rich feldspars through a two-step density separation using a sodium polytungstate solution at 2.58 g/cm^3 and 2.53 g/cm^3. The

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second density separation step (with sodium polytungstate density of 2.53 g/cm^3) was necessary to remove a pumice fraction from the feldspar extracts. A hand magnet was used to separate any magnetic residue in the feldspar fraction. The remaining non-magnetic fraction was then re-sieved within the target fraction (200–250 µm) before the final luminescence measurement.

Figure 2: Luminescence sampling on modern floodplains of the Maipo (a) and Allipén (b) rivers during the field campaign in 2022.

2.3 Instrumentation and luminescence measurements

All luminescence measurements were carried out on an automated Risø TL/OSL reader (DA-20) equipped with a $^{90}Sr/^{90}Y$ beta source for irradiation, delivering a dose rate of ~0.066 Gy/s at the sample position, and a single-grain attachment (Bøtter-Jensen et al., 2003). A 140 mW, 830 nm centred IR laser stimulated the grains, and the blue emission (~410 nm) was detected through a combination of a 2 mm Schott BG-39 filter and a 3 mm Corning 7-59 glass filter. A Schott RG-780 filter was inserted in front of the laser to block secondary emissions below 780 nm by the 830 nm laser.

For all D_e and residual dose (remaining dose after 2 days of bleaching in a Hönle Sol2) measurements, single grains of K-feldspar were mounted in a standard single-grain disc featuring a 10 by 10 grid of 100 holes, each measuring 300 µm in depth and 300 µm in diameter. Grains were then analysed following the protocol outlined in Table 1. From the single-grain luminescence measurements, the net post-IR $IRSL_{200}$ signal was calculated from the signal integrated over the first 0.25 s with subtraction of the background estimated from the last 0.50 s (Fig. S4). All D_e and residual dose estimates were derived and analysed using the numOSL (Peng et al., 2013; Peng and Li, 2017) and the Luminescence package (Kreutzer et al., 2023) within the R environment. A measurement error for the regenerative dose signal (L_x) and the corresponding test dose signal (T_x) of 2% was used for calculations. Parameters used for growth curve fitting were: "general-order kinetic model" (Guralnik et al., 2015) and "forced through origin". The acceptance criteria for both single-grain D_e and residual dose estimates include a test dose signal intensity following natural dose measurement (T_n) > 3 sigma above background, relative standard error of $T_n \leq 20\%$, and recycling ratio within the range of 0.8 to 1.2 (unity ± 20%) for all available recycling points. A figure-of-merit of 15% was used as a measure of the goodness of growth curve fitting for all single-grain measurements (Peng and Li, 2017; Riedesel et al., 2025).

To examine the feldspar luminescence signal behaviour and identify the most appropriate measurement protocol for D_e estimation using single-grains, dose-recovery and residual preheat plateau tests were conducted on two samples (CHLEA-6 and CHLEA-11) using multi-grain aliquots (2 mm diameter) of coarse-grain (200–250 µm) K-feldspar following the protocol outlined in Table S3 and temperature combinations outlined in Table S4. Among the various post-IR IRSL signals evaluated, the post-IR $IRSL_{200}$ signal provided the most reliable dose recovery results for both samples, with dose recovery ratios ranging from 0.9 to 1.1 (Fig. S1a). Based on this performance, the post-IR $IRSL_{200}$ protocol was selected for further analysis. To assess the protocol's suitability at the single-grain level, single-grain dose recovery tests were subsequently

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conducted on four samples (CHLEA-6, CHLEA-9, CHLEA-10, and CHLEA-11) following the protocol in Table S3. While the residual-corrected single-grain dose recovery ratios showed slight underestimation relative to unity (Fig. S2), all samples except CHLEA-11 fell within the acceptable range of 0.9 to 1.1 when 1 sigma uncertainties were considered. These results thus confirm the effectiveness of the post-IR $IRSL_{200}$ protocol in accurately recovering known laboratory doses. Additional details regarding the preheat plateau and dose recovery experiments, including kernel density estimate plots from single-grain dose recovery tests (Fig. S3), are provided in section S2 of the supplementary material.

Table 1: Post-IR $IRSL_{200}$ measurement protocol. [a]For equivalent dose (D_e) measurement, the given regenerative doses were 0, 2, 5, 10, 30, 50, 100, 200, and 400 Gy. [b]For residual dose measurement, the given regenerative doses were 0, 2, 5, 10, and 30 Gy. [c]For D_e measurement, a test dose of 20 Gy was used for all measurements and for residual dose measurement, a test dose of 10 Gy was used for all measurements.

Step	Treatment	Observed
1	Beta dose (or Natural / Residual dose)[a,b]	
2	Preheat 225 °C, 60 s	
3	IRSL 50 °C, 2 s	
4	post-IR IRSL at 200 °C, 3 s	L_x
5	Test dose[c]	
6	Preheat 225 °C, 60 s	
7	IRSL 50 °C, 2 s	
8	post-IR IRSL at 200 °C, 3 s	T_x
9	IR LEDs at 200 °C, 300 s	
10	Repeat steps 1 to 9 for a range of regenerative doses (incl. zero and repeat dose, zero dose measured after the natural and largest regenerative dose)	

2.4 Laboratory bleaching experiment

All laboratory bleaching experiments were carried out at the CLL using a Hönle Sol2 (Sol2) laboratory solar simulator following the protocol outlined in Table 2. For the bleaching experiment, we chose four samples (CHLEA-3, CHLEA-7, CHLEA-10, and CHLEA-11). Their catchments are characterised by diverse lithologies (Fig. 1a), as well as different climatic and geomorphological properties (Fig. 1b), representing the overall heterogeneity present within all catchments. An additional reason for the selection of these samples was the higher yield of luminescent grains (Table 3); thus, measuring a few discs would provide a robust dataset for the bleaching experiment.

