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Time-resolved infrared stimulated luminescence of the blue and yellow-green emissions – insights into charge recombination in chemically and structurally different alkali feldspars

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Time-resolved infrared stimulated luminescence of the blue and yellow-green emissions – insights into charge recombination in chemically and structurally different alkali feldspars

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Abstract

Time-resolved luminescence measurements can be used to explore luminescence processes in minerals and the defects involved. It has also been applied to feldspars and knowledge has been gained regarding potential crystal defects associated with luminescence productions in these minerals, but also regarding processes governing electron-hole recombination leading to luminescence emission.

Here we present time-resolved infrared stimulated luminescence (IRSL) signals measured for a range of mineralogically well characterised single crystal alkali feldspars. We explore time-resolved luminescence for the blue (~410 nm) and the yellow-green emission (~550 nm) in response to different irradiation doses and by comparing different IRSL signals. Firstly, we explore whether the lifetimes measured represent excited state or recombination lifetimes. Secondly, we investigate sample-dependent changes in blue and yellow-green time-resolved signals and link those to physical properties of the samples.

Our results show that the timescales on which the blue and the yellow-green emission occur differ significantly, with the blue signal on the µs-scale, and the yellow-green emission on the ms-scale. We do not observe any dependence of the time-resolved signal on signal integration, dose given or IRSL signal measured. However, inter-sample variability is shown for both emissions. In the blue we only observe small differences in decay time scale between single-phase feldspars and perthites, however larger differences are measured between samples that were artificially disordered compared to ordered feldspars. Longer lifetimes observed for disordered feldspars are suggested to be linked to either changes in the recombination centre or to increased band-tail states transport due to an increase in the width or density of the sub-conduction band-tail states. The data indicates the potential

of using time-resolved IRSL of the blue emission to get an indication of the state of order of a feldspar. For the yellow-green emission slow signal decays are observed for single-phase feldspars, likely indicating a spin-forbidden transition. Interestingly, similar lifetimes were observed for K- and Na-feldspar end members.

Keywords

Time-resolved luminescence, lifetime, feldspar, recombination, band-tail states

1 Introduction

Conventional luminescence measurements use continuous wave (CW) stimulation to excite trapped electrons and enable their migration through the crystal lattice, resulting in recombination at a recombination centre. If the recombination process is radiant it leads to the emission of photons. In time-resolved (TR) luminescence measurements samples are stimulated using pulsed light, meaning that a TR measurement consists of multiple stimulation light pulses, separated by so-called off-times, during which no optical stimulation occurs (Sanderson and Clark, 1994; Lapp et al., 2009). This method not only enables an improved discrimination of excitation and emission wavelengths, but also gives information on recombination processes in minerals (Sanderson and Clark, 1994). During on-times of pulsed stimulation, electrons are excited from the ground state of the electron trapping centres and migrate to recombination centres, while the off-time allows investigations into the decay of different luminescence emissions after the optical stimulation has been turned off. Thus, TR-luminescence measurements make it possible to measure recombination lifetimes and excited state lifetimes of the luminescence centres. For feldspars, TR-luminescence measurements have previously been performed to gain insights into electron-hole recombination processes (e.g. Sanderson and Clark, 1994; Jain and Ankjærgaard, 2011) and to understand defects involved in luminescence production and their locations within the crystal lattice (e.g. Clark and Bailiff, 1998). Despite this previous research, it is still unknown, how different chemistry and structure of feldspars impact luminescence production and how these factors influence excited state and recombination lifetimes of feldspar infrared stimulated luminescence (IRSL). In this paper we use TR-IRSL with detection in the blue (~410 nm) and yellow-green (~550 nm) wavelength regions to explore recombination processes and potentially involved defects in chemically and structurally different alkali feldspars.

Time-resolved luminescence with emissions in the UV, blue, yellow-green or red to near-infrared, have been investigated, mainly to understand the defects and transitions involved in the recombination process. The blue luminescence emission has been associated with a hole centre located on Al-O-Al

bridges (Finch and Klein, 1999; Riedesel et al., 2021a) and it has been shown that its intensity and stability is dependent on the degree of order on the Si, Al-framework and on the presence and type of interfaces in perthites (Riedesel et al., 2021a). However, it is unknown whether lifetimes of the blue emission are also affected by changes to the crystal structure. Previous research investigating lifetimes of the blue emission indicated very fast decaying signals with lifetimes on the sub-µs to few µs-scale (e.g. Clark et al., 1997; Clark and Bailiff, 1998). Besides those very fast lifetimes, Ankjærgaard and Jain (2010) observed very long lifetimes for the blue emission on the ms- to s-scale. These authors suggest band-tail state transport as the source of these long lifetimes.

For the yellow-green emission two likely defect sites have been proposed: (i) The emission at ~560 nm has been assigned to Mn^{2+} substituting for Ca^{2+} in plagioclases resulting in a spin-forbidden transition with long lifetimes on the ms-scale (e.g. Geake et al., 1971, 1973, 1977; Telfer and Walker, 1978); (ii) Alternatively, the emission was suggested to result from Mn^{2+} substituting for Al^{3+} on tetrahedral sites (T sites) in alkali feldspars, creating a lattice stabilising hole centre on Si^{4+}-O^{-}-Mn^{2+} (Telfer and Walker, 1978; Kirsh et al., 1987). This second possibility would result in shorter lifetimes, due to the defect being located at a lattice site. Clark and Bailiff (1998) have indeed observed very fast lifetimes (on the ns-scale) for the emission at ~560 nm, supporting a lattice site defect for the yellow-green emission. From phosphorescence data Prasad et al. (2016) observed dominant lifetimes of the yellow-green emission of the order of hundreds of microseconds to less than a fraction of a millisecond – also an observation against a spin forbidden transition of a defect located on cation sites (M sites). Riedesel et al. (2021a) observed a strong yellow-green emission centred around 560 nm in alkali feldspar end members albite and microcline, with all three samples having zero to negligible concentrations of MnO as determined by x-ray fluorescence analysis. Thus, the source of the yellow-green emission in chemically different alkali feldspars needs further investigation.

Besides using TR-luminescence to link certain defect types to luminescence emissions, feldspar TR-luminescence has been used to improve the understanding of electron-hole recombination processes and to infer possibilities to extract a more stable luminescence signal for dating. As part of this work, it has been debated whether the TR-luminescence signal of feldspars represents the excited state lifetime of the luminescence centre (the time needed for the electron to transition from the excited state to the ground state of the luminescence centre, cf. e.g. Clark et al., 1997) or the recombination lifetime (the time needed for the excited electron to move from the electron trapping centre to a recombination centre) (e.g. Ankjærgaard et al., 2009; Tsukamoto et al., 2010), and which role band-tail states play in this process (e.g. Jain and Ankjærgaard, 2011; Pagonis et al., 2012).

The current understanding of feldspar luminescence is primarily based on a proximity model, where the electron-hole pairs are separated by a distribution of distances and where it is understood that recombination will occur at the nearest recombination centre (e.g. Huntley, 2006; Jain et al., 2012). Feldspars containing a higher density of recombination centres will thus have less stable luminescence signals, compared to feldspars with a lower density, because it will be more likely for electrons to recombine at a proximal luminescence centre, even more likely through tunnelling processes (e.g. Huntley, 2006; Jain et al., 2012). Subsequently, one would expect faster recombination lifetimes in a system with a higher density of recombination centres, compared to systems with a lower recombination centre density. Ankjærgaard et al. (2009) explored whether the TR-luminescence signal of feldspars (green (532 nm) laser or blue (470 nm) LED stimulation and UV detection) reflected the excited state or the recombination lifetime. They found arguments for either of the two processes controlling the lifetimes measured. One argument supporting the recombination lifetime hypothesis was shown by TR-OSL measured at different stimulation temperatures resulting in the same decay shape, i.e. not giving rise to thermal quenching. However, Ankjærgaard et al. (2009) also found counter arguments, thus supporting the excited state lifetime hypothesis: A systematic decrease in lifetime with increasing preheat temperature was observed for feldspar TR-OSL. The authors argued that longer lifetimes were expected for higher preheat temperatures, as a high preheat would result in a depletion of recombination centres, making recombination more difficult and thus increasing the recombination lifetime. Ankjærgaard et al. (2009) further explored whether different stimulation times could affect the lifetimes and decay shape of the signals, expecting an increase in lifetimes with increasing stimulation time. If the lifetimes measured would correspond to recombination lifetimes, then one would expect longer lifetimes with decreasing hole concentrations due to longer stimulation lifetimes. However, no clear trend was observed. Tsukamoto et al. (2010) compared TR-OSL and TR-OSE (optically stimulated exo-electron) measurements of quartz, feldspar and NaCl and found that the decay of TR-OSE signals are faster than TR-OSL in the case of NaCl and quartz, with TR-OSE signals decaying on timescales <1 μs, while NaCl and quartz TR-OSL signals decay with a lifetime of ~40 μs. TR-OSE and TR-OSL of feldspars decay on similar timescales. The very fast decaying TR-OSE signals are understood as rapid emptying of the electron population in the conduction band immediately after turning off the stimulation light source. In contrast, the slower decay of the TR-OSL signals is interpreted as arising from relaxation processes within the recombination centre, thus being governed by the excited state lifetime of these defects and the internal transitions.

Since the physical source of various TR-luminescence signals is still under debate, and it is still unclear whether the off-time of TR-signals represents the excited or the recombination lifetime, different

approaches have been used to describe TR-luminescence signals, particularly focussed on the off-time signal. Most commonly a sum of multiple first order exponential functions have been used to describe the TR off-time signal (e.g. Clark et al., 1997; Clark and Bailiff, 1998; Tsukamoto et al., 2006; Ankjærgaard et al., 2009). However, feldspar luminescence is not a first order process (e.g. Huntley, 2006) and thus it has been proposed that fitting a sum of multiple first order exponential functions might be inappropriate (e.g. Ankjærgaard, 2009; Pagonis et al., 2012, 2016). Jain and Ankjærgaard (2011) thus visually separated the off-time signal into a "fast" and a "slow" TR-signal, with the "fast" signal describing the initial decay, and the "slow" signal governing the TR-signal after 70 µs in the off-time. Pagonis et al. (2012) applied a linear combination of exponential and stretched exponential functions. These authors interpreted the part of the TR-signal fitted by a stretched exponential as being caused by transport via the band-tail states. Later Pagonis et al. (2016) developed analytical equations describing feldspar TR-luminescence, which are based on the nearest-neighbour recombination model by Jain et al. (2012). However, there are still many unknowns in the physical processes involved in luminescence production in feldspars, so no definite answer can yet be given regarding the optimal signal analysis procedure.

The research presented in this paper is focussed on creating a better understanding of defects and processes involved in blue and yellow-green luminescence production. Therefore, we measure TR-luminescence resulting from pulsed IR stimulation with emissions in the blue and yellow-green wavelength region of a suite of representative single crystal alkali feldspars including single-phase feldspars, perthites and artificially disordered feldspars. These are explored to investigate whether the measured TR luminescence signal and its lifetimes and decay shape are governed by the recombination or excited state lifetime and which role band-tail states might potentially play. We compare TR luminescence resulting from different IRSL signals, different irradiation doses and of chemically and structurally different feldspars.

2 Materials and methods

2.1 Samples

Samples investigated here are single crystal alkali feldspar specimens. Their chemical composition, structural state and mineral phases present have been characterised previously and details can be found in Riedesel et al. (2021a). The sample suite represents the chemical and structural range of the alkali feldspar solid solution series and its end members. The chemical composition, mineral phases present and the structural state of the samples was determined using x-ray fluorescence and x-ray diffraction. FSM-13 is a single-phase microcline (98.5 % K-feldspar) and CLBR a single-phase albite (0.5

% K-feldspar). FSM-3 (82.5 % K-FS), FSM-6 (74.4 % K-FS) and FSM-5 (74.8 % K-FS) are perthites. FSM-3 and FSM-6 are cryptoperthites consisting of albite and microcline (FSM-3) or orthoclase (FSM-6). FSM-5 is a macroperthite consisting of albite and microcline. FSM-13LH and FSM-6LH are artificially disordered samples. To obtain these samples, powdered sample material of FSM-13 and FSM-6 was heated in Pt crucibles in a furnace to 1050 °C and then rapidly cooled to room temperature to retain the disordered high-temperature structure, with Al^{3+} ions distributed randomly across tetrahedral sites on the (Si,Al)-framework. Details of these experiments and a comparison of the x-ray diffraction pattern of the ordered/disordered sample pairs can be found in Riedesel et al. (2021a). For each sample three aliquots were measured.

2.2 Instrumentation and measurement protocol

Time-resolved luminescence measurements were made on a Risø TL/OSL DA20 reader equipped with a $^{90}Sr/^{90}Y$ beta source delivering ~0.1 Gy s^{-1} at the sample position and a Detection And Stimulation Head (DASH) including an automated filter changer (Lapp et al. 2015). For the measurements presented in this paper infrared stimulated luminescence (IRSL) was detected using a PDM 9107Q-AP-TTL-03 (sensitive wavelength region: 160-630 nm) photomultiplier tube. For detection of the blue emission (~410 nm) we used a combination of Schott BG39 (2 mm) and BG3 (3 mm) filters and for the yellow-green emission (~550 nm) a combination of Schott BG39 (2 mm) and OG550 (2 mm) filters. Dependent on the brightness of the sample ND 1.0 or ND 2.0 filters were added to the chosen filter combination. The emission windows of the individual filters and the chosen filter combinations are displayed in Figs. 1D and 1E. The stimulation was achieved using 850 nm (300 mW cm^{-2}) IR LEDs, operating at 90 % power.

