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Quantifying the effect of recent relief changes on age–elevation relationships

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Abstract

The effect that recent relief changes may have on the distribution of rock ages with elevation is investigated for a range of thermochronometers. From the solution of the heat transport equation in a crustal block undergoing uplift and surface erosion, the temperature history of rock particles that are exhumed at the Earth's surface today is computed. These *T-t* paths are then used to calculate apparent isotopic ages for the (U–Th)/He system in apatite, characterized by a low ($\approx$70°C) closure temperature. The results show that recent relief changes strongly affect the distribution of ages with elevation (notably the slope of the age–elevation relationship). The calculations presented here predict that, in most situations, regions that have undergone a steady decrease in surface relief in the recent past should be characterized by an inverted age–elevation relationship, that is older ages should be found near valley bottoms and younger ages near summit tops. It is also shown how the wavelength of the topography, the geothermal gradient, the exhumation rate and the duration of the relief reduction event affect this result. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: age; altitude; topography; relief; Th/U; U/He; absolute ages; numerical models; thermochronology

1. Introduction

Regions of past or present tectonic uplift are subject to more or less rapid erosion. This leads to rock exhumation and cooling. This cooling has been documented by thermochronometry, from estimates of the time at which a given mineral has passed through a given temperature (called the closure temperature of the chronometer). As shown by many authors [1,2] and illustrated in Fig. 1a, rocks that are exhumed near a mountain top have cooled through the closure temperature before rocks that are exhumed near the bottom of a valley. The difference in time is greater for high temperature systems (Fig. 1a) than for low temperature ones (Fig. 1b). This is because the thermal perturbation caused by a finite surface topography decreases exponentially with depth [3]. The amplitude of this perturbation can be parameterized by the vertical deflection of the closure temperature isotherm relative to the amplitude of the surface topography. As shown in Fig. 1b, we call this ratio α. Deep within the crust, isotherms are not affected by surface topography and $\alpha = 0$; in

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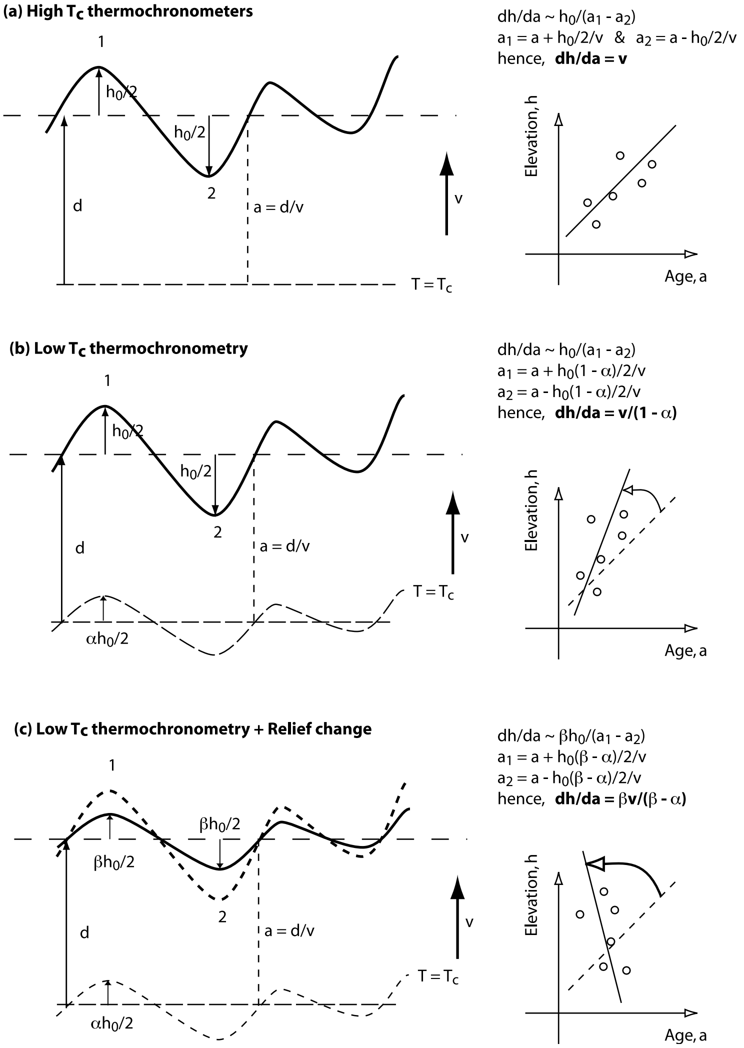

Fig. 1. Three scenarios in which exhumation rate can be estimated from the slope of an AER. (a) High-T thermochronometers, the slope is equal to the exhumation rate. (b) Low-T thermochronometers, the slope overestimates the exhumation rate. (c) A decrease in relief leads to a further overestimate of the exhumation rate from the AER. A large decrease in relief can even lead to a negative slope.

the vicinity of the surface, the isotherm follows exactly the surface topography and $\alpha = 1$.

Consequently, in an actively uplifting and eroding area characterized by a finite topography, there should be a well-defined relationship between height and apparent age for any thermochronometer [1]. In slowly eroding areas and/or for high closure temperature chronometers ($\alpha \approx 0$), the slope of this relationship is equal to the exhumation rate. In rapidly eroding environments or for thermochronometers characterized by a low closure temperature ($0 < \alpha < 1$), the closure temperature isotherm is perturbed by the surface topography and the slope of the age–elevation relationship (AER) gives an overestimate of the real exhumation rate [4].