The experimental protocol was designed to evaluate the post-IR $IRSL_{200}$ signal response of K-feldspar grains under controlled bleaching and irradiation conditions. Initially, the grains were subjected to bleaching in the Sol2 for 2 days to reset the luminescence signal, followed by the measurement of the residual dose using the protocol outlined in Table 1. After residual dose measurements, grains were selected following the acceptance criteria described in section 2.3 and the residual doses of selected grains were calculated. Only these selected grains were tracked in the subsequent bleaching steps and analysed for further interpretation.

Subsequently, a beta dose of 30 Gy was administered, and the resulting signal (L_x/T_x) was recorded without exposing the grains to the solar simulator. The grains were then dosed with another 30 Gy and exposed to 1 minute of bleaching before measuring the signal again. This process was repeated with varying bleaching durations ranging from 10 to 30000 minutes to examine the impact of prolonged bleaching on the signal. For all steps in the bleaching experiment, a test dose of 10 Gy was applied. Repeated measurements were conducted for specific bleaching durations (10, 1,000, and 2,880 minutes) to evaluate measurement reproducibility. The L_x/T_x ratios of all bleaching steps were normalised to the L_x/T_x value of the no-exposure measurement (Table 2, step 5) to facilitate comparisons of signal change across bleaching steps.

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Table 2: Protocol of the bleaching experiment carried out in this study.

Steps	Actions
1	2 days of bleaching in Sol2
2	Residual dose measurement (full dose-response curve)
3	Dose (30 Gy)
4	0 minute of bleaching in Sol2 (i.e., no exposure)
5	L_x/T_x measurement
6	Dose (30 Gy)
7	L_x/T_x measurement following varying bleaching time (1, 10, 100, 1000, 2880, 10000, 30000 minutes)

2.5 Single-grain geochemistry

To measure the major element concentration of individual grains, grains from single-grain discs were embedded in epoxy and polished, following the method described in Maßon et al. (2024). Geochemical analyses were conducted on a JEOL JXA-8900RL electron microprobe at the Institute of Geology and Mineralogy of the University of Cologne. The major element composition of selected feldspar grains was determined by wavelength dispersive X-ray spectrometry with an accelerating voltage of 15 kV, a beam current of 15 nA, and a beam diameter of 3 µm. The elements Na, Al, and Si were analysed on a TAP spectrometer crystal, Fe on a LIF spectrometer crystal, K and Ca on a PET spectrometer crystal, and Ba on a LIFH spectrometer crystal. For the calibration, albite (Na, Al), quartz (Si), almandine (Fe), orthoclase (K), plagioclase (Ca), and baryte (Ba) mineral standards from an Astimex Standard Ltd. mount were used. All elements were measured for 10 seconds on the peak and 5 seconds on the background before and after the peak, except for Fe, Mn, and Ba, which were analysed for 20 seconds on the peak and 10 seconds on the background before and after the peak. The results were corrected according to the ZAF procedure from the instrument software. Orthoclase from the P&H standard block were analysed as secondary reference materials before and after each measurement session to monitor precision and accuracy (Table S6).

Unfortunately, geochemical data could not be obtained for every selected grain meeting the acceptance criteria after residual dose measurement. Some grains were lost or misplaced during the transfer from the discs to the epoxy. Two to four point measurements were performed on each selected grain (Fig. S9) to maximise surface coverage and improve the reliability of the microprobe data. The average of these measurements was calculated for each grain and was considered to represent the geochemical composition of the entire grain.

3 Results

3.1 Equivalent and residual doses

We measured up to 2900 and up to 2200 single grains for D_e and residual dose determination, respectively. Following the recommendation by Rodnight et al. (2008), we aimed to obtain at least 50 single-grain dose estimates for each sample. However, we limited this number to 30 for residual dose measurements due to the lack of sample material and due to the very low recovery ratio of luminescence-sensitive grains for our Andean samples. For example, sample CHLEA-8 provided grains with a very limited sensitivity, and we obtained only 21 dose estimates despite measuring 2200 grains (Table 3); thus, only ~1% of the feldspar grains provided a suitable dose estimate.

To quantify the equivalent dose of the samples based on the best-bleached grain population, we employed the 3-parameter unlogged minimum age model (MAM, Arnold et al., 2009). The presence of a limited number of negative D_e values within the D_e distributions of the samples required the application of the unlogged MAM with the input of an absolute sigma-b (overdispersion) value. To obtain this, we calculated the unlogged central age model (CAM) D_e for all samples (Table S5), providing us with an absolute estimate for the overdispersion (Table S5). Plotting the absolute overdispersion against the CAM D_e (Riedesel et al., 2018) showed a positive correlation (Fig. S5). Extrapolating this linear relationship to a

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hypothetically ideally bleached sample with a dose of 0 Gy provides a y-axis intercept and overdispersion of 8.58 Gy. This result was thus used as the absolute sigma-b value for all unlogged MAM calculations.

The MAM D_e values range from 5.8 ± 1.7 to 22.2 ± 1.3 Gy (Table 3). For residual dose quantification, we calculated the arithmetic mean and standard error from all single-grain-based residual measurements of the individual samples. The obtained mean residual doses range from 2.4 ± 0.3 to 9.5 ± 0.4 Gy (Table 3). Further details regarding other luminescence results, including kernel density estimate plots of single-grain D_e and residual dose (Fig. S6), can be found in Section 3 of the supplementary material.

Table 3: Feldspar single-grain post-IR $IRSL_{200}$ data for all samples measured in this study. n_{De} (%): absolute and relative number of accepted grains, mean equivalent dose (Mean D_e), CAM D_e calculated using unlogged central age model, MAM D_e calculated using a 3-parameter unlogged minimum age model, $n_{Residual}$ (%): absolute and relative number of accepted residual dose grains, and mean residual dose (mean residual dose for laboratory bleached samples). All uncertainties indicate one standard error.

