Ancient TL

Spotlight Review

Not fade away – The persistence of fading in feldspar luminescence

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Abstract

Feldspars are widely used as natural luminescence dosimeters to constrain past geological, geomorphological and archaeological events and processes. Unfortunately, the luminescence of feldspars suffers from an unwanted signal loss over time, termed fading, which affects the reliability, precision, and accuracy of all these applications. This review presents an overview of the research conducted into the cause of and the physical processes behind fading, as well as of research focussed on circumventing, minimising or correction for fading. Fading has been shown to be ubiquitous in feldspars, affecting both thermoluminescence as well as optically (infrared) stimulated luminescence signals. The most widely accepted physical explanation for fading is quantum mechanical tunnelling of trapped electrons from the ground state of the electron trapping centre to a nearby recombination centre, however, other mechanisms have been proposed, and some of these different explanations are outlined here. Since fading causes an underestimation of the luminescence age, it is necessary to accurately constrain the rate of fading for a given sample, as well as to develop robust methods for correcting the obtained luminescence signal for fading. This review explains how the rate of fading can be determined in the laboratory, and how this can be used to correct the obtained luminescence signal or luminescence age for fading. This review aims at presenting key findings and selected studies as a means to introduce the topic to new researchers in the field of luminescence dating, while hoping that more experienced luminescence researchers might also discover some new information.

Keywords: Feldspar, Luminescence, Fading, Fading correction, Dating, Chronometry, Geochronology

1. Introduction

Feldspars, the most abundant mineral group in the Earth's crust, are widely used in luminescence-based geochronological studies to constrain past geological, geomorphological or archaeological events and processes. Their ubiquity, the mostly bright luminescence signal, and a signal saturation at a few hundred Gy make them an often favoured target for dating purposes. However, an undesired signal loss over time complicates their applicability. For accurate luminescence dating, it is usually expected that charge trapped within defects in the crystal lattice is stable over geological time scales (i.e., hundreds of thousands of years), with Aitken (1985) suggesting that the lifetime of trapped charge should at least be one magnitude longer than the period to be dated. However, the luminescence signal of feldspars exhibits an unwanted signal loss over time, which is referred to as *(anomalous) fading*. Measurements of fading rates all over the globe have shown the ubiquitous nature of this process (e.g. Spooner, 1994; Huntley and Lamothe, 2001; Valla et al., 2016), questioning the validity of the term "anomalous" fading.

Fading, a known process in many luminescence phosphors (e.g., Riehl, 1970; Delbecq et al., 1974, for ZnS or KCl:AgCl and KCl:TiCl, respectively), has already been shown in the 1970s to affect the luminescence of feldspars

(e.g. Garlick and Robinson, 1972; Wintle, 1973). However, despite its ubiquity and the multi-decade long awareness of this process affecting the luminescence of feldspars, many aspects of it remain under debate.

This review aims to present (i) a historical overview of the observation of fading in the luminescence of feldspars, (ii) different physical explanations and models developed to explain the processes behind fading in feldspars, and (iii) methods developed to minimise or circumvent fading, or to correct for its effects on the luminescence signals or ages calculated.

2. First approaches to understand fading in feldspars

The first experimental observations of fading of the feldspar luminescence signal were published in the 1970s for both lunar and Earth feldspars. Garlick and Robinson (1972) showed that when TL curves are measured following storage at different isothermal temperatures the luminescence intensity decreases with increasing storage times, even for storage at ambient temperatures. Based on this experimental evidence, Garlick and Robinson (1972) proposed that two processes lead to the loss of trapped charge in these feldspars: a thermally activated process and a non-thermal process. The rate of decrease in TL intensity with storage time follows a power-law decay, thus decreasing linearly with log(time) (Garlick and Robinson, 1972), an observation which was further explored by Huntley (2006). Garlick and Robinson (1972) proposed a simple model explaining the athermal loss. They based their model on first order kinetics, with the electron-hole recombination occurring via ground state to ground state transition and the power-law decay being explained through the random spatial distribution of electron and hole trapping centres.

Wintle (1973) presented results of anomalous fading of the TL signal of various feldspars and other minerals. The 20 feldspar samples studied showed a loss of TL signal after four weeks of storage of < 5 % to 40 %. Interestingly, storing a sample of fluorapatite at 77 K, 173 K, and 255 K revealed a smaller loss of TL at lower temperatures, suggesting that the process is not strictly athermal. However, it is unclear if this is also the case for feldspars.

Later, Wintle (1977) expanded her research into fading in feldspars and performed TL measurements after storage at temperatures as low as 20 K and observed a loss of TL even at cryogenic temperatures, with the amount of lost TL being independent of temperature up to 255 K. Recording any phosphorescence which might be emitted by the samples during storage revealed that the phosphorescence accounts only for 5 % of the total TL signal measured for a given sample. Wintle (1977) thus suggested that fading is likely only a weakly radiative or even non-radiative process. She proposed three different possible explanations for the physical processes behind fading: i) diffusion of defects, ii) direct transfer of an electron from the ground state of an electron trap to a nearby recombination centre (as suggested by Garlick and Robinson, 1972), and iii) reduction of the number of available recombination centres (hole movement).

Visocekas (1985) further explored whether athermal tunnelling recombination causes "anomalous" fading and if yes, why the afterglow intensity observed by Wintle (1977) was too low to account for the observed fading. Visocekas (1985) introduced a model of radiative tunnelling-based electron-hole recombination. Furthermore, measurements of a potential tunnelling afterglow revealed that such a signal could not have been detected previously, because of a spectral shift in the emission. Whilst below ambient temperatures the luminescence is primarily emitted in the red and infrared part of the spectrum, temperatures above room temperature show larger visible and UV components, which are detectable using standard photomultiplier tubes. This is in line with an earlier suggestion by Riehl (1970), based on ZnS, that the tunnelling afterglow should occur at wavelengths longer than the measured thermoluminescence.

With these studies published in the 1970s and 1980s, the existence of fading of feldspar luminescence was proven and first explanations were given. The following decades, until today, have been characterised by studies working towards a better understanding of the physical processes that govern fading in feldspars and by research towards correcting for fading or isolating a non-fading feldspar luminescence signal.

Figure 1 shows a timeline from the 1960s until the 2020s, highlighting some of the published work on experimental observations of fading in feldspars, models proposed for explaining the mechanism behind fading, as well as studies exploring potential ways of minimising fading or correcting for it. The timeline also highlights some selected publications, which were instrumental in understanding luminescence processes (in feldspars).

3. Potential physical causes of fading

Fading is not only ubiquitous in feldspars, but also in other materials. Prior (and in parallel) to its observation in feldspars, fading has been observed in ZnS (Riehl, 1970), KCl:AgCl and KCl:TiCl (e.g., Delbecq et al., 1974), zircon (e.g., Templer, 1986), calcite (e.g., Visocekas et al., 1976; Visocekas, 1979), CaSO$_4$:Dy (e.g., Visocekas et al., 1983), α-Al$_2$O$_3$ (e.g., Wood et al., 1990), and many more. Based on experimental observations on these various materials, potential physical explanations behind the fading process and corresponding models have been developed.