This point is illustrated in Fig. 2 where fission track age–elevation data from the Huayna Potosi Pluton (Bolivian Andes) are shown. One set of ages comes from fission track analysis of apatite

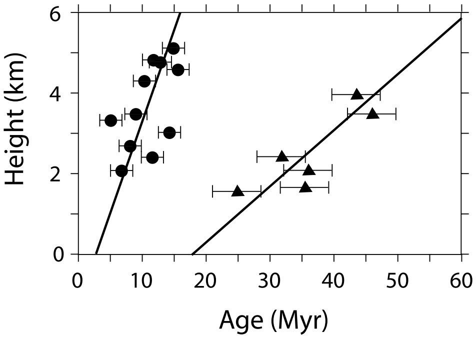

Fig. 2. Fission track ages from the Huayna Potosi Pluton (Bolivian Andes) from [6]. Circles correspond to apatite FT ages, triangles are zircon FT ages.

(circles) which has a closure temperature of ≈115°C, the other comes from FT analysis of zircon (triangles) which has a closure temperature of ≈250°C. The slope of the AER is significantly greater for the apatite ages compared to the zircon dataset. Neglecting the effect of the finite amplitude topography on the underlying temperature field, one would predict that the exhumation rate has significantly increased from 0.15 km Myr^{-1} to 2.2 km Myr^{-1} between the time the rocks cooled through the 250°C isotherm, i.e. 25–45 Myr ago, and the time they cooled through the 115°C isotherm, i.e. 6–16 Myr ago. Conversely, this dataset can also be interpreted as evidence for steady exhumation at 0.1–0.2 km Myr^{-1} during the past 45 Myr. In this scenario, the difference in slope between the two age–elevation datasets is a direct consequence of the thermal perturbation caused by the finite amplitude topography, which is significantly larger at depths of 1–2 km (where the apatite FT ages were set) than at depths of 5–6 km (where the zircon FT ages were set).

AERs have been documented in a large number of tectonically active areas such as the European Alps [5], the Andes [6], Alaska [7], and the Southern Alps of New Zealand [8], as well as in regions of past tectonic activity such as the Transantarctic Mountains [1], the Sierra Nevada [9] or Southeastern Australia [10]. In all areas, age increases with elevation, as predicted by the so-called 'thermal topography' argument described above.

The argument relating the slope of an AER to exhumation rate is based, however, on the assumption that surface topography does not evolve with time. As illustrated in Fig. 1c, it is clear that recent changes in surface relief amplitude (i.e. that took place since the rocks cooled through the closure temperature) have a strong effect on the slope of the AER. We assume that local changes in relief amplitude can be represented by a single parameter, β, defined as the ratio of present-day relief to past relief, i.e. at a time defined by the 'mean age' of rocks for a given thermochronometer. Our purpose here is to investigate whether AERs can provide information on the current rate of change of surface relief, especially for the newly developed thermochronometer (U–Th)/He in apatite, which, because of its low closure temperature, is regarded by many as the most likely candidate among the various thermochronometric systems to provide constraints on the rate at which surface processes are able to respond to more or less rapid changes in tectonic and/or climatic environment [11].

Many questions have recently been raised relating tectonics, relief and climate. For example, the current debate on the effect of Cenozoic climate change on the recent evolution of the Earth's surface relief remains clearly open. Molnar and England [12] and, more recently, Peizhen et al. [13] have argued that the rapid cooling experienced by the Earth's atmosphere over the last 2–3 Myr has been accompanied by increased erosion rates and a net increase in topographic relief, especially in large tectonically active areas such as the Himalayas and the Andes. According to Molnar and England [12], this relief production has led to uplift of mountain peaks by isostatic compensation and may have, therefore, caused, or at least enhanced, the climate shift by promoting precipitation. The debate is whether this feedback mechanism exists. Some have produced arguments based on geomorphological considerations [14,15] that increased precipitation and/or a cooler climate should lead to a reduction (or, at most, a very small increase) in topographic relief; others have provided direct evidence, from cosmogenic radionuclide concentrations in the Sierra Nevada, that, locally, relief has increased in the last 3 Myr [16] but that, because of the small lateral extent of many mountain ranges, this has not led to substantial isostatically induced peak uplift. Other thermochronological data [17] indicate that the Sierra Nevada was characterized by substantial and probably much greater surface relief some 60–80 Myr ago and that the area has experienced a net decrease in relief since [17]. That different datasets/methods provide support to apparently conflicting opinions on the evolution of surface relief suggests that a better understanding of how surface topography influences thermochronometric data is needed.

Here the evolution of the temperature beneath an evolving, finite amplitude surface topography is computed, from which synthetic AERs can be derived. To achieve this, a newly developed numerical method to solve the basic partial differential equation governing heat transfer in the crust is used [18]. AERs are predicted for a range of parameter values representing different initial conditions (geothermal gradient), tectonic situations (rate of exhumation) and landforms (wavelength and rate of change of the surface topography).

2. Relief change and AER

The main purpose of the work presented here is to determine how finite amplitude topography and changes in surface relief affect the temperature distribution in the underlying crust, and how this information can be retrieved from AERs obtained for low temperature thermochronometers such as (U–Th)/He in apatite. To achieve this, the transient, two-dimensional heat transfer equation is solved, which may be written as [19]:

$$\rho c\left(\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial z}\right)=\frac{\partial}{\partial x}k\frac{\partial T}{\partial x}+\frac{\partial}{\partial z}k\frac{\partial T}{\partial z}+\rho A \quad (1)$$

where $T(x,z,t)$ is the temperature, ρ is rock density, c is heat capacity, v is the vertical velocity of rocks with respect to the base of the crust/lithosphere ($z=-L$), k is conductivity and A is radioactive heat production. This equation must be solved for a given initial temperature distribution:

$$T_0 = T_0(x,z,t=0) \quad (2)$$

and a set of boundary conditions:

