Radioactive decay of naturally occurring nuclides provides the basis for the nearly all quantitative temporal constraints on geophysical phenomena, from climate dynamics on scales of $10^2$-$10^3$ yr, to planetary differentiation over $10^8$-$10^9$ yr. In general there are few geologic problems that are not accessible by radioisotopic chronometers, partly because of the wide range of radioactive parent nuclides (and decay rates), contrasting chemical behaviors of parent and daughter atoms during common geologic processes, and ever-advancing geoanalytical techniques. Despite broad success however, radioisotopic techniques are still difficult to apply to many important geologic phenomena requiring temporal constraints, such as the timing and rates of shallow crustal processes that are critical aspects of geomorphology and neotectonics. Motivated partly by the need for such low-temperature chronometers, the last 10-15 years has seen renewed interest in the chronometric potential of uranium and thorium decay to helium. Unusual characteristics of the (U-Th)/He system, which originally led to its premature diagnosis as unreliable, actually make it uniquely suited for a wide range of many previously inaccessible geologic problems.

(U-Th)/He chronometry is based on the $\alpha$-decay of (production of $^4$He nuclei from) uranium and thorium (a generally insignificant amount of $^4$He is also produced by $^{147}$Sm$\rightarrow^{143}$Nd decay). The fundamental age equation for the system is:

$$t = \frac{8^{238}U[\exp(\lambda_{238}t) - 1] + 7^{235}U[\exp(\lambda_{235}t) - 1] + 6^{232}Th[\exp(\lambda_{232}t) - 1]}{\lambda_{238} + \lambda_{235} + \lambda_{232}},$$

where $^{4}$He, $^{238}$U, $^{235}$U, and $^{232}$Th are the present-day atoms, $\lambda$’s are their decay constants, and $t$ is the (U-Th)/He age. Although the U and Th half-lives are fairly long ($\sim 10^9$-$10^{10}$ yr), six to eight $\alpha$ are produced for each parent, because of the multi-step decay chains for $^{238}$U, $^{235}$U, and $^{232}$Th that ultimately result in stable $^{206}$Pb, $^{207}$Pb, and $^{208}$Pb, forming the bases of the well-known U/Pb and Th/Pb dating techniques. Multiple parent nuclides is only one of the unusual features of the (U-Th)/He system, as compared with other decay schemes such as K/Ar or U/Pb. Other characteristics, including strongly contrasting parent/daughter behaviors and energetic recoil and long stopping distance of the daughter nuclide also distinguish the application and interpretation of He dating among more traditional radioisotopic decay schemes, as illustrated by the checkered past of the technique.
Around 1905, not long after the discovery of natural radioactivity and its association with uranium, Ernest Rutherford became the first radioisotopic geochronologist, by using concentrations of U and He (and Ra) in samples of fergusonite and other U-rich minerals to calculate their ages of at least 40-500 Ma. Following Rutherford’s lead, several notable geochemists and physicists of the time, including R.J. Strutt, A. Holmes, F. Paneth, and W. Urry, vigorously applied He dating to a wide variety of samples, with the primary goal, popular at the time, of establishing an absolute geologic timescale. Although critical in establishing the relative antiquity of terrestrial rocks and foreshadowing the importance of radioisotopic dating in earth science in general however, He dating quickly fell into disuse and, to some degree, disrepute, in the next few decades. By about 1940, as comparisons between radioisotopic ages determined by both U-He and U-Pb systems became widely available, it became clear that in most cases He ages were younger than Pb ages, and He ages from stratigraphically similar rocks were inconsistent. The probable culprit, as recognized by Rutherford in his earliest studies, was He loss, rendering He dates only minimum estimates of the time elapsed since their formation. Several subsequent studies encountered limited success in dating of various types of accessory minerals and other geologic specimens, but the general conclusion, through the mid 1980’s, was that the problem of He “leakage” made (U-Th)/He ages suspect and difficult if not impossible to interpret.

