

# (U-Th)/He thermochronometry in the Bighorn Mountains, Wyoming: Constraints on the timing of exhumation

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## INTRODUCTION

Apatite retains radiogenic helium at low but not high temperatures. Because the apatite (U-Th)/He thermochronometer is sensitive to temperatures that occur in the upper few kilometers of crust, it is useful for studying the exhumation of mountain ranges. (For more about (U-Th)/He thermochronometry, see Crowley and Reiners, this volume.) We applied (U-Th)/He thermochronometry to Precambrian granitoids and gneiss from the central core of the Bighorn Mountains. The geologic history that is relevant to (U-Th)/He thermochronology began in the Precambrian when the surface that would become the Precambrian/Cambrian unconformity was exposed. At that time, the sample rocks were cold relative to the apatite closure temperature, and helium was accumulating within the apatite crystals. Subsequently, burial by Paleozoic and Mesozoic sediments heated the basement. As sediment accumulated, the temperature increased to the point at which helium was at least partially lost from the apatite. The layer cake deposition was permanently interrupted by structural deformation that produced the Bighorn Mountains. During the exhumation related to structural deformation and uplift, quantitative retention of helium in apatite resumed as the rocks approached the surface. The earliest sedimentary evidence for exhumation of the Bighorns falls in the range of 65-70 Ma, as determined from the Bighorn Basin to the west and the Powder River Basin to the east (Dickinson et al., 1988; also see Crowley and Reiners, this volume).

## METHODS

**Sample collection.** The general sampling strategy was to collect samples along elevation transects, though site selection was limited by accessibility and rock type. A differentially corrected GPS point was obtained at most sample sites. Elevation was determined from an altimeter, from the DEM based on the GPS point location, and/or from the 7.5" topographic map.

**Lab methods.** Apatite was separated using standard methods. Robert Giegengack of the University of Pennsylvania provided apatite separates for six sites. From the apatite separates, we selected approximately six to ten grains for each sample run, aiming to obtain inclusion free, large, euhedral grains. Grain dimensions were measured for the alpha ejection correction (Farley et al., 1996).

Helium was measured in Ken Farley's lab at the California Institute of Technology by isotope dilution with a quadrupole mass spectrometer. Uranium and thorium were also measured by isotope dilution using a double-focusing sector ICP-MS and the same crystals from which helium had been extracted. The samples of Durango apatite that we ran as a standard yielded ages of  $29.6 \pm 1.8$  Ma,  $29.8 \pm 1.8$  Ma, and  $32.4 \pm 1.9$  Ma, with an expected age of about 31 Ma (Zeitler et al., 1987).

**Sources of error.** The  $2\sigma$  reproducibility of standards is about  $\pm 6\%$  (Farley, 1999). Only 2 out of 15 of our replicates had ages within 6% of each other. The poorer than expected reproducibility probably results from two main factors: 1) Grain size affects helium retention, and thus age, of grains that reside in the partial retention zone (PRZ) for a long duration. (See Crowley and Reiners, this volume, for an explanation of the PRZ.) In the PRZ, large crystals lose less of their helium, and thus produce older ages, than small crystals. Although this relationship could be a valuable source of information, our sample runs contained mixed grain sizes. Therefore, our data set is not ideal for evaluating the expected relationship, but the poor reproducibility may be a result of the effect. 2) Inclusions cause anomalously old ages (as discussed by Kaye, this volume). Indicators in the analysis that suggested the presence of an inclusion justified the discard of some ages. A few of the ages have unexplainable error, as they did not have indicators of inclusions, nor did they follow the expected pattern for the effect of grain size on age in the PRZ.