$$T(x,z=-L,t)=T_1 \quad (3)$$

$$T(x,z=S(x,t),t)=0 \quad (4)$$

$$\frac{\partial T}{\partial n}=0 \text{ along the side boundaries} \quad (5)$$

A finite element code (**Pecube**) was recently developed to solve this equation, including the variable geometry boundary conditions [18]. It is used here to solve a simple two-dimensional problem in which the initial surface topography is assumed to be a periodic function (of given wavelength λ and amplitude h_0) of horizontal distance x, and is imposed to grow or decrease in amplitude in the recent past (i.e., over a period δ). The wavelength and shape of the topography is assumed to remain constant, i.e. valleys and interfluves are regarded as 'static' features that do not move with respect to each other. It is assumed that, over a relatively longer period, t_m, the crust has experienced tectonic uplift balanced by erosion, leading to a mean exhumation rate v. The value of t_m is chosen to ensure that rocks that reach the surface at the end of the numerical experiment were originally at a temperature of at least 300°C, for the imposed basal temperature of 1000°C at a depth L.

At first, to demonstrate how the slope of AERs is affected by relative relief change, a series of three experiments was performed in which the relief is assumed to remain constant at $h_0 = 2$ km (Expt. 1), the relief increases from 1 to 2 km (Expt. 2) and decreases from 4 to 2 km (Expt. 3), respectively, over the last $\delta = 10$ Myr of the experiment. The initial and final topographies have a wavelength of $\lambda = 50$ km. The exhumation rate (v) is set to 0.3 km Myr^{-1} and $t_m = 100$ Myr. Because crustal heat production by radiogenic elements is neglected, the depth to the 1000°C isotherm is fixed at $L = 50$ km in such a way that the initial, conductive temperature distribution is characterized by a linear, geothermal gradient of 20°C km^{-1}. For each experiment, **Pecube** computes the temperature experienced through time by each rock particle that is ex-

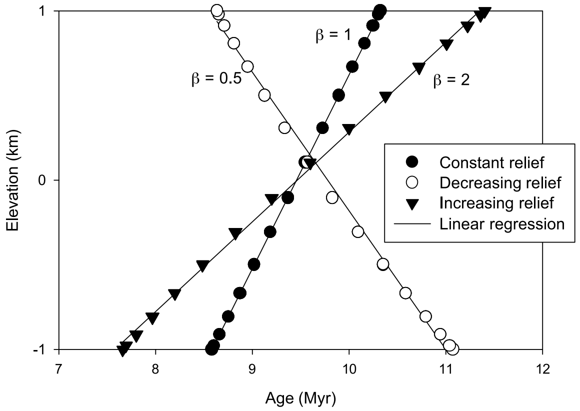

Fig. 3. Predicted (U–Th)/He AERs for a range of relief evolution scenarios.

humed at the surface of the model at the end of the experiment. From these *T-t* paths, synthetic (U–Th)/He apatite ages are computed, following the procedure given in Wolf et al. [20] and Farley [21]. A frequency factor (D_0/a^2) of 50.1×10^6 s^{-1} and activation energy (E_a) of 151.5×10^3 kJ mol^{-1} are used. The results are shown in Fig. 3.

2.1. *Constant relief amplitude*

In all experiments, the model calculations show a linear relationship between (U–Th)/He ages and elevation (height) (Fig. 3). As stated earlier, this relationship is termed an age–elevation relationship or AER. In the first experiment, where the relief does not change with time, the slope of the AER is 1.14 km Myr^{-1} whereas the imposed exhumation rate is only 0.3 km Myr^{-1}. As shown in Fig. 4a, the 75°C isotherm (corresponding, approximately, to the closure temperature for (U–Th)/He in apatite) has been strongly deformed by the presence of the finite amplitude topography. As demonstrated by Stüwe et al. [4] and illustrated in Fig. 1b, this is the reason why the slope of the apparent AER provides an overestimate of the exhumation rate. Note that similar synthetic AERs can be constructed from the computed *T-t* paths for a range of thermochronometers. As expected, the results indicate that the apparent exhumation rate derived from the slope of the AER decreases with increasing closure temperature. For example, for the fission track chronometer (closure temperature of ≈115°C), the predicted apparent exhumation rate is 0.77 km Myr^{-1}, whereas for K–Ar in biotite (closure temperature of 300°C) and muscovite (closure temperature of 340°C), the apparent exhumation rate is 0.395 and 0.444 km Myr^{-1}, respectively.

Our first conclusion is thus that the shape of the 75°C isotherm is affected by the presence of finite amplitude topography at the Earth's surface and, therefore, that, even in regions characterized by low exhumation rate (300 m Myr^{-1} in our experiment), the slope of an AER derived from (U–Th)/He dating in apatite always overestimates the real exhumation rate. As demonstrated in previous work [4], the slope of an AER obtained from a higher temperature thermochronometer provides a more accurate estimate of exhumation rate.

2.2. *Varying relief amplitude*

If, as in the second experiment, the relief is set to increase from 1 to 2 km over the last 10 Myr of the experiment, the slope of the AER decreases to predict an apparent exhumation rate of 0.53 km Myr^{-1} (Fig. 3). Note that relief change is imposed with respect to mean elevation, i.e. exhumation is decreased along ridge tops and increased in valley bottoms. Conversely, if, as in the third experiment, the amplitude of the relief is set to decrease linearly from 4 to 2 km over the same 10 Myr time interval, the slope of the AER is inverted, with the youngest ages observed at the ridge peaks and the oldest ages in the valley bottoms (Fig. 3). The mechanism responsible for these important changes in the slope of the AER is described in Fig. 1c where the present-day surface relief is assumed to be smaller than it was when the rocks now at the surface crossed the closure temperature isotherm (a situation similar to that of Expt. 3). For the rocks that will be collected at the top of ridges, relief reduction leads to a shortening of the distance travelled between the time the rocks crossed the closure temperature and the time they reached the surface. Conversely, the rocks found at valley bottoms will see that distance increase (in comparison with the case where relief remains constant). This leads to a reduction

