Determining the cooling age using luminescence-thermochronology

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Abstract

Luminescence technique has been shown to have great potential in low-temperature (<100 °C) themochronology. This study investigates the kinetic process of luminescence in a cooling system. We present a new formula that can be used for determining the cooling age based on luminescence-thermochronology. The cooling rate can be obtained directly from a plot of luminescence age versus the present temperature. We show that the application and capacity of luminescence-thermochronology are significantly controlled by the saturation of luminescence and environmental dose rate.

1.   Introduction

Thermochronology refers to determining or constraining the thermal history of a specific rock, mineral, or geologic unit using various dating techniques. Different techniques in thermochronology have been developed using various dating techniques, such as fission track dating of zircon and apatite, K-Ar and Ar-Ar dating of K-feldspars, (U-Th)/He dating of zircon and apatite and $^{4}He/^{3}He$ dating, etc. A full review of thermochronology has been provided by Reiners et al (2005). In terms of low-temperature thermochronology, radiation damage dating techniques, such as electron spin resonance (ESR) dating (Grün et al., 1999) and thermoluminescence (TL), are applied (Johnson 1966). Recently, in the study of the relief evolution and exhumation rates within the last glacial cycle in the Southern Alps of New Zealand, a new low-temperature

thermochronology has been introduced using the technique of optically stimulated luminescence (OSL) dating of quartz (Herman et al., 2010) .

Luminescence refers to the light emitted by irradiated crystal materials in response to external stimulus, such as heat (TL), visible light (OSL) and infrared (IRSL). During the geological processes, the minerals contained in geological materials (e.g. rocks and sediments) are exposed to ionization radiation (alpha and beta particles and gamma rays) emitted by the decay of radioactive isotopes within the minerals themselves and the surrounding matrix. The high-energy ionizing radiation can create free electrons and holes which may be subsequently trapped at the structural defects and chemical impurities inside the crystal lattice. When the minerals are stimulated by heat or light, the trapped electrons are ejected and recombined with holes. The evicted electrons diffuse around the crystal lattice and some of them may recombine with a different kind of site, called 'recombination centres'. When recombination occurs at the recombination centres, excess energy is released in the form of heat or luminescence. Therefore, the luminescence intensity is a measure of the concentration of trapped electrons and thus is a function of the dose of radiation absorbed by the sample. This forms the basic concept of luminescence dating, i.e. the age is determined by measuring the luminescence signal accumulated since the last event which reset the signal (either by heat or light).

Luminescence dating relies on the assumption that the trapped electrons are stable over the geological period of interest. In fact, once an electron is trapped, it reaches a semi-stable condition and has a probability of escape due to the vibrations of the lattice. There are many kinds of electron traps in any given crystal. Some of these traps are emptied very quickly while others can hold electrons for millions of years or more at ambient temperatures. For these traps, the probability of electrons escaping increases as the temperature is raised, provided that there is no significant athermal fading, which is, for example, present in several feldspar species. For an idealised system, the probability of escape can be described by first-order kinetics (Aitken, 1985), which is similar to the diffusion process in a chemical/isotopic system. Hence, luminescence dating technique can also be used as a thermo-chronological tool for revealing the thermal history of the sample of interest.

A large number of quantitative studies on thermochronology rely on the concept of closure temperature (T_c) developed for a cooling radioactive isotopic geochronological system (Dodson, 1973). In radiometric dating, closure temperature refers to the temperature at the time corresponding to its radiometric age. The

concept assumes that a chemical/isotopic system has cooled sufficiently fast so the isotopic or chemical system becomes "frozen" and there is no longer any significant diffusion of elements or daughter isotopes out of the system and into the external environment at the time given by its apparent age. Under the condition of fast cooling, the concept of closure temperature offers a simple means to determine the cooling age using luminescence-thermochronology. However, during slow cooling, there may be a gradual reduction in the loss of one or more component of the thermochronological system; thus, the concept of closure temperature will not be applicable. Utilizing the concept and formula of closure temperature of Dodson (1973), Herman et al. (2010) showed that the fast component of quartz OSL has exceptionally low closure temperature (ca. 30-35 °C). By comparing the results of OSL thermochronology with a thermal model from which thermal histories were extracted and used to compute ages, it was suggested that OSL may be used to measure relief evolution and exhumation rates.

It has been demonstrated that OSL technique has great potential in low temperature thermochronology (e.g. Herman et al., 2010). However, so far there is no systematic investigation of the kinetic process of luminescence in a cooling system, which is essential for the application of luminescence-thermochronology. Since the number of traps or defects in any given crystal is limited, there is an upper limit of the number of charges to be trapped. This means, if irradiation continues after all the electron traps have been filled, any further dose of radiation will not result in more luminescence. This condition is referred to as ''saturation'', which does not exist in the solid diffusion processes (e.g. radiogenic isotopic system). Because the formula of closure temperature of Dodson (1973) was developed for the latter process with no "saturation" in the increment of interest (e.g. the daughter isotopes), it is necessary to re-investigate the effect of saturation in a cooling system and its influence to luminesence-thermochronology. This study aims to develop a theoretical framework for an idealised luminescence system, e.g. purely first-order kinetics. It is noted that the degree to which this approach will work requires both a consideration to the degree of which real samples follow theoretical behaviour, and the successful application of this method in comparison to other thermochronometers.