## RESULTS and DISCUSSION

Figure 1 shows the spatial distribution of the samples and their apparent ages, which range from  $62 \pm 4$  Ma

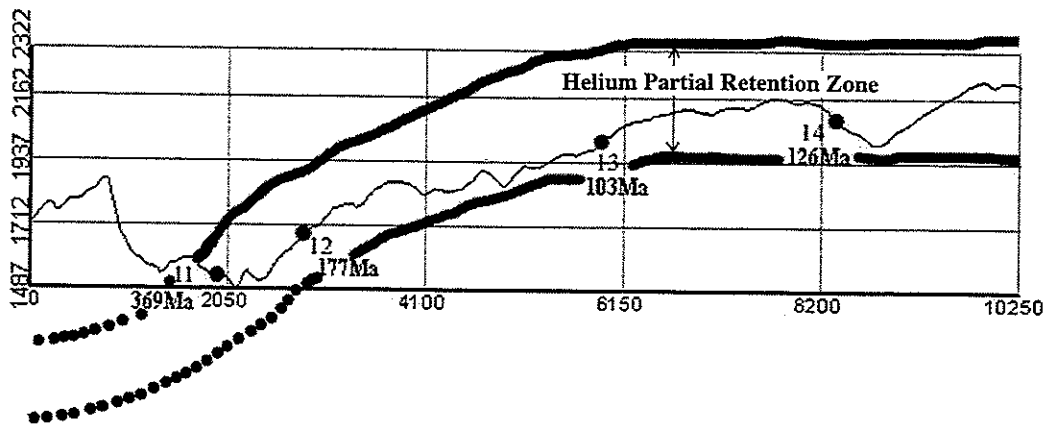


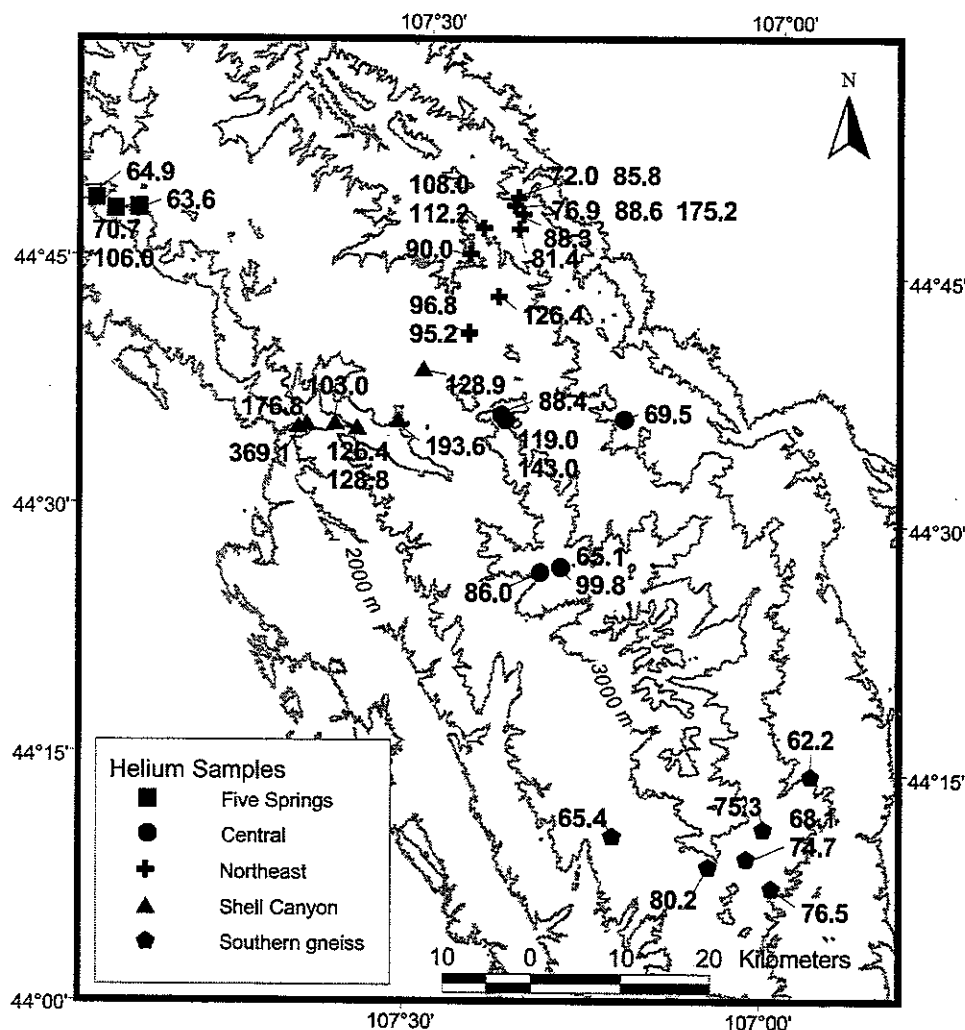
Figure 4. Schematic cross-section through bottom of Shell Canyon, showing reconstructed paleo-PRZ at ~65 Ma. Thin black line denotes modern-day erosional surface. Apatite He ages are noted next to each sample. Elevation and horizontal distance units are given in meters. Vertical exaggeration is 3.