**Cooling ages and useful phases for (U-Th)/He chronometry**

In retrospect, rumors of the demise of He dating were greatly exaggerated, and were in fact due partly to a limited definition of radioisotopic age. The possibility that (U-Th)/He ages could represent cooling, rather than formation, ages, was first proposed by Zeitler et al. in 1987. They showed that He ages of quickly-cooled apatites matched those derived by other techniques and that on geologic timescales, He is largely retained in apatite at temperatures below approximately 100°C. Current understanding of He diffusion in apatite confirms that rather than unsystematic “leakage,” He loss from apatite is dominantly a highly predictable and systematic process of thermally activated volume diffusion. Step-heating diffusion experiments indicate that in rocks with common (~10°C/myr) monotonic cooling histories, apatite crystals of typical size yield He ages that estimate the time elapsed since cooling through about 68±5°C [Farley, 2000, and references therein]. Thus, in general apatite He ages provide estimates of the timing and rates of relative movement between rocks in the upper 2-4 km of crust, and the earth’s surface, which are central to many tectonic and geomorphologic problems. This approximately 70°C closure temperature is considerably lower than the ~110°C closure temperature of the well-known apatite fission-track dating method, which relies on temperature-dependent annealing rates of natural U fission tracks in crystals. Because many neotectonic and geomorphic problems (especially in regions of recent tectonic activity or limited exhumation) relate to movement of rocks through only the upper ~2-4 km of
crust, where temperatures are typically 40-100°C, the relatively low closure temperature of the apatite (U-Th)/He system makes it desirable for constraining the timing and rates of these processes in the geologic record. Apatite He dating is also well suited for constraining thermal histories of rocks in the upper few km of sedimentary basins [e.g., House et al., 1999], where knowledge of time-temperature paths are important for accurate constraints on hydrocarbon reservoir potential.

Prior to the 1990’s (U-Th)/He dating was also attempted, with varying degrees of success, on a variety of phases other than apatite. While some minerals, such as hematite [e.g., Wernicke and Lippolt, 1997, and references therein] proved broadly successful, in general, the problem of apparently “too-young” ages also plagued these attempts. Following experimental approaches taken with apatite however, the conceptual bases and technical methods of both titanite [Reiners and Farley, 1999] and zircon [Reiners et al., 2002] have also recently been developed. He diffusion in both of these common accessory minerals is considerably slower than in apatite, yielding closure temperatures (for typical cooling rates and crystal sizes) of approximately 180-200°C. He diffusion in zircon is significantly more complex than in apatite however. Step-heating diffusion results show several types of complexities that may reflect the presence of multiple diffusion domains or heterogeneous He distributions. Some of these complexities may be due to radiation damage and/or heterogeneous U-Th distribution effects. Nonetheless, numerous titanite and zircon (U-Th)/He dates from a wide range of both quickly- and slowly-cooled samples provide consistent formation and cooling ages. Where thermal histories of slowly-cooled rocks are constrained by thermochronologic ages from other techniques such as 40Ar/39Ar, the titanite and zircon (U-Th)/He ages consistently suggest a closure temperature of approximately 180-200°C. Typical geothermal gradients place the 200°C isotherm at approximately 6-10 km depths, making these thermochronometers useful for constraining the timing and rates of upper/mid-crustal exhumation in orogenic terranes.

(U-Th)/He analyses and α ejection

Because of variable intercrystal U-Th concentrations, sufficiently precise He ages require measurement of parents and daughter in the same aliquot. Fortunately, U and Th do not appear to be lost from apatite, titanite, and zircon crystals heated to even extremely high temperatures (provided crystals are not heated directly by laser [Reiners and Farley, 1999]). This permits step-wise analysis of He by degassing, followed by U-Th analysis by dissolution. Degassing of crystals is typically accomplished by either furnace or laser (CO2 or Nd-YAG) heating; laser extraction requires heating of small metal foil packets encapsulating the dated crystal(s). ³He is typically measured by quadropole mass spectrometry using ³He isotope dilution and cryogenic purification, to a precision of about 1%. Retrieved crystals are then dissolved and measured by isotope dilution on an ICP-MS, with comparable uncertainties. The final
step in calculating He ages requires a very significant correction, unique among other geochronometers in both origin and magnitude: the $\alpha$-ejection correction.

Relatively large kinetic energies (typically 4-5 MeV), and therefore long stopping distances of $\alpha$ particles (~15-20 um), result in separation of radiogenic helium from parent nuclides by significant distances relative to the size of typically dated crystals (~50-400 um). The most important implication of this for He dating is that some fraction of the total He produced by U-Th series decay is ejected from crystals, resulting in “too-young” ages, even after accounting for low-temperature diffusive loss. Dating only the interior portions of crystals from which the outer 15-20 um have been removed may be possible for some samples such as quickly-cooled crystals with uniform U-Th concentrations, but for slowly-cooled, partially reset, or U-Th heterogeneous crystals, this approach cannot be used. A more general solution is to correct measured He ages for ejected $\alpha$’s based on measured crystal dimensions and geometry [Farley et al., 1996]. Fortunately, actinide $\alpha$-stopping distances are well known, so, provided the U-Th distribution in the crystal is accurately known or can be assumed to be uniform, the fraction of ejected $\alpha$’s can be estimated with reasonable accuracy. The magnitude of such corrections for typical apatite crystals (i.e., with hexagonal prism widths of ~80-200 um) generally range from about 17-40%. The largest corrections, and therefore greatest uncertainty from the effects of $\alpha$-ejection, are associated with the smallest crystals, since these have the largest surface area to volume ratios. In practice, $\alpha$-ejection corrections may, mainly through the uniform U-Th distribution assumption, indirectly be a primary source of error in (U-Th)/He dating, as discussed below.