Sample ID	n_{De} (%)	mean D_e (Gy)	CAM D_e (Gy)	MAM D_e (Gy)	$n_{Residual}$ (%)	mean residual dose (Gy)
CHLEA-11	307 (61)	18.0 ± 1.7	15.5 ± 0.9	11.3 ± 0.6	603 (38)	3.4 ± 0.1
CHLEA-1	109 (22)	39.9 ± 7.0	28.7 ± 4.3	6.9 ± 1.1	92 (13)	2.4 ± 0.3
CHLEA-8	52 (2)	46.6 ± 11.4	22.9 ± 4.3	7.4 ± 1.9	21 (1)	4.8 ± 1.3
CHLEA-6	78 (4)	47.9 ± 6.2	37.8 ± 4.2	10.6 ± 2.4	39 (2)	4.5 ± 0.8
CHLEA-7	262 (52)	57.8 ± 3.4	50.6 ± 2.4	22.2 ± 1.3	132 (33)	9.5 ± 0.4
CHLEA-10	66 (13)	33.7 ± 4.9	26.1 ± 2.4	16.1 ± 1.9	49 (5)	6.4 ± 0.5
CHLEA-3	78 (16)	73.1 ± 11.4	41.4 ± 5.2	13.0 ± 1.6	73 (15)	5.0 ± 0.5
CHLEA-2	77 (8)	57.0 ± 10.3	34.4 ± 5.1	5.8 ± 1.7	71 (7)	2.7 ± 0.5
CHLEA-4	72 (3)	32.8 ± 6.1	15.9 ± 2.3	5.9 ± 1.8	43 (3)	2.7 ± 0.5
CHLEA-9	63 (13)	44.0 ± 8.3	30.4 ± 4.1	8.9 ± 2.0	36 (4)	4.5 ± 0.5
CHLEA-5	60 (3)	25.8 ± 4.2	22.3 ± 3.3	9.6 ± 1.8	30 (2)	2.5 ± 0.6

3.2 post-IR $IRSL_{200}$ laboratory bleaching behaviour

Despite lithological, geomorphological and environmental variability at the catchment scale, all four samples investigated for their post-IR $IRSL_{200}$ laboratory bleaching behaviour exhibited similar bleaching trends at the sample average level (Fig. 3a). Initially, the signal experienced a rapid reduction, followed by a more gradual decrease and eventual stabilisation. After 1 minute of exposure in Sol2, the signal is reduced by ~24%. After 100 minutes of bleaching, ~79% of the initial signal has been depleted, and after 1000 minutes, only 10 % of the initial signal remains. By 2880 minutes (2 days), the signal reaches a rather stable level with ~4% (equivalent to 1.2 Gy) of the initial signal remaining. We also examined the bleaching trend of the $IRSL_{50}$ signal (Fig. S8). However, it bleaches more rapidly than the post-IR $IRSL_{200}$ signal. Notably, ~95% of the $IRSL_{50}$ signal depletes after only 100 minutes of bleaching, and the stabilisation of signal reduction occurs between 2880 minutes and 30000 minutes, with ~1% signal remaining.

At the single-grain level, individual grains exhibited significant variation in bleaching rates (Fig. 3b, Fig. S9), each responding differently to varying light exposure duration. For all four samples, three representative grains (designated as grains 1, 2, and 3) were selected based on their initial bleaching responses following 1 minute of Sol2 exposure (Fig. 3b, Fig. S9): grain-1 (fast-bleaching rate) exhibited the fastest initial bleaching thus retained the least luminescence signal, grain-2 (moderate-bleaching rate) had a signal either equal or closest to the mean of the distribution, and grain-3 (slow-bleaching rate) retained the most signal. In Fig. 3b, single grain-1 lost ~54% of its initial luminescence signal after 1 minute of light exposure, whereas single grain-3 lost only ~8%. After 1000 minutes, signal depletion increased to ~88% and ~95%, respectively. Following prolonged bleaching (30000 minutes), depletion reached ~96% and ~99%. It is interesting to note

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that a grain with a high initial bleaching rate does not necessarily retain the least luminescence signal at later steps, and a grain with a low initial bleaching rate may not always have the highest remaining signal (Fig. 3b).

