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Modeling of the temperature sensitivity of the apatite (U–Th)/He thermochronometer

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Abstract

Apatite (U–Th)/He apparent ages will generally reflect residence for extended periods at temperatures where helium is neither quantitatively retained nor lost by diffusion. To characterize the response of apatite He ages to thermal histories involving partial He retention, we explored solutions to the He production–diffusion equation. Under thermally static conditions, the analytical solution to this equation, coupled with published diffusivity data, demonstrates that the zone of partial He retention extends from about ~ 40°C to ~ 85°C. This zone lies at temperatures ~ 35°C cooler than the analogous fission track partial annealing zone. He ages within the partial retention zone ultimately achieve a balance between He production and loss, yielding a steady state age. Both the ultimate age and the time it takes to achieve this age are temperature dependent. For example, an apatite held at 75°C equilibrates to an age of ~ 2 Ma after ~ 17 Myr, regardless of whether equilibrium is approached from a higher or a lower initial He age. For representative dynamic thermal histories, we evaluated apatite He ages using a numerical solution to the ingrowth–diffusion equation. The results illustrate the sensitivity of He ages to various geologic histories and are useful for understanding He age–elevation relationships and for testing time–temperature paths derived from apatite fission track length distributions. In addition, although He diffuses rapidly from apatite at shallow crustal temperatures, modeling of ambient temperature fluctuations indicates that He ages are nearly unaffected by surficial processes.

Keywords: Apatite; He; Dating; Modeling

1. Introduction

Laboratory diffusion measurements indicate that radiogenic He is retained in apatite under mean Earth surface conditions, but is lost by diffusion at only slightly higher temperatures (Zeitler et al., 1987; Lippolt et al., 1994; Wolf et al., 1996). As a consequence, apatite (U–Th)/He ages are sensitive to very low temperatures (< 100°C) and in many cases will record details of the apatite's cooling history. Because apatite He ages are sensitive to temperatures lower than other thermochronometers, they have the potential to provide new information on the time–temperature evolution of rocks (Wolf et al., 1997). The closure temperature (Dodson, 1973) provides one means for interpreting cooling ages based on laboratory diffusivities; assuming a cooling rate of 10°C/Ma, the He closure temperature in apatite is about 75°C (Wolf et al., 1996). However, in many

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cases, the assumptions required for application of the closure temperature concept, such as simple monotonic cooling, are not met. This is particularly true at the low temperatures relevant to He in apatite, where the tectonic and erosional processes which expose rocks at the Earth's surface are likely to yield complicated cooling histories. Here we explore solutions to the full radiogenic ingrowth–diffusion equation for a variety of geologic situations to illustrate the sensitivity characteristics of the apatite (U–Th)/He thermochronometer.

Our model of He production and diffusion assumes that He is produced only by the decay of uniformly distributed uranium and thorium in secular equilibrium, and that it is lost only by volume diffusion. We assume a spherical diffusion geometry, consistent with laboratory measurements of He diffusion from apatite (Wolf et al., 1996). The local He concentration gradients resulting from ejection of high energy α particles from grain surfaces (Farley et al., 1996a) can be ignored because the diffusion domains are much smaller than the physical grain size (Wolf et al., 1996); i.e., this phenomenon does not affect most of the diffusion domains. Furthermore, because the diffusion domains are smaller than the grains themselves, our results apply to apatites in general, rather than only to those of some particular physical grain size.

Given these assumptions the He age equation is:

$$
\begin{aligned}
{}^{4}\mathrm{He} = {} & 8\,{}^{238}\mathrm{U}(t)\left(e^{\lambda_{238}t}-1\right) + 7\,{}^{235}\mathrm{U}(t)\left(e^{\lambda_{235}t}-1\right) \\
& + 6\,{}^{232}\mathrm{Th}(t)\left(e^{\lambda_{232}t}-1\right) \qquad (1)
\end{aligned}
$$

where ${}^{4}\mathrm{He}(t)$, $\mathrm{U}(t)$ and $\mathrm{Th}(t)$ are amounts present at time t, and λ's are the decay constants. As a consequence of radiogenic production and diffusive loss, the concentration of He as a function of the dimensionless radial position r within the spherical diffusion domain of radius a, is:

$$
\begin{aligned}
& \frac{\partial\,{}^{4}\mathrm{He}(r,t)}{\partial t} \\
& = \frac{D(t)}{a^{2}}\left[\frac{\partial^{2}\,{}^{4}\mathrm{He}(r,t)}{\partial r^{2}} + \frac{2}{r}\,\frac{\partial\,{}^{4}\mathrm{He}(r,t)}{\partial r}\right] \\
& \quad + 8\lambda_{238}^{238}\mathrm{U}(t) + 7\lambda_{235}^{235}\mathrm{U}(t) \\
& \quad + 6\lambda_{232}^{232}\mathrm{Th}(t) \qquad (2)
\end{aligned}
$$