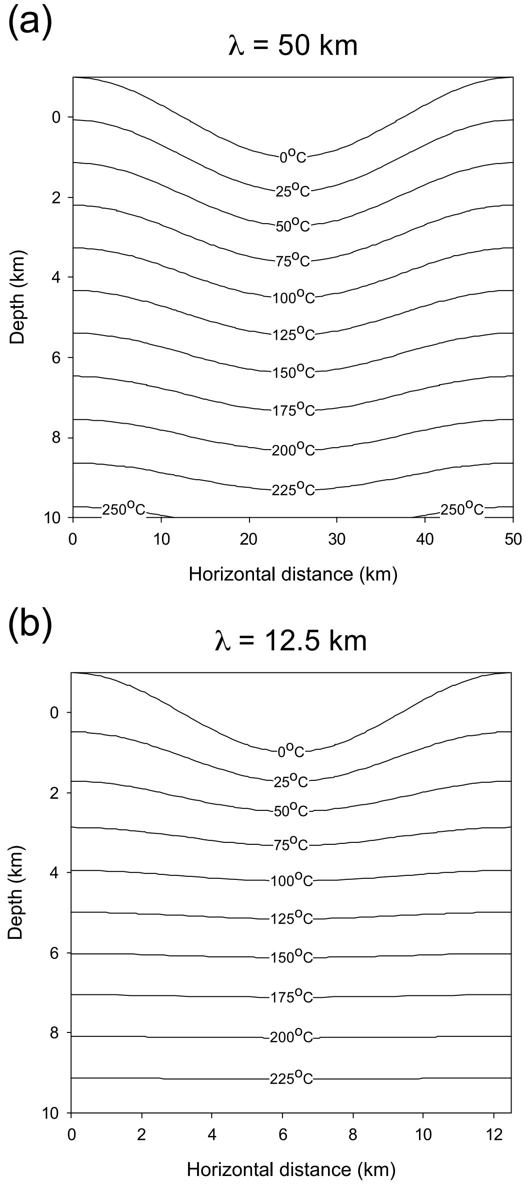

Fig. 4. (a) Computed temperature distribution in Expt. 1 where the wavelength of the relief, λ, is 50 km. Other parameter values are given in the text. All isotherms between 0 and 200°C are deflected in response to the finite surface topographic relief. (b) Temperature distribution for $\lambda = 12.5$ km; the finite surface topography affects only the temperature structure below 100°C.

in apparent age at the ridge tops and an increase in apparent age at the valley bottoms and, thus, a counter-clockwise rotation of the AER (and, potentially an inversion in slope). Our second conclusion is thus that the slope of an AER derived from (U–Th)/He apatite dating is strongly affected by relative relief changes.

2.3. *Effect of relief amplitude variations as a function of closure temperature*

To assess in more detail how AER slopes vary in response to relative changes in surface relief, a large number of numerical experiments were performed covering the full range of relative relief change from $\beta = 0.5$ (decrease by a factor of 2) to $\beta = 2$ (increase by a factor of 2). For each experiment, the slope of the AERs obtained for a range of closure temperatures (from 0 to 300°C) was computed. Note that in these plots the age estimates used to compute the slope of the AER correspond to the time the rock cooled through a given closure temperature; the effect of cooling rate or grain size on closure temperature [22] is not taken into account. The results are summa-

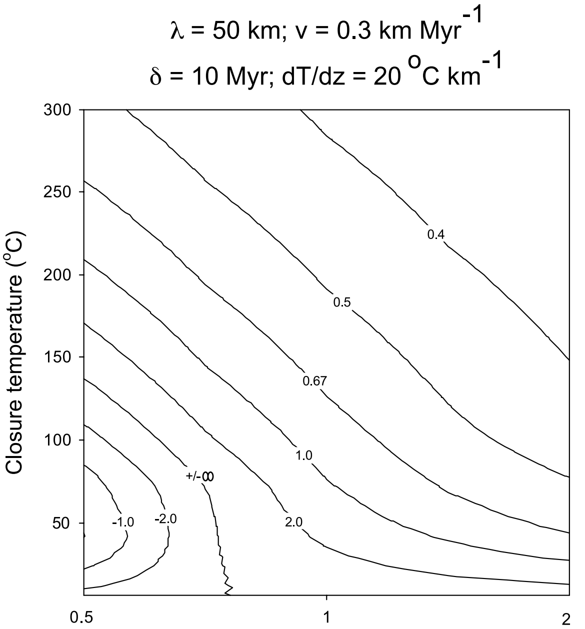

Fig. 5. Contours of the apparent exhumation rate (in km Myr^{-1}) derived from the slope of AERs computed for a range of closure temperatures. The 'real' (or imposed) exhumation rate is 0.3 km Myr^{-1}.

rized in Fig. 5 as a contour plot of the computed AER slope as a function of β, the relative relief change (ratio of present-day to past relief amplitude) and closure temperature. Note that all model parameters (apart from the initial relief) have similar values to those used in the first experiment.

The results indicate that AER slope is affected by any relative relief change for all thermochronometers characterized by a closure temperature below 300°C. For any thermochronometer, the slope increases when relief decreases, whereas the slope decreases when relief increases. Note, however, that comparing AERs obtained from two different thermochronometers cannot constrain the rate of relief evolution. Whether relief has recently increased ($\beta > 1$) or decreased ($\beta < 1$), the slope of the AER (or apparent exhumation rate) always increases with decreasing closure temperature (Fig. 5).