3.1. Quantum mechanical tunnelling from the ground state and tunnelling afterglow

The most widely accepted explanation for fading in feldspars is quantum mechanical tunnelling. It describes the recombination of electrons and holes through the overlap of their wavefunctions. This process has been found to be accompanied by the emission of photons, referred to as
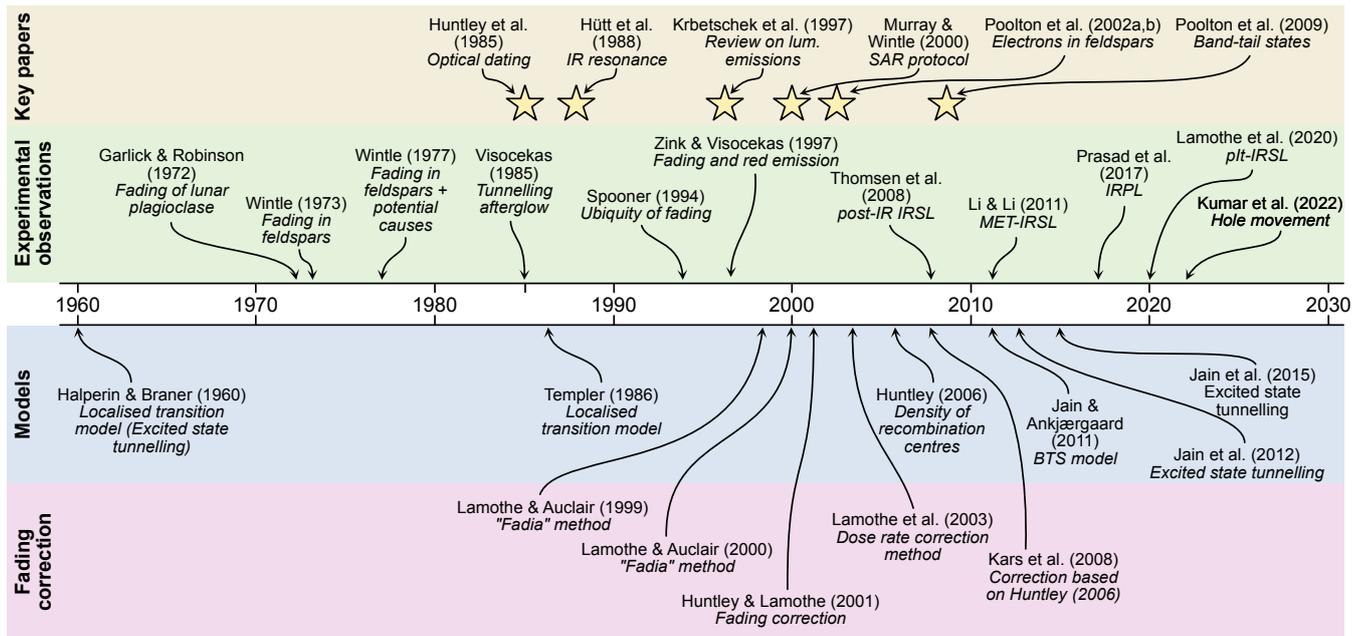
Figure 1: A timeline illustrating published research on experimental observations of fading in feldspars, the proposed models to explain the fading mechanism, and studies investigating potential methods to reduce or correct for it. Additionally, the timeline highlights key publications that have significantly contributed to understanding luminescence processes (in feldspars). Some terms have been abbreviated for the figure: IRSL = infrared stimulated luminescence, IRPL = infrared photoluminescence, BTS = band-tail states, MET = multiple elevated temperature, pIt-IRSL = post-isothermal IRSL.

tunnelling afterglow – the phosphorescence observed during storage at cryogenic temperatures (for example at liquid nitrogen temperature) following irradiation of the sample (e.g. Riehl (1970) for ZnS; Visocekas et al. (1985) for feldspars). Visocekas (1979) showed that the luminescence of calcite lost during storage is proportional to log(time). Following this, Visocekas (1985) suggested expressing fading as percent per decade of time, with the term decade describing the time steps from 1 to 10 to 100 etc. This power-law behaviour was used as argumentation for fading being caused by tunnelling of electrons from the ground state of the electron trapping centre to a nearby recombination centre (Fig. 2c), rather than by thermally induced detrapping. The latter would be expected to follow an exponential decay (see Aitken, 1985). The lifetime of the tunnelling process is thought to depend on the distance between the trapped electron and the trapped hole (Delbecq et al., 1974; Aitken, 1985).

Huntley (2006) proposed a theoretical model, which describes the power-law decay of luminescence and fading, based on tunnelling of electrons from the ground state of the electron trapping centres to nearby recombination centres (Fig. 2c). The model by Huntley (2006) is based on a couple of assumptions: (1) A crystal contains defects, which function as electron trapping centres, with electrons being trapped at some of these centres with an unknown distribution. (2) The crystal contains other defects, with a higher density and a random distribution to which electrons can tunnel. Since their density is assumed to be much higher than