$D(t)$ is the time dependent diffusion coefficient obeying an Arrhenius relationship such that:

$$
\frac{D(t)}{a^{2}} = \frac{D_{0}}{a^{2}}\exp\left[-\frac{E_{\mathrm{a}}}{RT(t)}\right] \qquad (3)
$$

where D_0 is the diffusivity at infinite temperature and E_{a} the activation energy measured in laboratory experiments, R is the gas constant, and $T(t)$ is an arbitrary thermal history. We assume a zero concentration boundary. In all of the illustrations discussed below, we adopt a present day ${}^{238}\mathrm{U}/{}^{235}\mathrm{U}$ ratio of 137.88 and a Th/U ratio of 1. The results are insensitive to the Th/U ratio because the half-lives of these two isotopes and the amount of He they yield during decay are similar.

The diffusion characteristics of He from apatite have been investigated by several groups (Zeitler et al., 1987; Lippolt et al., 1994; Wolf et al., 1996), with somewhat varying results. For the purposes of this paper, we adopt the diffusivities measured by Wolf et al. (1996), as these were measured with the highest precision and at temperatures requiring the smallest extrapolation to the conditions of geologic interest. Adoption of values from other workers would lead to qualitatively similar but quantitatively different results. Unless otherwise stated, for our calculations, we used the diffusion parameters measured on Durango apatite, which have the smallest analytical uncertainty. In several cases, we also investigated the effects of using diffusivities obtained on other apatites, from broadly granitic rocks. These apatites vary with respect to chemical composition and grain size, yet, like Durango apatite, yield a narrow range of closure temperatures, 75 ± 5°C (assuming a cooling rate of 10°C/Ma).

2. Isothermal diffusion: an analytical solution

The simplest case to investigate is that of an isothermal apatite, in which diffusivity does not vary with time. By making the assumption that He production is constant, the ingrowth–diffusion equation can be solved analytically. This assumption is justified for timescales over which the parent abundances vary only slightly, $< \sim 3 \times 10^{8}$ yr. For instance, over 2×10^{8} yr, $(e_{238}^{\lambda t} - 1)$ differs from $\lambda_{238}t$ by only 1.6%, and thorium by even less (${}^{235}\mathrm{U}$ varies by much more, but its He contribution can be ignored, e.g., over 2×10^{8} yr it contributes only 0.5% of the He produced by ^{238}U decay). Therefore, Eq. (1) can be rewritten as:

$$^{4}\mathrm{He} = 8\,^{238}\mathrm{U}\lambda_{238}t + 6\,^{232}\mathrm{Th}\,\lambda_{232}t = Pt \qquad (4)$$

where P is the constant production rate. The general solution to the ingrowth–diffusion equation using Eq. (4) is (Ozisik, 1989):

$$\frac{^{4}\mathrm{He}}{P} = t' = \frac{a^{2}}{D}\left[\frac{1}{15} - \sum_{n=1}^{\infty}\frac{6}{\pi^{4}n^{4}}\exp\left(-n^{2}\pi^{2}\frac{D}{a^{2}}t\right)\right] + \frac{^{4}\mathrm{He}*}{P}\sum_{n=1}^{\infty}\frac{6}{\pi^{2}n^{2}}\exp\left(-n^{2}\pi^{2}\frac{D}{a^{2}}t\right) \qquad (5)$$

where t' is the He age, t is the time over which isothermal diffusion and production occur, and $^{4}\mathrm{He}*$ is the concentration of He present at $t = 0$ (assumed homogeneously distributed within the diffusion domain). Note that $^{4}\mathrm{He}*/P$ is effectively the initial He age of the system.