Time-resolved luminescence measurements were possible through a photon timer attachment (TimeHarp 260) in combination with the pulsed optically stimulated luminescence (OSL) unit (Lapp et al., 2009). The TimeHarp 260 photon timer enables the detection of individual photons with a time resolution of up to 1 ns. The pulsed IRSL plug-in board allows on- and off-times to be adjusted between 0.6 µs and 10 s. Additionally, different gating intervals can be selected. For time-resolved IRSL measurements with emission detection in the blue wavelength region we used on-times of 50 µs, followed by an off-time of 200 µs. Due to the much slower decay of the yellow-green time-resolved IRSL signal, on-times were 5 ms, followed by an off-time of 45 ms. The time-resolved IRSL signals for both emissions were recorded over a period of 200 s.

Time-resolved IRSL measurements were performed using a post-$IR_{50}IRSL_{225}$ protocol with a 60 s preheat at 250 °C. The IR stimulation time was 200 s for the $IRSL_{50}$ and post-IR $IRSL_{225}$ signals. Prior to

each measurement using the post-IR IRSL protocol the samples were annealed to 450 °C to ensure complete signal resetting (Table 1). All samples were irradiated after the 450 °C clean-out. Blue time-resolved IRSL measurements were performed after irradiation doses of 50, 200 and 800 Gy. Yellow-green time-resolved IRSL measurements were conducted after doses of 200 or 800 Gy. In case of samples FSM-5 and FSM-6 the yellow-green emission was not intense enough after a dose of 200 Gy, thus these samples were irradiated with 400 Gy instead. Results of these dose-dependent measurements are presented in section 3.1.3 for the blue emission. Results of these experiments for the yellow-green emission are not shown, but results obtained from fitting are given in Tables S3a and S3b in the supplementary material.

Table 1: Measurement protocol used.

Step	Treatment	Purpose
1	TL to 450 °C, 1 °C s^{-1}	Signal clean out
2	Beta dose 50, 200, 400 or 800 Gy	Irradiation, dose dependent on experiment
3	Preheat to 250 °C, 2 °C s^{-1}, 60 s	
4	$IRSL_{50}$, 2° °C s^{-1}, 200s Blue emission: 50 µs on-time, 200 µs off-time Yellow-green emission: 5 ms on-time, 45 ms off-time	Obtain time-resolved $IRSL_{50}$ signal
5	post-IR $IRSL_{225}$, 2 °C s^{-1}, 200s Blue emission: 50 µs on-time, 200 µs off-time Yellow-green emission: 5 ms on-time, 45 ms off-time	Obtain time-resolved post-IR $IRSL_{225}$ signal

Fitting of time-resolved luminescence signals was done in R using the nls() function (Bates and DeRoy, 2018) using equation 1 for the on-time signal and equation 2 for the off-time signal, where I is the intensity at time t, A_i is the saturation intensity of the i'th component and a_i the intensity at time t_1, where t_1 is the on-time duration, and k is a constant, representing a stable linear background (Chithambo, 2003; Tsukamoto et al., 2006). The data were normalised to the intensity of the last data point of the on-time. The sole purpose of fitting the data was to enable a numerical comparison between the samples used in this paper and to also be able to compare the data obtained here to previously published time-resolved IRSL data (e.g. Clark and Bailiff, 1998; Tsukamoto et al., 2006, 2010). It is not our intention to make any suggestions regarding the physical processes by using the numerical results obtained through fitting the data using a sum of multiple first order exponentials. Later sections discussing potential physical properties of the samples and their influence on the TR-luminescence signals are based on qualitative descriptions and sample-to-sample comparisons.

$$I(t) = \sum A_i \left[1 - \exp\left(\frac{-t}{\tau_1}\right)\right] \quad [1]$$

$$I(t) = \sum a_i \exp\left[-\left(\frac{t-t_1}{\tau_1}\right)\right] + k \quad [2]$$

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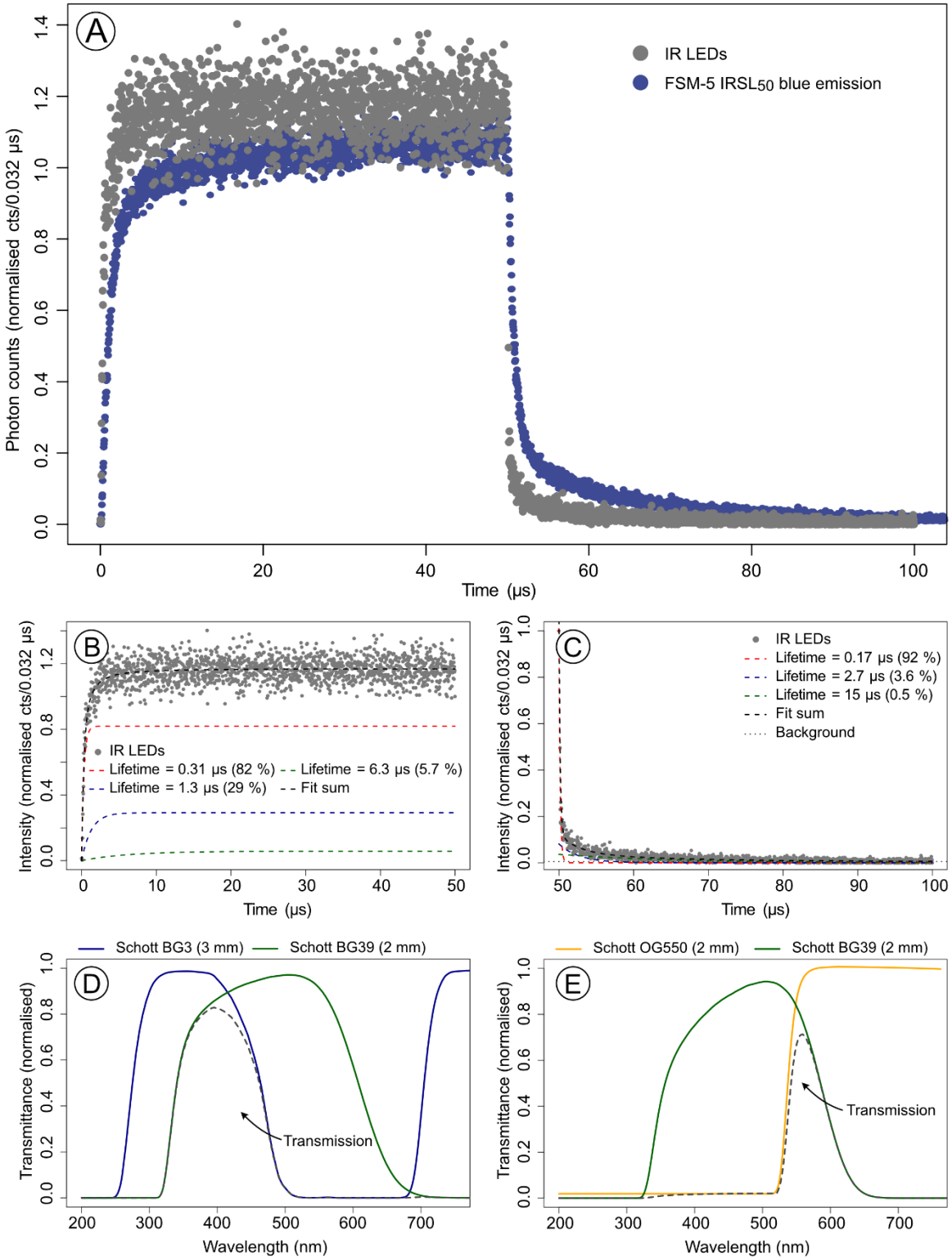

Fig. 1. A) The response of the IR LEDs measured through a ND filter for deadtime correction, and the signal was recorded using a red-sensitive photomultiplier tube (PMT). The signal of FSM-5, the fastest decaying signal from all samples measured, was recorded through the BG39 + BG3 combination visualised in D and was detected using a UV-sensitive PMT. This sample was chosen in comparison as it has the fastest decay in the off-time. B) Fitted LED on-time and C) off-time signal. The signal was normalised to the last point of the on-

time, and the scatter of the data means that some measurement points lie above 1. D) Transmission of the BG3 and BG39 filter combination. E) Transmission of the OG550 and BG39 filter combination.

3 Blue TR-IRSL emission – Results and Discussion

The blue luminescence emission (~410 nm) is the emission commonly detected when using feldspars for luminescence dating, thus this emission and potential variations of this emission between different feldspars is of particular interest. In the following we investigate variations in the lifetimes of on- and off-times of the blue TR-IRSL signals as a function of integration interval, irradiation dose, and IRSL signal investigated. To enable a direct comparison all on- and off-time signals were fitted using a sum of multiple first order exponential functions. We have also attempted to use a linear sum of single exponential function and stretched exponential function (Pagonis et al., 2012) to describe our data. However, fitting our data using the equation given by Pagonis et al. (2012) in R and SigmaPlot yielded parameters values of infinity. The only samples we were able to fit using a linear sum of single exponential function and stretched exponential function were the disordered samples FSM-13LH and FSM-6LH. Thus, we only present lifetimes based on fitting with a linear sum of multiple first order exponential functions.

3.1 Lifetimes

In the following we first investigate the effects of changing the integration interval, the IRSL signal ($IRSL_{50}$ compared to post-IR $IRSL_{225}$) or the given dose on the on- and off-time lifetimes. To enable a numerical comparison, we here use the results obtained from fitting using a sum of multiple exponentials.

All results presented in the following sections are based on TR-luminescence signal fitting using between one and four exponential functions (eq. 1 and 2). The number of components used for fitting is based on the lowest residual signal obtained from fitting with different number of components, thereby avoiding redundancy in the fitting. Using this approach, we obtained lifetimes ranging from 0.5 µs to over 100 µs. Faster lifetimes could not be detected due to the decay time of the IR LEDs (~0.3 µs, cf. Fig. 1A, B, C). Generally, lifetimes could be arranged into three lifetime groups for the on-time signal: <5 µs, 8-20 µs and > 20 µs, and into four lifetime groups for the off-time: < 1 µs, 3-9 µs, 12-16 µs and > 20 µs. This grouping was done by identifying similar lifetimes between different samples and the two signals investigated and are only used for visualisation purposes in figures and tables. Differences in on- and off-time lifetimes might be related to the different time intervals used: 50 µs on-time compared to 200 µs off-time, leading to an improved description of the longer off-time

265 duration compared to the shorter on-time. All numerical fitting results can be obtained from the
266 supplementary material.

267

Integration intervals

The TR-IRSL signals were recorded over a stimulation period of 200 s, for the $IRSL_{50}$ and post-IR $IRSL_{225}$ signal, respectively. An example of IRSL decay curves measured during the on- and off-time is given for sample FSM-13 in Fig. S1. Using the software PTanalyse, we extracted photon arrival time distributions of the following time intervals for a comparison: 0-2 s, 0-5 s, 0-10 s, 0-50 s and 0-200 s, 10-50 s, 50-100 s and 100-200 s. To be able to make an absolute comparison, we selected two samples, FSM-3 and CLBR, and fitted the extracted photon arrival time distributions of the on- and off-time of the $IRSL_{50}$ and post-IR $IRSL_{225}$ signals using equation 1 and 2. Figure S2 in the supplementary material shows the results of FSM-3, results for CLBR are not shown, but are similar to those of FSM-3. We did not observe any significant and consistent changes in lifetime with integration interval selected for either of the IRSL signals or any samples. However, increasing the integrated time interval resulted in a better goodness of fit, expressed as the square sum of residuals of the fit, with the best fit obtained when integrating the photon arrival time distribution of the entire IRSL signal (total 200 s stimulation). Subsequently, all data presented in this paper are based on whole IRSL signal integration.

Signals investigated – $IRSL_{50}$ compared to post-IR $IRSL_{225}$

Post-IR IRSL signals are observed to be more stable compared to the $IRSL_{50}$ signal measured as part of the post-IR IRSL protocol (e.g. Thomsen et al. 2008), likely due to the post-IR IRSL signal probing more distant electron-hole-pairs (Jain and Ankjærgaard, 2011). TR-IRSL signal differences have also been observed: Jain and Ankjærgaard (2011) defined a “fast” and a “slow” TR-signal and found different behaviour of these two for the IRSL and post-IR IRSL signals measured in the UV at elevated temperatures, and that the relative signal intensity between the fast and slow signal contribution changes.

Here we compare lifetimes obtained for the two IRSL signals measured in the blue using a post-IR_{50} $IRSL_{225}$ protocol. Figure 2 shows lifetimes of all samples obtained by fitting on- and off-time signals of the $IRSL_{50}$ and post-IR $IRSL_{225}$. Figs. 2A and B show a direct comparison of all measured lifetimes and their distribution around a 1:1 line, for the on- and off-times respectively. Especially at faster lifetimes and in the off-time signal, $IRSL_{50}$ and post-IR $IRSL_{225}$ yield similar results and even the slower signals show results scattered around the 1:1 line (Fig. 2 A, B). Sample-dependent lifetimes presented in Figs. 2C and D indicate variations in the presence of different lifetimes in the samples investigated. Further details regarding sample-to-sample variations are discussed qualitatively in section 3.2. However, what is also visible from Figs. 2C and D is that in some samples, some lifetimes only occur in either the $IRSL_{50}$

299 or the post-IR $IRSL_{225}$ signal (e.g. Lifetime 1 in the on-time of sample FSM-6). Such points are not visible
300 from the diagrams in Figs. 2A and B. Despite these minor deviations and some observed variability, it
301 can be concluded that overall similar lifetimes can be obtained for all samples regardless of the IRSL
302 signal chosen.