the density of trapped electrons, their density is assumed to be constant. (3) The tunnelling process is random with a lifetime, which is dependent on the attempt-to-escape frequency, the distance covered by the tunnelling process, and a constant which describes a sphere with a certain radius (referred to as α). (4) Electrons tunnel to the most proximal recombination centre. From these four assumptions, it is interesting to note that according to assumption (2) there would exist excess holes, causing charge imbalance of the crystal. Unless some of the defects acting as recombination centres would not contain a hole, but that would also make them unavailable for recombination, thus decreasing the density of centres available for recombination. For quartz it is suggested that so-called 'deep' electron traps exist, which are extremely thermally and optically stable (e.g., Bailey, 2001; Kijek and Chruścińska, 2017; Peng et al., 2022). Bailey (2001) reasons that during multiple burial-exposure cycles, the number of electrons trapped at these 'deep' traps increases, thus also increasing the number of trapped holes elsewhere in the crystal. It is unclear, if a similar system could exist in feldspars. Generally, the model by Huntley (2006) was developed to explain luminescence phenomena caused by ground state tunnelling, but it might be applicable to tunnelling of electrons from the excited state of the electron trapping centres to a nearby recombination centre (Fig. 2b), when the model is adjusted.
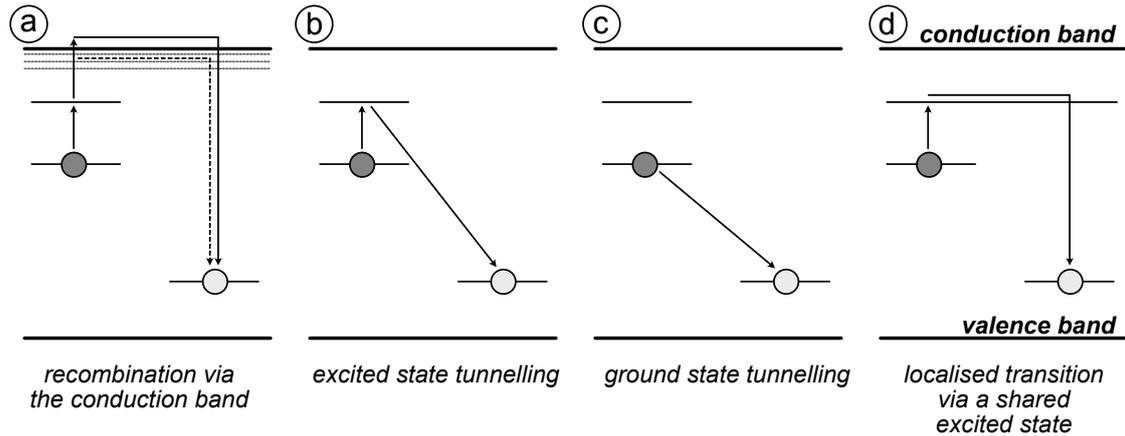
Figure 2: Schematic figure presenting the different luminescence processes considered for feldspars, specifically highlighting mechanisms proposed as explanation of fading in feldspars. (a) Recombination via the conduction band. Since this process is not occurring in feldspar IRSL, a recombination route via the sub-conduction band-tail states is indicated with dashed lines (cf. Jain and Ankjærgaard, 2011). (b) Tunnelling-recombination via the excited state (e.g., Halperin and Braner, 1960; Jain et al., 2012, 2015). (c) Ground state tunnelling (see Visocekas, 1985; Huntley, 2006). (d) Localised transition via an excited state common between the electron and the hole trap (following Templer, 1986).

3.2. Excited state tunnelling and other explanations

Halperin and Braner (1960) proposed a model which explains luminescence as the results of trapped electrons being thermally excited to the excited state of their trapping centre, from where they tunnel to a trapped hole, with this process being referred to as excited state tunnelling (Fig. 2b). Jain et al. (2012) used the model by Halperin and Braner (1960) as basis for their version of a localised transition model of feldspar luminescence. This model describes the luminescence resulting from excited state tunnelling taking place within randomly distributed donor-acceptor pairs, with the tunnelling distance dependent on the defect density, expressed as the density of recombination centres. The model was further extended by Jain et al. (2015) to account for truncated trapped electron-hole pair distributions, as these will be more likely, because fading (but also preheating in the laboratory) will have already caused the recombination of proximal electron-hole pairs. Other explanations for fading or models accounting for fading have been given. For example, Templer (1986) proposed a localised transition model, according to which trapped electrons can recombine with proximal holes via a shared excited state of the electron and hole trap (Fig. 2d). Kumar et al. (2022) investigated whether an unstable hole population is the cause behind fading in feldspars. They proposed that the blue luminescence recombination centre population is depleted due to fading between an electron trapping centre different to the one involved in infrared stimulated luminescence (IRSL) (and in infrared photoluminescence, IRPL), thus resulting in a reduced recombination efficiency for the trapped electrons and holes involved in IRSL. Already Wintle (1977) considered the possibility of fading being caused by the reduction of available hole centres.

3.3. Defect density, random distribution, and defect clustering

Most of the above presented models require a certain proximity between the electron trapping centres as donors and the recombination centres as acceptors. Two questions arise: (1) How close do these donor-acceptor pairs have to be to allow for tunnelling to occur, either from the ground or from the excited state? (2) How are these donor-acceptor pairs distributed within the crystal? For the latter question it should be mentioned that some of the earlier localised transition models assumed a fixed distance between donors and acceptors (e.g., Halperin and Braner, 1960), whilst others based their model on random distributions (e.g., Huntley, 2006; Jain et al., 2012).

Poolton et al. (2002) compared the possibility of both, ground and excited state tunnelling in feldspars, under the consideration of a simple electronic model assuming a defect analogous to a hydrogen atom. Using this, they calculated the extent of the electron wave functions of the ground and first excited state of such a defect, as the extent of these wave functions give information on the radius within which a recombination centre needs to occur to allow for the tunnelling process to take place (Fig. 3a). Poolton et al. (2002) thus presented the tunnelling recombination probability functions and inferred that the largest recombination probability from the ground state occurs at a distance of 1.6 Å, with only a 1 % probability of ground state tunnelling-based recombination to occur at a distance of 8 Å (Fig. 3a), with unit cell parameters for albite of ~8.15 Å, ~12.87 Å and ~7.1 Å, for a, b, and c, respectively (Prewitt et al., 1976). For comparison, in microcline, these unit cell parameters are slightly larger with a, b and c being ~8.57 Å, 12.97 Å, and 7.22 Å, respectively (Blasi et al., 1987). For the excited state, calculations by
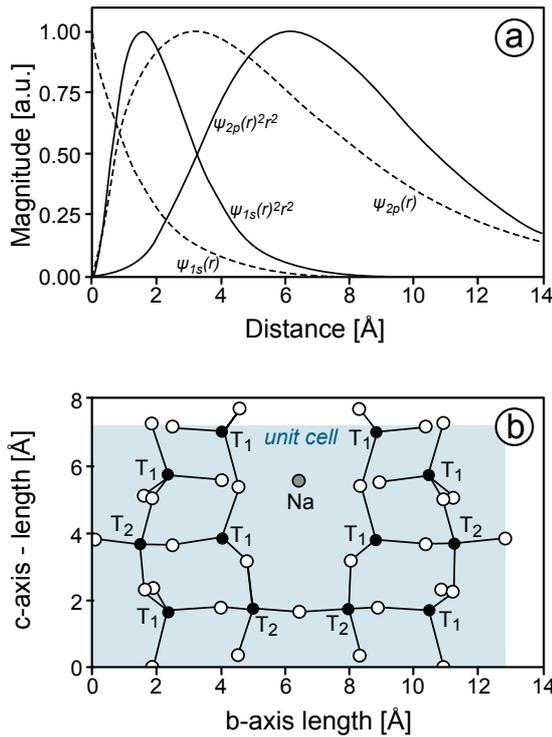
Figure 3: (a) Radial extent of the wavefunctions (Ψ) of the ground and first excited state of a trapped electron, calculated assuming a hydrogen-like model for Na-feldspar, by solving Schrödinger's equation. (b) Simplified crystal structure of Na-feldspar projected onto the (100) plane. Please note the same scale on the x-axis of both subfigures. The figures are redrawn from Poolton et al. (2002).