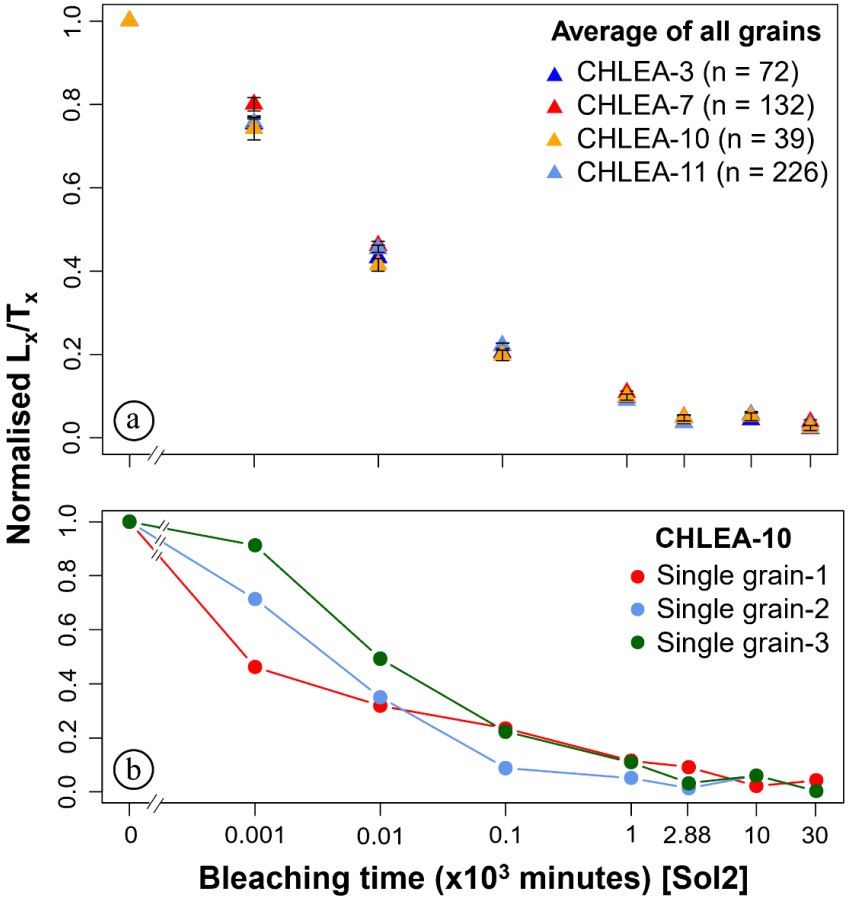

Figure 3: Normalised luminescence signal (L_x/T_x) as a function of bleaching time. Bleaching behaviour of the post-IR $IRSL_{200}$ signal as sample average ± standard error (a) and at the single-grain level, with three grains of the sample CHLEA-10 selected exemplarily (b).

Additionally, Figure 4 shows the single-grain distributions of non-normalised L_x/T_x values measured after different bleaching steps for samples CHLEA-3, CHLEA-7, CHLEA-10, and CHLEA-11. As expected, the size of the doses of the individual grains decreases with increasing bleaching time. Notably, for all samples, the spread of the distribution decreases with longer bleaching durations, with the interquartile range of the distribution narrowed significantly, from 0.44 at 0 minutes (the widest distribution) to 0.06 at 30000 minutes (the narrowest), reflecting a nearly one-order-of-magnitude reduction.

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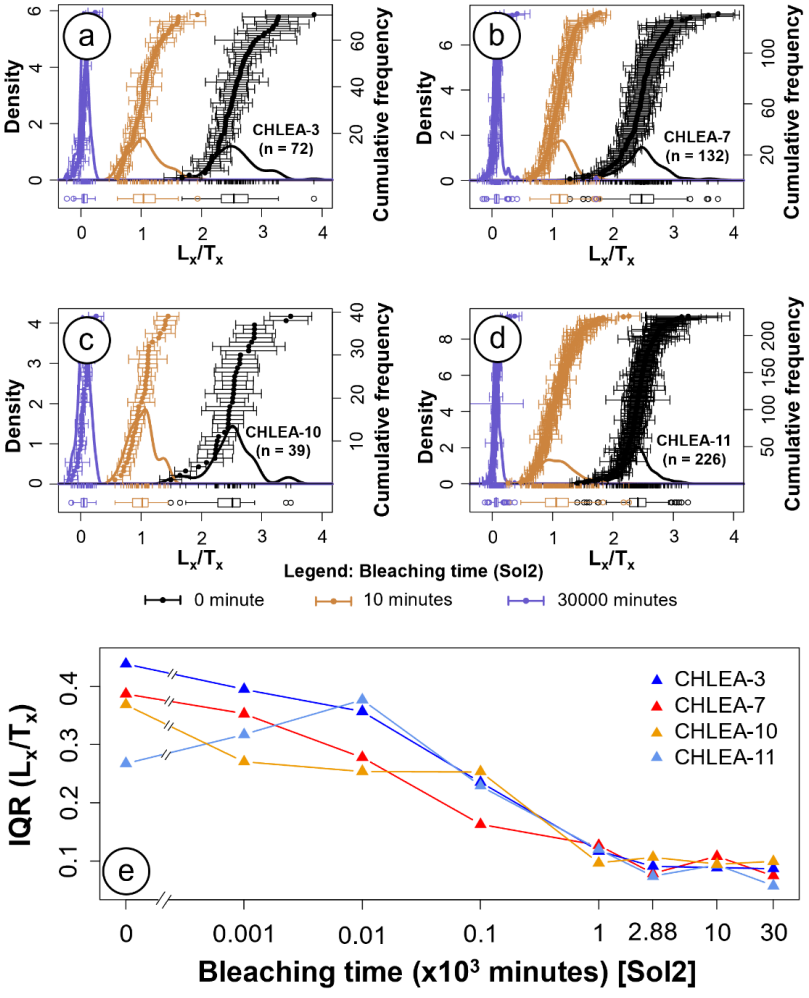

Figure 4: Panels (a) to (d) show kernel density estimate (KDE) plots of non-normalised single-grain L_x/T_x values obtained after different bleaching durations for samples CHLEA-3, CHLEA-7, CHLEA-10, and CHLEA-11. For visualisation purposes, a single datapoint with either high L_x/T_x or high error from each sample (n = 1) has not been shown in the plots. KDE plots were generated using the default bin width nrd0 (0.9 times the minimum of the standard deviation and the interquartile range divided by 1.34 times the sample size to the negative one-fifth power, unless the quartiles coincide when a positive result will be guaranteed) of the Luminescence package in the R programming environment (Silverman, B. W., 1998). Panel (e) shows the change in interquartile range (IQR) of non-normalised L_x/T_x from different bleaching durations (0 to 30000 minutes) for all four samples. Note that the change in IQR depicts the successive decrease in the spread of the L_x/T_x distribution with prolonged bleaching duration in the Sol2.

3.3 Single-grain geochemical composition

Electron microprobe analyses were performed on 121 grains from the four samples subjected to the bleaching experiment, with the following grain distributions: CHLEA-3 (n = 30), CHLEA-7 (n = 32), CHLEA-10 (n = 14), and CHLEA-11 (n = 45). Two to four point measurements were made per grain to ensure maximum surface coverage. Heavily altered zones (Fig. S10c) were avoided during measurements to reduce the likelihood of errors, typically indicated by spectrally inconsistent energy-dispersive X-ray spectroscopy peaks identified through visual inspection. Detection limits for the EPMA data were calculated according to Potts (1992), and individual element concentrations were filtered out when below the detection limit (section S5, Table S7).