Solutions to Eq. (5) for various temperatures and starting conditions are shown in Fig. 1. The exponential terms in Eq. (5) disappear for large values of $(D/a^{2})t$, and equilibrium between He production and loss is ultimately achieved to yield a steady-state He age of $(1/15)(D/a^{2})^{-1}$. The e-folding time for approach to equilibrium is well-approximated by the first term in the summations ($n = 1$), and is given by $t* = (D/a^{2})^{-1}\pi^{-2}$. In $5t*$, the approach to equilibrium is largely complete. For example, an apatite held at 75°C will reach a steady-state He age of 2.3 Ma after being held for ∼17 Myr. In contrast the same apatite held at 25°C will ultimately equilibrate to a He age of $\sim 10^{10}$ yr but will require $> 10^{11}$ yr to get there. The steady-state age and e-folding time are the same whether equilibrium is approached from a lower or a higher initial He age. The latter is useful for interpreting He ages in sedimentary apatites. For example, an apatite with a provenance age of 100 Ma instantaneously heated to 100°C will equilibrate to a steady state age of ∼0.07 Ma after just ∼0.5 Myr, but will require nearly 200 Myr to equilibrate to 24 Ma at 60°C.

Fig. 1 illustrates how He ages change with time at different temperatures, but does not clearly demonstrate how He ages differ with temperature for a constant holding time t. Such a view would be useful for considering He age variations with depth in the crust. Fig. 2 shows He ages as a function of tempera-

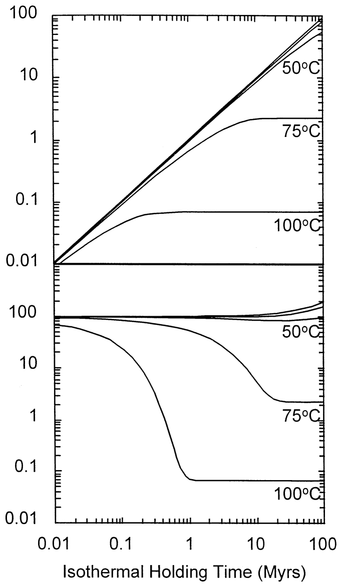

Fig. 1. Helium age evolution as a function of time (t' vs. t) for apatites held isothermally at various temperatures (labeled). In the upper panel, the apatites are assumed to have no initial He. In the lower panel, the apatites have an initial He age of 100 Ma. Unlabeled curves represent 25°C and 40°C.

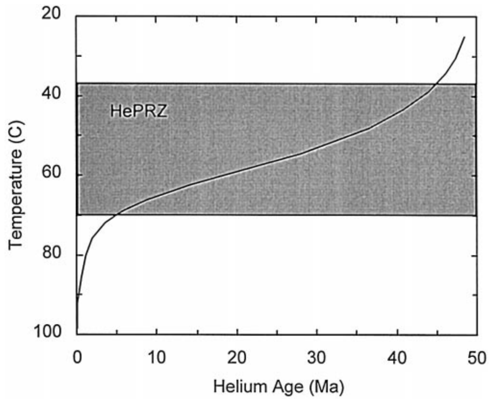

Fig. 2. Apatite He age as a function of temperature for an isothermal holding time of 50 Myr. The helium partial retention zone (HePRZ) is defined to be the temperature range over which He ages range from 10% to 90% of the holding time, i.e., in the temperature range where He age changes most rapidly with temperature (shaded region). Calculated from Eq. (5) with no initial He.

ture for a holding time of 50 Myr and with no initial He. The He ages change rapidly over a fairly narrow temperature range which we call the He partial retention zone, HePRZ. The HePRZ is analogous to the fission track partial annealing zone (e.g., Gleadow and Duddy, 1981; Gleadow et al., 1983; Gleadow and Fitzgerald, 1987; Wagner et al., 1989). We operationally define the HePRZ to be the range of temperatures where He ages fall from 90% to 10% of the holding time (i.e., $0.1 \leq t'/t \leq 0.9$). For a holding time of 50 Myr, the HePRZ is between ~ 40°C and 70°C (Fig. 2). One consequence of defining the HePRZ in this way is that the temperature range of the HePRZ depends on holding time. Whereas the HePRZ lies between ~ 50°C and ~ 83°C for a holding time of 10 Myr, it lies between ~ 38°C and ~ 67°C for a holding time of 100 Myr. In a typical 20°C/km geothermal gradient, the HePRZ resides at ~ 2 ± 1 km over 10^6 to 10^8 yr timescales.