(U-Th)/He Thermochronology

Tectonic activity at or near plate margins results in orogenic uplift and exhumation of rocks in the earth’s crust by erosion or faulting. These phenomena link the dynamics and origins of surficial processes, such as geomorphic and climatic evolution, with lithospheric plate motions and their larger-scale origins and influences such as mantle convection. Detailed knowledge of the timing and rate of orogenic activity thus provides important links between a wide range of earth processes. The most direct links between tectonic and geomorphic processes are provided by low-temperature thermochronometers, because of their sensitivity to movement of rocks through the uppermost crust. The ~70-200°C closure temperatures of apatite, zircon, and titanite (U-Th)/He thermochronometers (Fig. 1) are particularly useful for these purposes. Complementary constraints from other thermochronometers, including apatite and zircon fission-track dating (with closure temperatures of about 110°C, and 240°C, respectively), and $^{40}$Ar/$^{39}$Ar dating of different phases (~200-300°C for K-feldspar, and higher temperatures for micas and
amphibole), also provide potential for highly detailed thermal histories over a wide range of temperature for rocks that have undergone even complex orogenic histories.

The timing and rate of crustal exhumation in orogenic regions is commonly deduced from either cooling age differences between two minerals with different closure temperatures, or from age-elevation (or age-paleodepth) relationships in samples collected in (near-) vertical transects. As rocks move towards the surface via exhumation, they sequentially cool through a chronometer’s closure temperature, recording a sequence of cooling ages that typically increase with increasing elevation (or paleodepth) for a given chronometer. In general, the difference in age and elevation between two samples with the same closure temperature, or alternatively, the difference in cooling age between two minerals with different closure temperatures at the same elevation, yield cooling rate or exhumation rate. Changes in mineral-pair age differences or changes in age-elevation slopes for single minerals in the elevation or paleodepth transect, reflect changes in cooling/exhumation rate.

A common observation of thermochronologic approaches of this type is that the high elevation (or shallow paleodepth) samples yield old ages and apparently low exhumation rates (typically <0.1 mm/yr or km/myr), but there is a sharp break-in-slope in the age-elevation correlation, such that samples at lower elevations or greater paleodepths have younger ages and imply higher exhumation rates. In many cases the upper part of the age-elevation transect is thought to represent a period of little to no exhumation that preceded the orogenic activity that produced the vertical relief or paleodepth exposure itself. In this upper zone, samples approached steady-state He contents reflecting a balance of retention and diffusive loss (He partial retention zone, or PRZ). The depth range of the PRZ corresponds to a temperature range within which the rate of He diffusion changes dramatically (e.g., between 10-90% He retention), and the base of the PRZ typically corresponds approximately to the closure temperature of the thermochronometer. Below the PRZ, the slope of the age-elevation correlation represents the more recent exhumation rate, and the age associated with the break-in-slope between these sections of the age-elevation relationship represents the onset of exhumation.