Poolton et al. (2002) predict the highest recombination probability to occur at a distance of 6.2 Å. According to these, there remains only a 0.03 % probability at 28 Å (Fig. 3a), which is just double the length of the longest unit cell parameter, *b*. Despite the simplicity of the hydrogen model, it becomes apparent that donor-acceptor pairs have to be within one unit cell (Fig. 3b), if recombination were to occur from the ground state of the electron trap, and within two unit cells, if the excited state would be considered.

These direct donor-acceptor recombination models require a high enough defect density to allow for this direct transition. Based on TL intensity, Sanderson (1988) calculated the number of electron and hole pairs (in his example: 10^7–10^8), which would participate in the luminescence process. For a sample which consist of $\sim 10^{20}$ atoms, this would result in a distance of 10^4 atoms when a random distribution of the electron hole pairs is assumed – a distance too large to be covered by direct donor-acceptor tunnelling recombination. If the ionisation density and the donor and acceptor defects are randomly distributed, then one would see a strong dependence of fading on the size of the dose given (Sanderson, pers. comm.). Alternatively, defects could occur clustered in certain regions of the crystal, resulting in

shorter electron-hole pair distances in such areas (see Sanderson, 1988).

Wintle (1977) tested potential dependences of fading on differently ionising irradiation types (α, β, γ) and found fading rates within 5 % of each other, suggesting no dependence of fading on the quality of irradiation. Visocekas (1988) showed that average fading rates of TL in CaSO$_4$:Dy doubled when irradiated using α-particles, compared to β-particles. Morthekai et al. (2013) performed fading tests for the IRSL signal of feldspars following irradiations with different ionisation densities (β-particles, X-rays and protons). They found that fading rates increased with increasing ionisation densities and concluded that fading does not occur across strongly coupled donor-acceptor pairs with constant donor-acceptor distances. The observed strong correlation between ionisation density (and thus trapped charge density) and fading rate is, according to Morthekai et al. (2013), an indication of a random distribution of defects. However, these observations only dismiss models assuming a fixed donor-acceptor distance (e.g., Randall and Wilkins, 1945; Halperin and Braner, 1960). They do not dismiss the idea of defect clustering in certain areas of the crystal (see Sanderson, 1988).

Besides the effect of different radiation types, studies have explored the effect of dose size administered with the same ionisation density (β-particles): Huntley (2006) observed an increase in IRSL fading rate with increasing dose for a feldspar sample. They further were able to show that the fading rate of a feldspar sample in field saturation (the equilibrium state between electron trap filling due to dosing and trapped charge depletion due to thermal annealing and fading) was higher when the sample had been bleached. Based on the models proposed by Huntley (2006) and Kars et al. (2008) and on own experimental data, Li and Li (2008) observed a dose-dependency of fading rates of natural and laboratory irradiated feldspars. They explained this increase in fading with increasing dose with the greater number of electron-hole pairs generated by large doses. They furthermore proposed that there exists a competition between stable and unstable electron traps in feldspars. At low doses and over short irradiation times, it will be similarly likely to have electrons trapped at both these types of traps. On the contrary, at high doses, charge trapped at stable electron traps will remain there whilst electrons will continue to fade out of the unstable traps, making electron trapping at these unstable traps more likely during longer irradiation times.

4. The *g*-value – Means to quantify the fading rate

Despite the ongoing debate of the physical processes governing fading in feldspars, the loss of luminescence signal at ambient temperatures affects the application of feldspars in luminescence dating. Thus, efforts have been made to quantify the signal loss and to correct for it. This chapter presents the method by Auclair et al. (2003), which is widely used for

estimating the rate of fading over laboratory time scales.

Usually, the fading rate is expressed as the *g*-value, which corresponds to the percentage of luminescence lost due to fading per decade of time (Aitken, 1985; Visocekas, 1985). The *g*-value can be obtained by fitting a series of L_x/T_x values, obtained after repeated regenerative doses of the same size, but after different delay (or storage) times between the irradiation and the luminescence measurement, and their respective storage times, using Eq. 1 (Auclair et al., 2003):

$$I = I_c \left[1 - \frac{g}{100} \log_{10} \left(\frac{t}{t_c} \right) \right] \quad (1)$$

In this equation, *I* represents the luminescence intensity measured after time *t*. I_c refers to the luminescence intensity when $t = t_c$. According to (Auclair et al., 2003), t_c is an arbitrary time, but usually the time since irradiation for the prompt measurement is used. However, this time may vary for different aliquots or samples measured, or dependent on the instrument used for the measurement or the size of the irradiation dose. Thus, it is suggested to normalise t_c to a fixed value, and here commonly a t_c-value of 2 days is used (Huntley and Lamothe, 2001; Auclair et al., 2003).

For constraining the *g*-value, it is crucial to properly estimate the time between the irradiation and the luminescence measurement, usually referred to as time since irradiation, and introduced as t^* (Aitken, 1985). There exist two possibilities of deriving t^*. Following Aitken (1985), and modified by Auclair et al. (2003):

$$t^* = t_0 \cdot 10^{\left[\frac{t_2 \log\left(\frac{t_2}{t_0}\right) - t_1 \log\left(\frac{t_1}{t_0}\right) - 0.43(t_2 - t_1)}{t_2 - t_1} \right]} \quad (2)$$

Here, $0.43 = \frac{1}{\ln(10)}$. Additionally, t_0 can be set to 1, as it is regarded as an arbitrary constant (cf. Auclair et al., 2003). Equation 2 can thus be shortened to:

$$t^* = 10^{\left[\frac{t_2 \log t_2 - t_1 \log t_1}{t_2 - t_1} - \frac{1}{\ln 10} \right]}, \quad (3)$$

as given in the Analyst manual (Duller, 2016). The second possibility is an approximation presented by Auclair et al. (2003):

$$t^* \cong t_1 + \frac{t_2 - t_1}{2} \quad (4)$$

The parameter t^* can be estimated using either Eq. 3 or 4, with the parameters of these equations being displayed in Figure 4.

Auclair et al. (2003) furthermore explored different possible measurement designs for the determination of fading for a given sample. They observed that the *g*-value is dependent on the method used, with the most robust results being obtained using a SAR procedure (see Murray and Wintle, 2000; Wallinga et al., 2000) during which the sample is stored for different periods of time following irradiation and preheating.
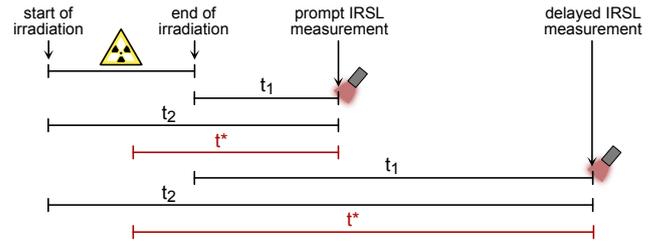

Figure 4: Graphical representation of the parameters involved in the calculation of t^*. The length of the timelines is arbitrary. The figure has been modified from Auclair et al. (2003).

