Using Apatite (U-Th)/He Thermochronometry to Study the Low-Temperature Thermal History of Shell Canyon, Northwestern Bighorn Mountains, Wyoming

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INTRODUCTION

The Bighorn Mountains of north-central Wyoming provide an excellent opportunity to study the uplift and exhumation of crystalline basement in the Rocky Mountain region. (U-Th)/He dating, a recently refined (Wolf et al., 1996; House et al. 1997) technique for studying the low temperature thermal history of apatite-bearing rocks, provides important constraints on the timing and geometry of uplift and exhumation of crust. The structure of the Bighorns and their marginal basins typifies mountain ranges uplifted in the Rocky Mountain region during the Laramide Orogeny, which lasted from ~75 to ~45Ma (Snoke, 1992). Crustal shortening during this period caused Precambrian crystalline rocks to bulge upwards beneath Paleozoic and younger sediments, causing the sedimentary layers to dip steeply along the margins of the uplifted crystalline rocks into what are now the Powder River and Bighorn basins. The general structure of the Bighorns resembles a large-scale asymmetric anticline (see Figure 3). Easily accessible outcrops of Precambrian crystalline rock are found today throughout the range along US Route 14 through Shell Canyon over Granite Pass. Many petrologic and structural studies have been done on the Bighorn Mountains (e.g., Darton, 1906; Wise and Obi, 1992). Despite the extensive research done on the Bighorns and other Laramide ranges, little is known about their low-temperature exhumation history, and the (U-Th)/He ages obtained in this study provide valuable details about the timing and geometry of uplift and exhumation.

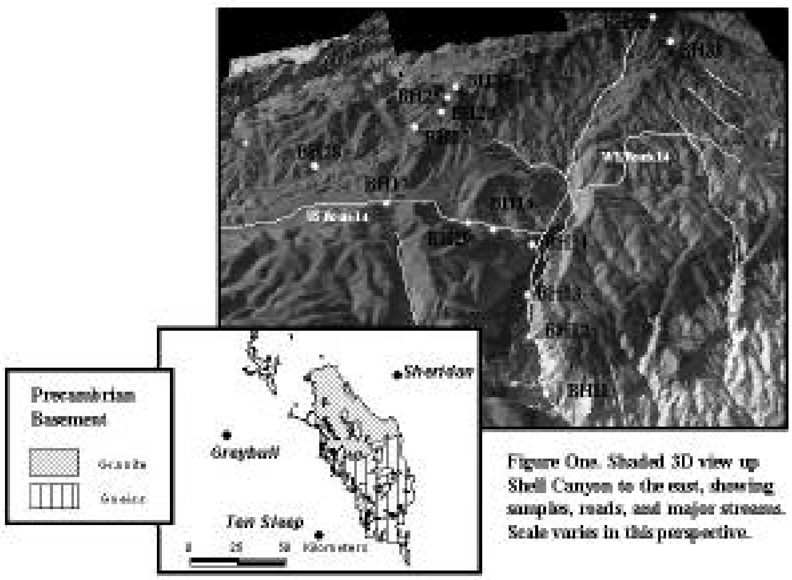

Figure One. Shaded 3D view up Shell Canyon to the east, showing samples, roads, and major streams. Scale varies in this perspective.

METHODS

Field – Bighorns

Samples collected from the Bighorn Mountains come from five geographic areas (Reuter, Fig. 2, this volume). They are (Table 1): an east-side elevation transect, a west-side elevation transect through Shell Canyon, a central plateau group consisting of range-parallel equal elevation samples, a group collected near Five Springs (northwest part of the range), and samples from the gneissic rocks comprising the southern part of the range. Because accurate location and elevation information are crucial in using He dates to constrain orogenic events, both GPS and an anaeroid altimeter were used to locate the samples (~2-3 kg each) and their elevations. The location of each sample with respect to the Precambrian/Cambrian unconformity was also noted when possible. "BH##" samples were processed by 1999 Bighorns Keck Project participants, while "BHM-###" samples were He dated from separates provided generously by Dr. Robert Giegengack of the University of Pennsylvania.

Laboratory – Caltech

At Caltech, (U-Th)/He apatite separates were prepared from samples using standard techniques. Samples were crushed, pulverized, washed, and sieved to 50 and 230 mesh. Apatite was separated using standard magnetic and heavy liquid techniques. Only euhedral, inclusion-free grains (~80 microns in width and ~200 microns in length), were selected for dating. Typically, six to seven grains per sample were selected, measured, weighed, and placed in stainless steel vessels for ^{4}He analysis. ^{4}He contents were determined by outgassing the samples at 950°C, spiking with ^{3}He, and measuring ^{4}He/^{3}He on a quadrupole mass spectrometer in the Noble Gas Isotope lab of Kenneth Farley. Samples were then dissolved in HNO_3, and U and Th concentrations were determined by isotope dilution on a sector ICP-MS.