3. Sensitivity to model parameters

The variation of AER slope with relative relief change for a given closure temperature is also a function of the assumed model parameters. These include the wavelength of surface topography (λ), the exhumation rate (v), the average geothermal gradient (T/L) and the time scale of surface relief change (δ). To demonstrate this dependence, a number of sets of experiments were performed in which the amplitude of the relative change in relief, β, is systematically varied from 0.5 to 2. In each set, one model parameter has been modified from its 'reference' value, i.e. the value used in the reference set of experiments summarized in Fig. 5.

3.1. Timing of relief change timing

In Fig. 6 are shown the results of two sets of model runs which differ from the reference set by the timing of the imposed relative relief change. In Fig. 6a, results are shown for model runs in which the imposed relief change took place in the last 2 Myr; in Fig. 6b, the imposed relief change took place over the last 50 Myr. The model results show that perturbations to the slope of the AER caused by a change in relief amplitude are most important when those changes take place in the recent past. More generally, a given thermochronometer can only provide information on relief

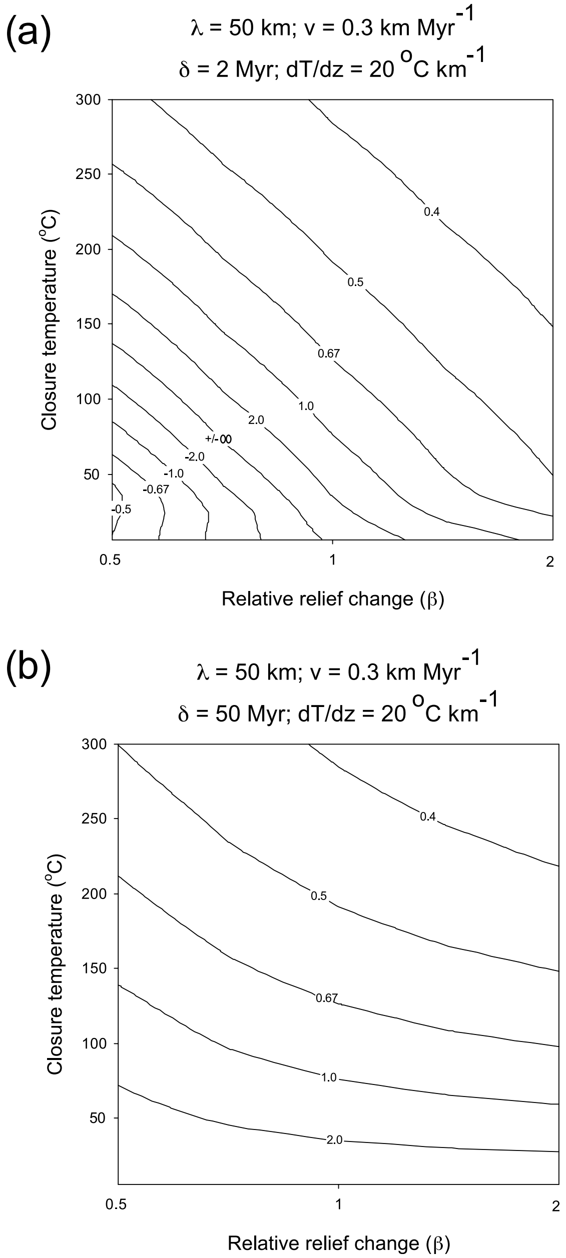

Fig. 6. Contours of the apparent exhumation rate derived from the slope of AERs computed for a range of closure temperatures. (a) The relief change takes place over the last 2 Myr and (b) 50 Myr.

change that took place since the rocks crossed the closure temperature, i.e. the time corresponding to the mean cooling age at the surface.

In tectonically active areas, where exhumation rates can be as high as 10–15 km Myr^{-1}, low-T thermochronometers provide information on very recent changes in surface morphology, like those that might have resulted from the recent transition from glacial to fluvial erosion in many high elevation, high latitude regions of the globe, such as the Andes or the Southern Alps of New Zealand. In these regions, high-T thermochronometers potentially provide information on the longer-term evolution of landform, including features such as the stability of deeply incised valleys.

In tectonically quiet regions, characterized by much lower exhumation rates, such as along a passive margin escarpment or within a past orogenic zone, low-T thermochronometers provide constraints on the long-term evolution of landform, such as the rate of escarpment retreat or the rate of decay of syn-orogenic, high relief, landforms. High-T thermochronometers are unlikely to provide useful information on surface topography evolution as, at low exhumation rate, rock ages were most likely set during the previous orogenic phase.

3.2. Mean exhumation rate

To determine the dependence of the system response to changes in mean exhumation rate, v, two sets of experiments were performed where v was set to 1 and 0.1 km Myr^{-1}, respectively. The results are summarized in Fig. 7.

In rapidly exhuming regions such as active convergent orogens, the isotherms are usually compressed near the surface due to the vertical advection of heat to form a thin thermal boundary layer. All ages, regardless of the closure temperature of the thermochronometer, are therefore relatively young. The thermal perturbation caused by the surface topography affects a greater range of isotherms [23] and the slope of AERs is always an overestimate of the real exhumation rate (Fig. 7a), regardless of the thermochronometer closure temperature. Because of the rapid advection of rock towards the surface, the effect of relief production on AER is enhanced whereas relief reduction does not perturb AERs to the same degree, i.e. AER slopes are not inverted fol-