2.   Formula for a fixed temperature

Assuming first-order kinetics, the process of charge trapping and escaping during irradiation at a given temperature can be described by the following equation (Huntley and Lian, 2006; Randall and Wilkins, 1945):

$$\frac{dn}{dt} = \frac{\dot{D}}{D_0}(N-n) - \frac{n}{\tau} = \frac{\dot{D}}{D_0}(N-n) - nse^{-\frac{E}{kT}}$$

(eq. 1)

where n is the number of trapped charges at time t, N is the total number of traps, D_0 (Gy) is the characteristic dose of saturation, $\dot{D}$ (Gy/ka) is the dose rate of radiation, τ is the lifetime of the trapped charges which can be described by:

$$\tau = s^{-1}e^{\frac{E}{kT}}$$

where T (K) is the temperature, E (eV) is the activation energy (or energy depth) of the traps of interest, s (s^{-1}) is the frequency factor (which can be regarded as the number of attempts to escape per second) and k is the Boltzmann constant.

For a fixed temperature and assuming an initial condition of n(t=0)=0, the solution of eq.1 is

$$\frac{n}{N} = \frac{\dot{D}}{D_0}\tau'(1 - e^{-\frac{t}{\tau'}})$$

(eq. 2)

where $\tau' = (\frac{\dot{D}}{D_0} + \frac{1}{\tau})^{-1}$.

In practice, the natural radiation dose (or equivalent dose) received is determined by comparing the intensity of the luminescence signal accumulated in natural process (so called 'natural' signal, L_n) with those regenerated by the laboratory irradiation (L_R) applied at room temperature in laboratory. For the laboratory irradiation, its dose rate $\dot{D}$ is usually so high that the relation of $\frac{\dot{D}}{D_0} >> \frac{1}{\tau}$ is satisfied. For this case, eq. 2 becomes:

$$\frac{n}{N} = 1 - e^{-\frac{\dot{D}t}{D_0}} = 1 - e^{-\frac{D}{D_0}}$$

(eq. 3)

where D is the regenerative dose given in the laboratory irradiation and $D = \dot{D}t$.

Since the intensity of luminescence signals (both L_n and L_R) is proportional to the number of trapped charges, from eq. 2 and eq. 3, we have

$$\frac{n}{N} = \frac{L_n}{L_0} = \frac{\dot{D}}{D_0}\tau'\left(1 - e^{-\frac{t}{\tau}}\right) = \frac{L_R}{L_0} = 1 - e^{-\frac{D_a}{D_0}} \qquad \text{(eq. 4)}$$

where L_0 is the saturation intensity when all traps are filled (i.e. when n=N), and D_a denotes the apparent dose (or equivalent dose). D_a is given by solving eq.4:

$$D_a = -D_0 \ln\left[1 - \frac{\dot{D}}{D_0}\tau'\left(1 - e^{-\frac{t}{\tau}}\right)\right] \qquad \text{(eq. 5)}$$

For the condition of $D_a \ll D_0$, the relation of $e^{-\frac{D_a}{D_0}} = 1 - \frac{D_a}{D_0}$ is satisfied, and the above expression can be simplified to

$$D_a = \dot{D}\tau'\left(1 - e^{-\frac{t}{\tau}}\right) \qquad \text{(eq. 6)}$$

The above expression (eq. 6) is in the same form with that given by Debusyst et al (1984) and Grün (1999) except that the lifetime τ is replaced by τ', where $\tau' = \left(\frac{\dot{D}}{D_0} + \frac{1}{\tau}\right)^{-1}$. However, τ' is usually much smaller than τ at ambient temperatures (e.g. ~10°C). If D_a increases and becomes significant compared to D_0, the above expression no longer holds, and eq.5 should be used in this case. Hence the apparent age t_a is given as:

$$t_a = \frac{D_a}{\dot{D}} = -\frac{D_0}{\dot{D}}\ln\left[1 - \frac{\dot{D}}{D_0}\tau'\left(1 - e^{-\frac{t}{\tau}}\right)\right] \qquad \text{(eq. 7)}$$

The above expression can be used to reconstruct the changes of apparent age (t_a) with time (t) at different temperatures.

Since one of the critical assumptions in luminescence dating is that the trapped electrons used for dating are stable over the time-span being estimated, it is important to ensure that the luminescence signals selected for dating are associated with deep traps with a long kinetic lifetime at the ambient temperature at which the sample was stored. This is explored for a virtual 'quartz sample' by assuming that its OSL signal is

associated with the traps that have the following parameters: E=1.6 eV, s=1x10^{13} s^{-1} and D_0=200 Gy. These parameters were chosen as they are close to the experimental values for natural quartz OSL signals, so that the results are representative for typical quartz samples (e.g. Li and Chen, 2001; Murray and Wintle, 1999). The changes of apparent OSL age with time (or true age) for this 'quartz sample' under a dose rate of $\dot{D}$=3 Gy/ka at different environmental temperatures ranging from 10 to 50 °C is shown in Fig. 1. The results show that reliable age can only be obtained when the environmental temperature is low (e.g. <30 °C). Considerable age underestimation is expected for samples older than ~100 ka at environmental temperatures of 30 °C and above.