eastern end of Shell Canyon experienced burial beneath pre-Laramide sediments sufficiently thick enough to keep the basement heated to greater than ~70°C prior to about 120Ma. Variations in the thickness of sedimentary cover over the Bighorns likely produced the wide variability in measured apatite (U-Th)/He ages.

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to  $369 \pm 22$  Ma. Ages greater than 175 Ma were obtained for 4 of the 29 sites. Many of the ages are older than expected for the Laramide orogeny based on the sedimentary record.



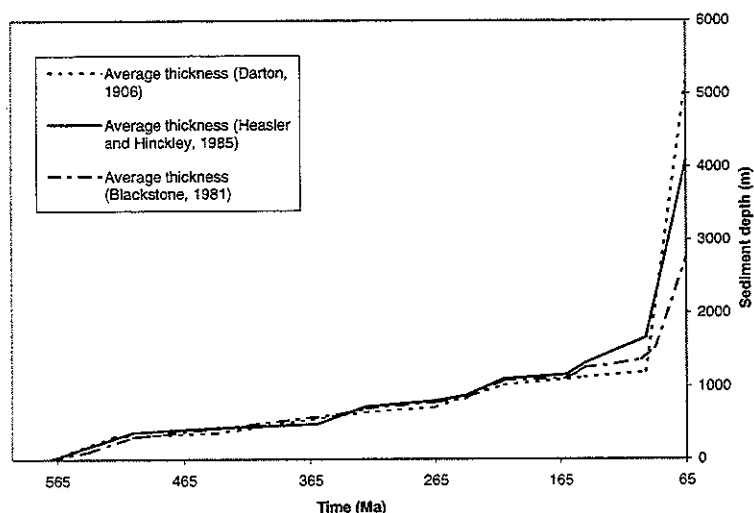
**Figure 1.** Map of the Bighorn Mountains with apparent helium ages (Ma). For samples with replicates, the result of each sample run is shown. Helium ages are tabulated in Kaye, this volume.

Contour interval: 500 m.

**The oldest ages in the context of the PRZ, and implications for sediment thickness.** Samples from sites near the unconformity that produced the oldest ages (such as  $369 \pm 22$  Ma and  $194 \pm 12$  Ma) did not record the time of Laramide exhumation. To explain these unexpectedly old ages, an understanding of how helium is retained must be combined with the known geologic history of the Bighorn Mountains. In a range of temperatures from about  $45^{\circ}\text{C}$  to  $85^{\circ}\text{C}$ , helium is only partially retained in apatite. (See Crowley and Reiners, this volume.) The age calculation assumes that the apatite went directly from a helium free state to one in which all helium was retained. This assumption is not met for rocks that resided in the PRZ for an extended period of time, and the ages of such rocks do not represent the amount of time since the rock cooled below a known closure temperature. Prior to the Cretaceous, at the time reflected by the very old apparent ages, the sediment was not thick enough (and thus the basement near the basal Cambrian unconformity was not hot enough) for the apatite ages to reset through the complete loss of helium (Fig. 2). Furthermore, the ages were not reset at the time of the expected maximum sediment thickness (near the end of the Cretaceous), as the ages are much older than that. Therefore, these ages are a result of extended PRZ residence. Helium accumulation began in the Precambrian; helium was partially lost as the basement was heated due to burial by sediments, but the rocks were not heated enough to reset the ages prior to Laramide exhumation.