Thermochronometric work on the Gold Butte crustal section in southeastern Nevada provides an example of this approach, as well as the utility of He dating in constraining the kinematics and geometry (Fig. 2) of crustal-scale structures. Gold Butte has been interpreted as a 15-20 km thick vertical section of crust that was rapidly exhumed by deep Basin and Range normal faulting at about 16 Ma, and steeply tilted to the east about a roughly north-south axis [Reiners et al., 2000, and references therein]. It therefore provides an opportunity to document the long-term thermal history of the mid- to upper-crust in the Basin and Range-Colorado Plateau transition zone, as well as compare (U-Th)/He chronometric results with those of other thermochronometers. The overall distribution of (U-Th)/He, fission-track, Ar/Ar, and U/Pb ages of various phases from paleo-vertical transects in the crustal block support a simple
conception of the structural and thermal history of Gold Butte. Assuming a 20-25°C/km geothermal gradient, the ages in each system increase from ~15-20 Ma to older ages at or very close to depths corresponding to the isotherm of the closure temperature for each phase. This suggests that little or no exhumation or burial of the block occurred for a long period of time (~100-200 Ma), allowing old ages to develop in shallow samples (held at temperatures below the system’s closure temperature), but maintaining a zero- or near-zero age in samples at greater depths (held at temperatures higher than the system’s closure temperature). At about 15-20 Ma, Basin and Range extension rapidly exhumed the deepest parts of the block, cooling deep samples below their closure temperatures. The rate of exhumation, and therefore fault slip, must have been quite rapid (> about 7-10 km/m yr), to produce the lack of observable age-elevation correlation in apatite He ages or in other samples at deep levels. In general, although more detailed sampling may change the details of the story, all available (U-Th)/He, fission-track, $^{40}$Ar/$^{39}$Ar, and U/Pb dating performed in the Gold Butte block supports the model of a 15-20 km deep vertical crustal section that was rapidly exhumed during Basin and Range extension. Exactly why and how such a thick vertical slice of crust remained largely intact during apparently rapid extension and large degrees of tilting is puzzling. The general westward increase in extension-related exhumation ages in the Basin and Range at this latitude and the relatively cool pre-extension geothermal gradient may suggest that the initial crustal failure in this part of the rift was through relatively cold, brittle crust, and cut exceptionally deep.

**Thermal histories from multiple thermochronometers**

Aside from structural and kinematic analysis, thermochronometry in a deep crustal sections such as Gold Butte facilitate the synthesis of cooling ages of different chronometers to constrain the long-term thermal histories at different crustal depths. Reconstructing meaningful long-term rock thermal histories in this way however, obviously requires accurate intercalibration of each method. All thermochronometers suffer from uncertainties resulting from unique characteristics of each technique. Much progress has been made in the last decade on the behavior of fission track annealing in both apatite and zircon, but unresolved questions remain about fundamental annealing controls, rates, and influences of composition and radiation damage. Likewise, despite thousands of results that are apparently broadly consistent with other available thermal and geologic constraints, several fundamental assumptions of the method of multi-domain $^{40}$Ar/$^{39}$Ar dating of K-feldspar have recently been called into question. Questions surrounding the robustness of $\alpha$-ejection corrections in (U-Th)/He dating and relative youth of the method also motivate cross-checking against other chronometers. Because many thermochronometers are restricted to temperature ranges that do not overlap with those of other systems however, historically it has been difficult in many cases to cross-check thermal histories derived from different chronometers.
The low closure temperature of ~110°C accessible by apatite fission-track dating and track length analysis for example, has, until the advent of apatite He dating, been largely uncontestable by other radioisotopic techniques. Gaps in temperature sensitivity between $^{40}$Ar/$^{39}$Ar and fission track dating have also prevented rigorous interchronometer calibrations. Development of (U-Th)/He dating of apatite, zircon, and titanite will provide many opportunities for such comparisons in a wide variety of orogenic settings. Preliminary results of such cross-calibrations look promising (Fig. 3). Long term thermal histories of rocks derived from eight or more dating techniques with different closure temperatures in the Coast Mountains of Southeast Alaska, for example, suggest strikingly smooth hyperbolic cooling paths reflecting slow post-orogenic and post-plutonic exhumation through the mid Miocene, similar to thermal histories from apatite and zircon (U-Th)/He age-elevation relations in both SE Alaska and British Columbia. Preliminary comparisons between cooling histories derived from zircon and apatite (U-Th)/He and K-feldspar $^{40}$Ar/$^{39}$Ar multidomain modeling also provide indicate good agreement between the two techniques (Fig. 3).