5. Correcting for fading

Different methods for correcting the feldspar IRSL signals for fading were developed. This includes an isochron method termed "fadia" (Lamothe and Auclair, 1999, 2000), which was further investigated by Lamothe et al. (2012) and Li et al. (2016), as well as the dose rate method by Lamothe et al. (2003). However, for the purpose of this review, we will focus on the two most commonly used correction methods, which are also applicable to SAR-based IRSL results: The fading correction method by Huntley and Lamothe (2001) and the method by Huntley (2006), which was adapted for dating purposes by Kars et al. (2008).

5.1. Fading correction following Huntley and Lamothe (2001)

The fading correction method by Huntley and Lamothe (2001) is based on the quantum mechanical tunnelling model. It is predicted that the luminescence intensity *I*, measured over time *t* follows Eq. 5, where *k* is a constant, which is sample-dependent and varies with t_c. I_c is the intensity when time $t = t_c$.

$$I = I_c \left[1 - k \ln \left(\frac{t}{t_c} \right) \right] \quad (5)$$

For further details and a differential form of the equation, the reader is referred to the original publication by Huntley and Lamothe (2001). Regarding the correction of luminescence ages, Eq. 6 is used:

$$\frac{\text{measured age}}{\text{true age}} = 1 - k \left[\left(\frac{\text{true age}}{t_c} \right) - 1 \right] \quad (6)$$

Here "true" age denotes the luminescence age, if no fading had occurred. The parameter t_c is chosen as the time between the laboratory irradiation and the luminescence measurement, whereas *k* is defined dependent on t_c. In their example, Huntley and Lamothe (2001) used $t_c = 2$ days. Since their study in 2001, fading rates obtained in various studies have conventionally been normalised to 2 days.

The model by Huntley and Lamothe (2001) assumes that the fading rate is constant over the initial part of the dose re-
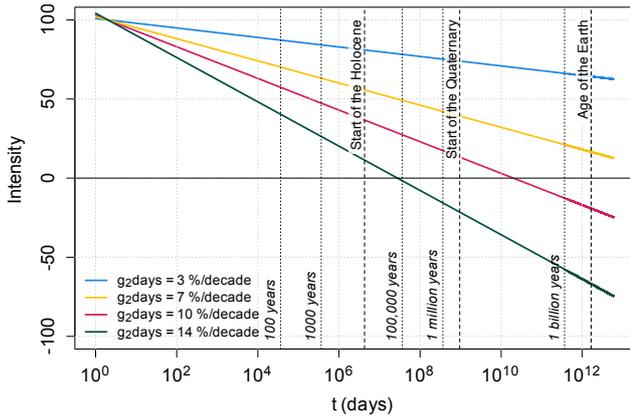
Figure 5: Following Huntley and Lamothe (2001), the decrease in luminescence (indicated as intensity) is predicted for up to 10^{13} days ($\sim$27 billion years) for visualisation purposes using four different g-values. The g-values were normalised to 2 days and the t_c value was set to 2 days. For this prediction the following equation was used: $y = I_c \cdot (1 - (\frac{g}{100}) \cdot \log_{10}(\frac{t}{t_c}))$. Here, I_c was set to be 100. This figure shows that the model by Huntley and Lamothe (2001) results in large values at very short time scales (see mismatch between predicted lines) and negative values at very long time scales. The latter occurs only for very high g-values. In the case of smaller g-values, negative values will eventually be reached, but as the example shows, only at time scales irrelevant for luminescence dating.

sponse curve, which can still be fitted using a linear function. However, on short time scales their model predicts too large values (Fig. 5). Physically, this is explained by the probability of electron-hole pairs being very proximal (Huntley and Lamothe, 2001). At long time scales, their model predicts negative intensities (Fig. 5). At higher doses, trapped electrons have a chance of tunnelling to the nearby recombination centres, thus opening the possibility of their former trap to be repopulated and emptied by tunnelling again (referred to as repetitive filling and emptying by Huntley and Lamothe, 2001). Interestingly, Buylaert et al. (2008) have shown the successful applicability of this correction method to doses ranging from $\sim$100 Gy to $\sim$150 Gy.

5.2. Huntley (2006) and Kars et al. (2008) – Density of recombination centres

Huntley (2006) described electron-hole recombination due to ground state tunnelling in feldspars as a function of the lifetime of the tunnelling decay (τ), the distribution of distances (r) between electron and hole trapping centres, and the density of recombination centres (ρ'). According to Huntley (2006), fading and the number of electrons remaining trapped after time t depends on ρ'. Eq. 7 describes the relationship of the trapped electron density n remaining after time t, compared to the initial trapped electron population n_i. The parameter s represents the attempt-to-escape frequency,

which is assumed to be 3×10^{15} s^{-1} (Huntley, 2006).

$$\frac{n}{n_i} = \exp\left(-\rho' \left[\ln\left(1.8st\right)\right]^3\right) \qquad (7)$$

Equation 7 shows that n determined after delay time t is dependent on ρ', and the luminescence signal intensity (for example the IRSL intensity) is the result of the number of trapped charges recombining. Kars et al. (2008) rewrote Eq. 7 to:

$$\text{IRSL}_{\text{faded}} = \text{IRSL}_{\text{initial}} \cdot \exp\left(-\rho' \left[\ln\left(1.8st\right)\right]^3\right) \qquad (8)$$

$\text{IRSL}_{\text{initial}}$, the unfaded IRSL signal, is thus obtained by dividing the faded IRSL signal by $\exp\left(-\rho' \left[\ln\left(1.8st\right)\right]^3\right)$. This procedure can be applied to each point of a dose response curve. Correcting each point for the signal loss due to fading gives the unfaded dose response. The parameter ρ' is obtained by plotting L_x/T_x values measured during a SAR fading experiment against time and fitting the points using Eq. 8.

Furthermore, the model by Kars et al. (2008) allows for the construction of a natural dose response curve. For this approach the dose rate ($\dot{D}$) in Eq. 9 needs to be adapted to the natural conditions (see Kars et al., 2008; King et al., 2018). In Eq. 9, A is a pre-exponential factor, corresponding to the maximum asymptote of the dose response curve, and D_0 is the characteristic dose, which describes the curvature of the dose response curve.

$$\frac{L_x}{T_x}(t) = \exp\left(-\rho' \left[\ln\left(1.8st\right)\right]^3\right) \cdot A \left(1 - \exp\left(-\frac{\dot{D}t}{D_0}\right)\right) \qquad (9)$$

The model by Huntley (2006) and its adaptation for luminescence dating purposes by Kars et al. (2008) enable the fading correction of older samples. However, Li and Li (2008) raised criticism in response to the use of a constant ρ'-value for fading correction of older samples and for the construction of a natural dose response curve. They observed a dose dependency of fading rates, suggesting that ρ' will change over time during which a sample is exposed to ionising radiation (Li and Li, 2008). Thus, these authors suggested to determine ρ' for different regenerative doses – rendering the fading correction method more complex.