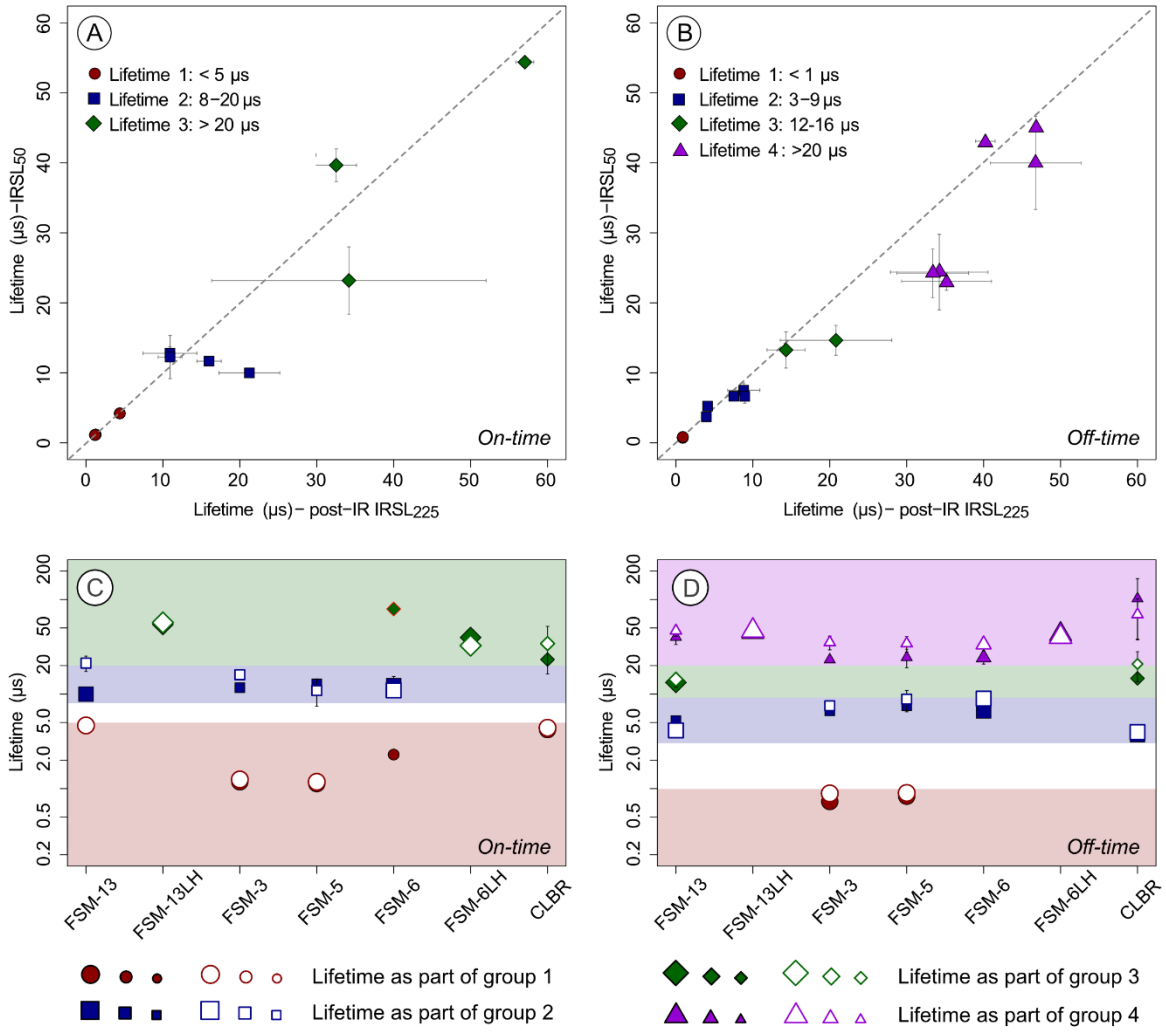

Fig. 2. Comparison of lifetimes obtained for the $IRSL_{50}$ and post-IR $IRSL_{225}$ signals for the on-time (A) and off-time (B) of the blue emission (50 Gy given dose). The dashed line in the graphs represent the one-to-one line. The data shown here is for all samples measured. The same data is shown in (C) and (D) where the fitted lifetime components are resolved for the individual samples. The data points in all figures represent the mean of three aliquots and their standard deviation. The diamond with red border (C) shows a lifetime, which only observed in one aliquot.

303

304 ***Dose dependency***

305 Ankjærgaard et al. (2009) compared TR-OSL (470 nm LED and 532 nm laser stimulated) lifetimes
306 measured in the UV for different feldspars following irradiation doses of 5 Gy and 1000 Gy, dependent

307 on sample brightness, and showed that lifetime determination is independent of the dose
308 administered. However, Ankjærgaard et al. (2009) did not explore IRSL or post-IR IRSL signals. Here we
309 show the results of a systematic investigation of potential lifetime-dependencies for the blue emission
310 ($IRSL_{50}$ and post-IR $IRSL_{225}$) for irradiation doses of 50 Gy, 200 Gy and 800 Gy (Fig. 3). The fitting results
311 presented in direct comparison for the different doses in Fig. 3 scatter around the one-to-one line,
312 indicating independence of the lifetimes of the doses given and thus supporting earlier work by
313 Ankjærgaard et al. (2009) for OSL of feldspars.

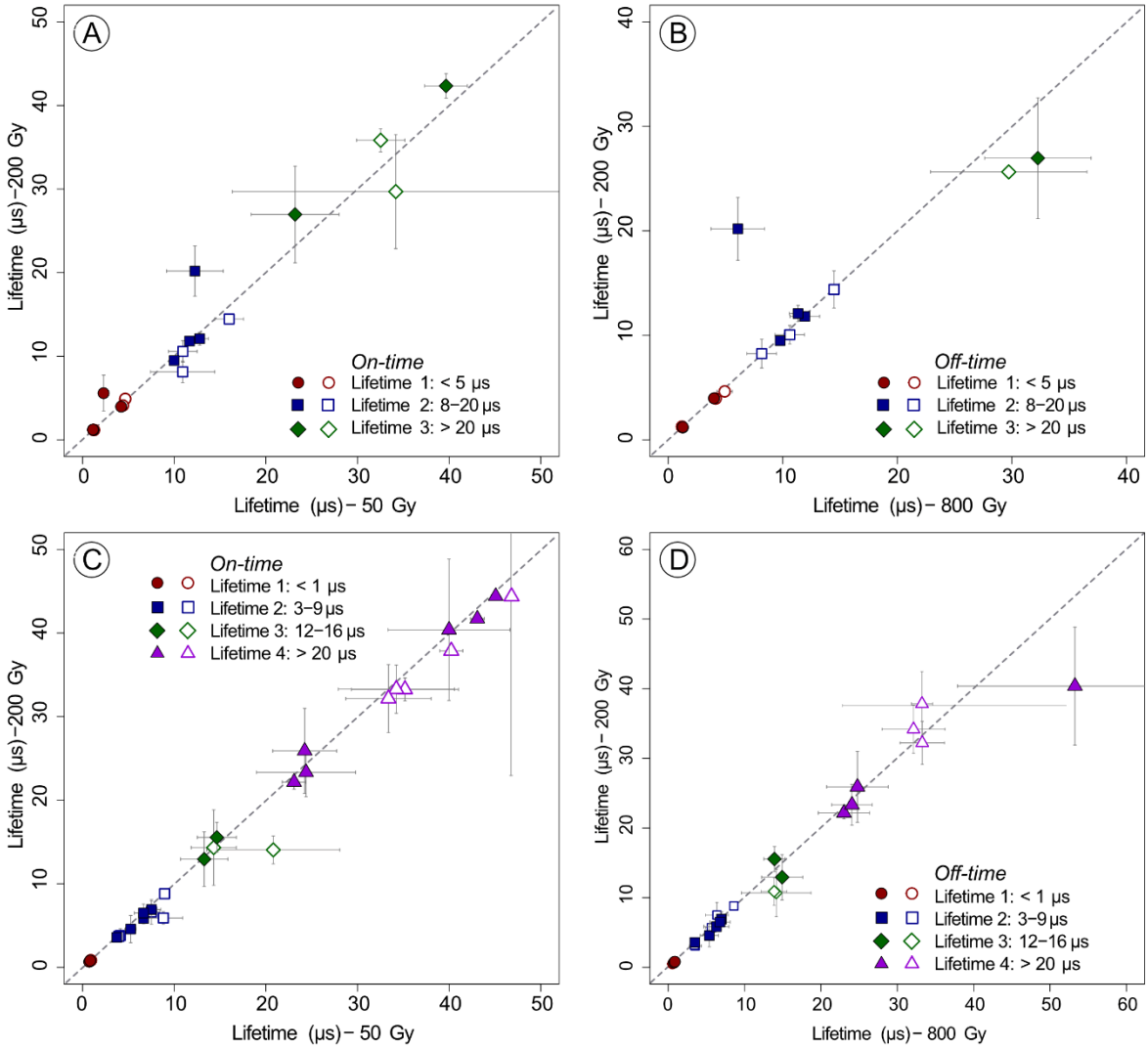

Fig. 3. Testing potential dose dependencies on the lifetimes of the $IRSL_{50}$ (filled symbols) and the post-IR $IRSL_{225}$ signal (open symbols) signal of the blue IRSL emission (on-time: A and B, off-time: C and D). Four doses were tested for this experiment, where the results of lifetimes obtained in response to 50 Gy are compared to 200 Gy (A and C) and 200 Gy are compared to 800 Gy (B and D).

314

315 **Lifetimes compared to literature values**

Measurements performed in this paper resulted in lifetimes spanning the following time scales: On-time: (1) < 5 μs, (2) 8-20 μs, (3) > 20 μs. Off-time: (1) < 1 μs, (2) 3-9 μs, (3) 12-16 μs, (4) > 20 μs. These lifetimes, obtained for the $IRSL_{50}$ and post-IR $IRSL_{225}$ signal, are in good agreement with previous work: Clark and Bailiff (1998) presented very fast lifetimes of different emissions measured for various chemically different feldspar samples using pulsed 850 nm laser stimulation. Their lifetimes range from a few ns to the μs-scale. Due to instrumental limitations, we are unable to detect lifetimes faster than 0.3 μs, but lifetimes measured on the μs-scale in this paper are similar to those obtained by Clark and Bailiff (1998). Using the sum of three exponential functions to describe the off-time decay, Tsukamoto et al. (2006) measured blue IRSL lifetimes of 0.61, 2.4 and 19 μs for a Na-feldspar sample (grain mixture) and 1.1, 4.3 and 19 μs for a K-feldspar sample (grain mixture). These values and the number of exponentials used to describe the decay are similar to the results obtained in the present study (cf. Fig. 2). Ankjærgaard et al. (2009) compared lifetimes of chemically different single crystal feldspars and feldspar grain mixtures. These authors observed the UV emission of 532 nm laser and 470 nm diode stimulated feldspars and enabled a comparison by using the sum of multiple first order exponentials for fitting their off-time signals. The feldspars investigated showed lifetimes for the UV emission on the μs-scale, with the fastest lifetimes (<0.1 μs) obtained through pulsed 532 nm laser stimulation. Longest lifetimes measured ranged from ~10 μs to <100 μs, and are thus within the range of lifetimes obtained in the present study, but it should be noted that stimulation and emission wavelengths differ from our study.

Excited state vs. recombination lifetime?

Here we compared lifetimes of different feldspars, measured using two different IRSL signals, obtained from different IRSL integration intervals, and after different irradiation doses. Figs. 2 and 3, and Fig. S1 showed that the lifetimes seem to be largely independent of the given dose, the signal integration interval and IRSL signal measured. This observation is in support of the excited state lifetime hypothesis if one assumes a random distribution of donor and acceptor pairs in a proximity model. However, the recombination lifetime might still be considered as a valid explanation, if the defect density is so high that changes to e.g. the number of populated defects through different doses might be so small that changes to the lifetime cannot be observed.

3.2 Sample-to-samples variations in the blue time-resolved $IRSL_{50}$ signal

We showed in section 3.1 that neither the on- nor the off-time of the blue IRSL signal depends on the IRSL signal integration interval, or the dose given. We also showed that the $IRSL_{50}$ signal and the post-

IR $IRSL_{225}$ signal result in similar lifetimes. Thus, these findings support the excited state lifetime hypothesis, unless the defect density is too high to observe any potential changes of the populated defects and their effect on the lifetimes. In the following we investigate TR-IRSL (blue emission) of a suite of chemically and structurally well-constrained alkali feldspars for which previous studies (Riedesel et al., 2021a) have demonstrated how their different compositions and structure impact the blue and infrared luminescence emissions and fading rates. This will enable us to study variations in TR-luminescence signals and their potential physical causes. Since no dependence on dose and IRSL signal investigated were found in the previous experiments all results shown in the following are based on the $IRSL_{50}$ signal which was recorded after a dose of 200 Gy. The discussion is based on qualitative comparisons between samples, as we will make some statements regarding potential physical processes in feldspars. Except in cases where time-resolved signals can be fitted using a single exponential function, no quantitative assessments are made, to avoid confusion about the kinetic order of feldspar luminescence.