3.   Formulas of thermochronometer for a cooling system

Here we consider a geochronological process with a constantly changing temperature, i.e. a cooling process. Rearranging eq. 1 we have

$$\frac{d(\frac{n}{N})}{dt} = \frac{\dot{D}}{D_0}\left(1 - \frac{n}{N}\right) - \frac{1}{\tau}\frac{n}{N} = \frac{\dot{D}}{D_0} - \left(\frac{\dot{D}}{D_0} + \frac{1}{\tau}\right)\frac{n}{N}$$

(eq. 8)

Assuming that the temperature T is a function of time t, i.e. $\dot{T} = \frac{dT(t)}{dt}$, for a process with a constant cooling rate,

$$T(t) = T_0 - \eta t$$

(eq. 9)

where η is the cooling rate, T_0 is the initial temperature.

Recalling from eq.3 and rearranging it, we have

$$D_a = -D_0 \ln\left(1 - \frac{n}{N}\right)$$

(eq. 10)

Hence the change rate of D_a as a function of t is given by differentiating the above expression and then substituting eq.8 and eq.3 into the result:

$$\frac{dD_a}{dt} = \frac{dD_a}{d\left(\frac{n}{N}\right)}\frac{d\left(\frac{n}{N}\right)}{dt} = \frac{D_0}{e^{-\frac{D_a}{D_0}}}\left[\frac{\dot{D}}{D_0} - \left(\frac{\dot{D}}{D_0} + \frac{1}{\tau}\right)\frac{n}{N}\right] = \left[e^{\frac{D_a}{D_0}}\dot{D} - \left(\dot{D} + D_0\frac{1}{\tau}\right)\left(e^{\frac{D_a}{D_0}} - 1\right)\right]$$

6

Rearranging the above expression gives:

$$\frac{dD_a}{dt} = \dot{D} - \frac{D_0}{\tau}\left(e^{\frac{D_a}{D_0}} - 1\right)$$ (eq. 11)

Numerical integration of eq. 8 and eq. 11 can yield the trapped charges concentration ($\frac{n}{N}$) and apparent dose

(D_a) or apparent age (t_a) as a function of temperature, which are explored in the next section. It is noted that τ

is a function of temperature in eq.9, which means that, apart from a cooling process with a single cooling rate,

eq.11can be applied to different processes with a known function of changing temperature T(t).

4.   Numerical simulation results

In thermochronological studies, one of the most straightforward methods to extract information on

cooling rate is to construct the relationship between the apparent age (A) and temperature (T) for a variety of

cooling rates (referred to as 'A-T plot' here) (e.g. Grün et al., 1999).The cooling rate is determined from the

apparent age (t_a) and the present temperature (T_p) of samples in the A-T plot. The A-T plot can be constructed

based on Eq.11, provided that all parameters ($\dot{D}$, D_0 and τ) are known. The values of $\dot{D}$ and D_0 can be

measured using the samples studied. The lifetime (τ) is based on the activation energy (E) and frequency

factor (s), which can be determined by various methods in kinetic studies, e.g pulse annealing and isothermal

tests on the samples examined (e.g. Li and Chen, 2001; Li et al., 1997; Murray and Wintle, 1999). Since

different samples from different geological settings may have different dose rates and different luminescence

characterisitics (or different E, s, D_0 values), it expected that there may be different A-T plots for different

samples.

Fig. 2a shows the fraction of trapped charges as a function of temperature for a variety of cooling rates

based on eq. 8 and eq. 11 for a virtual 'quartz' with the parameters: E=1.6 eV, s=1x10^{13} s^{-1}, $\dot{D}$=3 Gy/ka and

D_0=200 Gy. It is noted that these parameters may vary from sample to sample and one needs to measure and

determine the true values based on the samples studied. It is shown in Fig.2a that the traps remain nearly

empty at temperatures higher than ~70 °C and they are not filled until the temperature drops below ~70 °C.

The rate of trapping filling is dependent on the cooling rate, e.g. a lower cooling rate results in saturation at a

higher temperature. For example, the traps are saturated at ~30 °C for a cooling rate of 10 °C/Ma or less,

7

whereas for a cooling rate of 1000 °C/Ma only ~50% of the total traps are filled even though the temperature has dropped to 0 °C. This result indicates that the early saturation of the luminescence signal may prevent the application to geological systems with lower cooling rates.