Inclusions (such as zircon) present problems for U-Th/He analyses (Wolf et. al., 1996) by introducing anomalously high amounts of apparently parentless ^{4}He, giving inaccurately old ages. Extreme care in selecting inclusion-free grains was taken by scrutinizing them under cross-polarized light for uniform and invariant extinction. Also, during ^{4}He analysis, the “re-extract” process served to eliminate dates calculated from samples whose apatite grains possibly contained previously undetected inclusions. Apatite should completely outgas all ^{4}He during heating to ~950°C for about 20 minutes, but in some instances, additional ^{4}He was released from grains during a second heating step. This “re-extracted” helium may have originated from an inclusion of a mineral other than apatite in the sample grains. Ages obtained from samples that experienced “re-extracts” during analyses were discarded. When possible, additional grains were chosen from the remaining separates of samples, and additional He dating was performed on the second aliquot of apatite grains.

An additional correction was applied in the age calculation of each sample to account for loss of energetic ^{4}He from small grains (F_t correction, Farley et al., 1996). ^{4}He can be lost disproportionately from alpha decay of ^{238}U atoms situated at the outer margins of an apatite crystal. F_t values for each sample, indicative of the degree of the correction necessitated by the size of the sample grains, are given in column four of Table 1.

Region	Sample	He Age (Ma)	Elev. (m)	Age Err. (Ma)	Ft
	BH11B	369	1497	22	0.64
	BH12	177	1673	11	0.74
	BH13B	103	1887	6	0.72
Shell Canyon	BH13C	155	1887	9	0.75
	BH14	126	2027	8	0.72
	BH16	194	2405	12	0.79
	BH17	129	2716	8	0.76
	BH5SPR	65	2012	4	0.76
Five Springs	BH2	71	2448	4	0.74
	BH3	64	2603	4	0.53
	BH4B	65	2563	4	0.67
	BH8	62	2505	4	0.73
	BH10	80	2984	5	0.75
South Gneiss	BHM-739	77	2566	5	0.78
	BHM-508	68	2633	4	0.8
	BHM-508B	75	2633	4	0.78
	BHM-507	75	2929	5	0.78

Region	Sample	He Age (Ma)	Elev. (m)	Age Err. (Ma)	Ft
	BH18	72	1948	4	0.75
	BH18B	86	1948	5	0.78
	BH19B	89	2225	5	0.71
	BH19C	77	2225	5	0.77
East Side	BH20B	88	2298	5	0.68
	BH21	81	2417	5	0.68
	BH22	112	2557	7	0.62
	BH30	126	2655	8	0.81
	BHM-725	95	2609	6	0.77
	BH23	108	3301	6	0.67
	BH23B	119	3301	7	0.64
	BH25	88	3139	5	0.52
Central	BH32B	100	3414	6	0.78
	BH33	86	2890	5	0.66
	BHM-618	70	2377	4	0.8

Table 1. (U-Th)/He ages of samples from all locations in the Bighorns. Samples with letters indicate replicate analyses.

RESULTS

(U-Th)/He ages for samples from all locations are shown in Table 1, and a plot of elevation vs. He age is given in Figure 2. Ages of samples from Shell Canyon range from as old as ~369 Ma to as young as ~126 Ma.

Samples taken from the lowest elevations at the western end of Shell Canyon yield the oldest ages, while those collected from the crest of the range at higher elevations give ages that generally cluster around ~120 Ma.

DISCUSSION

The Shell Canyon He ages exhibit an unusual age-elevation trend. According to the gently arched structural geometries proposed for the western side of the Bighorns near Shell Canyon (Figure 3), He ages of the Shell Canyon samples should be younger at lower elevations and gradually become older towards the top of the range. This pattern would be expected if the basement had been uniformly and deeply buried prior to the Laramide, and then during uplift simply bulged upwards beneath the overlying Paleozoic and Mesozoic sedimentary cover. In this scenario, exhumation of the uplifting block would have unroofed the central part of the range before the margins, and the higher samples (BH23, BH25, BH32) would have begun accumulating ^{4}He before the lower sample (BH11), giving the lower sample a relatively younger age. Ages calculated in this study, however, are oldest at the lowest elevations, (BH11, age 369 Ma) and younger towards the higher elevations at the top of the range (e. g. BH14 age 126Ma).

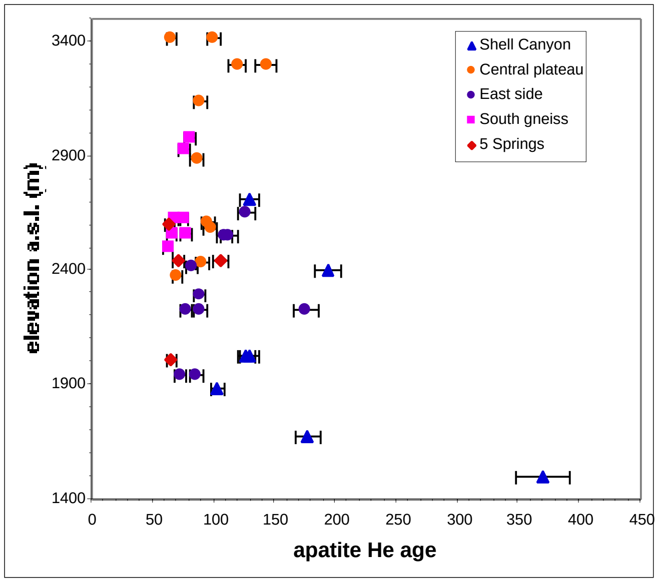

Figure 2. Plot of apatite (U-Th)/He ages vs. elevation above sea level.