The curve in Fig. 2 was computed using the diffusion characteristics measured on Durango apatite. To assess the sensitivity of the HePRZ to small variations in D_0/a^2 and E_a, we recomputed the curve using the diffusion parameters we measured on several granitic apatites (Fig. 3). The resulting curves are shifted relative to that for Durango, by a maximum of ~ 8°C. Because these diffusion parameters are essentially the same within analytical uncertainty, Fig. 3 provides a reasonable estimate of the uncertainty in the temperature range of the HePRZ based on presently available diffusivity data.

Like apatite He ages, apatite fission track ages are sensitive to low temperatures, and it is useful to compare the two systems. Assuming an arbitrary holding time of 120 Myr, the model HePRZ lies between ~ 38° and ~ 65°C (Fig. 4). Under the same conditions, the fission track partial annealing zone (FTPAZ) defined in an analogous fashion to the HePRZ, resides between ~ 70°C and ~ 105°C (using AFTSolve; Ketcham et al., in review). The HePRZ lies ~ 35°C cooler than the FTPAZ (Fig. 4), and in typical geothermal gradients of ~ 15–35°C/km will reside ~ 2 ± 1 km shallower. Thus, we predict that He ages will always be ≤ fission track ages. In addition, the HePRZ and the FTPAZ do not overlap; He ages approach zero just as the fission track ages begin to decrease. We predict that in some cases (situations including as much as ~ 2 km of exhumation), He ages could be almost completely reset in samples which do not exhibit the effects of fission track age reduction.

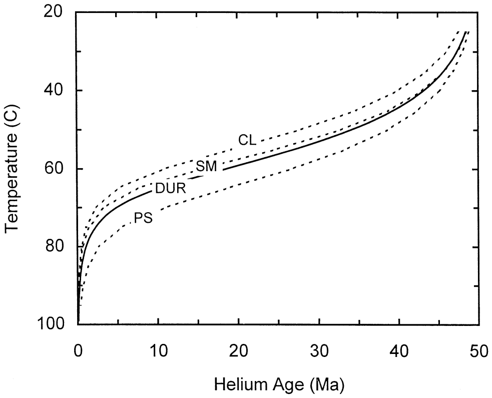

Fig. 3. The HePRZ plotted for several different measured diffusion parameters and a 50 Myr holding time (DUR, Durango apatite; SM, San Marcos gabbroic apatite; CL, Camp Lackey tonalitic apatite; PS, Palm Springs mylonitic apatite; Wolf et al., 1996). Within uncertainties propagated from the measured diffusion parameters, the curves overlap.

Measured He ages from the Otway Basin of Australia provide one possible test of the predicted relationship between the HePRZ and the FTPAZ, as well as a test of the applicability of laboratory He diffusion data to natural systems. Apatite fission track data from this location document an unusually complete and simple FTPAZ and provide an impor-

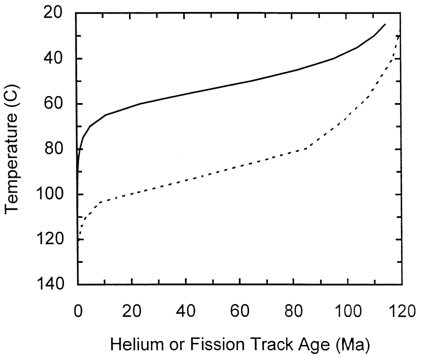

Fig. 4. Variation with temperature of He ages (solid line) and fission track ages (dashed line; modeled using AFTSolve; Ketcham et al., in review) in an apatite held for 120 Myr. The HePRZ is ~ 35°C cooler than the FTPAZ, and the two zones do not overlap.

tant calibration for annealing in the natural environment (Gleadow and Duddy, 1981; Gleadow et al., 1983; Green et al., 1989). There is only a subtle difference between the inferred thermal history for the Otway Basin sediments (Green et al., 1989) and an isothermal history held for 120 Myr, so the model HePRZ in Fig. 4 should closely resemble He ages measured on Otway Basin apatites if the (U–Th)/He system behaves as expected. Analyses of Otway Basin apatites are presently in progress.