The plot of apparent ages versus environmental temperature (A-T plot) can be constructed by numerically integrating eq.11 for different cooling rates (Fig.2b). In Fig. 2b, the parameters used are the same as those in Fig. 2a. For a specific temperature, a lower cooling rate will yield a higher apparent age. Although Fig.2b shows, theoretically, the apparent age up to 500 ka, this cannot be achieved in practice because of the early saturation of the quartz OSL, especially for low cooling rates (Fig. 2a). If the maximum dose which can be measured accurately equals $2D_0$ (Wintle and Murray, 2006), the maximum age experimentally obtainable is about 133 ka for a dose rate of 3 Gy/ka. This suggests that only the data inside of the shaded area of Fig. 2b can be experimentally obtained. As a result, unless the present temperature of the sample is exceptionally high (e.g. >30 °C), the exact information for low cooling rates may not be revealed using quartz OSL dating; only the maximum cooling rate is given. For example, if the present temperature of the sample is ~ 0 °C, one cannot effectively distinguish the cooling rate lower than ~300 °C/Ma, according to Fig. 2b. Hence the capacity of OSL-thermochronology to reconstruct cooling rate is strongly dependent on the saturation dose, D_0.

The effect of the saturation dose was further investigated in Fig. 3a and 3b, in which the results based on D_0 values of 500 Gy and infinity (or no saturation) are shown, respectively. For the D_0 value of 500 Gy, a maximum age that is experimentally measurable (within $2D_0$) is about 333 ka for a dose rate of 3 Gy/ka (see the shaded area in Fig. 3a). Hence, compared with the results of D_0=200 Gy in Fig. 2b, the capacity to reconstruct cooling rate is significantly improved for a higher D_0. For example, for a present temperature of ~ 0 °C, a cooling rate as low as ~120 °C/Ma can be distinguished (Fig. 3a). It obvious that no limitation is present for an infinitely large D_0 value ($D_0 \rightarrow \infty$) (Fig. 3b), and all cooling rates can be effectively distinguished since there is no age limit in this case. The case in Fig. 3b is not applicable in luminescence-thermochronology, and is only applicable in the case of an isotopic decay system where no saturation in the concentration of the daughter isotopes is expected.

From eq.11 we see that the apparent age or D_e is not only dependent on the saturation dose (D_0) but also dependent on the dose rate $\dot{D}$. The effect of dose rate on the thermochronology was also investigated. Fig. 4a

and 4b show the apparent ages obtained by assuming dose rates of 1 Gy/ka and 5 Gy/ka, respectively. According to the $2D_0$ rule (here D_0 is 200 Gy), the maximum ages that can be experimentally obtained are 400 ka and 80 ka for the two conditions, respectively (see the shaded regions in Fig. 4a and 4b). It is shown that, for a present temperature of ~0 °C, it is possible to distinguish a cooling rate at or higher than100 °C/Ma for a dose rate of 1 Gy/ka (Fig. 4a), while only a cooling rate higher than 500 °C/Ma can be distinguished for a dose rate of 5 Gy/ka (Fig. 4b). Therefore, the application of luminescence-thermochronology is also strongly controlled by the environmental dose rate.

It has been demonstrated that the concept of closure temperature offers a simple mean to determine the cooling age for luminescence-thermochronology (Herman et al., 2010). The effect of the saturation in luminescence to thermochronology and the application of the closure temperature are investigated. Fig 5 shows the apparent ages changes with time obtained using eq.11, assuming a saturation dose of D_0=200 Gy, and those based on closure temperature model for different cooling rates. It is shown that a large deviation is observed between the closure temperature model and the expectation for low cooling rates (<200 °C/Ma). The obtained slopes based on the concept of closure temperature are generally larger than that based on eq.11, especially for lower cooling rates. Such difference decreases and a consistent slope at low temperatures was obtained for higher cooling rates (>200 °C/Ma). The results of Fig.5 suggest that, under the condition of fast cooling and low present temperatures (T_p), the concept of closure temperature offers a simple mean to determine the cooling age using luminescence-thermochronology. However, significant errors may be introduced for the cases of slow cooling and high present temperatures.

5. Discussions and conclusions

New formula and method are presented to calculate the relationship between apparent age and temperature when luminescence dating techniques are used to study the thermal history of rocks or minerals. Given the similar principle and kinetic processes involved in the ESR dating technique, these formulas are expected to be equally applied to the ESR thermochronology. Our results show that the saturation of luminescence signals may cause limitation on its application in thermochronology. Such limitation becomes significant for low cooling rates and high environmental dose rates. We also show that the concept of closure temperature proposed by Dodson (1973) may not be simply adopted into luminescence thermochronology, especially for low cooling rates and high environmental dose rate, because of the saturation effect in

luminescence. For the case of non-first-order kinetics, the closure temperature should be avoided, but instead, an age-temperature (A-T) plot should be used for determining the cooling rate.