The He ages obtained in this study mandate that the lower, western side of the Bighorns must have occupied a high structural position since at least ~369 Ma, if not longer. The lower elevation sample, BH11, has been accumulating ^{4}He for at least ~369Ma, which indicates that the western slope of the Bighorns along Shell Creek has probably not experienced temperatures warmer than ~70°C since at least the early Paleozoic Era. In all likelihood, this region has probably been cooler than ~70°C since the Precambrian, as the calculated age of BH11 assumes a transition from complete ^{4}He loss to total ^{4}He retention at 369 Ma. In reality, this region of the basement may have resided in the ^{4}He Partial Retention Zone (PRZ) for much longer than the last 369 Ma (see Reiners and Crowley, this volume, for further explanation of the ^{4}He PRZ). Samples with younger He ages from the core of the range likely occupied deeper structural positions (see Figure 4, cross section of Shell Canyon, for details).

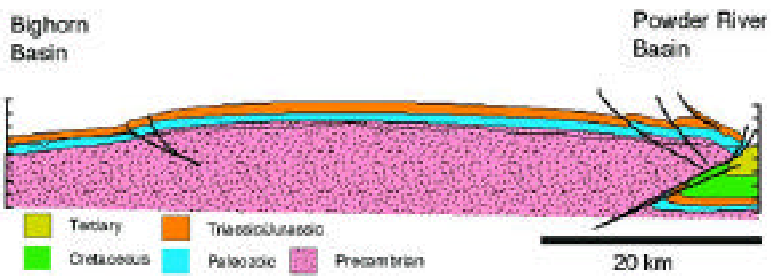

Figure 3. Schematic cross-section through the Bighorns. after Stone, 1993.

The presence of older He age samples at lower elevations than younger He age samples in Shell Canyon requires that the basement and the He PRZ in this region were never deeply buried, and were strongly folded during the Laramide. The Precambrian/Cambrian erosional surface across the Bighorns remains today as an north-south trending antiformal arch atop basement that folded as a result of Laramide crustal shortening, suggesting that the basement did flex ductilely as compressional deformation took place (see Figure 3 and Figure 4).

CONCLUSIONS

Apatite (U-Th)/He ages from Shell Canyon indicate that asymmetrical folding of the crystalline basement in this region occurred during the Laramide Orogeny. He ages also demonstrate that the far-western region of the basement in Shell Canyon has not experienced temperatures above ~70°C since at least 369 Ma due to extended shallow burial (no greater than 2 km) beneath pre-Laramide sediments. In addition, a colder than normal geotherm (~15°C/km) has probably existed through the crust in this region since the early Paleozoic. The higher elevation

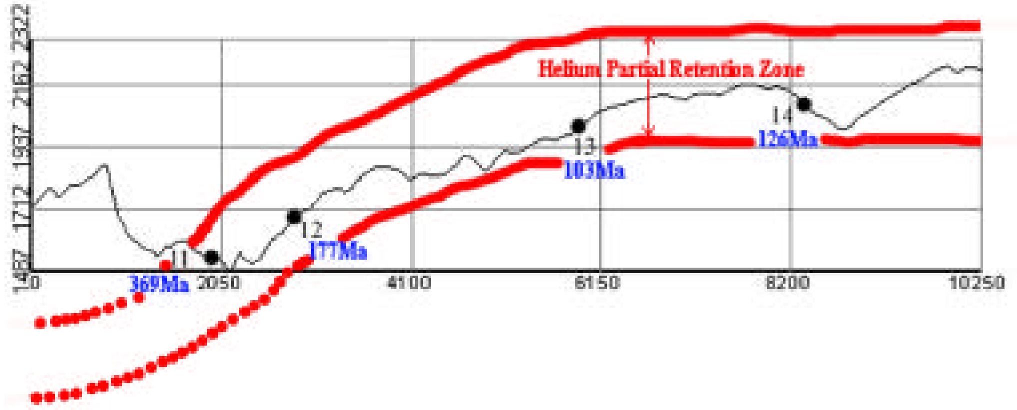

Figure 4. Schematic cross-section through bottom of Shell Canyon, showing reconstructed paleo-PRZ at ~65 Ma. Thin black line denotes modern-day erosional surface. Apatite He ages are noted next to each sample. Elevation and horizontal distance units are given in meters. Vertical exaggeration is 3.

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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