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The geochemical composition of single grains revealed that the K_2O concentrations ranged from 0.20 wt% to 16.60 wt%, reflecting a broad range with a mean (± standard error) of 10.80 ± 0.32 wt%. The average concentrations of Na_2O and CaO ranged from 0.21 wt% to 10.99 wt% and 0 wt% to 11.31 wt%, respectively. The mean (± standard error) concentrations for Na_2O and CaO are 3.58 ± 0.19 wt% and 0.60 ± 0.12 wt%, respectively. Details of microprobe measurements, including electron backscatter images of individual grains (Fig. S10), are provided in section S5 of the supplementary materials.

4 Discussion

4.1 Factors influencing the bleachability of the post-IR $IRSL_{200}$ signal

Our study revealed substantial variation in the magnitude of mean residual doses measured after two days of Sol2 bleaching, with values ranging from 2.4 ± 0.3 to 9.5 ± 0.4 Gy across all samples (Table 3). This variability is also apparent at the single-grain level within individual samples (Fig. 5a). Given this variability, we now discuss the potential influence of bleaching duration, grain-specific geochemical composition, catchment-scale lithological variability and natural dose on the magnitude of both residual and remnant dose to constrain the dominant factors influencing bleachability of the post-IR $IRSL_{200}$ signal.

4.1.1 Influence of bleaching duration

On average, our laboratory bleaching experiments conducted on four samples revealed consistent post-IR $IRSL_{200}$ signal bleaching behaviour (Fig. 3a), despite their origin from spatially distributed catchments with diverse lithological, geomorphological, and environmental settings. A bleaching plateau based on the normalised L_x/T_x data was reached after two days of Sol2 exposure (Fig. 3a).

At the single-grain level, bleaching rates varied substantially among grains (Fig. 3b, Fig. S9), each responding differently to the duration of light exposure. This finding is consistent with those of Smedley et al. (2015) and Choi et al. (2024). Notably, we show that high initial bleaching rates did not consistently correspond to low final signals, and vice versa, implying that the magnitude of the normalised residual dose is independent of a grain's bleaching rate, and thus, bleaching rates cannot account for the observed spread in the absolute single-grain residual dose estimates. Furthermore, Figure 4 shows that prolonged bleaching substantially reduces the variability of the remaining signal (non-normalised L_x/T_x) distributions, with the interquartile range decreasing by nearly a factor of ten.

This demonstrates that while the bleaching duration fundamentally influences the magnitude of the residual dose until a bleaching plateau is reached based on the normalised L_x/T_x data, it cannot account for the observed spread in single-grain residual dose estimates. Nevertheless, prolonged exposure plays a key role in dose homogenisation, strongly supporting its effectiveness in minimising grain-to-grain variability in the post-IR $IRSL_{200}$ signal.

4.1.2 Influence of geochemical composition

To evaluate whether variations in the bleaching extent of individual grains are influenced by their geochemical composition, we examined the relationship of grain-specific average major oxide concentrations (K_2O, Na_2O, and CaO) with corresponding residual doses (Fig. 5a). Moreover, we analysed the relationship between K_2O concentration and normalised L_x/T_x values after 1 minute and 30000 minutes of bleaching (Fig. 5b) to assess the potential role of geochemistry and especially the K-concentration of the feldspars in controlling bleaching rates. We also extended the analysis to include comparisons with other oxide concentrations (Fe_2O_3, BaO, SiO_2, Al_2O_3) and normalised L_x/T_x values after 1 minute, 1000 minutes and 30000 minutes of Sol2 bleaching durations. A correlation matrix for the entire dataset (Fig. S11) revealed no statistically significant correlation (p-value > 0.05) between major oxide concentrations (wt%), normalised L_x/T_x values and residual doses, except for a few cases showing very weak correlations, with correlation coefficient (r) ranging between -0.19 and 0.22. (Normalised L_x/T_x of 1 minute vs. Al_2O_3, r = -0.19; normalised L_x/T_x of 1000 minutes vs. Na_2O, r = -0.20; normalised L_x/T_x of 1000 minutes vs. K_2O, r = 0.22; residual dose vs. SiO_2, r = -0.19; residual dose vs. CaO, r = 0.19). These

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comparisons suggest that neither the extent of bleaching nor the rate at which individual grains bleach is influenced by their geochemical composition.