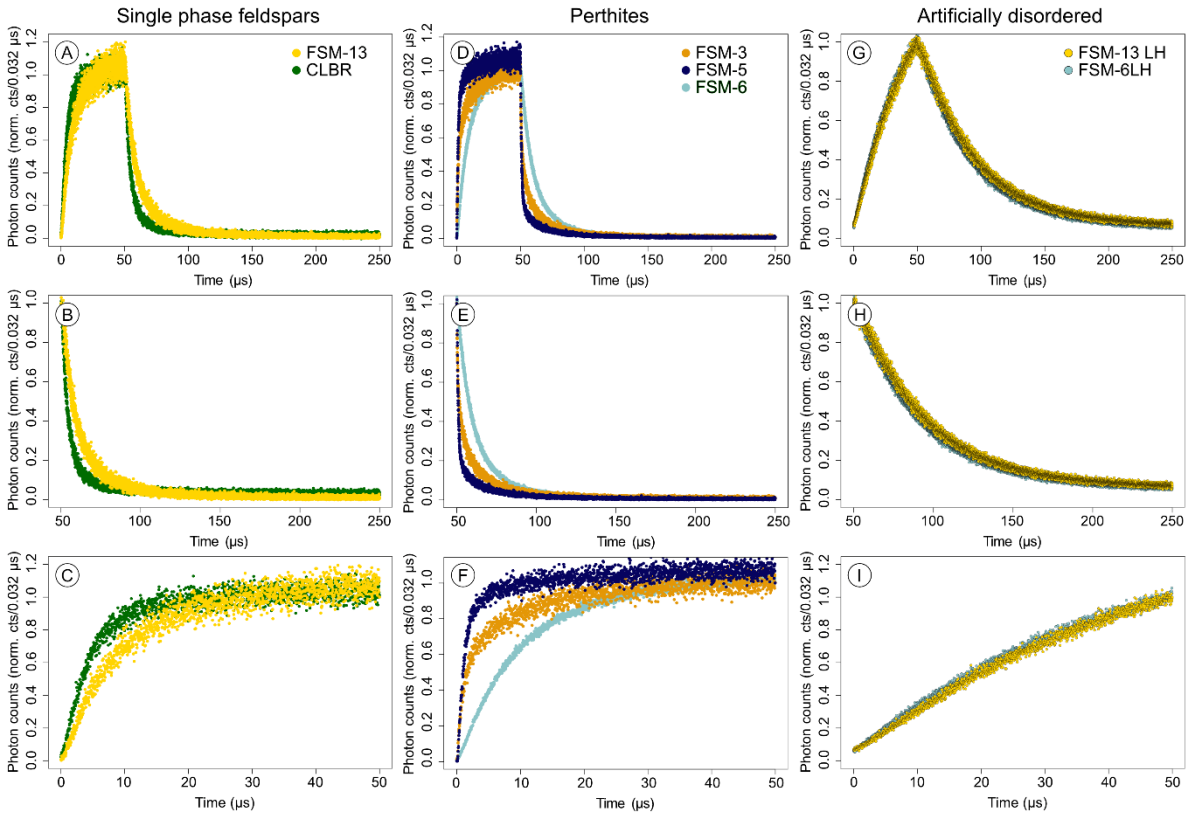

Fig. 4. Time-resolved $IRSL_{50}$ of the blue emission (200 Gy) for single phase feldspars, perthites and artificially disordered samples. A, D and G show the whole signals, B, E and H the off-time signal and C, F and I the on-time.

Figure 4 shows a comparison of blue time-resolved $IRSL_{50}$ signals obtained for the different samples. For the seven feldspars investigated we observed a range of different TR-luminescence signals. Whilst all samples show an on-time signal increase and an off-time decay on the µs-scale, there are subtle differences between samples. The fastest rise and decay can be found in macroperthite FSM-5 (Fig. 4D-F), followed by K-rich cryptoperthite FSM-3, where the short lifetime components appear to be dominating the shape. Perthitic sample FSM-6 and the two single phase feldspars microcline FSM-13 and albite CLBR show similar TR-signals, although CLBR shows faster signal increase and decay compared to FSM-13 (Fig. 4A-C). The slowest rise and decay of the TR-IRSL signal can be found in the two artificially disordered feldspars FSM-13LH and FSM-6LH (Fig. 4G-I), where the longer lifetime components appear to be dominating the shape. A direct comparison between the artificially disordered samples FSM-13LH and FSM-6LH and their ordered counterparts is shown in Figure 5. When comparing the artificially disordered samples FSM-13LH and FSM-6LH it is evident that the two samples show very similar on- and off-time signal behaviour, with samples FSM-6LH showing only slightly faster signals. Fitting of the TR-luminescence signals of these two artificially disordered samples was possible by using a single exponential function plus a constant background signal (i.e. k in eq. 2) and lifetimes obtained are around ~45 µs.

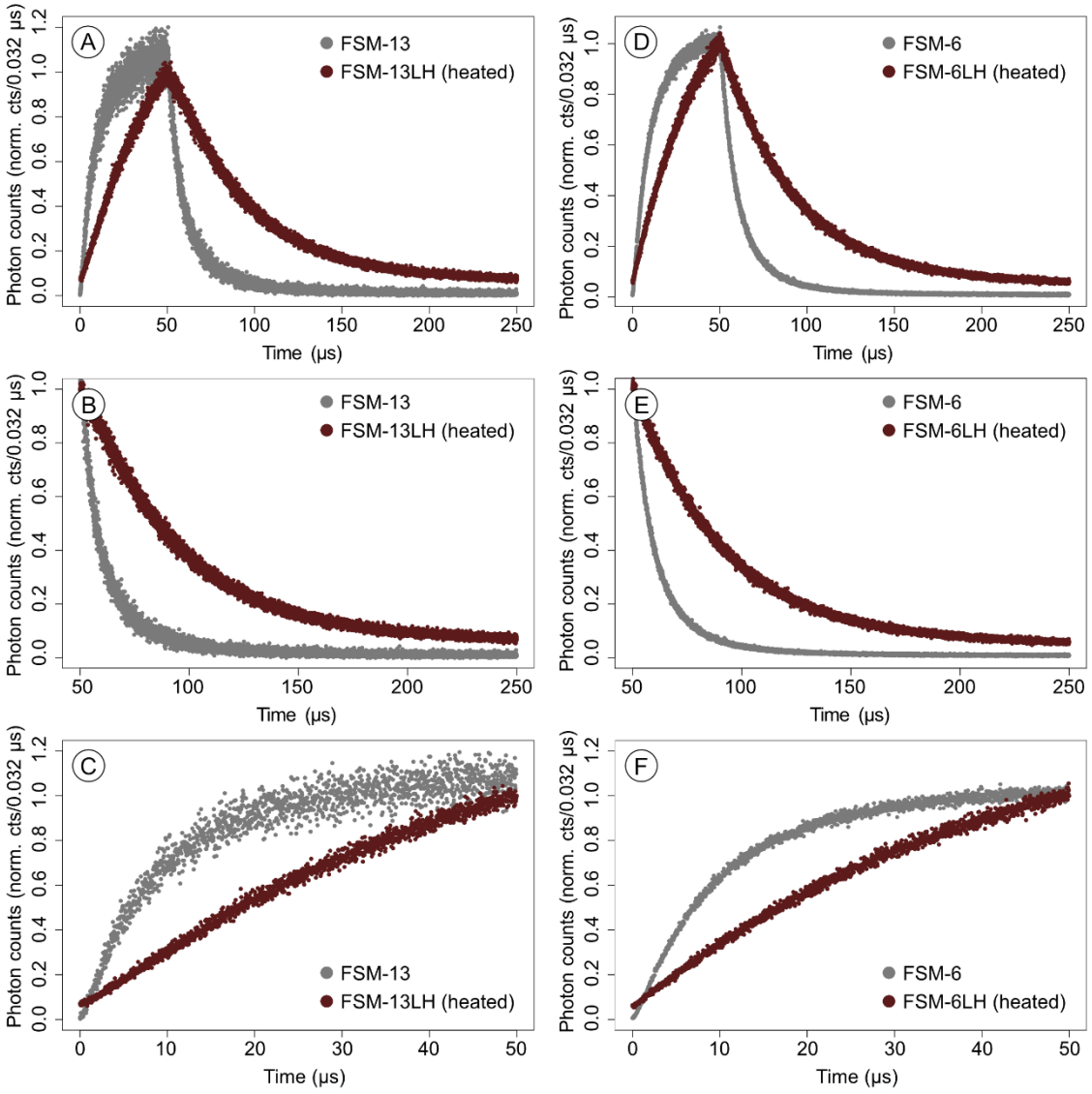

Fig. 5. Time resolved signals of the blue $IRSL_{50}$ emissions (200 Gy) of unheated and heated sample pairs FSM-13 and FSM-13LH (A, B, C) and FSM-6 and FSM-6LH (D, E, F).

This slow rise and decay and the lifetimes obtained from fitting using a single exponential function are similar to results obtained for quartz elsewhere (e.g. Bailiff, 2000; Chithambo 2003; 2007). One other feature of quartz TR-luminescence signals is a significant decrease in lifetime with increasing stimulation temperature, which has been associated with thermal quenching (Bailiff, 2000; Chithambo, 2003). Bailiff (2000) observed a decrease in the decay lifetime of synthetic quartz from~40 µs to 8 µs, when increasing the stimulation temperature from room temperature to 210 °C. These observations are supported by similar experiments made by Chithambo (2003) on natural sand-sized quartz. To test potential influence from thermal quenching on lifetimes and TR-luminescence signals of artificially disordered feldspars, we measured TR-IRSL signals at different stimulation temperatures. The signals

were recorded using the protocol described in Table 1. We varied the stimulation temperature of the post-IR IRSL signal (step 5 in Table 1) from 50 °C to 225 °C in 25 °C steps. In contrast to observations made on quartz, our artificially disordered feldspars do not show thermal quenching (cf. Fig. 6) and lifetimes measured remain at a constant level around ~45 µs. Thus, we conclude that artificially disordering influences the lifetime of the blue emission, however, the resulting emission and related processes seem to differ from what has been observed for quartz, and thus do not show any thermal quenching effects.

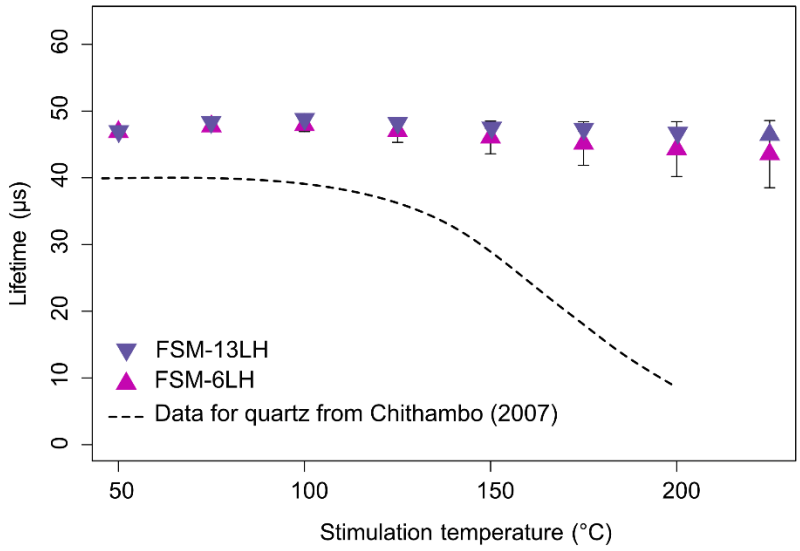

Fig. 6. Effect of varying the stimulation temperature of the post-IR IRSL signal on the lifetimes of the second IRSL signal in the post-IR_{50} $IRSL_{50\text{-}225\ °C}$ protocol on disordered (heated) samples FSM-13LH and FSM-6LH. The lifetimes are compared to data obtained from quartz (Chithambo, 2007). Data points from this study represent the average and standard deviation of measurements of three aliquots.

The sample-to-sample variations in rise and decay of the TR-IRSL signals are striking, particularly showcasing the changes observed for the ordered and disordered samples pairs. Whilst we observe these variations in TR-signals, we so far cannot explain what causes these. However, these samples have been investigated previously and thus some information regarding their luminescence characteristics are known, enabling potential links between existing information and the newly gathered time-resolved results.

When comparing TL emission spectra and fading rates of the same single-phase feldspars and perthites as explored in the present study, Riedesel et al. (2021a) observed differences in emission intensities and fading rates of the samples investigated. Whilst single-phase feldspars (microcline and albite) only showed weak blue luminescence and no fading, cryptoperthites were characterised to have intense and broad blue emissions and fading rates ranging from ~2 to ~7 %/decade. Macroperthites exhibited

the highest fading rates with up to 12 %/decade. Riedesel et al. (2021a) found that these observations support a location for the defect responsible for the blue emission on Al-O-Al bridges (cf. Finch and Klein, 1999). The data presented by Riedesel et al. (2021a) suggests that potentially higher densities of these defects can be found along the interfaces in perthites. TR-IRSL measurements of single-phase feldspars, albite (CLBR) and microcline (FSM-13), and perthites (FSM-3, FSM-5 and FSM-6), revealed slightly slower TR-IRSL on-time rise and off-time signal decay for single-phase feldspars compared to perthites (Fig. 4A-C compared with Fig. 4D-F). Macroperthite FSM-5 shows the fastest signals. However, perthite FSM-3 shows very similar TR-IRSL signals when comparing it to the two single-phase feldspars investigated. This suggests that either the excited state lifetime of the recombination centre is similar in perthites and single-phase albite and microcline or that the recombination lifetimes are on similar time scales. The latter would then suggest similar recombination routes and likely similar defect concentrations in these different feldspars. However, this is not reflected by the blue TL emission intensities and fading rates observed by Riedesel et al. (2021a).