6. Methods for minimising or circumventing fading

Whilst fading correction is possible, it is advantageous if a non-fading luminescence signal could be used in dating applications. Despite the ubiquitous nature of fading, differences in fading rate between chemically and structurally different feldspars have been observed. Wintle (1973) reported high fading rates in feldspars of volcanic origin and Spooner (1992, 1994) observed differential fading rates between mineralogically different feldspars. These results are

supported by more recent work by Riedesel et al. (2021), who showed that IRSL fading rates depend on the structure of the feldspars investigated, with ordered K- and Na-feldspar end-members exhibiting only little to no fading. While this suggests that specific types of feldspars could be used for dating without having to correct for fading, the rarity of these feldspar types severely limits this approach. Other options, such as selecting grains based on their luminescence sensitivity (Lamothe et al., 2012) or detecting luminescence in specific emission windows (e.g., Spooner, 1992; Zink and Visocekas, 1997; Stokes and Fattahi, 2003) to minimise the influence of fading, have been suggested.

However, the focus has been on modifying measurement procedures for both TL and IRSL to circumvent or minimise fading, with most of them involving storage or preheat treatments to isolate a more stable signal (e.g., Clark and Templer, 1988; Molodkov and Bitinas, 2006). Further advances over the past two decades resulted in protocols using multiple successive IRSL measurements at increasing temperatures to separate a more stable feldspar IRSL signal for dating (Thomsen et al., 2008; Li and Li, 2011). The basis of these protocols, involving two consecutive (post-IR IRSL, Thomsen et al., 2008) or three to five consecutive IRSL measurement steps (multiple-elevated temperature, MET-protocols; Li and Li, 2011), is a random distribution of electron and hole traps in the crystal. The trapped electrons are understood to tunnel to the nearest recombination centre. The preheat and the following lower temperature IRSL measurement steps (e.g., 50 °C) will result in the recombination of trapped electrons with the most proximal holes (see Jain and Ankjærgaard, 2011), leaving only the more distal holes available for recombination during the higher temperature post-IR IRSL or MET steps. Since fading to these holes is less likely, due to the greater donor-acceptor distance, the thus obtained luminescence signal is expected to be more stable (cf. Jain and Ankjærgaard, 2011). These post-IR IRSL and MET-IRSL protocols have been widely applied, and lower fading rates were generally observed for the higher temperature IRSL steps (e.g., Buylaert et al., 2012). However, this is at the cost of signal bleachability, with higher temperature IRSL signals resetting slower during sunlight exposure, compared to signals measured at lower temperatures (e.g., Colarossi et al., 2015).

Interestingly, Lamothe et al. (2020) took advantage of the different fading rates of IRSL signals stimulated at different temperatures. They propose a measurement protocol, which facilitates a modified post-IR IRSL procedure to find a thermal treatment resulting in the same equivalent dose for the low and the high temperature IRSL measurements within a post-IR IRSL protocol: the post-isothermal IRSL (pIt-IRSL) protocol. Whilst the natural (L_n/T_n) cycle is measured following the conventional post-IR IRSL protocol, a thermal annealing step with different annealing durations at a temperature higher than the preheat is inserted after the L_x preheat. (Lamothe et al., 2020) tested the proposed protocol on three different samples and obtained ages in agreement with independent age control for two samples. The third sample

was used to test the validity of the protocol against signal saturation with satisfying results. Ataee et al. (2025) tested the pIt-IRSL on polymineral fine grain material and observed good performance of the protocol, as long as the first IRSL signal is not saturated. For this case, Ataee et al. (2025) presented a modified pIt-IRSL protocol.

All these methods use recombination-based luminescence, thus involving electron traps and hole traps in the luminescence production. To minimise fading, alternative, non-recombination based methods have also been explored. Infrared radioluminescence or radiofluorescence (IR-RF; Trautmann et al., 1998, 1999) measures the filling of a specific type of electron trap in feldspars. Here, luminescence is recorded in the infrared, which arises due to ionised electrons being trapped in electron traps below the conduction band. This type of electron trap can also be sensed using IRPL (Prasad et al., 2017; Kumar et al., 2018). IRPL arises from the non-destructive probing of the trapped electron population in feldspars by stimulating the sample with IR photons. For both methods only little information on fading is available. Krbetschek et al. (2000) reported that it was possible to date samples using IR-RF, which were expected to be saturated. Kumar et al. (2021) showed that IRPL measurements exhibit lower fading, compared to conventional recombination-based luminescence techniques. However, further studies testing the applicability of IRPL to date Pleistocene sediments need to be performed to fully evaluate its benefits.

7. Conclusions

This review presents an overview of the research history into fading of feldspar luminescence, as well as into the research developments of the past decades, which focussed on developing a better understanding of the physical processes behind fading in feldspars, the ubiquity of this phenomenon, and into ways of circumventing, minimising or correcting for fading. Particularly worth highlighting are the following points:

- Fading, a loss of the luminescence signal at ambient temperatures, does not only occur in feldspars, but also in other luminescence phosphors.

- Fading seems to be ubiquitous in feldspars, with very few examples showing low fading feldspars.

- Ground state tunnelling is the most widely accepted explanation for fading. However, it has been indicated that this process might have limitations, and that excited state tunnelling might be the more likely explanation.

- Fading appears to be dependent on the ionisation density and size of the irradiation dose administered.

- It is possible to constrain the rate of fading in the laboratory and to use this information to correct for fading that occurred over geological time scales.

- Different options are available to access a luminescence signal exhibiting lower fading rates, unfortunately, often at the cost of lower bleachability. However, it has not been possible to fully eliminate fading.

References

Aitken, M., 1985. Thermoluminescence Dating. Academic Press, London, United Kingdom. doi: 10.1016/C2009-0-06368-8.

Ataee, N., Roberts, H.M., Duller, G.A.T., 2025. Assessing the potential of a modified post-isothermal IRSL (pIt-IR) protocol to circumvent the problems posed by anomalous fading in polymineral fine grains. Quaternary Geochronology 88, 101676. doi: 10.1016/j.quageo.2025.101676.

Auclair, M., Lamothe, M., Huot, S., 2003. Measurement of anomalous fading for feldspar IRSL using SAR. Radiation Measurements 37, 487–492. doi: 10.1016/S1350-4487(03)00018-0.

Bailey, R.M., 2001. Towards a general kinetic model for optically and thermally stimulated luminescence in quartz. Radiation Measurements 33, 17–45. doi: 10.1016/S1350-4487(00)00100-1.

Blasi, A., De Pol Blasi, C., Zanazzi, P.F., 1987. A re-examination of the Pellotsalo microcline: Mineralogical implications and genetic considerations. The Canadian Mineralogist 25, 527–537.