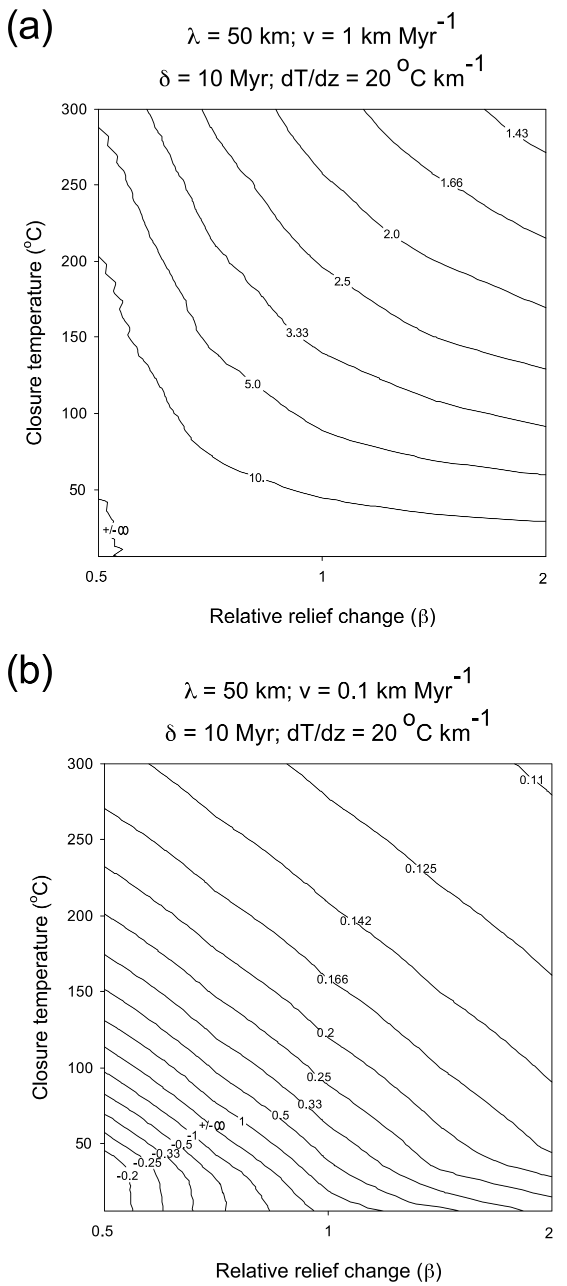

Fig. 7. Same as Fig. 5 but for (a) a faster exhumation rate of 1 km Myr^{-1} and (b) a slower exhumation rate of 0.1 km Myr^{-1}.

lowing a reduction of relief, even for thermochronometers with very low closure temperatures (Fig. 7a).

In slowly exhuming regions, such as mountain belts in their 'post-orogenic collapse phase' where uplift and exhumation are isostatically driven, the opposite is true: an increase in surface relief does not perturb the slope of AERs to the same degree as a decrease (Fig. 7b). Negative slope AERs are predicted for low-T thermochronometers (i.e. <75°C).

3.3. Geothermal gradient

In regions of high geothermal gradient, high-T isotherms are affected by the surface topography [4]. This is clearly shown in the results of another set of experiments in which the depth at which the temperature is fixed at 1000°C has been varied from 50 km to 25 km (Fig. 8a) and 100 km (Fig. 8b), corresponding to a geothermal gradient of 40°C km^{-1} and 10°C km^{-1}, respectively. In the high temperature gradient case (Fig. 8a), the slope of the AER is affected by relief change for all thermochronometers, even those characterized by a high closure temperature. In the low temperature gradient case (Fig. 8b), the low closure temperature thermochronometers only are affected. Note that, in both cases, the relationship between AER slope and relative relief change is almost identical to that shown in Fig. 5, corresponding to the 'reference' situation with a geothermal gradient of 20°C km^{-1}.

3.4. Surface topography wavelength

The thermal perturbation caused by finite amplitude surface topography decays with depth as the wavelength of topography [19]. This means that short wavelength topography (i.e. <10 km) does not significantly affect the distribution of ages with elevation for almost any thermochronometer. This is illustrated in Fig. 9 (top) where contour plots of the apparent exhumation rate (derived from the slope of the AER) are shown for a series of experiments performed with a short wavelength topography. For most chronometers characterized by closure temperatures above 50°C, the apparent exhumation rate is similar to the imposed value of 0.3 km Myr^{-1}.

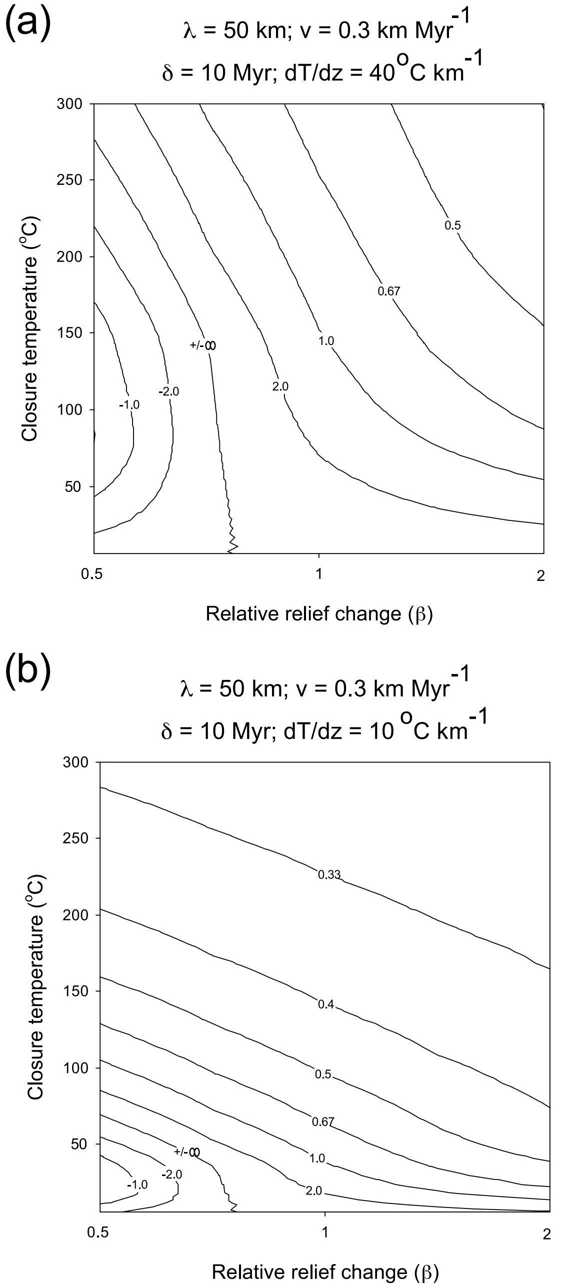

Fig. 8. Same as Fig. 5 but for (a) a higher geothermal gradient of 40°C km^{-1} and (b) a lower geothermal gradient of 10°C km^{-1}.