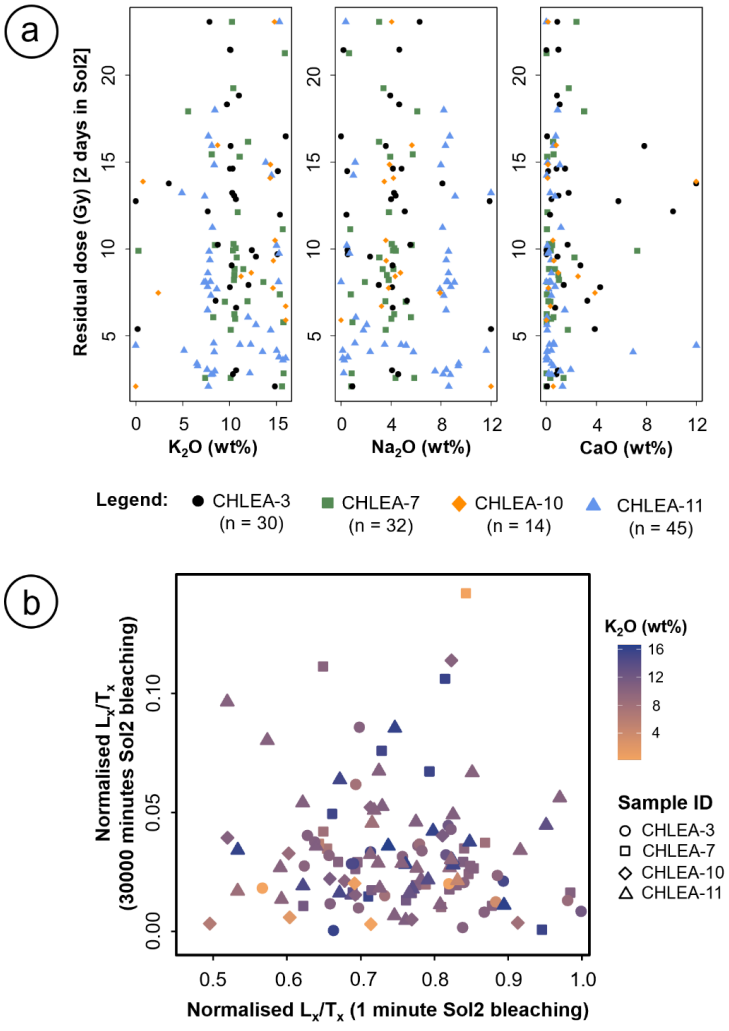

Figure 5: (a) Residual dose measured after two days of Sol2 bleaching plotted against K_2O, Na_2O, and CaO concentrations of individual feldspar grains from four samples (CHLEA-3, 7, 10, 11) used in the bleaching experiment. Despite compositional variability, no systematic geochemical control on the residual dose is evident. (b) Relationship between normalised luminescence signals after 30,000 minutes and 1 minute of Sol2 bleaching. No clear correlation is observed with the initial bleaching response. Data points are colour-coded by the K_2O concentration (wt%). Uncertainties are not shown for clarity.

4.1.3 Influence of catchment-scale lithological variability

All four samples included in the bleaching experiment exhibited similar bleaching behaviour (Fig. 3a), despite notable variability in catchment-scale lithological composition (Table S1). We examined whether a provenance relationship exists between the distribution of lithological units, MAM D_e values, and the mean residual doses across all catchments (Fig. S13). The results suggest that neither the MAM D_e values nor the residual doses are directly influenced by catchment lithology. Furthermore, we evaluated whether the dominant lithological unit (i.e., the unit with the highest proportion), exerts any control on the size of the MAM D_e and residual dose. No consistent correlation was observed between the dominant lithological unit, MAM D_e and residual dose (Fig. S13). For example, CHLEA-4 and CHLEA-7 originate from catchments

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with similar dominant lithologies (Table S1), yet both their MAM D_e and residual dose estimates differ markedly (Table 3), while CHLEA-6 and CHLEA-9 exhibit comparable MAM D_e and residual dose values (Table 3, Fig. S6) despite different dominant lithologies (Table S1). These observations align with grain-specific residual dose variability and associated geochemical compositions (Fig. 5a). Collectively, these findings suggest that the bleaching behaviour of the post-IR $IRSL_{200}$ signal is not directly controlled by catchment-scale lithological variability. However, such external factors may influence the bleaching opportunities (i.e., exposure duration in natural settings), contributing to variability in natural D_e distributions.

4.1.4 Influence of natural dose (i.e., comparing laboratory bleaching with natural bleaching of modern analogues)

Sohbati et al. (2012), Buylaert et al. (2012), Kars et al. (2014), and Yi et al. (2016) compared the size of the natural D_e with the size of measured residual doses and observed a positive correlation between these two variables, with the size of the residual doses increasing with increasing D_e. Following these findings, for all of our modern analogues, we compared the mean residual doses with their corresponding mean D_e. In contrast to previous studies, we found only a weak positive linear correlation ($R^2 = 0.16$; Fig. S7) between mean residual dose and mean D_e. However, our samples are derived from modern floodplains with fluvial transport potentially leading to heterogeneous bleaching of the luminescence signal (Guyez et al., 2023). To account for this, we compared the mean residual dose to the D_e of the best-bleached grain population, obtained using the unlogged MAM, for each sample. For this, we observed a strong ($R^2 = 0.86$) positive exponential relationship (Fig. 6), suggesting a dose-dependent bleaching efficiency. The fitted curve has an intercept of 1.88 ± 0.54 Gy, which we interpret as the characteristic dose in theoretically fully bleached samples, reflecting a persistent unbleachable component inherent to all samples at the time of deposition. This is also evident for four samples where the lowest observed laboratory residual doses are in the same dose range as the unbleachable component. These findings suggest that residual dose magnitude, as determined through laboratory bleaching, is primarily governed by the natural dose of the best-bleached grain population in natural settings. This relationship also helps to explain the variability observed at the single-grain level and suggests the presence of a persistent, unbleachable component at the time of deposition.

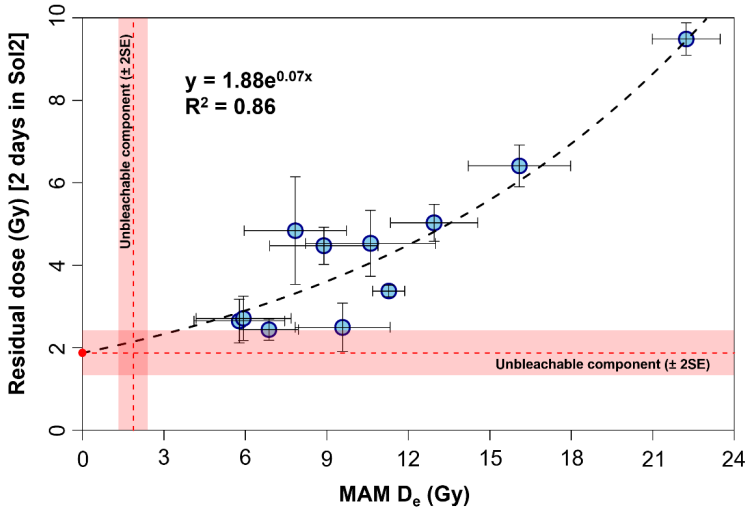

Figure 6: Relationship between the residual dose and the MAM D_e for modern floodplain samples. Each data point represents a sample, with uncertainties indicating one standard error. The dashed black line shows an exponential fit to the data, suggesting a positive, exponential relationship between the residual dose and MAM D_e. The horizontal dashed red line, together with the shaded red band, denotes the estimated unbleachable component (±2 standard errors). A corresponding vertical red dashed line and shaded band on the x-axis denote the same unbleachable component in terms of MAM D_e, facilitating visual comparison and emphasising the systematic overestimation of MAM D_e relative to the true bleaching limit.