**Crystal-size-age relationships**

A fundamental but oversimplified assertion often made for geochronometry in general is the requirement of “closed system”; that is, no radioisotopic parent or daughter has been gained or lost since the time being dated (formation or cooling). In truth, this assumption is rarely met for any geochronometer, and is often farther from reality for low-temperature thermochronometry such as (U-Th)/He dating, in which the transition from loss to retention of radiogenic He can be slow and incomplete. In the case of slow cooling or prolonged residence He PRZs, the measured He age of a sample may have little to do with any specific time or temperature and instead represents a potentially complex low-T thermal history. In such cases, the effects of otherwise unimportant crystal characteristics on He diffusion, and therefore He age, may be greatly magnified. One such characteristic is crystal size. Because the length scale of He diffusion in apatite, titanite, and possibly zircon is correlated with the size of the (intact, crack-free) crystal itself, in conditions of partial He retention, larger crystals retain a significantly larger fraction of their radiogenic He than smaller crystals. This means that even in single hand samples with certain thermal histories, apatite crystal size will be correlated with He age, and the details of this correlation is a sensitive, though non-unique, record of thermal history at temperatures below the system’s nominal closure temperature. Apatite He ages from granitic basement in the Bighorn Mountains, in northern Wyoming show well-developed crystal-size-age correlations (Fig. 4), with crystals of 30-90 µm radii varying from ~100 to 350 Ma. These correlations are consistent with thermal histories involving residence at temperatures less than about 70-90°C from as early as the Precambrian to just before Laramide uplift of the range at ~65 Ma (Reiners and Farley, 2001). This requires either unusually low
pre-exhumation geothermal gradients or ancient topographic relief in the presently exposed Bighorns that predated Laramide (~65 Ma) uplift. Crystal-size-age correlations may also work with zircon, titanite, or other phases as well, and may provide more detailed thermal history constraints than single cooling ages in a variety of environments, including sedimentary basins, and rocks that have undergone only limited exhumation (< about 2-3 km), as is common in ancient orogenic settings.

**Paleogeomorphology**

One of the most innovative and promising uses of (U-Th)/He thermochronology derives from the uniquely low closure temperature of the apatite He system, and its sensitivity to temperature variations in the uppermost 2-3 km of crust. At these depths, the depth and geometry of ~100°C isotherms can be strongly affected by topography. For certain combinations of topographic wavelength and relief, isotherms are strongly “bent” by valleys and ridges, resulting in higher geothermal gradients beneath valleys than ridges. Simply put, this means that rocks exhumed from under ridges will cool through their closure temperature later than those exhumed under valleys. If the topographic relief is sufficiently old relative to rock exhumation, apatite He ages of samples collected at similar elevations in transects across this relief will be higher in valley regions than in ridge regions. House et al. [1998] demonstrated the utility of this approach in a groundbreaking study documenting the 60-80 Ma antiquity of topographic relief of several major river valleys on the western side of the Sierra Nevada. These results carry a multitude of important implications for tectonic, geomorphic, and structural history of the Sierra and the greater western U.S. Cordillera. In general, the apatite He dating holds great potential for paleogeomorphologic problems, which have historically been resistant to applications of radioisotopic geochronometry.

**Challenges and potential of (U-Th)/He chronometry**

Improved understanding of He diffusion in crystals and the development of practical analytical techniques (including treatment of α-ejection) have overcome many of the early problems with (U-Th)/He chronometry. A growing appreciation for its relatively straightforward thermochronometric constraints is generating intense interest in the technique for many applied geologic studies. But a clear-cut happy ending to the story of the ugly-duckling-technique of radioisotopic dating would be premature. Several problems and possibly unavoidable limitations to the technique remain. Some of these, such as poor understanding of some aspects of He diffusion in apatite at high temperature, and in titanite and to a lesser degree, zircon, in early step-heating cycles, may be largely irrelevant to the practical utility of the technique. But other poorly understood or difficult to constrain aspects of the system cannot be ignored, such as the potential for α implantation in dated crystals from previously adjacent U-Th bearing grains, or
the potential for non-zero He concentrations in intergranular media or adjacent grains that may affect diffusion characteristics in dated grains. Other problems are more practical, but frequently vexing. Many rock types do not yield dateable minerals (especially apatite) of sufficient purity, abundance, or morphology for reliable He dating. Routine techniques for dating of small, inclusion-rich, anhedral apatites have not yet been developed, mainly because of potential difficulties with $\alpha$-ejection corrections caused by U-Th rich inclusions and uncertainty of grain geometry during He ingrowth. Yet such “crapatite” crystals comprise the bulk of the natural sample population, especially in sedimentary rocks.

Another potential problem is poor reproducibility of He ages of both single- and multi-grain aliquots in some samples, particularly those that have experienced slow cooling or prolonged residence at temperatures of partial He retention. In most cases, although formal analytical precision on (U-Th)/He ages rarely exceeds 1-2%, reproducibility on most samples is about 6-8% ($2\sigma$). This probably reflects incorrect assumptions involved in the $\alpha$-ejection correction such as original crystal dimensions/geometry, or more likely, uniform zonation of U and Th in dated crystals. These uncertainties probably limit routinely achievable (U-Th)/He age reproducibilities to no better than ~5%. But in some cases, including apatites from Archean gneisses from the Wind River range, Wyoming, multiple repeat analyses of both single and multi-grain aliquots are not reproducible to better than about 15-20% ($2\sigma$), and these ages do not correlate with crystal size, as in the Bighorn Mtns (Fig. 4). Ion probe analyses of these samples show complex U-Th concentration variations of factors ~5-15 both within and among crystals, which would be expected to generate age variations on the order of 15% in multiple- and single-crystal aliquots. Accounting for the effects of U-Th zonation in He dating may be one of the most significant limitations of the technique at present. While it may be possible to document such zonation in populations of grains, identification and correction for these effects in individual dated crystals is not yet possible.