The conclusion that at least some of the structurally shallow samples did not become hot enough to completely de-gas before Laramide exhumation can be used to place constraints on the depth of burial by Paleozoic and Mesozoic sediments. Estimates of the amount of sediment that was deposited can be made based on the sedimentary rocks that are exposed on the flanks of the mountains and those in the adjacent Powder River and Bighorn Basins (Fig. 2). Whether or not ages were reset depends on the conditions under which apatite will de-gas,

as well as the rate at which the temperature profile equilibrates as sediment is deposited. Degassing of apatite is dependent not only on the maximum temperature achieved, but also on the duration for which high temperatures were maintained. According to Wolf et al. (1998), apatite held at 75°C would nearly reset after about 17 Ma, while at 100°C the age would essentially reset in a million years. Based on a one-dimensional numerical thermal model with sedimentation rates implied by Figure 2, the thermal profile should adjust rapidly enough for temperature to be almost directly related to the sediment thickness. Therefore, five kilometers of sediment is incompatible with the helium data, as even the shallowest ages would have been reset. The low-end estimate is most reasonable.



**Figure 2.** Paleozoic and Mesozoic sediment accumulation over time based on sediment thicknesses on the flanks of the mountains and in the adjacent basins. Unconformities within the section were ignored, as they are assumed to be irrelevant for helium ages. Data from Darton (1906), Blackstone (1981), and Heasler and Hinckley (1985).

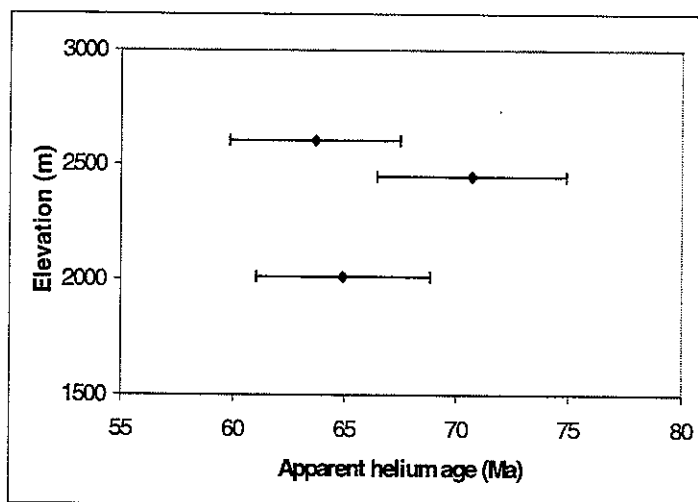
**Interpretations for the intermediate ages.** Two alternative interpretations follow to explain the remaining ages (except those from Five Springs): 1) The ages are old because they reflect PRZ conditions; the timing of exhumation is younger than suggested by the apparent ages, and possibly consistent with the sedimentary record. 2) The ages accurately reflect exhumation beginning earlier than suggested by the sedimentary record, as early as 100 million years ago or more.

The graph of age vs. elevation shows a poor correlation because of the influence of structural relief. (See Kaye, this volume, for this graph and for further explanation). Because of the poor correlation, the age-elevation plot does not reveal whether samples were collected across the base of a fossil PRZ, so it does not assist in determining the extent to which each of the above interpretations can account for the ages. However, variation in age between replicates, which could result from the effect that grain size has on helium retention in the partial retention zone, suggests strong PRZ influence.

**Five Springs: Degassing due to hot fault-related fluids?** The youngest group of ages in the Bighorns was recorded in the Five Springs region, and these ages are invariant across about 600 meters of topographic relief (Fig. 3). Sample BH2, which was within approximately 15 meters of the basal Cambrian unconformity, has a much younger age than other sites located near the unconformity.