3. Arbitrary thermal histories: a numerical solution

When temperature and diffusivity vary with time, there is no general analytical solution to the He production–diffusion Eq. (2). We used a numerical approach (the Crank–Nicolson method; Crank and Nicolson, 1947) to calculate the He concentration as a function of time for prescribed time–temperature paths. By inserting the integrated He concentration into the age Eq. (1), we calculated the evolution of He age along the path.

3.1. Variable thermal histories and He age–elevation profiles

To determine the sensitivity of He ages to typical dynamic time–temperature paths, we modeled He ages for several illustrative scenarios (Fig. 5). Comparable exercises have been undertaken for apatite fission track ages, with qualitatively similar results (Green et al., 1989; Gallagher, 1995; Ketcham et al., in review). In History 1, an apatite is cooled quickly to 15°C and held there for 40 Myr; He retention is quantitative at this temperature, so this path represents simple closed-system evolution as might apply to a volcanic rock. All of the other histories include extended periods at temperatures where He is only partially retained. History 2 is monotonic cooling from 135°C to 15°C over 100 Myr. The transition from total loss to total retention is apparent in this He age trajectory. In this case of constant cooling, the closure temperature can be calculated from the cooling rate to be ~62°C (Dodson, 1973). This type of history may apply to rocks experiencing erosional exhumation, in this case corresponding to a rate of 1.2°C/Myr. In History 3, a sample held at ~60°C for ~80 Myr is rapidly cooled at ~20 Myr to 15°C. On this path, the He age approaches an equilibrium value over the first ~80 Myr, then rises linearly for the remaining ~20 Myr. This history might apply to a rock tectonically exhumed 20 Ma ago. History 4 involves 25 Myr of cooling followed by an isothermal period at 60°C for 50 Myr, followed by continued cooling. The He age trajectory for this history is similar to that of History 3. Thermal histories of this type have often been proposed from modeling of fission track length distributions (Lutz and Omar, 1991; Corrigan, 1991). History 5 shows the He age trajectory of a sample experiencing heating from an initial value of 15°C at 100 Ma to a maximum value of ~65°C at 5 Ma, followed by cooling back to 15°C at 0 Ma. This He age trajectory shows an initial rise eventually followed by decreasing ages as the sample's He content begins to exceed the equilibrium value for the ambient temperature. This type of history could apply to a slowly subsiding sedimentary basin tectonically reactivated at 5 Ma.

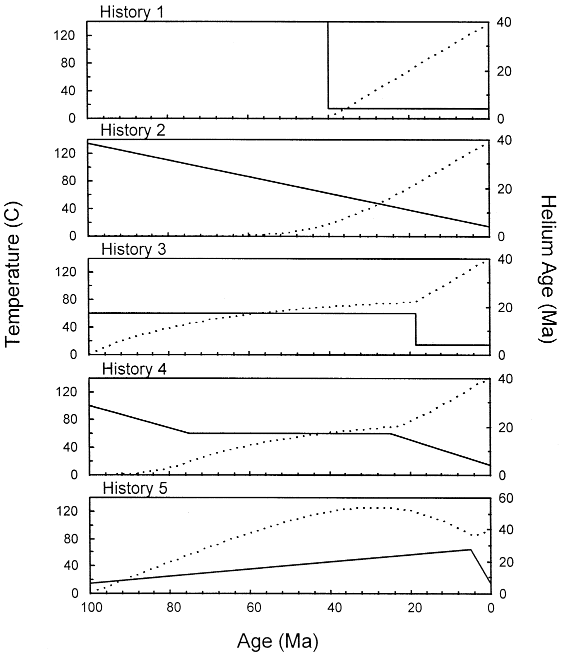

Fig. 5. Apatite He age evolution curves (dotted lines) for several representative time–temperature paths (solid lines) using the Crank–Nicolson model. All paths yield a He age of 40 Ma.