Riedesel et al. (2021a) compared TL emission spectra and fading rates of the same ordered and disordered sample pairs as investigated here. They found that the blue luminescence emission intensity and the IRSL fading rate increased with framework disorder. This was interpreted as the result of an increase in recombination centre density due to framework disorder. A denser defect population would, if the recombination lifetime hypothesis holds true, result in a faster TR signal. However, the contrary is observed here (cf. Fig. 5), potentially indicating a change in the blue luminescence centre properties and thus a change to the excited state lifetime of this luminescence centre.

Whilst large differences in fading rate and blue luminescence emission intensity were found across different feldspars, electron trapping centres, understood to be involved in feldspar IRSL (e.g. Prasad et al., 2017; Kumar et al. 2018), seem to be largely independent of changes to the sample chemistry or structure (Riedesel et al., 2019, 2021b). Riedesel et al. (2019, 2021b) showed that the electron trapping centre depth as well as emissions related to trapping and retrapping at electron trapping centres are similar across the alkali feldspar group.

If the electron trapping centres are independent of the sample's chemistry or structural state, then changes in lifetime of the blue luminescence emission in ordered and disordered sample pairs and across the chemical range of alkali feldspars, are either related to changes in the blue luminescence centre itself or to parts of the crystal unrelated to electron trapping centres. Ankjærgaard and Jain (2010) and Jain and Ankjærgaard (2011) suggested that the slower part of the TR decay could result from recombination via the band-tail states. Pagonis et al. (2012) further investigated this hypothesis

by exploring TR-IRSL of four feldspar museum specimens. Pagonis et al. (2012) applied a fitting approach which combined a single exponential and a stretched exponential function, where the authors related the results of the stretched exponential to the band-tail states. The observed increase in TR-IRSL lifetime with increasing disorder of the framework in this paper could be related to a higher density of band-tail states or a wider band-tail due to disorder of the crystal. A wider or denser sub-conduction band tail could potentially result in an increased transport of charge via these states – resulting in slower recombination processes than would be expected for excited state tunnelling (cf. Jain and Ankjærgaard, 2011).

4 Yellow-green TR-IRSL emission – Results and Discussion

The yellow-green emission is rarely used in luminescence dating applications, however, it has been identified as a common emission in many plagioclase feldspars (e.g. Geake et al., 1971, 1973, 1977; Telfer and Walker, 1978), and was also recorded in microcline samples (c.f. Rendell and Clarke, 1997; Riedesel et al., 2021a). Whilst being present as a distinct emission in some samples, the broad emission recorded for perthites often spans from the blue into the yellow wavelength region (cf. Riedesel et al., 2021a) and might thus include this emission. Two potential defects have been proposed for causing this emission: (i) Mn^{2+} substituting for Ca^{2+} on M sites (e.g. Geake et al., 1971, 1973, 1977; Telfer and Walker, 1978) or (ii) Mn^{2+} substituting for Al^{3+} on T sites (Telfer and Walker, 1978; Kirsh et al., 1987; Clark and Bailiff, 1998). In the following we show the recorded TR-IRSL signals for the yellow-green emission and the sample-to-sample variations we observed for this emission. The results shown in this section are based on TR measurements of the $IRSL_{50}$ signal, measured after an irradiation dose of 200 Gy (or 400 Gy, in case of FSM-5 and FSM-6).

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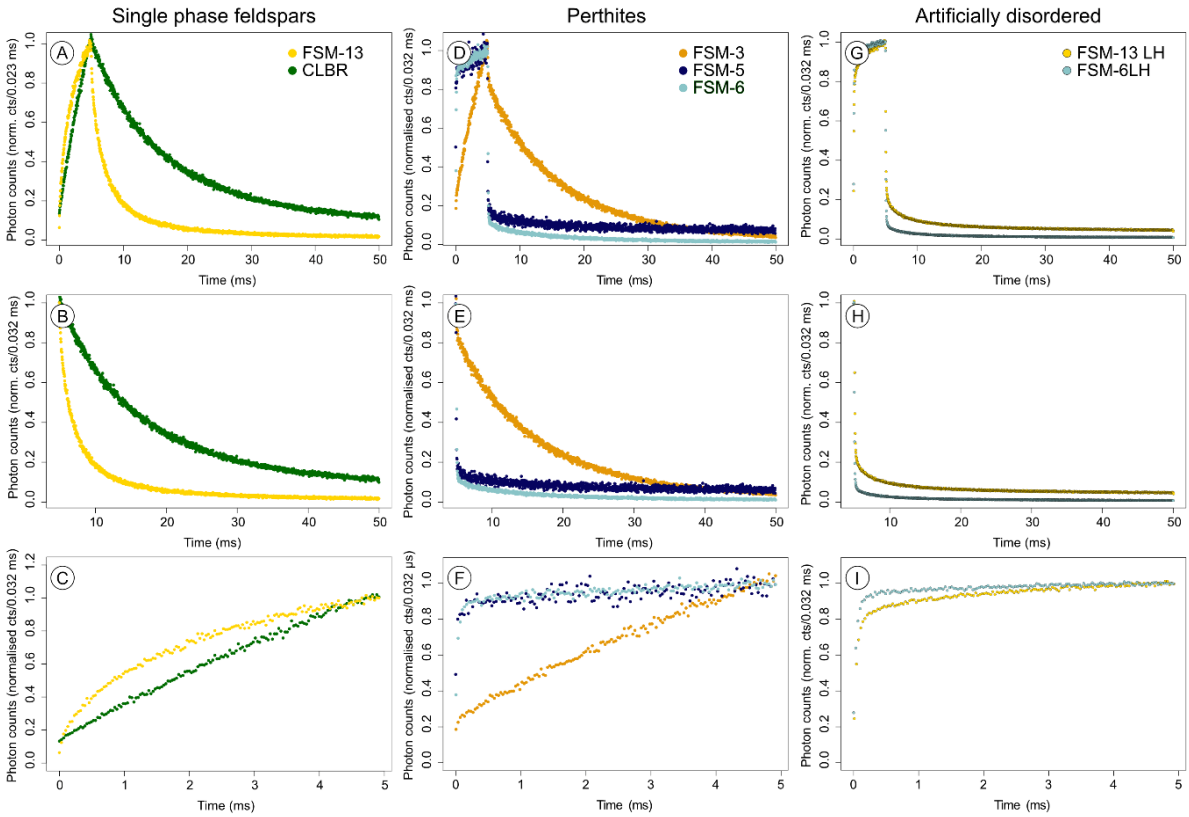

Fig. 7. Time-resolved $IRSL_{50}$ of the yellow-green emission for single phase feldspars, perthites and artificially disordered samples. The signals were recorded after an irradiation dose of 200 Gy (400 Gy in case of FSM-5 and FSM-6). A, D and G show the whole signals, B, E and H the off-time signal and C, F and I the on-time.

459

460 For all samples we observed TR-IRSL signals on the ms-scale (Fig. 7), which is much slower compared
461 to most of the observations made for the blue emission (Fig. 8). However, the different samples contain
462 varying proportions of the slower part of the TR signal. Especially in perthitic and disordered samples
463 the yellow-green emission is dominated by a very fast component, visible by the sharp increase at the
464 beginning of the on-time and the sharp decrease at the start of the off-time (cf. Figs. 7 D-I). TR on-and
465 off-time signals of single-phase feldspars FSM-13 and CLBR and perthite FSM-3 are significantly slower
466 compared to the other samples (cf. Fig. 7A-C, D-F).

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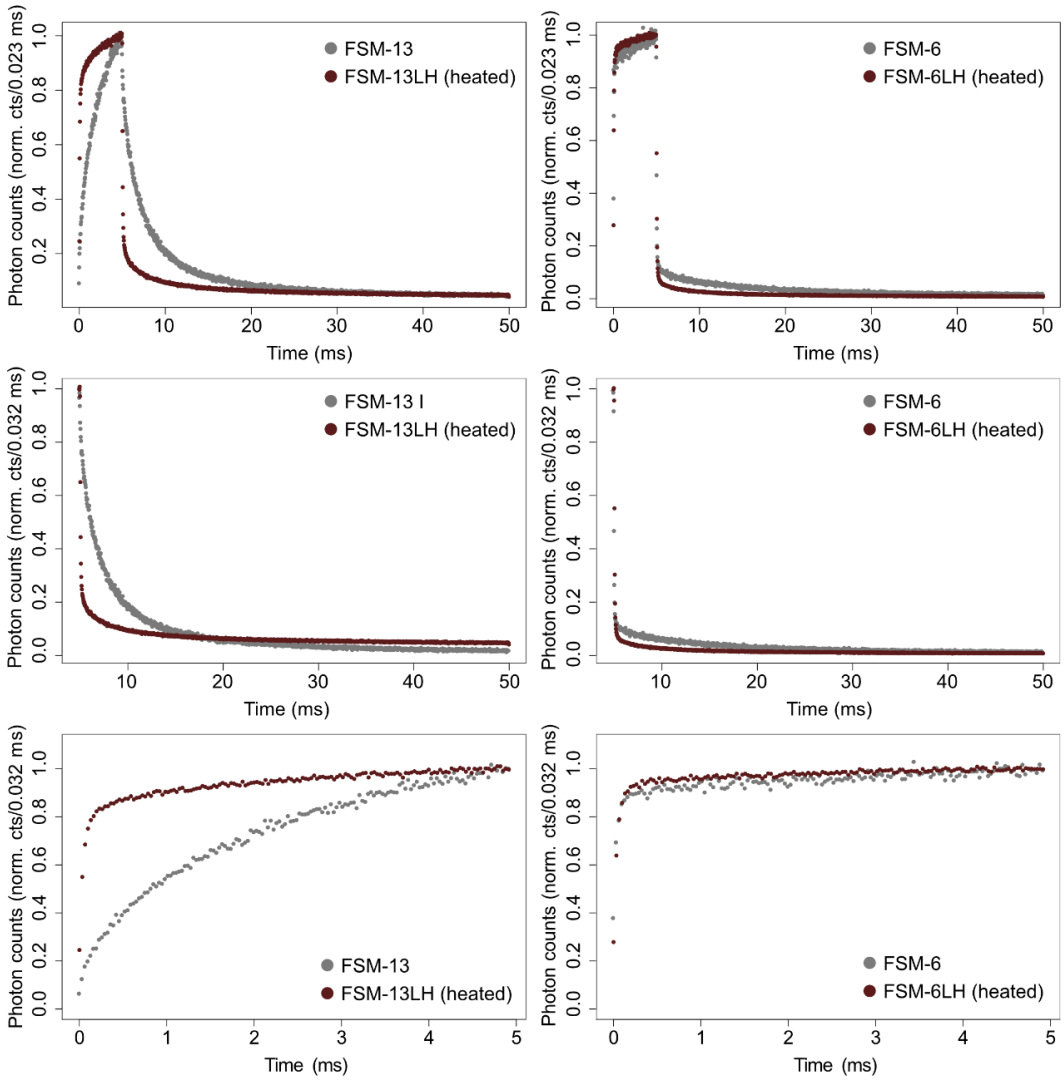

Fig. 8. Time resolved signals of the yellow-green $IRSL_{50}$ emissions of unheated and heated sample pairs FSM-13 andFSM-13LH (heated) (A, B, C) and FSM-6 andFSM-6LH (heated) (D, E, F).

A comparison of the ordered and disordered sample pairs reveals that the yellow-green emission becomes faster during the on- and off-time when the sample is disordered (Fig. 8). The effect is more visible in the case of FSM-13 and FSM-13LH, compared to FSM-6 and FSM-6LH. However, from TL emission spectra it becomes apparent that disordering results in a significant increase in blue TL emission intensity (Riedesel et al., 2021a). This could potentially result in breakthrough of this strong blue emission into the emission window we used to record the yellow-green emission. This might also explain the fast initial rise and decay in samples FSM-3 and FSM-5. Alternatively, the fast signals recorded for the yellow-green emission could originate from the defect being located on a tetrahedral site, as previously suggested by Clark and Bailiff (1998). These authors observed very fast lifetimes for the yellow-green emission, even on the ns-scale, when fitting their TR-signals.

Whilst we proposed a potential influence of band-tail states as the explanation for longer lifetimes of the blue emission in disordered samples, this hypothesis would not hold in case of the yellow-green emission, as the slowest signal rise and decay is found in ordered end member samples.