The interpretation for the Five Springs ages must account for the young age near the unconformity and the lack of an age-elevation relationship. One reasonable explanation is that hot fluids associated with the basement faulting affected the apatite helium ages. A similar conclusion was drawn for shear zone apatite fission track ages in the Beartooth Mountains (Omar et al., 1994). Supporting evidence for this explanation comes from both field and isotope work. The rocks in the Five Springs area are pervasively fractured and faulted. Furthermore, an oxygen isotope study completed as a part of this Keck project produced data from the Five Springs area that demonstrate fluid flow at temperatures in the range from 325-425°C (Esser, this volume). At these temperatures, (U-Th)/He ages would be reset rapidly, so the Five Springs ages may closely constrain a time of activity on the fault. The age of approximately 67 Ma from these samples corresponds approximately to the time of earliest sedimentary evidence for exhumation (Dickinson et al., 1988). The possibility of using this method to constrain the time of fault activity is intriguing and worthy of additional study, as it may provide a way to determine the time of uplift from structural deformation, rather than the time of exhumation.

**Figure 3.** Five Springs age-elevation plot. These samples, which span about 600 m of topographic elevation, represent the same age within standard 6% error. From highest to lowest elevation, the samples are BH3, BH2, and BH5SPR. One anomalous replicate of BH2 was omitted from this graph.



## CONCLUSIONS

At least some of the apparent ages are anomalously old due to residence in the partial retention zone, while the youngest ages from Five Springs may have been reset by hot fault-related fluids. The results are compatible with the timing of exhumation based on the sedimentary record, but alternative interpretations are possible, as ages do not uniquely constrain the time-temperature history experienced by the rocks.

## ACKNOWLEDGMENTS

In addition to those acknowledged in the project overview, I would like to thank the following people: Robert Giegengack of the University of Pennsylvania for providing apatite separates from six sites in the Bighorns; Mark Garcia of Caltech for assistance with rock crushing and apatite separation; Tony Soeller for assistance in the GIS lab at Caltech; and, of course, my advisors, the other members of my Keck project, and Carleton Geology. In addition to the Keck Consortium funding, I received generous support from the Duncan Stewart Fellowship.

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# An exploration of U,Th-Pb ICP-MS dating

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## INTRODUCTION

The decay of U and Th to Pb in minerals is a well-established geochronologic system (Faure, 1986). Traditionally, U, Th, and Pb isotopic compositions are measured using thermal ionization mass spectrometry (TIMS). The TIMS method yields very precise dates, but it is expensive and time consuming. An alternate method of obtaining U,Th-Pb dates involves measuring U, Th, and Pb isotopic compositions with inductively coupled plasma-mass spectrometry (ICP-MS). This study was conducted to test the feasibility of using single-collector, sector ICP-MS to obtain U,Th-Pb dates from igneous and metamorphic rocks from the Precambrian basement of the Bighorn Mountains in north central Wyoming (Fig. 1). TIMS and K-Ar dates obtained by Heimlich and Banks (1968) show the Precambrian gneisses and granites of the Bighorn Mountains to be ~2.31-2.78 Ga, and 2.9 Ga, respectively. The purpose of this study was to compare ICP-MS U,Th-Pb dates obtained from apatite and titanite, with the TIMS and K-Ar dates of Heimlich and Banks (1968) obtained from zircon and monazite. The internal consistency of our data is also checked in order to determine the precision of the ICP-MS technique.

## GEOLOGIC SETTING AND SAMPLE LOCATIONS

The Bighorn Mountains, located in north central Wyoming, are a Laramide age thick-skinned uplift (Darton, 1906; Crowley and Reiners, 2000). A large block of basement rock was uplifted due to compression (Darton, 1906; Crowley and Reiners, 2000). Paleozoic sedimentary rocks deposited on top of the Precambrian crystalline core of the range form drape folds on the east and west margins of the uplift. Due to erosion, the Precambrian core of the range is exposed along the axis of the uplift (Fig. 1). The Precambrian section can be divided into two general units; granitic through dioritic rocks crop out in the north, while gneisses dominate the southern part. Samples PRBH28 and BZBH6 were taken from the Precambrian granitoids in the north and sample PRBH10 was taken from the Precambrian gneisses (Fig. 1). BZBH6 was taken from the same general locality as a quartz monzonite that was previously dated with TIMS by Heimlich and Banks (1968).