Buylaert, J.P., Jain, M., Murray, A.S., Thomsen, K.J., Thiel, C., Sohbati, R., 2012. A robust feldspar luminescence dating method for Middle and Late Pleistocene sediments. Boreas 41, 435–451. doi: 10.1111/j.1502-3885.2012.00248.x.

Buylaert, J.P., Murray, A.S., Huot, S., 2008. Optical dating of an Eemian site in Northern Russia using K-feldspar. Radiation Measurements 43, 715–720. doi: 10.1016/j.radmeas.2008.01.027.

Clark, P.A., Templer, R.H., 1988. Dating thermoluminescence samples which exhibit anomalous fading. Nuclear Tracks and Radiation Measurements 14, 139–141. doi: 10.1016/1359-0189(88)90054-4.

Colarossi, D., Duller, G.A.T., Roberts, H.M., Tooth, S., Lyons, R., 2015. Comparison of paired quartz OSL and feldspar post-IR IRSL dose distributions in poorly bleached fluvial sediments from South Africa. Quaternary Geochronology 30, 233–238. doi: 10.1016/j.quageo.2015.02.015.

Delbecq, C.J., Toyozawa, Y., Yuster, P.H., 1974. Tunneling recombination of trapped electrons and holes in KCl:AgCl and KCl:TlCl. Physical Review B 9, 4497–4505. doi: 10.1103/PhysRevB.9.4497.

Duller, G.A.T., 2016. Analyst v4.31.9 user manual. Technical report. 83 pp.

Garlick, G.F.J., Robinson, I., 1972. The thermoluminescence of lunar samples. Proceedings of the International Astronomical Union 47, 324–329. doi: 10.1017/S0074180900097631.

Halperin, A., Braner, A.A., 1960. Evaluation of Thermal Activation Energies from Glow Curves. Physical Review 117, 408–415. doi: 10.1103/PhysRev.117.408.

Huntley, D.J., 2006. An explanation of the power-law decay of luminescence. Journal of Physics: Condensed Matter 18, 1359–1365. doi: 10.1088/0953-8984/18/4/020.

Huntley, D.J., Lamothe, M., 2001. Ubiquity of anomalous fading in K-feldspars and the measurement and correction for it in optical dating. Canadian Journal of Earth Science 38, 1093–1106. doi: 10.1139/cjes-38-7-1093.

Jain, M., Ankjærgaard, C., 2011. Towards a non-fading signal in feldspar: Insight into charge transport and tunnelling from time-resolved optically stimulated luminescence. Radiation Measurements 46, 292–309. doi: 10.1016/j.radmeas.2010.12.004.

Jain, M., Guralnik, B., Andersen, M.T., 2012. Stimulated luminescence emission from localized recombination in randomly distributed defects. Journal of Physics: Condensed Matter 24, 385402. doi: 10.1088/0953-8984/24/38/385402.

Jain, M., Sohbati, R., Guralnik, B., Murray, A.S., Kook, M., Lapp, T., Prasad, A.K., Thomsen, K.J., Buylaert, J.P., 2015. Kinetics of infrared stimulated luminescence from feldspars. Radiation Measurements 81, 242–250. doi: 10.1016/j.radmeas.2015.02.006.

Kars, R.H., Wallinga, J., Cohen, K.M., 2008. A new approach towards anomalous fading correction for feldspar IRSL dating – tests on samples in field saturation. Radiation Measurements 43, 786–790. doi: 10.1016/j.radmeas.2008.01.021.

Kijek, N., Chruścińska, A., 2017. On the equivalence of natural and laboratory growth curves in luminescence dating - The effect of deep traps and luminescence centres. Radiation Measurements 106, 477–482. doi: 10.1016/j.radmeas.2017.05.014.

King, G.E., Burow, C., Roberts, H.M., Pearce, N.J.G., 2018. Age determination using feldspar: Evaluating fading-correction model performance. Radiation Measurements 119, 58–73. doi: 10.1016/j.radmeas.2018.07.013.

Krbetschek, M.R., Trautmann, T., Dietrich, A., Stolz, W., 2000. Radioluminescence dating of sediment: methodological aspects. Radiation Measurements 32, 493–498. doi: 10.1016/S1350-4487(00)00122-0.

Kumar, R., Kook, M., Jain, M., 2021. Sediment dating using infrared photoluminescence. Quaternary Geochronology 62, 191147. doi: 10.1016/j.quageo.2020.101147.

Kumar, R., Kook, M., Jain, M., 2022. Does hole instability cause anomalous fading of luminescence in feldspar? Journal of Luminescence 252, 119403. doi: 10.1016/j.jlumin.2022.119403.

Kumar, R., Kook, M., Murray, A.S., Jain, M., 2018. Towards direct measurement of electrons in metastable states in K-feldspar: Do infrared-photoluminescence and radioluminescence probe the same trap? Radiation Measurements 120, 7–13. doi: 10.1016/j.radmeas.2018.06.018.

Lamothe, M., Auclair, M., 1999. A solution to anomalous fading and age shortfalls in optical dating of feldspar minerals. Earth and Planetary Science Letters 171, 319–323. doi: 10.1016/S0012-821X(99)00180-6.

Lamothe, M., Auclair, M., 2000. The fadia method: a new approach in luminescence dating using the analysis of single feldspar grains. Radiation Measurements 32, 433–438. doi: 10.1016/S1350-4487(00)00124-4.

Lamothe, M., Auclair, M., Hamzaoui, C., Huot, S., 2003. Towards a prediction of long-term anomalous fading of feldspar IRSL. Radiation Measurements 37, 493–498. doi: 10.1016/S1350-4487(03)00016-7.

Lamothe, M., Barré, M., Huot, S., Ouimet, S., 2012. Natural luminescence and anomalous fading in K-feldspar. Radiation Measurements 47, 682–687. doi: 10.1016/j.radmeas.2012.04.018.

Lamothe, M., Brisson, L.F., Hardy, F., 2020. Circumvention of anomalous fading in feldspar luminescence dating using Post-Isothermal IRSL. Quaternary Geochronology 57, 101062. doi: 10.1016/j.quageo.2020.101062.

Li, B., Li, S.H., 2008. Investigations of the dose-dependent anomalous fading rate of feldspar from sediments. Journal of Physics D: Applied Physics 41, 22502. doi: 10.1088/0022-3727/41/22/225502.

Li, B., Li, S.H., 2011. Luminescence dating of K-feldspar from sediments: A protocol without anomalous fading correction. Quaternary Geochronology 6, 468–479. doi: 10.1016/j.quageo.2011.05.001.

Li, B., Roberts, R.G., Brumm, A., Guo, Y.J., Hakim, B., Ramli, M., Aubert, M., Grün, R., Zhao, J.X., Saptomo, W., 2016. IRSL dating of fast-fading sanidine feldspars from Sulawesi, Indonesia. Ancient TL 34, 1–13. doi: 10.26034/la.atl.2016.503.