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To further investigate the observed natural dose-dependent bleaching efficiency, we conducted additional laboratory bleaching experiments on CHLEA-7 and CHLEA-11 (supplementary material, section S6). For each sample, doses of 30, 60, and 120 Gy were added to their respective natural doses, followed by a 2-day bleaching period in the Sol2 (Table S8). Subsequent measurements of residual dose revealed contrasting behaviours between the two samples (Fig. S12; Table S9). CHLEA-7 exhibited no discernible dose-dependent trend, whereas CHLEA-11 showed a weak but noticeable increase in residual dose with increasing laboratory dose. Together with the results shown in Figure 6, these observations indicate that bleaching efficiency may be inversely related to the natural dose level, with samples of lower natural dose exhibiting inherently more effective bleaching under laboratory conditions. The underlying mechanisms responsible for this phenomenon remain unclear. Further investigations, potentially focusing on trap characteristics, are warranted to elucidate the processes involved. However, such exploration lies beyond the scope of the present study.

4.2 Assessment of recuperation dose as a proxy for bleachability

Based on the observations of Choi et al. (2024), who reported a positive linear relation between recuperation dose and residual dose, and proposed the former as a potential proxy for evaluating bleachability, we examined the relationship between absolute recuperation dose and residual dose at both single-grain and sample-average levels across all samples (section S8 of the supplementary material). At the single-grain level, the majority of samples showed statistically significant positive relationships (Fig. S14a, Table S10); however, the proportion of variance in residual dose explained by recuperation dose, as quantified by the coefficient of determination (R^2), was consistently low (Table S10). Likewise, at the sample-average level, a weak positive linear trend (Fig. S14b) was observed ($R^2 = 0.27$), though the association did not reach statistical significance ($p > 0.05$). These findings suggest that, despite the presence of positive trends for the majority of the samples, the recuperation dose accounts for only a small fraction of the variability in residual dose, and therefore may not serve as a robust standalone proxy for bleachability.

4.3 Implications for dating and sediment tracing applications

4.3.1 Dating sedimentary archives

Previous studies, including Reimann et al. (2011), Reimann and Tsukamoto (2012), and Fu and Li (2013), have subtracted laboratory-determined residual doses from paleodoses when dating K-feldspar fractions of young sedimentary deposits. While a small residual component (<2 Gy) might have minimal influence on the age estimates of older deposits, it may significantly impact the dose estimates of young deposits. Consequently, the validity of this approach has been questioned, particularly due to uncertainties in whether artificial bleaching replicates natural bleaching processes (Kars et al., 2014).

Thus, to improve age accuracy, Ollerhead & Huntley (2011) and Kars et al. (2014) have proposed to subtract remnant doses of modern analogues from calculated palaeodoses. However, substantial uncertainties remain due to limited knowledge of the bleaching conditions, such as the transport medium, duration of transport, and number of depositional cycles. In our investigation of modern fluvial analogues, we addressed this challenge by using single-grain analysis and isolating only the best-bleached grain population. We adopted the MAM D_e values as proxies for remnant doses and compared them to laboratory-determined residual doses obtained after 2 days of bleaching in Sol2 (Fig. 6).

Our results reveal a strong positive correlation between the MAM D_e values and laboratory residual doses (Fig. 6), indicating a systematic relationship between natural and laboratory bleaching processes. Importantly, we also observe that even the MAM D_e values of our modern analogues systematically overestimate the unbleachable component. The MAM D_e values of our best bleached modern analogues overestimate the unbleachable component by ~3 to 4 Gy whereas the MAM D_e values of the poorest bleached sample overestimate the unbleachable component by more than 20 Gy (see Fig. 6). This indicates that even the best-bleached grain population isolated via the minimum age model retains inherited dose contributions that exceed the true bleaching limit. Notably, we observe a large variation in remnant doses of the modern analogues. Therefore,

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subtracting the remnant dose of a (random) modern analogue is not a reliable method for correcting palaeodoses from sedimentary archives. Instead, we evaluate three options for addressing this issue, each with its own advantages and limitations.

1. **Not correcting the palaeodose for the size of the remnant dose:**
   - Advantage: Jain et al (2004) argued that modern analogues possess undefined preservation potential and therefore cannot be reliably compared to geological archives, which are preserved due to their inherently higher preservation potential. Furthermore, although all our samples were collected from a modern floodplain environment, the data exhibit considerable variability in remnant dose magnitudes, ranging from 5.78 ± 1.67 to 22.23 ± 1.25 Gy (Table 3, Fig. 6). This pronounced scatter supports the rationale for avoiding any corrective measures.
   - Limitation: While not correcting palaeodoses for the size of a potential remnant dose may be preferred in light of the scatter observed for remnant doses of the modern analogues in the present study, it risks significant age overestimation in samples where remnant doses are particularly high.
2. **Using the remnant doses for palaeodose correction:**
   - Advantage: In our dataset, all eleven modern analogue doses (i.e., remnant doses) are substantially higher than both the laboratory residual doses and the unbleachable component (Fig. 6). This consistent disparity, coupled with the pronounced scatter in remnant dose values across samples, underscores the limitations of applying individual remnant doses directly for palaeodose correction. Instead, one could propose estimating the remnant dose and its associated uncertainty based on the observed variability within our set of modern analogues. A comparable approach was applied in Joordens et al. (2015), where they used the average remnant dose and a large uncertainty based on available literature values encompassing a broad range of remnant doses from well-bleached aeolian deposits to heterogeneously bleached glacial outwash deposits for dating of fluvial samples from Java (Indonesia) using the $pIRIR_{290}$ protocol.
   - Limitation: Although using an average remnant dose based on the dose distribution of the modern analogues with large scatter might be helpful for dating older sedimentary archives, it risks overcorrecting palaeodoses in younger deposits, potentially leading to age underestimation. The reliability of this approach strongly depends on the match of available modern analogue-based remnant doses and the set of samples to be dated in terms of bleaching behaviour, statistical treatment of the data and bleaching opportunities.
3. **Using the unbleachable component for palaeodose correction:**
   - Advantage: This method involves using the lowest dose level that cannot be further reduced through bleaching, the unbleachable component (Fig. 6), as a correction factor. This component is reproducible with high confidence and carries minimal risk of overcorrection, making it a stable and quantifiable basis for palaeodose correction.
   - Limitation: This unbleachable component is significantly lower than the remnant doses in our modern analogues, even after applying the MAM to extract the best bleached dose component from single-grain data. Thus, given the scatter in remnant dose of our data (Fig. 6), use of unbleachable component would introduce a one-directional systematic error, as this would systematically undercorrect the true inherited dose (Fig. 6). Based on our data, in optimal scenarios, this undercorrection could amount to approximately 3 to 4 Gy; however, in less favourable cases, the discrepancy may exceed 20 Gy.