Observing significant differences in the time scale of signal rise and decay could indicate that the emission indeed results from two different defect types. Long lifetimes obtained here for single-phase microcline FSM-13 and albite CLBR suggest a metal ion site defect as source of the yellow-green emission, even in alkali feldspars, supporting the Mn^{2+} substituting for Ca^{2+} on M site hypothesis by e.g. Telfer and Walker (1978). In this case, a spin-forbidden transition would explain the lifetimes on the ms-scale. However, short lifetimes (µs-scale) would be expected for a defect resulting from Mn^{2+} substituting for Al^{3+} on T sites (cf. Clark and Bailiff, 1998). In this case the defect responsible for the yellow-green emission would be a lattice stabilising hole centre on Si^{4+}-O^{-}-Mn^{2+}, as the hole centre on the O ion would help in charge neutralisation, due to the introduced imbalance by Mn^{2+} substituting for Al^{3+} (Telfer and Walker, 1978; Kirsh et al., 1987). If this type of defect is indeed present in our samples, then one would expect that framework disorder influences the lifetime of this signal, as is also shown in Fig. 8. Unfortunately, we cannot completely rule out any influence of breakthrough of the blue emission, so no definite answer can be given here. However, it is striking that the strong yellow-green emission can be found in the single-phase microcline, which also shows on-time increase and off-time decrease in TR-IRSL measurements on similar time-scales as seen for the albite specimen. This could indicate that whatever the type of defect, it is not restricted to plagioclase feldspars and might thus not be Mn^{2+} substituting for Ca^{2+} on M sites.

5 Conclusions

In this paper we presented time-resolved infrared stimulated luminescence signals measured for a range of single crystal alkali feldspars, including K- and Na-feldspar end members (microcline and albite, both single phase), for the blue emission (~410 nm) and the yellow-green emission (~550 nm) using a post-IR_{50} $IRSL_{225}$ protocol. The timescale on which the blue and the yellow-green emissions occur differ significantly; the blue signal on the µs-scale, and the yellow-green emission on the ms-scale. For each emission the lifetimes are independent of the signal integration interval, the IRSL signal investigated, and the dose given.

For the blue emission there is a slight difference in decay time scale between single-phase feldspars and perthites, however more significant differences are observed when the feldspars are artificially disordered. Our new observations show that artificially disordering the framework significantly

increases the rise and decay time of the on- and off-time, and that the signals can now be described using a single exponential fit. The lifetimes obtained from the disordered feldspars are similar to those measured for quartz elsewhere (c.f. Bailiff 2000, Chithambo 2003), but unlike the quartz signals the TR-signals here do not show any thermal quenching. The longer lifetimes observed for disordered feldspars could (i) either result from a change of the blue recombination centre, resulting in longer excited state lifetimes of the defect itself, (ii) or increased disorder of the lattice could cause changes to the band-tail state width or density, increasing the likelihood of recombination occurring via the band-tail states, resulting in longer recombination lifetimes (c.f. Jain and Ankjærgaard, 2011; Pagonis et al., 2012).

Time-resolved signals of the yellow-green emission vary between samples, with single-phase microcline and albite specimens showing the slowest signals. These slow time scales could indicate a spin-forbidden transition, as has been proposed for a defect resulting from Mn^{2+} substituting for Ca^{2+} on M sites. However, the Ca content of the microcline specimen is negligible and the Mn content so low that it could not be detected.

In contrast to slow signals in the single-phase samples, perthitic and disordered samples show a large proportion of a fast signal decay in the off-time, before a slow component describes the remaining part of the TR-signal. The fast signal could either indicate a different type of defect for this emission or, alternatively, it could be an artefact resulting from breakthrough of the blue emission. This needs further investigation in future measurements.

The data in this paper shows the potential for using time-resolved IRSL to gain information on the structural state of the feldspar investigated and thus helping in understanding variations in luminescence properties across a range of chemically and structurally different feldspars.

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613 **Supplementary Material**

614 **Time-resolved infrared stimulated luminescence of the blue and yellow-green emissions –**
615 **insights into charge recombination in chemically and structurally different alkali feldspars**

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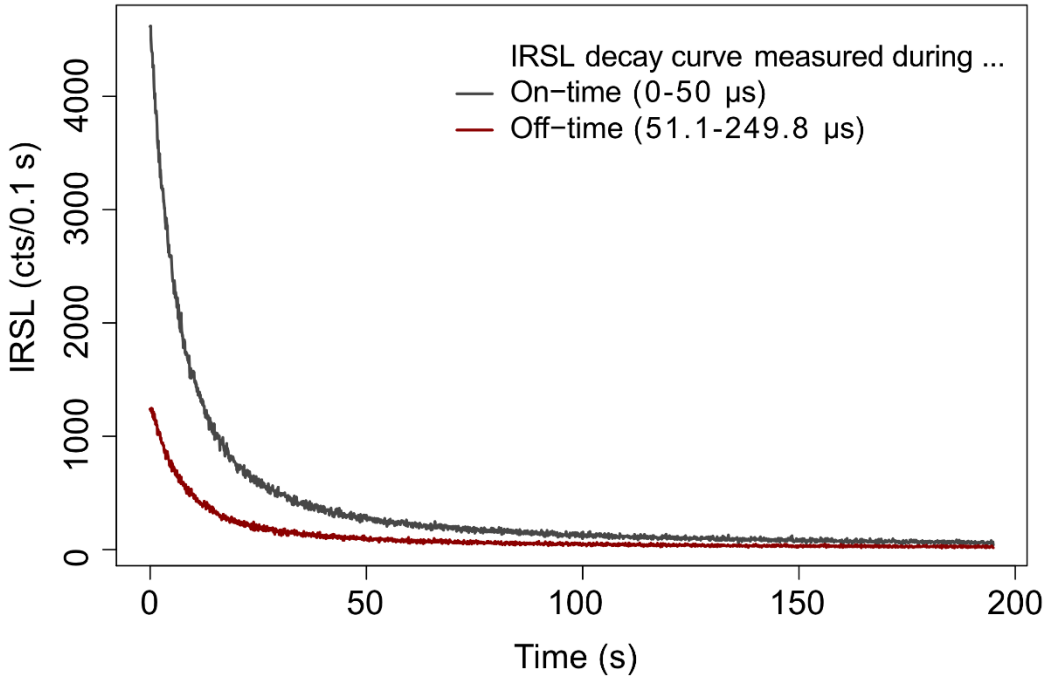

Fig. S1: $IRSL_{50}$ decay curves measured during the on- (0-50 µs, grey curve) and off-times (51.1-249.8 µs, red curve) of the TR-luminescence measurements recorded in the blue emission window.

617

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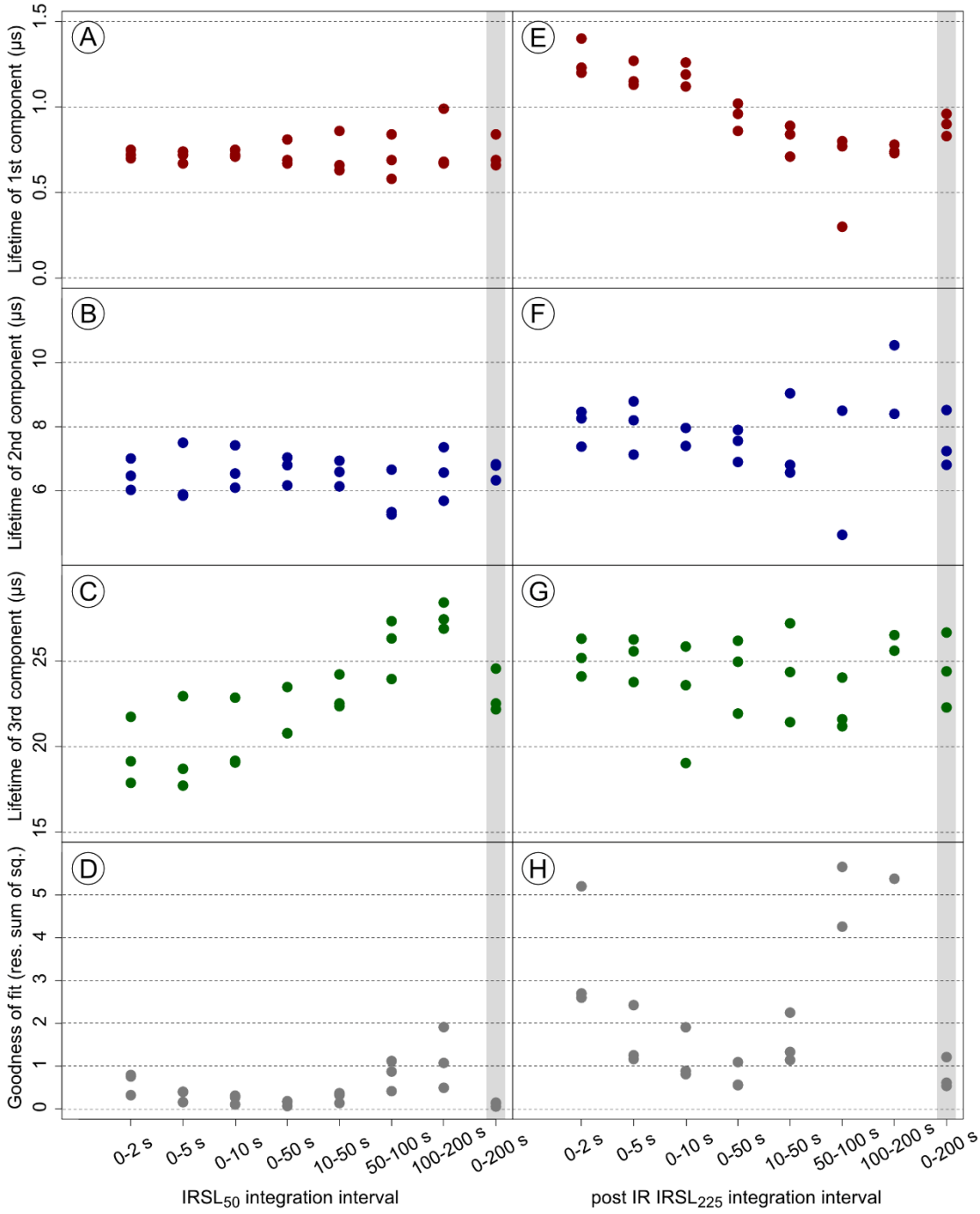

Fig. S2. Lifetimes and goodness of fit defined by the square sum of residuals for different integration time intervals for sample FSM-3. The data shown here is for the off-time signal of the blue emission and the two signals measured using the post-IR_{50} $IRSL_{225}$ protocol, with results for the $IRSL_{50}$ signal in the left panels (A-D) and for the post-IR $IRSL_{225}$ on the right (E-H). The individual points show results for three aliquots measured.

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*Table S1a: Lifetimes for the **blue IRSL$_{50}$** emission recorded in the **on-time** of the pulsed IRSL signal. I_i is the normalised intensity of the fitted lifetime τ_i (μs), k is a constant linear background. All values displayed are the average of three aliquots and the standard deviation. The data was normalised to the last data point of the on-time.*

Sample ID	Dose (Gy)	I_1	τ_1	I_2	τ_2	I_3	τ_3	I_4	τ_4	k	residual sum of squares
FSM-13	50			1.00 ± 0.05	9.99 ± 0.27					0.01 ± 0.01	2.43 ± 0.72
FSM-13LH	50					1.56 ± 0.04	54.38 ± 0.76			0.04 ± 0.00	0.29 ± 0.07
FSM-3	50	0.61 ± 0.09	1.18 ± 0.18	0.42 ± 0.08	11.67 ± 0.22					-0.03 ± 0.01	0.50 ± 0.21
FSM-5	50	0.96 ± 0.05	1.13 ± 0.01	0.18 ± 0.03	12.79 ± 0.94					-0.10 ± 0.00	1.38 ± 0.47
FSM-6	50	0.29 ± 0.00	2.29 ± 0.19	0.76 ± 0.09	12.26 ± 3.09	0.25[a]	79.39[a]			0.00 ± 0.00	1.42 ± 0.90
FSM-6LH	50					1.33 ± 0.03	39.66 ± 2.33			0.05 ± 0.00	0.06 ± 0.02
CLBR	50	0.88 ± 0.05	4.21 ± 0.54			0.18 ± 0.09	23.19 ± 4.80			0.01 ± 0.06	0.42 ± 0.18
FSM-13	200			0.92 ± 0.05	9.49 ± 0.24					0.02 ± 0.00	3.75 ± 0.99
FSM-13LH	200					1.60 ± 0.05	53.26 ± 1.00			0.04 ± 0.00	0.55 ± 0.18
FSM-3	200	0.60 ± 0.09	1.18 ± 0.18	0.43 ± 0.07	11.81 ± 0.10					-0.02 ± 0.01	1.21 ± 0.36
FSM-5	200	0.76 ± 0.06	1.22 ± 0.04	0.26 ± 0.02	12.09 ± 0.77					-0.08 ± 0.01	3.00 ± 0.98
FSM-6	200	0.57 ± 0.19	5.58 ± 2.15	0.53 ± 0.19	20.19 ± 3.00					0.01 ± 0.02	3.72 ± 2.81
FSM-6LH	200					1.39 ± 0.03	42.34 ± 1.46			0.05 ± 0.00	0.44 ± 0.37
CLBR	200	0.91 ± 0.08	3.97 ± 0.19			0.17 ± 0.07	26.96 ± 5.78			-0.03 ± 0.01	1.15 ± 0.56
FSM-13	800			1.01 ± 0.05	9.77 ± 0.27					0.01 ± 0.01	6.46 ± 2.67
FSM-13LH	800	*Not measured due to very high signal intensities saturating the PMT despite adding an ND 2.0 filter.*									
FSM-3	800	0.54 ± 0.04	1.28 ± 0.46	0.50 ± 0.06	11.93 ± 1.29					0.00 ± 0.01	3.40 ± 1.37
FSM-5	800	0.70 ± 0.04	1.27 ± 0.06	0.36 ± 0.02	11.33 ± 0.75					-0.06 ± 0.01	1.73 ± 0.49
FSM-6	800			0.57 ± 0.29	6.08 ± 2.34	0.48 ± 0.24	27.76 ± 13.17			0.00 ± 0.03	1.17 ± 0.84
FSM-6LH	800	*Not measured due to very high signal intensities saturating the PMT despite adding an ND 2.0 filter.*									
CLBR	800	0.87 ± 0.12	3.99 ± 0.19			0.17 ± 0.07	32.27 ± 4.65			-0.03 ± 0.01	3.34 ± 1.54