Despite their different t–T paths, all five temperature histories yield apatites at 15°C with indistinguishable He ages of 40 Ma. However, the five histories would produce very different profiles of He age against structural depth (or elevation). We have calculated He ages as a function of structural depth for each of the temperature paths in Fig. 5 by assuming a constant geothermal gradient of 20°C/km extending below the reference t–T path (Fig. 6). As shown in Fig. 6, the five histories are well-resolved in age–depth space. The profile for History 1 corresponds to an HePRZ evolved for 40 Myr, and is strongly concave-up. All other histories lie to the left of this curve (i.e., to lower He ages), consistent with the fact that they have all experienced higher temperatures more recently. The linear cooling of History 2 yields a nearly linear age–depth profile with a slope of 60 m/Myr, identical to the implied exhumation rate $(1.2°\text{C/Myr} \div 20°\text{C/km} = 60\ \text{m/Myr})$ that generated this t–T path. The sudden ~45°C cooling that occurs in History 3 at ~20 Ma is recorded by a sharp inflection in the profile at this age; similar inflections arising from rapid cooling have been recorded by apatite fission track ages (e.g., Fitzgerald et al., 1991, 1993). Although History 4 is generally similar to History 3, it produces an age profile that differs from it by as much as 10 Ma. Finally, the sharply concave-down profile produced by History 5 is clearly distinct from the concave-up equilibrium HePRZ, and would provide strong evidence for an active sedimentary basin.

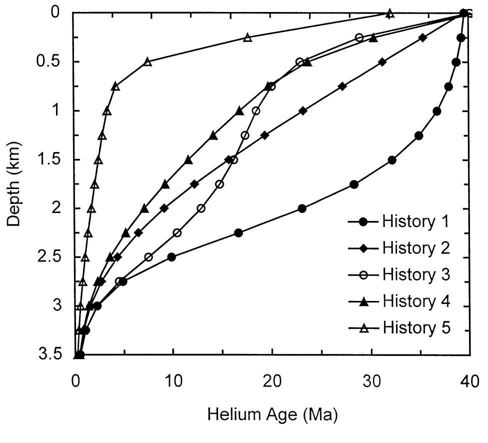

Fig. 6. He age as a function of structural depth in a 20°C/km geothermal gradient for the time–temperature histories shown in Fig. 5. The histories can be resolved with measurements of apatite He ages spanning ~1.5 km of structural relief; similar resolution using apatite fission track ages would require more than 2 km.

It is important to note that only a few samples taken from the uppermost ~1.5 km suffice to distinguish these profiles; samples drawn from several kilometers of structure are not required. In contrast, 1.5 km of structure would be insufficient to distinguish these paths using apatite fission track ages of typical precision. Although the exact details of the fission track age profiles are very dependent on the annealing model chosen, in general > 2 km would be required. For example, using the calibration of Durango apatite annealing by Laslett et al. (1987), and AFTSolve software (Ketcham et al., in review), age–depth profiles for Histories 3 and 4 become > 10% different in age only at depths of > 2.2 km.

3.2. *Sensitivity to measured diffusivities*

To illustrate the sensitivity of He ages to even modest variations in He diffusivity, we computed the final ages for apatites subjected to the thermal histories in Fig. 5, but instead of using the diffusion characteristics of Durango apatite, we used those measured on granitic apatites (Wolf et al., 1996). The quick cooling in History 1 precludes any dependence of age on He diffusivity. However, for the other histories, the differences can be substantial. The age ranges are as follows: History 2, 36–44 Ma; History 3, 30–54 Ma; History 4, 31–52 Ma; and History 5, 23–56 Ma. The differences are largest for the histories involving the longest residence in the HePRZ. Indeed the age differences can be related directly to the differences in the position of the HePRZ curves in Fig. 3. Because History 5 includes the longest duration within the HePRZ, it provides the greatest amplification of differences in diffusivity. These apatites have He closure temperatures that are the same within error (75 ± 5°C assuming 10°C/Ma cooling rate), yet the model He ages resulting from History 5 differ by as much as 30 Ma. Although this is an extreme example, it is clear that some applications of He thermochronometry may require a very accurate knowledge of the diffusion coefficients of the actual samples dated, especially if the relevant thermal histories involve long durations in the HePRZ.

3.3. Comparison with fission track length distributions

The distribution of fission track lengths in an apatite can provide powerful constraints on the low temperature (60–105°C) t–T path that it has experienced, but typically a family of cooling curves satisfies the distribution equally well (Lutz and Omar, 1991; Corrigan, 1991). Apatite He ages are sensitive to this same range of temperatures and can be measured on the same samples, so He ages can be used to reduce the number of acceptable histories (Farley et al., 1996b). Thermal histories which yield model He ages that do not agree with measured ages may be rejected.