Despite complications arising from effects such as U-Th zonation, unique aspects of the (U-Th)/He system provide great potential for innovative applications of method. The relatively rapid growth rate of $^4$He, for example, may be particularly suitable for dating young ($10^3$-$10^6$ Ma) samples. One hundred times more $^4$He atoms are produced from a typical apatite with only 25 ppm U and Th than $^{40}$Ar atoms are produced from a rock with 1% K ($10^7$ more $^4$He atoms are produced than the number of natural fission tracks). The relatively low He content of air (5 ppm, compared with 1% for Ar) also palliates analytical blank problems, which are the current limitation to measuring low-He samples and young ages. Several studies have demonstrated the utility of He dating young volcanic tuffs, with ~6-8% ($2\sigma$) precision results consistent with Ar ages, for ~300 ka apatites and zircons from New Zealand, and 100-400 ka titanites from the Canary Islands. In the case of titanite, glass adhering to crystals was intentionally included in the dating analyses to capture He generated within but ejected from the crystals and obviate $\alpha$-ejection corrections. Development of dating techniques for other phases may also permit
relaxation of $\alpha$-ejection correction requirements in some cases. For example, accurate dates on fayalite
phenocrysts and garnet porphyroblasts containing small (e.g., <5-10 microns) but extremely U-Th-rich
inclusions, suggest the potential for internal-source He dating in which host minerals capture inclusion-
generated He and control diffusivity and closure temperature.

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Figure 1. Minerals commonly dated by the (U-Th)/He technique: apatite [Ca$_5$(PO$_4$)$_3$(F,Cl,OH)]; closure temperature ($T_c$) $\sim$ 70°C], zircon [ZrSiO$_4$; $T_c$ $\sim$ 180-200°C], and titanite [CaTiSiO$_5$; $T_c$ $\sim$ 180-200°C].
Figure 2. **A.** Location and structural interpretation of the Gold Butte crustal section. **B.** (U-Th)/He and fission-track (FT) thermochronometric ages from Gold Butte, vs. paleodepth. Increasing paleodepth is towards the western part of the block. Ages are 15-20 Ma at paleodepths corresponding to temperatures above the closure temperature of each thermochronometer, and increase at shallower paleodepths. These results are consistent with rapid exhumation of a largely intact ~17 km thick crustal block, at 15-20 Ma. The horizontal colored ranges represent intervals of the closure temperatures of each chronometer, assuming geothermal gradient between 20-25°C/km. Apatite FT dates from Fitzgerald et al. [1991]; Zircon FT dates from Bernet et al. [in prep].

Figure 3. **A.** Thermal history of the Speel River pluton, near Holkham Bay, southeastern Alaska, showing continuous hyperbolic cooling pattern since crystallization at ~60 Ma, and consistent pattern from all available thermochronometers. Other data (apatite He ages vs. elevation) from this area suggest rapid cooling occurred no earlier than about 10 Ma. **B.** Comparison of low-T thermal history from K-feldspar $^{40}$Ar/$^{39}$Ar multidomain diffusion modeling and zircon and apatite He cooling ages, for sample from the eastern margin of the Tibetan Plateau [Kirby et al., in press].
Figure 4. Correlations between apatite crystal radius and (U-Th)/He age, for two samples from the Bighorn Mountains, Wyoming. Dashed grey lines are predicted size-age correlations from He production-diffusion models, for thermal histories of rocks at different depths beneath the Precambrian-Cambrian unconformity, with burial by 2.8 km of Phanerozoic sedimentary rocks prior to Cretaceous uplift and exhumation. Resolvable crystal-size-age correlations develop only in rocks that have cooled extremely slowly or resided at temperatures corresponding to partial He retention (~40-80°C for apatite) for long periods of time. X-axis error bars are $2\sigma$ standard deviation of apatite radii in each dated aliquot. Y-axis error bars are $2\sigma$ age uncertainty.