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*Table S1b: Lifetimes for the **blue IRSL$_{50}$** emission recorded in the **off-time** of the pulsed IRSL signal. I_i is the normalised intensity of the fitted lifetime τ_i (μs), k is a constant linear background. All values displayed are the average of three aliquots and the standard deviation. The data was normalised to the last data point of the on-time.*

Sample ID	Dose (Gy)	I_1	τ_1	I_2	τ_2	I_3	τ_3	I_4	τ_4	k	residual sum of squares
FSM-13	50			0.43 ± 0.13	5.25 ± 0.59	0.47 ± 0.14	13.27 ± 2.58	0.12 ± 0.02	39.99 ± 6.65	0.01 ± 0.00	0.88 ± 0.28
FSM-13LH	50							0.96 ± 0.02	45.08 ± 0.27	0.06 ± 0.00	0.63 ± 0.13
FSM-3	50	0.53 ± 0.08	0.73 ± 0.09	0.31 ± 0.05	6.65 ± 0.28			0.18 ± 0.04	23.08 ± 1.29	0.01 ± 0.00	0.11 ± 0.05
FSM-5	50	0.89 ± 0.04	0.83 ± 0.03	0.14 ± 0.02	7.52 ± 1.03			0.08 ± 0.01	24.39 ± 5.40	0.00 ± 0.00	0.16 ± 0.04
FSM-6	50			0.57 ± 0.10	6.64 ± 0.99			0.33 ± 0.05	24.24 ± 3.49	0.01 ± 0.00	0.58 ± 0.49
FSM-6LH	50							0.96 ± 0.01	43.08 ± 0.76	0.05 ± 0.00	0.21 ± 0.03
CLBR	50			0.78 ± 0.05	3.74 ± 0.26	0.16 ± 0.03	14.65 ± 2.13	0.03 ± 0.03	102.18 ± 64.17	0.06 ± 0.00	0.17 ± 0.08
FSM-13	200			0.40 ± 0.18	4.58 ± 1.63	0.45 ± 0.13	12.94 ± 3.26	0.11 ± 0.06	40.38 ± 8.46	0.001 ± 0.00	1.33 ± 0.45
FSM-13LH	200							0.99 ± 0.03	44.40 ±0.38	0.06 ± 0.00	1.12 ± 0.39
FSM-3	200	0.51 ± 0.10	0.67 ± 0.13	0.32 ± 0.05	5.84 ± 0.61			0.20 ± 0.03	22.16 ± 0.86	0.01 ± 0.00	0.27 ± 0.09
FSM-5	200	0.71 ± 0.05	0.81 ± 0.08	0.21 ± 0.02	6.92 ± 1.05			0.10 ± 0.02	23.33 ± 2.93	0.00 ± 0.00	0.38 ± 0.12
FSM-6	200			0.63 ± 0.11	6.50 ± 1.07			0.38 ± 0.08	25.90 ± 5.09	0.02 ± 0.01	1.66 ± 1.48
FSM-6LH	200							0.96 ± 0.00	41.71 ± 0.18	0.05 ± 0.00	0.64 ± 0.65
CLBR	200			0.82 ± 0.04	3.58 ± 0.06	0.18 ± 0.01	15.55 ± 1.79	0.03 ± 0.02	87.11 ± 31.14	0.03 ± 0.00	0.40 ± 0.24
FSM-13	800			0.51 ± 0.18	5.38 ± 1.20	0.47 ± 0.11	14.92 ± 2.69	0.06 ± 0.04	53.26 ± 15.37	0.01 ± 0.00	2.46 ± 1.32
FSM-13LH	800	*Not measured due to very high signal intensities saturating the PMT despite adding an ND 2.0 filter.*									
FSM-3	800	0.45 ± 0.04	0.74 ± 0.26	0.36 ± 0.09	6.31 ± 1.64			0.21 ± 0.03	23.01 ± 3.36	0.01 ± 0.00	0.76 ± 0.36
FSM-5	800	0.64 ± 0.06	0.86 ± 0.03	0.29 ± 0.02	6.96 ± 0.34			0.12 ± 0.01	24.06 ± 2.65	0.01 ± 0.00	0.27 ± 0.06
FSM-6	800			0.59 ± 0.15	6.78 ± 1.32			0.37 ± 0.10	24.78 ± 4.03	0.01 ± 0.01	0.55 ± 0.47
FSM-6LH	800	*Not measured due to very high signal intensities saturating the PMT despite adding an ND 2.0 filter.*									
CLBR	800			0.76 ± 0.09	3.49 ± 0.18	0.18 ± 0.02	13.91 ± 1.38	0.04 ± 0.04	68.07 ± 37.48	0.03 ± 0.00	1.15 ± 0.73

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*Table S2a: Lifetimes for the **blue post-IR IRSLI$_{225}$** emission recorded in the **on-time** of the pulsed IRSL signal. I_i is the normalised intensity of the fitted lifetime τ_i (μs), k is a constant linear background. All values displayed are the average of three aliquots and the standard deviation. The data was normalised to the last data point of the on-time.*

Sample ID	Dose (Gy)	I_1	τ_1	I_2	τ_2	I_3	τ_3	I_4	τ_4	k	residual sum of squares
FSM-13	50	0.53 ± 0.04	4.66 ± 0.07	0.48 ± 0.07	21.25 ± 3.95					0.03 ± 0.02	2.08 ± 0.87
FSM-13LH	50					1.28 ± 0.02	57.05 ± 1.16			0.26 ± 0.01	0.10 ± 0.02
FSM-3	50	0.71 ± 0.07	1.25 ± 0.10	0.19 ± 0.01	16.00 ± 1.58					0.13 ± 0.07	0.96 ± 0.42
FSM-5	50	0.80 ± 0.06	1.18 ± 0.02	0.29 ± 0.04	10.92 ± 3.50					-0.09 ± 0.01	1.01 ± 0.56
FSM-6	50			0.95 ± 0.04	10.94 ± 1.56					0.05 ± 0.03	0.70 ± 0.37
FSM-6LH	50					1.16 ± 0.04	32.53 ± 2.63			0.09 ± 0.01	0.04 ± 0.02
CLBR	50	0.81 ± 0.20	4.40 ± 0.37			0.31 ± 0.26	34.18 ± 17.84			0.04 ± 0.06	0.44 ± 0.23
FSM-13	200	0.60 ± 0.03	4.93 ± 0.67			0.39 ± 0.07	24.92 ± 5.48			0.01 ± 0.01	4.34 ± 0.14
FSM-13LH	200					1.24 ± 0.05	52.93 ± 1.67			0.25 ± 0.00	0.17 ± 0.04
FSM-3	200	0.63 ± 0.05	1.20 ± 0.08	0.17 ± 0.01	14.48 ± 0.06					0.17 ± 0.08	2.25 ± 0.82
FSM-5	200	0.80 ± 0.04	1.21 ± 0.08	0.25 ± 0.01	8.16 ± 1.29					-0.07 ± 0.01	2.34 ± 0.73
FSM-6	200			0.93 ± 0.07	10.61 ± 1.28					0.04 ± 0.03	1.23 ± 0.70
FSM-6LH	200					1.21 ± 0.03	35.87 ± 1.39			0.09 ± 0.00	0.28 ± 0.22
CLBR	200	0.80 ± 0.16	4.14 ± 0.24			0.24 ± 0.25[b]	29.73 ± 6.83[b]			0.06 ± 0.01	1.64 ± 0.72
FSM-13	800	0.57 ± 0.06	4.63 ± 0.41	0.45 ± 0.03	16.77 ± 2.37					0.00 ± 0.01	7.14 ± 3.32
FSM-13LH	800	*Not measured due to very high signal intensities saturating the PMT despite adding an ND 2.0 filter.*									
FSM-3	800	0.56 ± 0.14	1.26 ± 0.22	0.16 ± 0.01	14.39 ± 1.78					0.26 ± 0.12	6.52 ± 2.69
FSM-5	800	0.77 ± 0.02	1.23 ± 0.04	0.32 ± 0.02	8.25 ± 1.38					-0.06 ± 0.01	1.59 ± 0.48
FSM-6	800			0.97 ± 0.02	10.06 ± 0.88					0.03 ± 0.02	0.44 ± 0.29
FSM-6LH	800	*Not measured due to very high signal intensities saturating the PMT despite adding an ND 2.0 filter.*									
CLBR	800	0.79 ± 0.21	3.95 ± 0.38			0.45[a]	25.64[a]			0.06 ± 0.00	5.26 ± 2.42

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*Table S2b: Lifetimes for the **blue post-IR IRSL$_{225}$** emission recorded in the **off-time** of the pulsed IRSL signal. I_i is the normalised intensity of the fitted lifetime τ_i (μs), k is a constant linear background. All values displayed are the average of three aliquots and the standard deviation. The data was normalised to the last data point of the on-time.*

Sample ID	Dose (Gy)	I_1	τ_1	I_2	τ_2	I_3	τ_3	I_4	τ_4	k	residual sum of squares
FSM-13	50			0.45 ± 0.07	4.13 ± 0.27	0.35 ± 0.05	14.31 ± 2.46	0.12 ± 0.02	39.99 ± 6.65	0.01 ± 0.00	0.88 ± 0.28
FSM-13LH	50							0.96 ± 0.02	45.08 ± 0.27	0.06 ± 0.00	0.63 ± 0.13
FSM-3	50	0.65 ± 0.07	0.89 ± 0.07	0.14 ± 0.02	7.52 ± 0.89			0.18 ± 0.04	23.08 ± 1.29	0.01 ± 0.00	0.11 ± 0.05
FSM-5	50	0.75 ± 0.05	0.90 ± 0.03	0.27 ± 0.03	8.82 ± 2.09			0.08 ± 0.01	24.39 ± 5.40	0.00 ± 0.00	0.16 ± 0.04
FSM-6	50			0.77 ± 0.12	8.95 ± 0.27			0.33 ± 0.05	24.24 ± 3.49	0.01 ± 0.00	0.58 ± 0.49
FSM-6LH	50							0.96 ± 0.01	43.08 ± 0.76	0.05 ± 0.00	0.12 ± 0.03
CLBR	50			0.73 ± 0.20	3.96 ± 0.32	0.12 ± 0.06	20.81 ± 7.25	0.03 ± 0.03	102.18 ± 64.17	0.06 ± 0.05	0.31 ± 0.29
FSM-13	200			0.45 ± 0.13	3.81 ± 0.80	0.37 ± 0.09	14.33 ± 4.51	0.11 ± 0.07	62.84 ± 39.90	0.05 ± 0.01	1.96 ± 0.73
FSM-13LH	200							0.77 ± 0.02	44.37 ± 0.04	0.27 ± 0.00	0.46 ± 0.12
FSM-3	200	0.57 ± 0.06	0.84 ± 0.11	0.13 ± 0.01	6.62 ± 1.48			0.08 ± 0.02	33.25 ± 1.37	0.22 ± 0.07	2.45 ± 1.24
FSM-5	200	0.73 ± 0.02	0.84 ± 0.03	0.28 ± 0.02	5.90 ± 0.76			0.03 ± 0.01	33.28 ± 2.88	0.01 ± 0.00	0.31 ± 0.09
FSM-6	200			0.77 ± 0.13	8.81 ± 0.19			0.16 ± 0.07	32.15 ± 4.08	0.07 ± 0.01	0.89 ± 0.67
FSM-6LH	200							0.90 ± 0.00	37.86 ± 0.31	0.10 ± 0.00	0.47 ± 0.37
CLBR	200			0.72 ± 0.15	3.71 ± 0.11	0.11 ± 0.04	14.05 ± 1.67	0.08 ± 0.12	94.63 ± 42.70	0.12 ± 0.02	1.25 ± 0.70
FSM-13	800			0.38 ± 0.10	3.41 ± 0.42	0.48 ± 0.06	10.96 ± 3.37	0.13 ± 0.08	37.63 ± 14.26	0.05 ± 0.00	3.51 ± 1.50
FSM-13LH	800	*Not measured due to very high signal intensities saturating the PMT despite adding an ND 2.0 filter.*									
FSM-3	800	0.52 ± 0.11	0.84 ± 0.20	0.15 ± 0.04	7.80 ± 1.80			0.06 ± 0.02	37.87 ± 4.60	0.29 ± 0.11	7.88 ± 3.03
FSM-5	800	0.69 ± 0.01	0.87 ± 0.04	0.32 ± 0.02	6.01 ± 0.58			0.05 ± 0.01	32.31 ± 3.06	0.02 ± 0.00	0.29 ± 0.07
FSM-6	800			0.85 ± 0.06	9.10 ± 0.17			0.11 ± 0.05	34.26 ± 3.42	0.07 ± 0.01	0.29 ± 0.24
FSM-6LH	800	*Not measured due to very high signal intensities saturating the PMT despite adding an ND 2.0 filter.*									
CLBR	800			0.70 ± 0.15	3.52 ± 0.32	0.10 ± 0.04	11.18 ± 1.97	0.10 ± 0.14	133.61 ± 111.59	0.12 ± 0.00	4.33 ± 3.14