Molodkov, A., Bitinas, A., 2006. Sedimentary record and luminescence chronology of the Lateglacial and Holocene aeolian sediments in Lithuania. Boreas 35, 244–254. doi: 10.1111/j.1502-3885.2006.tb01154.x.

Morthekai, P., Jain, M., Dach, G., Elma, D.R., Prip, H., 2013. Dependence of (anomalous) fading of infra-red stimulated luminescence on trap occupancy in feldspars. Journal of Luminescence 143, 704–709. doi: 10.1016/j.jlumin.2013.05.040.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73. doi: 10.1016/S1350-4487(99)00253-X.

Peng, J., Wang, X., Adamiec, G., Zhao, H., 2022. Critical role of the deep electron trap in explaining the inconsistency of sensitivity-corrected natural and regenerative growth curves of quartz OSL at high irradiation doses. Radiation Measurements 159, 106874. doi: 10.1016/j.radmeas.2022.106874.

Poolton, N.R.J., Wallinga, J., Murray, A.S., Bulur, E., Bøtter-Jensen, L., 2002. Electrons in feldspar I: on the wavefunction of electrons trapped at simple lattice defects. Physics and Chemistry of Minerals 29, 210–216. doi: 10.1007/s00269-001-0217-3.

Prasad, A.K., Poolton, N.R.J., Kook, M., Jain, M., 2017. Optical dating in a new light: A direct, non-destructive probe of trapped electrons. Scientific Reports 7, 12097 doi=10.1038/s41598–017–10174–8.

Prewitt, C.T., Sueno, S., Papike, J.J., 1976. The crystal structures of high albite and monalbite at high temperatures. American Mineralogist 61, 1213–1225.

Randall, J.T., Wilkins, M.H.F., 1945. Phosphorescence and electron traps I. The study of trap distributions. Proceedings of the Royal Society A 184, 366–389. doi: 10.1098/rspa.1945.0024.

Riedesel, S., Bell, A.M.T., Duller, G.A.T., Finch, A.A., Jain, M., King, G.E., Pearce, N.J., Roberts, H.M., 2021. Exploring sources of variation in thermoluminescence emissions and anomalous fading in alkali feldspars. Radiation Measurements 141, 106541. doi: 10.1016/j.radmeas.2021.106541.

Riehl, N., 1970. Tunnel luminescence and infrared stimulation. Journal of Luminescence 1, 1–16. doi: 10.1016/0022-2313(70)90019-0.

Sanderson, D.C.W., 1988. Fading of thermoluminescence in feldspars: Characteristics and corrections. Nuclear Tracks and Radiation Measurements 14, 155–161. doi: 10.1016/1359-0189(88)90057-X.

Spooner, N.A., 1992. Optical dating: Preliminary results on the anomalous fading of luminescence from feldspars. Quaternary Science Reviews 11, 139–145. doi: 10.1016/1350-4487(94)90111-2.

Spooner, N.A., 1994. The anomalous fading of infrared-stimulated luminescence from feldspars. Radiation Measurements 23, 625–632.

Stokes, S., Fattahi, M., 2003. Red emission luminescence from quartz and feldspar for dating applications: an overview. Radiation Measurements 37, 383–395. doi: 10.1016/S1350-4487(03)00060-X.

Templer, R.H., 1986. The localised transition model of anomalous fading. Radiation Protection Dosimetry 17, 493–497. doi: 10.1093/rpd/17.1-4.493.

Thomsen, K.J., Murray, A.S., Jain, M., Bøtter-Jensen, L., 2008. Laboratory fading rates of various luminescence signals from feldspar-rich sediment extracts. Radiation Measurements 43, 1474–1486. doi: 10.1016/j.radmeas.2008.06.002.

Trautmann, T., Krbetschek, M.R., Dietrich, A., Stolz, W., 1998. Investigations of feldspar radioluminescence: potential for a new dating technique. Radiation Measurements 29, 421–425. doi: 10.1016/S1350-4487(98)00012-2.

Trautmann, T., Krbetschek, M.R., Dietrich, A., Stolz, W., 1999. Feldspar radioluminescence: a new dating method and its physical background. Journal of Luminescence 85, 45–58. doi: 10.1016/S0022-2313(99)00152-0.

Valla, P.G., Lowick, S.E., Herman, F., Champagnac, J.D., Steer, P., Guralnik, B., 2016. Exploring $IRSL_{50}$ fading variability in bedrock feldspars and implications for OSL thermochronometry. Quaternary Geochronology 36, 55–66. doi: 10.1016/j.quageo.2016.08.004.

Visocekas, R., 1979. Miscellanous aspects of artificial TL of calcite: emission spectra, athermal detrapping and anomalous fading. PACT 3, 258–265.

Visocekas, R., 1985. Tunnelling radiative recombination in labradorite: its association with anomalous fading of thermoluminescence. Nuclear Tracks 10, 521–529. doi: 10.1016/0735-245X(85)90053-5.

Visocekas, R., 1988. Comparison between tunnelling afterglows following alpha and beta irradiations. Nuclear Tracks and Radiation Measurements 14, 163–168. doi: 10.1016/1359-0189(88)90058-1.

Visocekas, R., Ceva, T., Marti, C., Lefaucheux, F., Robert, M.C., 1976. Tunneling Processes in Afterglow of Calcite. Physica Status Solidi 35, 315–327. doi: 10.1002/pssa.2210350134.

Visocekas, R., Ouchene, M., Gallois, B., 1983. Tunneling afterglow and anomalous fading in dosimetry with $CaSO_4$:Dy. Nuclear Instruments and Methods in Physics Research 214, 553–555. doi: 10.1016/0167-5087(83)90634-8.

Wallinga, J., Murray, A.S., Wintle, A.G., 2000. The single-aliquot regenerative-dose (SAR) protocol applied to coarse-grain feldspar. Radiation Measurements 32, 529–533. doi: 10.1016/S1350-4487(00)00091-3.

Wintle, A.G., 1973. Anomalous fading of Thermoluminescence in Mineral Samples. Nature 245, 143–145. doi: 10.1038/245143a0.

Wintle, A.G., 1977. Detailed study of a thermoluminescent mineral exhibiting anomalous fading. Journal of Luminescence 15, 385–393. doi: 10.1016/0022-2313(77)90037-0.

Wood, R.A., Townsend, P.D., Pells, G.P., Murphy, M.J., 1990. "Anomalous" fading in irradiated α-Al_2O_3. Nuclear Instruments and Methods in Physics Research B 46, 189–193. doi: 10.1016/0168-583X(90)90696-R.

Zink, A.J.C., Visocekas, R., 1997. Datability of sanidine feldspars using the near-infrared TL emission. Radiation Measurements 27, 251–261. doi: 10.1016/S1350-4487(96)00141-2.