The extensively studied main OSL signal from quartz, e.g. the rapid bleaching component associated with the 325 °C TL peak (e.g. Franklin et al., 1995; Jain et al., 2003), provides a promising candidate for thermochronological studies (Herman et al., 2010). There are several advantages for using the main OSL signal from quartz. Firstly, it has been shown that it is mainly associated with a single group of traps (e.g. Li and Chen, 2001; Murray and Wintle, 1999). Secondly, the thermal behaviour of the main OSL signal of quartz usually follows the first-order kinetics and its kinetic parameters have been well studied (e.g. Spooner and Questiaux, 2001; Li and Chen, 2001; Murray and Wintle, 1999; Singarayer and Bailey, 2003). Thirdly, the quartz OSL traps are deep (E=~1.6 eV) and hence sufficiently stable so that it can be applied to a time scale beyond ~100 ka. Finally, the single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000) was developed using quartz OSL signal, which allows an accurate determination of apparent age. However, the main OSL signal from quartz usually gets saturated at a low level of radiation dose (~300-400 Gy or even lower), which largely limits its application in thermochronology. We show in Fig. 2 that the low cooling rates may not be revealed using the main quartz OSL signal because of its early saturation. Further extension of the scope of quartz OSL-thermochronology can be achieved using high-saturation signals (Fig. 3), such as thermally-transferred OSL (Wang et al., 2006) and isothermal TL (ITL) (e.g. Buylaert et al., 2006).

In light of our results, a promising candidate in luminescence thermochronology is feldspar. Photostimulation of feldspars can be achieved using both visible and infrared wavelengths (Hütt et al., 1988). The IRSL signal from feldspars is particularly useful for dating because it has several advantages over the OSL signal of quartz. Firstly, it is commonly observed that the IRSL signal from feldspar does not saturate until much higher doses than those found for the quartz OSL signal; thus it has the potential for extending the time frame for thermo-chronology. We show that revealing the cooling history of a geological system at low cooling rates using quartz OSL is largely limited by its early saturation characteristics (Fig. 3). The high saturation dose (>~1000 Gy, e.g. Li and Li (2011a)) of feldspar IRSL makes it a better thermochronological tool than quartz OSL to study slowly cooling systems. A second advantage of feldspar over quartz is that, when using appropriate filters to reject the stimulation light in each case, the feldspar IRSL signals are usually much brighter than the quartz OSL signal; this enables high precision luminescence measurements to be made (Li et al., 2007). This may lead to a higher reproducibility in the natural dose measurements using feldspar

than using quartz OSL. It is thus expected that a more precise result on cooling rates can be obtained using feldspar, provided that the thermal kinetic process in feldspar is appropriately modelled.

Although dating feldspar has been hampered by the anomalous fading effect of IRSL signal from feldspar, i.e. the leakage of electrons from traps at a much faster rate than would be expected from kinetic considerations, has hampered the application of feldspar in optical dating (e.g. Huntley and Lamothe, 2001; Huntley and Lian, 2006; Li et al., 2007), recent progress in understanding anomalous fading of the trapped charges related to the IRSL signals in K-feldspar, has raised the prospect of isolating a non-fading IRSL component for the dating feldspars. This can be achieved using a post-IR IRSL (or pIRIR) signal at an elevated temperature (>200°C) (Thomsen et al., 2008; Thiel et al., 2011), or using a multiple elevated temperature (MET) stimulation procedure, the so-called MET-pIRIR protocol (Li and Li, 2011a). Furthermore, the pIRIR and the MET-pIRIR signals from feldspars have been found to be thermally stable up to 400 °C in pulse annealing tests (e.g. Li and Li, 2011b; Thomsen et al., 2011), suggesting that these signals are more thermally stable than the quartz OSL. It is thus expected that the closure temperature of feldspar IRSL is higher than that of quartz OSL. However, the thermal kinetic process involved in the electron trapping and escaping in feldspar is far more complicated than the process in quartz, because of the presence of band-tail states and excited states (Poolton et al., 2002, 2009; Jain and Ankjaergaard, 2011; Li and Li, submitted). Therefore, the formula presented in this study should only be applied to the luminescence signals obeying a first-order kinetics, e.g. quartz OSL. However, extension of the results for this study to a general-order kinetics can be obtained by replacing eq.1 with a corresponding general-order equation, provided that the kinetic order is known. For feldspars, it was shown that the charge recombination via band-tail states may result in underestimation of the activation energy of the IRSL trap when a first-order kinetics is assumed (Li and Li, submitted). Therefore, further integration of the process of charge movements via band-tail states and tunnelling into the model is required before its full potential in luminescence thermochonology is discovered.

Another potential candidate is the TL signals from quartz and feldspar. By definition, TL is thermally sensitive, and it is usually observed by heating the sample from a low temperature (e.g. ~20°C) to a high temperature (e.g. ~500°C) in a constant heating rate (e.g. 3°C/s). During the heating, one or more TL peaks may be observed, and different peak temperatures indicate different thermal stabilities. There are comprehensive studies on the kinetics and trap parameters associated with different TL peaks for quartz and feldspar (Chen and McKeewer 1997). If the TL peaks can be separated either mathematically or

experimentally, each of the TL peak will provide a thermometer. Hence, multiple thermometers can be obtained by analysing the TL glowcurves from a single mineral (e.g. quartz or feldspar). These thermometers record the same thermal history of the sample but in a different time scale, which may provide a higher resolution or multi-stage information in revealing the thermal history. The potential of TL signals in thermochronology needs to be explored further.