Conversely, large wavelength topography (i.e. >100 km) affects most thermochronometers.

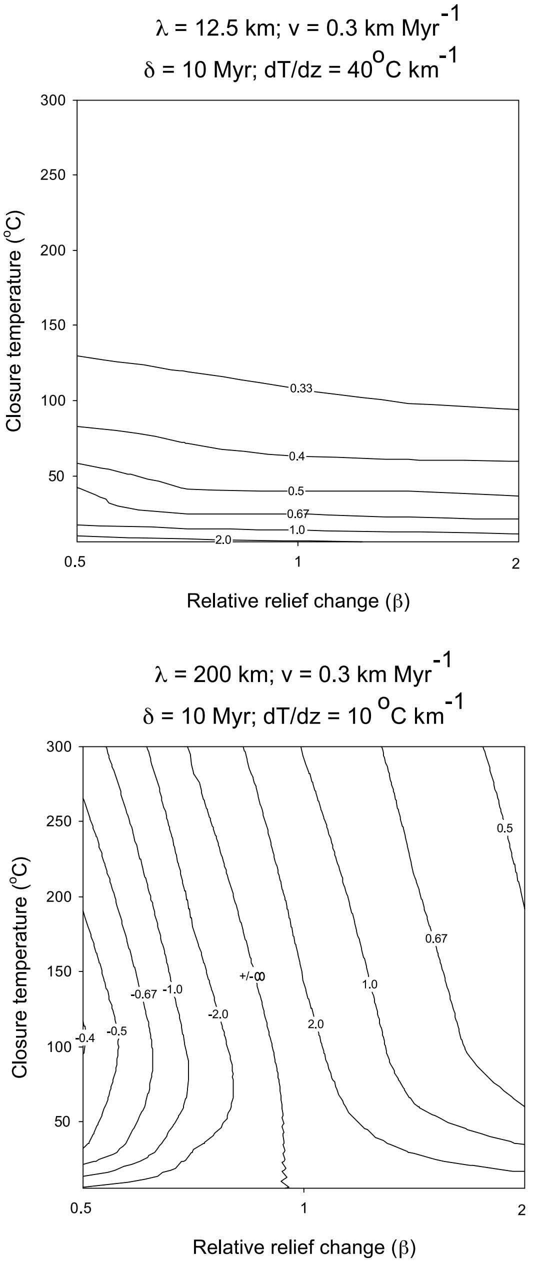

Fig. 9. Same as Fig. 5 but for (top) a smaller relief wavelength of 12.5 km and (bottom) a greater relief wavelength of 200 km.

This is shown in Fig. 9 (bottom), where contours of apparent exhumation rate are shown for a set of experiments in which the imposed surface topography has a wavelength of 200 km. In this case, all thermochronometers, including those characterized by high closure temperatures, such as K–Ar in muscovite, are affected by the surface topography and its changes.

4. Discussion

In this paper, a recently developed numerical method has been used to solve the heat transfer equation in the lithosphere undergoing uplift and erosion including the effects of a finite amplitude, time-varying surface topography. It is shown that the slope of AERs obtained by thermochronometry of rocks sampled in a region of finite relief is sensitive not only to the mean exhumation rate and the shape of the surface topography, but also to the rate of change of surface landform. This result demonstrates that low temperature thermochronometry has the potential to be a powerful tool to study the rate of landform evolution in a variety of tectonic and geomorphic environments.

It has also been shown how the dependence of AER slopes on relative relief changes is affected by the value of a range of parameter values, such as mean exhumation rate, geothermal gradient and the wavelength of topography. From the results presented here, an important question emerges: how can one use the model predictions to infer a relative change in relief from a thermochronological dataset, i.e. a ‘real’ set of ages obtained at a range of elevations? If one knows the dominant wavelength of surface topography, the exhumation rate, the geothermal gradient and the time scale of surface relief change, one can produce a contour map, similar to the one shown in Fig. 5 and extract from it a relative relief change based on the value of the observed AER for any given thermochronometer. In most cases, however, few of these parameters are known in a given study area and approximate values have to be used. This can lead to substantial error in estimating the relative relief change. As an example, bias in estimated exhumation rate can be very large as can be seen in Fig. 7. One could argue that an accurate estimate of exhumation rate can be obtained by considering age–elevation data for high temperature chronometers. In most cases (Figs. 7 and 8), one would obtain an accurate value by using an AER based on muscovite K–Ar ages (closure temperature > 300°C) for example, but in some cases (Fig. 9) it would not be sufficient. Note too that the higher the closure temperature, the 'older' the age. Consequently, high closure temperature systems can only provide us with estimates of exhumation rate averaged over relatively long periods of time.

A step towards the solution to this problem can be made by noting that, in almost all contour plots shown in Figs. 5–9, for closure temperatures above 50°C, all contour lines are parallel to each other, and dip approximately at 45°C. This means that, regardless of the value of the model parameters, AER slopes for all thermochronometers have the same sensitivity to a relative change in surface relief. There are two noticeable exceptions to this behaviour. Firstly, at high δ values and high exhumation rate (Figs. 6b and 7a), the contours are curved and become sub-horizontal at low closure temperatures. This is because, in those two sets of experiments, the mean cooling age obtained from the low-T thermochronometers becomes smaller than the time over which the imposed change in relief amplitude takes place. The reason for the curved contours is thus that a given thermochronometer can only be used to extract information about events that happened since the corresponding chronometric system closed (i.e. when the rocks cooled through the closure temperature).