## METHODS

The three rock samples were crushed, pulverized, and washed, and titanite and apatite were separated by Frantz, Mag-stream, and heavy liquids. Titanite and apatite grains were handpicked from the mineral separates. Grains used for dating were clean and inclusion free. Titanite aliquots of ~10 grains and apatite aliquots of ~40 grains were then added to 100  $\mu$ l of 2x distilled H<sub>2</sub>O and spiked with U-Th spike, containing 2.8 ng of <sup>230</sup>Th and 1.6ng of <sup>235</sup>U, and <sup>205</sup>Pb spike, containing 2.0 ng of <sup>205</sup>Pb. Apatite grains were dissolved in 100  $\mu$ l of HNO<sub>3</sub> and diluted with 2x distilled water. Titanite grains were dissolved in 350  $\mu$ l of HCl and 150  $\mu$ l of HF (sample BZBH6 was dissolved in HCl only) in closed Teflon vials on a hotplate. After the HF and HCl had evaporated from the titanite samples, 100  $\mu$ l of HNO<sub>3</sub> and 2 ml of 2x distilled H<sub>2</sub>O was added before ICP-MS analysis. A blank vial (containing no mineral grains) was sent through the entire procedure along with the aliquots. After ICP-MS analysis, the amount of Pb measured in the blank was subtracted from that of the samples.

## RESULTS

The isotope ratios of <sup>238</sup>U, <sup>235</sup>U, <sup>232</sup>Th, <sup>204</sup>Pb, <sup>205</sup>Pb, <sup>206</sup>Pb, <sup>207</sup>Pb, and <sup>208</sup>Pb were measured using a single collector, sector ICP-MS in apatite and titanite from samples PRBH10, PRBH28, and BZBH6. For PRBH10 and PRBH28, two apatite and three titanite aliquots were measured, and for BZBH6, five titanite aliquots were measured. For each aliquot that was sent through the ICP-MS a <sup>206</sup>Pb/<sup>238</sup>U, <sup>207</sup>Pb/<sup>235</sup>U, <sup>208</sup>Pb/<sup>232</sup>Th, and a <sup>207</sup>Pb/<sup>206</sup>Pb date was calculated and reported in Table 1.

For all three samples <sup>206</sup>Pb/<sup>238</sup>U dates range from 2756-3556 Ma, <sup>207</sup>Pb/<sup>235</sup>U dates range from 2733-3123 Ma, <sup>208</sup>Pb/<sup>232</sup>Th dates range from 3081-5756 Ma, and <sup>207</sup>Pb/<sup>206</sup>Pb dates range from 2649-2896 Ma. Concordia plots show that some of the aliquots fall on concordia while others plot above concordia (Fig. 2). The percent differences between the <sup>206</sup>Pb/<sup>238</sup>U dates and <sup>207</sup>Pb/<sup>235</sup>U dates and <sup>206</sup>Pb/<sup>238</sup>U-<sup>207</sup>Pb/<sup>235</sup>U averages are shown in Table 1 for each sample. For PRBH10 and PRBH28, the percent differences are below three percent with the exception of PRBH10t2. For BZBH6 the percent difference ranges from 2 to 12 percent.

## DISCUSSION

Average U-Pb dates for sample PRBH10, from the gneiss, are 2766±28 Ma and average U-Pb dates for samples PRBH28 and BZBH6, from the granitoids, are 2939±5 and 3152±147 Ma, respectively (Table 1). Averages were calculated using titanite and apatite dates from each sample because no systematic difference in dates from different minerals is apparent (Fig. 3). The average for PRBH10 does not include aliquot PRBH10t2 because it is significantly more discordant than the other aliquots from the same rock (Table 1).