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Suggestions: For aeolian and coastal deposits, where bleaching tends to be more complete and homogeneous, resulting in minimal dose scatter, the use of the unbleachable component may be appropriate. However, for fluvial and glacio-fluvial settings, characterised by heterogeneous bleaching and high dose scatter, the approach based on modern analogues may be more effective. However, an average remnant dose may not adequately represent the full distribution of modern analogues. Instead, using other statistical parameters based on the remnant dose distribution (such as the mode or median) could potentially yield more representative and meaningful corrections. Moreover, it is important to recognise that any correction approach is inherently linked to the protocol used for D_e estimation, aliquot size (e.g., multi-grain vs. single-grain), and selection of the statistical age model for dose estimation (e.g., CAM, MAM). Also, future work should focus on evaluating modern analogues across diverse depositional environments to determine whether correction strategies need to be tailored to specific settings.

4.3.2 Sediment tracing

Bleaching is a fundamental aspect of the luminescence-based sediment tracing method. Previous research has demonstrated that various geomorphic and environmental factors influence the bleaching opportunities of individual grains originating from different geomorphic settings (Chamberlain et al., 2017; Gemmell, 1985; Gray et al., 2018; Guyez et al., 2023; King et al., 2013, 2014; MacGuire and Rhodes, 2015). Therefore, a critical step in applying luminescence as a sediment tracer involves identifying grain populations according to their bleaching history, notably the well-bleached grains. This requires the development of a reliable threshold, which is sensitive to a given geomorphic setting to confidently distinguish well-bleached from partially bleached grains.

For instance, Guyez et al. (2023) employed the proportion of well-bleached versus non-bleached grains for tracing sediment pathways in New Zealand, using a threshold of 10 Gy for defining well-bleached grains based on residual dose measurements after 65 hours of bleaching in Sol2. While practical, this approach may oversimplify site-specific variability in bleaching. A more refined approach would involve characterising the bleaching efficiency for a subset of samples through controlled laboratory or natural bleaching experiments to establish a more precise bleaching threshold. For our modern fluvial samples, one approach to differentiate well-bleached from partially bleached grains is to use the unbleachable component, here 1.88 ± 0.54 Gy (Fig. 6), as a common threshold for all samples. Alternatively, a more sample-specific method involves classifying grains as well-bleached if their natural D_e falls within the two-sigma range around the mean of the single-grain residual dose distribution of each sample, provided a clear bleaching plateau is reached. The latter approach, though time-intensive, appears more appropriate and realistic, as it provides a sample-specific bleaching threshold. Although further testing is required to validate this method in sediment tracing studies, similar to the approach used by Guyez et al. (2023), these findings lay the groundwork for implementing more refined sediment tracing models that better account for grain-scale luminescence signal variability.

5 Conclusion

We examined the bleaching behaviour of the post-IR $IRSL_{200}$ signal in modern fluvial samples from the Southern Central Andes through controlled laboratory bleaching experiments at the single-grain level. The samples, sourced from catchments with diverse geological and geomorphological settings, were exposed to varying durations of light. Despite catchment-scale variations, all samples exhibited consistent bleaching trends at the sample-average level, reaching a bleaching plateau based on the normalised L_x/T_x data, after two days of exposure. At the single-grain level, however, bleaching rates and extents varied across exposure durations, indicating that while the bleaching duration fundamentally controls the magnitude of the residual dose, it does not account for the observed variability in single-grain residual dose estimates. Grain-specific luminescence and geochemical analysis showed that the variations in bleaching rates and corresponding residual doses are not linked to the geochemical composition (including the K-concentration) of individual feldspar grains. Instead, residual

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dose variability correlated with the size of the natural doses (MAM D_e), identifying natural doses as likely controlling the observed variability in residual dose estimates both within and among samples. Given the systematic overestimation of remnant doses of modern analogues relative to the unbleachable component and substantial variation in remnant doses across our dataset, we evaluate different possibilities of palaeodose correction and make suggestions for corrections, accounting for the depositional environment, and more importantly, for the measurement protocol, aliquot size, and statistical age model. Additionally, both the unbleachable component and sample-specific residual doses may aid in establishing effective bleaching thresholds to distinguish well-bleached from partially bleached grains, a key requirement in luminescence-based sediment tracing studies.

Data availability

Partly processed data will be made available on Zenodo.

Supplement

Authors's contribution

AB: methodology, investigation, data analysis, visualisation, writing–original draft; **SR:** conceptualisation, methodology, writing–review and editing; **LKB:** sample collection, writing–review and editing; **MH:** investigation, writing–review and editing; **AG:** sample collection, writing–review and editing; **SB:** funding acquisition, project management, sample collection, writing–review and editing; **TR:** conceptualisation, funding acquisition, project management, writing–review and editing.

Competing interest

The authors declare that they have no conflict of interest.

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