In conclusion, luminescence techniques have a large potential in low-temperature (<100 °C) thermochronology. However, the application of the techniques is largely limited by the saturation characteristics of the signals used, and extension of its geological application relies on more methodological studies which focus on seeking for signals that have higher saturation doses (D_0) and detailed modelling of the thermal kinetic process for these signals. A multi-thermometers using different luminescence signals from the same mineral or different minerals from the same rock may be possible.

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Figure captions:

Figure 1: The changes of apparent age with time at different environmental temperatures. The plot was produced based on eq.7 and by assuming E=1.6 eV, s=1x10^{13} s^{-1}, $\dot{D}$=3 Gy/ka and D$_0$=200 Gy, respectively.

Figure 2: (a) The fraction of trapped charges (n/N) as a function of temperature for a variety of cooling rates based on numerical integral of eq. 8 and assuming E=1.6 eV, s=1x10^{13} s^{-1}, $\dot{D}$=3 Gy/ka and D$_0$=200 Gy, respectively. (b) The apparent age as a function of temperature for a variety of cooling rates based on numerical integral of eq. 11 using the same parameters as Fig. 2a. The shading area shows the region in which a reasonable age can be obtained for the 'sample' used, i.e. the maximum dose that can be measured is within 2D$_0$, which corresponding to a maximum age of ~133 ka for a dose rate of 3 Gy/ka.

Figure 3: The apparent age as a function of temperature for a variety of cooling rates based on numerical integral of eq. 11 based on D$_0$ values of 500 Gy (a) and infinity (b), respectively. The other parameters used are E=1.6 eV, s=1x10^{13} s^{-1} and $\dot{D}$=3 Gy/ka for both (a) and (b). The shading area in (a) shows the region that experimental data can be obtained based on the 2D$_0$ rule (see text for explanation).

Figure 4: The apparent age as a function of temperature for a variety of cooling rates based on numerical integral of eq. 11 based on dose rates ($\dot{D}$) of 1 Gy/ka (a) and 5 Gy/ka (b), respectively. The other parameters used are E=1.6 eV, s=1x10^{13} s^{-1} and D$_0$=200 Gy/ka for both (a) and (b). The shading area in (a) and (b) shows the regions that experimental data can be obtained according to the 2D$_0$ rule (see text for explanation).

Figure 5: The apparent ages based on the closure temperature model (Dodson, 1973) (dashed line) compared with those obtained using eq.11 assuming a saturation dose of D$_0$=200 Gy (full line).The other parameters used are the same as those used in Fig.2 (E=1.6 eV, s=1x10^{13} s^{-1}, $\dot{D}$=3 Gy/ka and D$_0$=200 Gy).
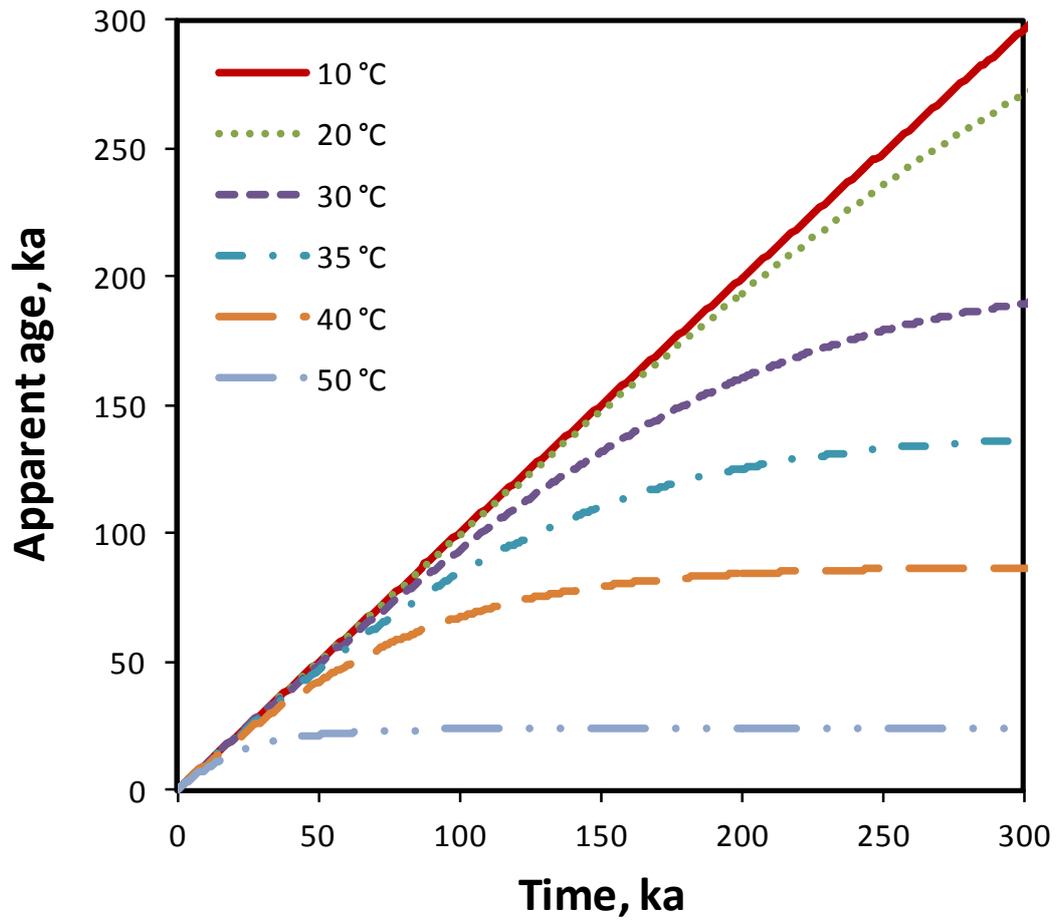
Figure 1