The advantage of this approach is that it relies on two different phenomena that are modeled in completely independent ways. The pair of techniques would provide important cross-validation of the resulting thermal histories provided the techniques are properly calibrated. However, such calibration clearly requires further work. For example, extrapolation of laboratory measurements of fission track length shortening to natural conditions remains problematic (Green et al., 1989). Similarly, there are only a handful of He diffusion measurements from apatite, and these are somewhat discrepant (Zeitler et al., 1987; Lippolt et al., 1994; Wolf et al., 1996). As shown above, even small differences in diffusivity can lead to large differences in age for some thermal histories; thus, this is an example of an application requiring highly accurate diffusivity data.

3.4. The effect of ambient temperature variations on He ages

Previous work has shown that forest/range fires and even ambient temperature fluctuations can cause the diffusive loss of cosmogenic ^{3}He from some minerals (Bierman and Gillespie, 1991; Trull et al., 1995). To assess whether radiogenic He in apatite is susceptible to these effects, we modeled the diffusive loss that occurs as a function of ambient conditions. In the case of fire, we assumed the surface of an exposed rock reaches a peak temperature of 600°C after being heated for 10 min (following Bierman and Gillespie, 1991). We computed the distribution of peak temperatures with depth in the rock by assuming that heat travels from a plane source in one direction with a thermal diffusivity of 0.01 cm^2/s. As an extreme case, we assumed that these peak temperatures are held for the entire 10 min duration of heating, and then used the relationship between time, diffusivity, and fractional diffusive loss published by Crank (1975) to determine how much He is retained by apatites as a function of distance from the heated surface. For this calculation, we assumed an initially constant He profile within the diffusion domains. For apatites at the rock surface, the fire's effect is large: more than 30% of the He is lost. However the retention rises rapidly with depth in the rock, reaching unity for apatites located at just 3 cm depth. Because granite tends to spall after a fire, and because typical sampling involves chipping away the outer weathered rind, we believe it is unlikely that apatite He ages will be substantially modified by the effects of natural fires.

To assess whether extremes in Earth surface temperatures can affect apatite He ages, we investigated the effects of high ambient temperatures as measured at Death Valley, CA. This site was selected because it routinely records some of the highest air temperatures on Earth (Fig. 7). The Western Regional Climate Center (1997) reports the daily temperature fluctuations averaged over the last quarter century (Fig. 7). The annual mean temperature at this site is 25°C, and daily highs range from 19°C in the winter months up to 45°C in the summer.

The temperature fluctuations experienced by a rock depend on its proximity to the Earth's surface. At the surface, the rock experiences the full diurnal temperature oscillation, possibly with an enhancement above the daily high as a result of direct solar heating. However, the diurnal and yearly oscillations are rapidly damped with the depth below the surface. Following Carslaw and Jaeger (1959), the daily oscillation of the diurnal cycle is damped to the daily mean value by ~ 85 cm depth, and the annual cycle is damped to the mean annual temperature by ~ 15 m depth.

At the Death Valley mean annual temperature of 25°C (experienced by a rock at > 15 m subsurface),