The second exception corresponds to experiments where the wavelength of the topography has been varied (Fig. 9). For long wavelength topography, the contours are vertical; for short wavelength topography, the contours are horizontal. This means that the sensitivity of the AER slope to relative relief change is a strong function of the wavelength of topography. In other words, at short wavelengths, even large changes in surface relief have no effect on the slope of the AER (and this is true for all closure temperatures above 75°C), whereas, at long wavelengths, small changes in surface relief produce large changes in AER slope and these changes are the same for all thermochronometers (i.e. for all closure temperatures).

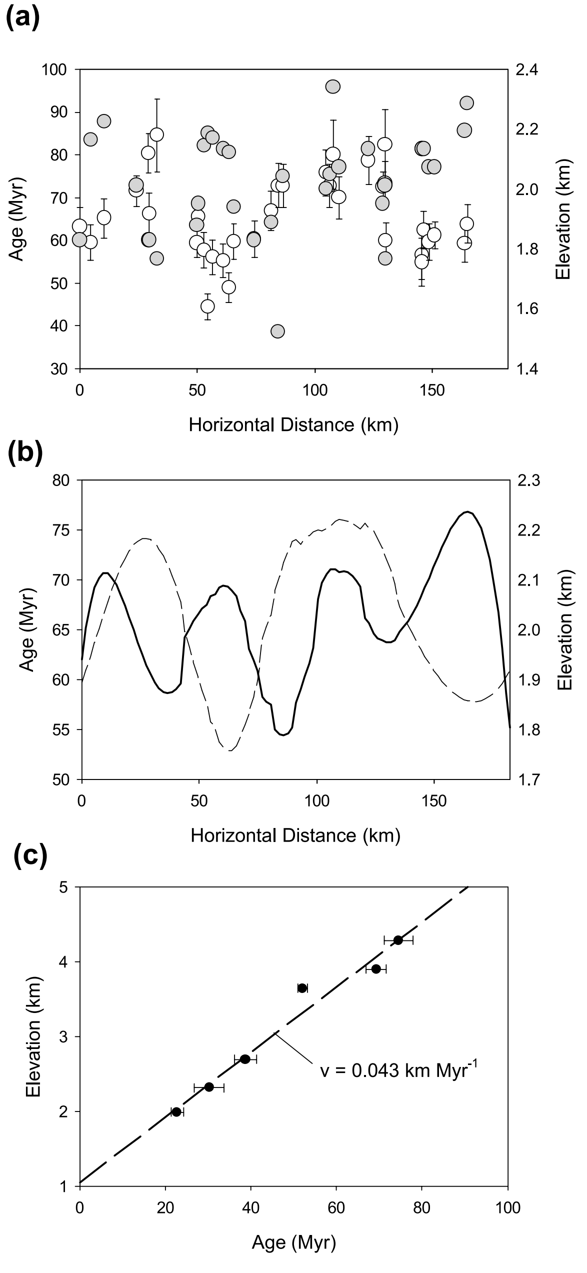

Fig. 10. (a) (U–Th)/He apatite ages (white circles) and elevation (grey circles) collected across the Sierra Nevada batholith (data from House et al. [17]). (b) The same data after interpolation and smoothing to remove short wavelength variations in the data (i.e. < 10 km); a strong anti-correlation between age and elevation is evidenced. (c) (U–Th)/He apatite ages from the same area but along a much shorter transect (< 10 km) (data from House et al. [9]); a strong correlation defining a positive slope and an apparent exhumation rate of 0.043 km Myr^{-1} is evidenced.

This strong dependence of the relationship between AER slope and relative relief change on the wavelength of surface topography offers the potential to extract information on surface relief evolution, independently from other parameters, and especially mean exhumation rate. We suggest that collecting samples in regions characterized by different topographic wavelengths should provide independent information on the rate at which rocks are exhumed and the rate at which the shape of the surface topography evolves through time. Conversely, one could determine the AER slope from rocks collected (a) along a cliff face or a steep valley wall and (b) across the width of a wide valley. The short sample would provide accurate information on mean exhumation rate, the long sample would constrain the local rate of relief evolution.

This strategy can be applied to existing datasets and is illustrated in Fig. 10a where (U–Th)/He apatite ages are shown that have been collected along a linear transect in the Sierra Nevada across a series of deeply incised valleys of varying width. This dataset has been smoothed to show the relationship between age and elevation at wavelength greater than 10 km (Fig. 10b). There is a strong anti-correlation between age and elevation across the wider features of the landscape (such as Kings Canyon). At long wavelengths, the AER is therefore characterized by a negative slope which implies that a significant reduction in relief took place in the area over the last 70 Myr (the mean age of the rock samples). Conversely, (U–Th)/He apatite data collected in the same area along a short transect along the side of Mount Whitney [9] shows a clearly defined positive AER slope (Fig. 10c). The slope of the AER at short wavelength provides an estimate (0.04 km Myr^{-1}) of mean exhumation rate in the last 70 Myr. The apparently conflicting information that is contained in those two datasets, i.e. one presenting a clear negative correlation between age and elevation, the other a clear positive correlation, can therefore be reconciled by considering the nature of the sampling strategy used in each case. Data collected across the large-scale features of the landform at wavelength greater than 10 km provide information on the rate of landform evolution, whereas data collected along a short transect (i.e. along a steep valley wall) provide information on the mean exhumation rate.

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