Figure 2
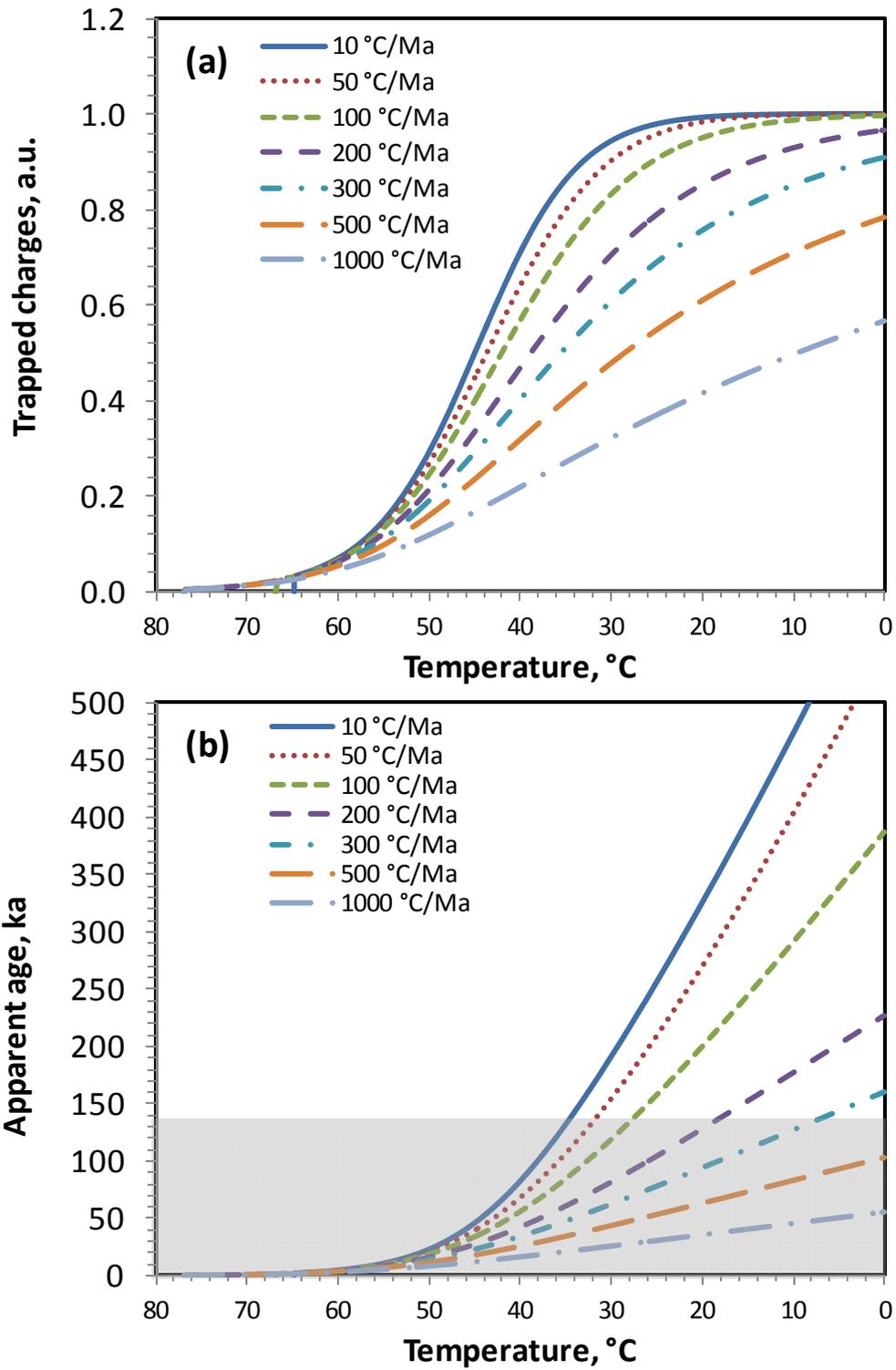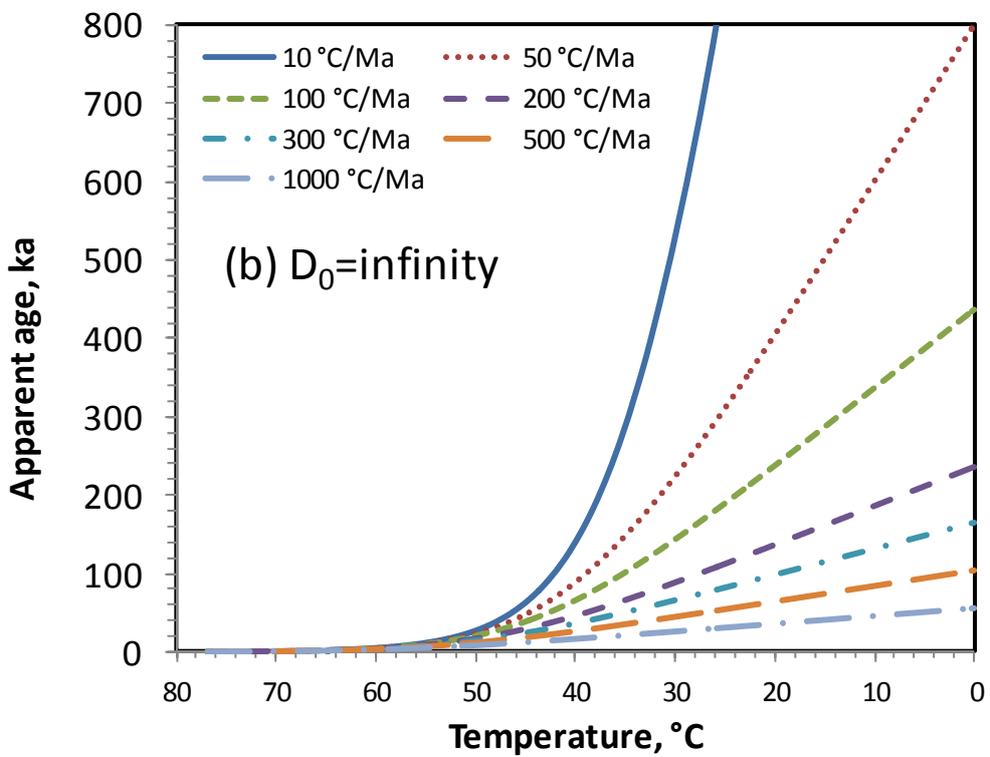