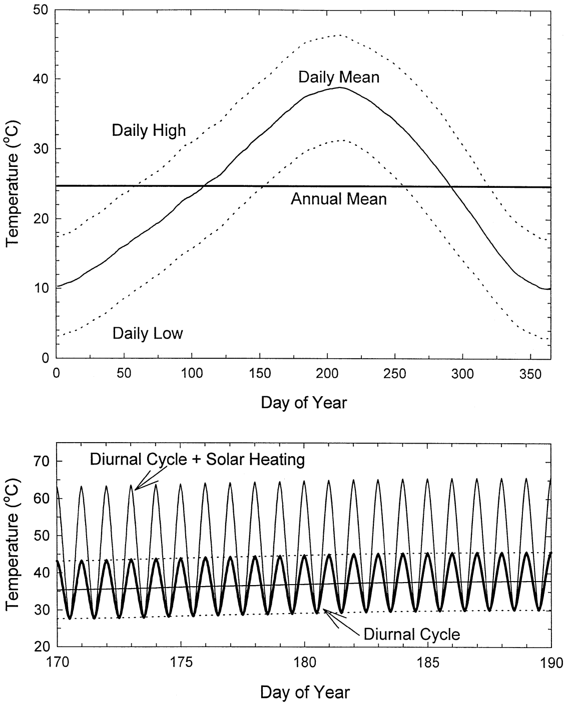

Fig. 7. The average temperature history of Death Valley, Ca, from the Western Regional Climate Center (1997). The upper panel shows the reported daily high and low temperatures and the daily and annual mean temperatures as a function of calendar day. The lower panel shows the diurnal temperature cycle and an estimate of the temperature enhancement arising from direct solar heating of rock surfaces for a short portion of the year. The temperature history experienced by a rock depends on its proximity to the surface. Based on these temperature variations we conclude that even the full diurnal cycle is unlikely to significantly affect He ages. However, under conditions where apatites may experience intense direct solar heating and where exposed surfaces are eroded slowly, some He loss may occur (see text).

Fig. 1 shows that He retentivity is nearly quantitative. To investigate the effects of the oscillating temperatures experienced closer to the surface, we computed the mean diffusivity over the annual cycle. Using this diffusivity and the fractional loss equation (Crank, 1975), we calculated how long it takes to lose 2% of an apatite's He (2% being an arbitrary estimate of significant He loss). For apatites shallow enough to experience the full annual cycle, but not the diurnal cycle (e.g., around 1 m subsurface, the curve labeled 'daily mean' in Fig. 7), the mean diffusivity is equivalent to a temperature of 31.3°C. At this effective temperature 2% He loss occurs after ~ 2 Myr (strictly speaking, some radiogenic He ingrowth occurs over this time period, but including this effect using our numerical solution to Eq. (2) does not alter this observation). For samples right at the surface, tracking the curve labeled 'diurnal cycle' in Fig. 7, the effective temperature is only slightly higher, 31.5°C, and again 2% loss requires 2 Myr. Because erosion rates are typically > 1 m/Myr, the duration over which these fluctuations are experienced will be small. It is unlikely that even these extreme temperatures significantly modify He ages.

An additional effect that would cause greater He loss is direct solar heating of the rock surface. The temperature increase associated with such heating is difficult to estimate in a general way, as it is very sensitive to specific geometric and radiative properties of the rock. In a study of granitic boulders in the Mojave desert, Roth (1964) found that rock surfaces exceeded the air temperature typically by no more than 20°C. Adopting this figure as a constant offset added to the daytime temperatures yields a reasonable upper limit to the temperature of rock surfaces in Death Valley (curve labeled 'diurnal cycle + solar heating' in Fig. 7). Under these conditions, the mean diffusivity is equivalent to a temperature of 48°C, and 2% loss occurs in just over 100 kyr. In environments where temperatures and insolation are high and erosion is slow, this effect may require consideration.

4. Conclusions

Apatite He ages reflect thermal histories involving varying amounts of time in the region where He retention is very temperature sensitive. We refer to this region as the He partial retention zone, and it resides between ~ 40° and ~ 85°C. Under isothermal conditions a steady state is achieved between radiogenic He production and diffusive loss; both the steady state He age and the time to achieve the steady state are temperature dependent and can be predicted directly from the He diffusion parameters.

The He partial retention zone does not overlap the fission track partial annealing zone, indicating that the apatite (U–Th)/He technique should record lower temperature histories and younger ages than the apatite fission track method. We predict that in some cases He ages may be essentially zero in apatites with comparatively high fission track ages. Like fission track ages, He age/structural depth profiles convey rich information on the cooling history of crustal blocks (cf. Wolf et al., 1997). Because He ages are sensitive to lower temperatures (hence shallower depths) than fission track ages, in some cases, less structural relief may be required to distinguish among various cooling histories using the He method.

Fission tracks are shortened within the He partial retention zone, so He ages should provide quantitative tests of track-length-derived thermal models. Comparison of the two can be used to validate laboratory calibrations of the two techniques. Once the two techniques are adequately cross-calibrated, He ages may be useful for reducing the number of possible thermal histories generated by inversion of the track-length distributions. For this application, it may be necessary to determine He diffusion parameters to higher precision than is now routine.

Although He diffuses rapidly from apatite at fairly low temperatures, natural fires and extreme Earth surface temperatures should not significantly affect He ages except under unusual circumstances.

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