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*Table S3a: Lifetimes for the **yellow-green IRSL$_{50}$** emission recorded in the **on-time** of the pulsed IRSL signal. I_i is the normalised intensity of the fitted lifetime τ_i (ms), k is a constant linear background. All values displayed are the average of three aliquots and the standard deviation. The data was normalised to the last data point of the on-time.*

Sample ID	Dose (Gy)	I_1	τ_1	I_2	τ_2	I_3	τ_3	I_4	τ_4	k	residual sum of squares
FSM-13	200	0.20 ± 0.01	0.22 ± 0.08	0.83 ± 0.02	2.50 ± 0.34					0.09 ± 0.01	0.06 ± 0.03
FSM-13LH	200	0.64 ± 0.06	0.05 ± 0.00	0.12 ± 0.05	2.52 ± 0.43					0.26 ± 0.00	0.01 ± 0.01
FSM-3	200	0.09 ± 0.03	0.02 ± 0.01			1.87 ± 0.18	8.52 ± 0.61			0.18 ± 0.02	0.04 ± 0.01
FSM-5	400	0.39 ± 0.01	0.02 ± 0.00	0.14 ± 0.00	3.93 ± 0.72					0.51 ± 0.01	0.27 ± 0.14
FSM-6	400	0.43 ± 0.14	0.04 ± 0.00	0.38 ± 0.49	4.04 ± 1.46					0.36 ± 0.11	0.05 ± 0.04
FSM-6LH	200	0.66 ± 0.01	0.04 ± 0.00	0.07 ± 0.00	2.13 ± 0.28					0.28 ± 0.00	0.01 ± 0.00
CLBR	200	0.10[a]	0.03[a]			2.43 ± 0.21	11.12 ± 1.55			0.13 ± 0.01	0.05 ± 0.05
FSM-13	800	0.20 ± 0.00	0.20 ± 0.04	0.82 ± 0.03	2.37 ± 0.19					0.09 ± 0.01	0.01 ± 0.01
FSM-13LH	800	0.66 ± 0.02	0.05 ± 0.00	0.08 ± 0.00	1.81 ± 0.08					0.27 ± 0.00	0.02 ± 0.01
FSM-3	800	0.11 ± 0.02	0.03 ± 0.01			1.57 ± 0.20	8.10 ± 0.67			0.20 ± 0.03	0.02 ± 0.01
FSM-5	800	0.38 ± 0.04	0.04 ± 0.00	0.15 ± 0.06	4.10 ± 2.38					0.53 ± 0.01	0.19 ± 0.06
FSM-6	800	0.37 ± 0.12	0.04 ± 0.00	0.65 ± 0.47	6.16 ± 1.76					0.31 ± 0.09	0.09 ± 0.06
FSM-6LH	800	0.64 ± 0.01	0.05 ± 0.00	0.08 ± 0.00	1.82 ± 0.41					0.27 ± 0.00	0.02 ± 0.01
CLBR	800	0.06[a]	0.04[a]			2.22 ± 0.10	9.66 ± 0.17			0.12 ± 0.01	0.01 ± 0.01

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*Table S3b: Lifetimes for the **yellow-green IRSL$_{50}$** emission recorded in the **off-time** of the pulsed IRSL signal. I_i is the normalised intensity of the fitted lifetime τ_i (ms), k is a constant linear background. All values displayed are the average of three aliquots and the standard deviation. The data was normalised to the last data point of the on-time.*

Sample ID	Dose (Gy)	I_1	τ_1	I_2	τ_2	I_3	τ_3	I_4	τ_4	k	residual sum of squares
FSM-13	200	0.19 ± 0.03	0.24 ± 0.06	0.57 ± 0.02	2.19 ± 0.17	0.14 ± 0.04	9.58 ± 1.12			0.01 ± 0.00	0.05 ± 0.02
FSM-13LH	200	0.52 ± 0.02	0.12 ± 0.01	0.07 ± 0.04	6.09 ± 0.39					0.03 ± 0.02	0.15 ± 0.04
FSM-3	200	0.13 ± 0.01	0.11 ± 0.01			0.75 ± 0.04	11.04 ± 0.06			0.03 ± 0.01	0.14 ± 0.08
FSM-5	400	0.40 ± 0.01	0.09 ± 0.00			0.08 ± 0.00	10.18 ± 0.70			0.06 ± 0.00	0.39 ± 0.04
FSM-6	400	0.37 ± 0.13	0.10 ± 0.00	0.08 ± 0.06	5.35 ± 2.24	0.15 ± 0.23	32.98 ± 21.06			0.03 ± 0.02	0.19 ± 0.00
FSM-6LH	200	0.52 ± 0.00	0.11 ± 0.00	0.04 ± 0.00	6.55 ± 0.06					0.01 ± 0.00	0.17 ± 0.18
CLBR	200			0.17 ± 0.05	3.90 ± 1.34	0.75 ± 0.03	13.53 ± 0.90			0.08 ± 0.01	0.21 ± XX
FSM-13	800	0.20 ± 0.01	0.24 ± 0.03	0.58 ± 0.01	2.13 ± 0.09	0.13 ± 0.02	8.56 ± 0.96			0.01 ± 0.00	0.02 ± 0.01
FSM-13LH	800	0.53 ± 0.01	0.11 ± 0.00	0.04 ± 0.00	6.52 ± 0.06					0.02 ± 0.00	0.18 ± 0.02
FSM-3	800	0.24 ± 0.16	0.10 ± 0.01			0.51 ± 0.37	10.55 ± 0.51			0.04 ± 0.00	0.15 ± 0.12
FSM-5	800	0.31 ± 0.16	0.10 ± 0.02			0.23 ± 0.25	9.59 ± 0.12			0.11 ± 0.11	0.23 ± 0.05
FSM-6	800	0.32 ± 0.12	0.10 ± 0.01	0.11 ± 0.04	4.23 ± 2.34	0.23 ± 0.18	19.80 ± 11.31			0.02 ± 0.02	0.21 ± 0.04
FSM-6LH	800	0.52 ± 0.01	0.11 ± 0.00	0.05 ± 0.00	6.33 ± 0.15					0.01 ± 0.00	0.17 ± 0.01
CLBR	800	0.04[a]	0.14[a]	0.24 ± 0.02	5.34 ± 0.29	0.69 ± 0.04	14.90 ± 0.31			0.07 ± 0.02	0.06 ± 0.05

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*Table S4a: Lifetimes for the **yellow-green post-IR IRSL$_{225}$** emission recorded in the **on-time** of the pulsed IRSL signal. I_i is the normalised intensity of the fitted lifetime τ_i (ms), k is a constant linear background. All values displayed are the average of three aliquots and the standard deviation. The data was normalised to the last data point of the on-time. [a]Only one aliquot of the three aliquots measured revealed this lifetime.*

Sample ID	Dose (Gy)	I_1	τ_1	I_2	τ_2	I_3	τ_3	I_4	τ_4	k	residual sum of squares
FSM-13	200	0.32 ± 0.03	0.12 ± 0.04	0.52 ± 0.04	1.92 ± 0.41					0.21 ± 0.02	0.07 ± 0.04
FSM-13LH	200	0.57 ± 0.00	0.05 ± 0.00	0.19 ± 0.00	2.06 ± 0.03					0.26 ± 0.00	0.01 ± 0.00
FSM-3	200	0.08 ± 0.01	0.03 ± 0.01			1.18 ± 0.20	7.14 ± 0.81			0.33 ± 0.03	0.11 ± 0.03
FSM-5	400	0.37[a]	0.02[a]	0.11[a]	2.80[a]					0.54	0.22
FSM-6	400	0.38 ± 0.02	0.04 ± 0.01	0.16 ± 0.01	2.35 ± 0.52					0.49 ± 0.00	0.06 ± 0.03
FSM-6LH	200	0.59 ± 0.00	0.04 ± 0.00	0.09 ± 0.01	1.59 ± 0.15					0.32 ± 0.00	0.01 ± 0.00
CLBR	200	0.24[a]	0.04[a]			2.39 ± 0.72	15.48 ± 4.07			0.31 ± 0.08	0.06 ± 0.06
FSM-13	800	0.32 ± 0.02	0.11 ± 0.01	0.52 ± 0.03	1.73 ± 0.18					0.19 ± 0.01	0.02 ± 0.01
FSM-13LH	800	0.56 ± 0.00	0.05 ± 0.00	0.19 ± 0.01	2.07 ± 0.12					0.27 ± 0.00	0.01 ± 0.00
FSM-3	800	0.08 ± 0.02	0.07 ± 0.07			1.10 ± 0.08	6.96 ± 0.56			0.35 ± 0.04	0.06 ± 0.02
FSM-5	800	0.33 ± 0.10	0.05 ± 0.03	0.09 ± 0.04	1.99 ± 0.63					0.58 ± 0.07	0.28 ± 0.11
FSM-6	800	0.44 ± 0.05	0.03 ± 0.00	0.13 ± 0.06	1.91 ± 0.30					0.46 ± 0.03	0.05 ± 0.04
FSM-6LH	800	0.59 ± 0.02	0.04 ± 0.00	0.11 ± 0.01	1.41 ± 0.36					0.31 ± 0.00	0.02 ± 0.01
CLBR	800	0.19[a]	0.05[a]			2.07 ± 0.45	12.35 ± 2.25			0.27 ± 0.06	0.02 ± 0.02

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*Table S4b: Lifetimes for the **yellow-green post-IR IRSL$_{225}$** emission recorded in the **off-time** of the pulsed IRSL signal. I_i is the normalised intensity of the fitted lifetime τ_i (ms), k is a constant linear background. All values displayed are the average of three aliquots and the standard deviation. The data was normalised to the last data point of the on-time. [a]Only one aliquot of the three aliquots measured revealed this lifetime.*

Sample ID	Dose (Gy)	I_1	τ_1	I_2	τ_2	I_3	τ_3	I_4	τ_4	k	residual sum of squares
FSM-13	200	0.33 ± 0.05	0.18 ± 0.04	0.33 ± 0.04	1.58 ± 0.02	0.12 ± 0.05	10.13 ± 0.82			0.07 ± 0.01	0.09 ± 0.03
FSM-13LH	200	0.47 ± 0.00	0.12 ± 0.00	0.10 ± 0.00	2.81 ± 0.09	0.05 ± 0.00	16.35 ± 0.79			0.05 ± 0.00	0.11 ± 0.00
FSM-3	200	0.13 ± 0.01	0.12 ± 0.02			0.56 ± 0.04	9.54 ± 0.22			0.18 ± 0.03	0.44 ± 0.12
FSM-5	400	0.42 ± 0.02	0.09 ± 0.00			0.05 ± 0.00	9.64 ± 0.70			0.02 ± 0.00	0.31 ± 0.07
FSM-6	400	0.40 ± 0.02	0.09 ± 0.00	0.06 ± 0.01	2.46 ± 0.31	0.06 ± 0.01	12.67 ± 0.03			0.06 ± 0.01	0.16 ± 0.02
FSM-6LH	200	0.50 ± 0.00	0.11 ± 0.00	0.04 ± 0.00	3.57 ± 0.07	0.01 ± 0.00	28.54 ± 2.43			0.02 ± 0.00	0.16 ± 0.01
CLBR	200	0.22[a]	0.14[a]			0.57 ± 0.03	11.36 ± 0.18	0.21 ± 0.00[b]	56.08 ± 17.86[b]	0.19 ± 0.08	0.23 ± 0.11
FSM-13	800	0.32 ± 0.02	0.18 ± 0.01	0.36 ± 0.03	1.58 ± 0.13	0.10 ± 0.03	9.87 ± 1.10			0.07 ± 0.01	0.04 ± 0.01
FSM-13LH	800	0.46 ± 0.00	0.12 ± 0.00	0.10 ± 0.00	2.68 ± 0.04	0.05 ± 0.00	16.15 ± 0.32			0.05 ± 0.00	0.11 ± 0.00
FSM-3	800	0.14 ± 0.02	0.12 ± 0.01			0.60 ± 0.09	9.73 ± 0.99			0.14 ± 0.10	0.22 ± 0.13
FSM-5	800	0.40 ± 0.02	0.09 ± 0.00			0.07 ± 0.01	7.23 ± 0.30			0.02 ± 0.00	0.25 ± 0.03
FSM-6	800	0.41 ± 0.03	0.09 ± 0.00	0.05 ± 0.02	4.13 ± 3.30	0.05 ± 0.01	13.96 ± 1.24			0.06 ± 0.01	0.18 ± 0.02
FSM-6LH	800	0.50 ± 0.00	0.11 ± 0.00	0.05 ± 0.00	3.30 ± 0.16	0.02 ± 0.00	21.06 ± 2.90			0.03 ± 0.00	0.16 ± 0.00
CLBR	800	0.17[a]	0.12[a]			0.36 ± 0.20	8.30 ± 3.36	0.37 ± 0.11	22.71 ± 7.49	0.19 ± 0.08	0.10 ± 0.07

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