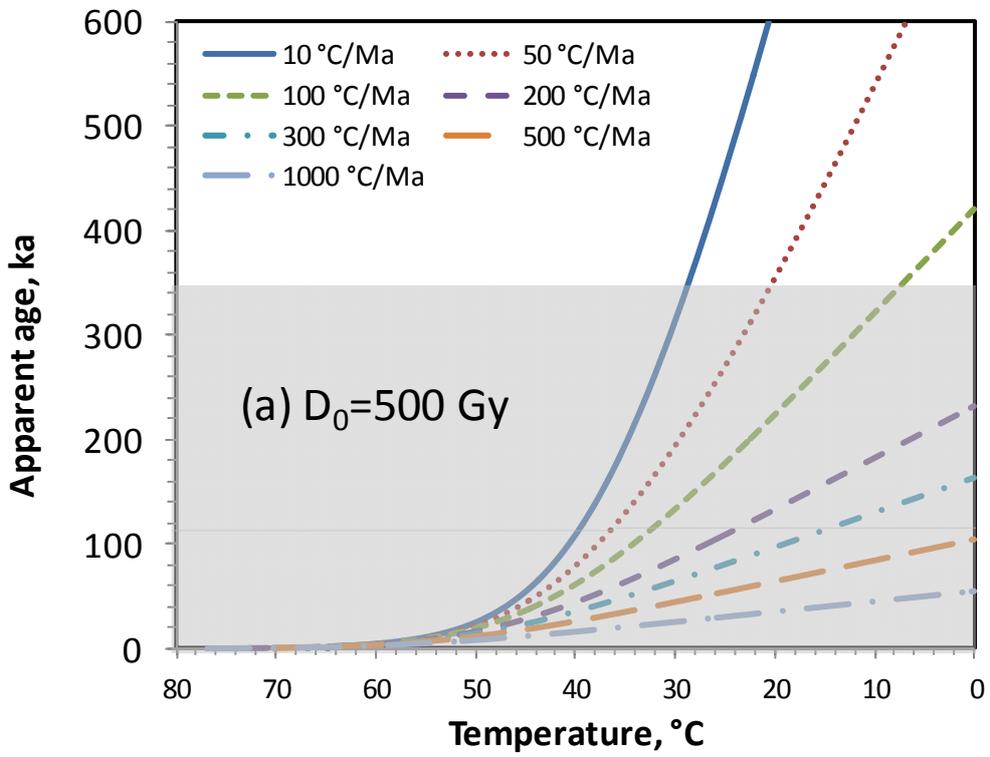
Figure 3

Figure 4

Figure 5