Isotopic Studies in the Bighorn Mountains, Wyoming: The U-Th/He Geochronology, Oxygen Isotope and Structural Perspectives

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INTRODUCTION

The Laramide Ranges of Colorado, Wyoming and Montana are dominant topographic features of the Rocky Mountain foreland. These ranges, generally cored by Precambrian crystalline basement rocks are somewhat enigmatic. They formed in the Cordilleran foreland from late Cretaceous to Eocene time (Dickenson et al., 1988) at distances of more than 1000 km from an active plate margin and have a basement-involved thick-skinned structural geometry that is not common in the forelands of orogenic belts.

Though the subject of long running controversies (e.g., Berg, 1962; Stearns, 1971; Blackstone, 1981) the structural geometries of the Laramide ranges are now relatively well constrained by structural mapping, oil exploration drilling (Greis, 1983) and reflection seismic profiling (Smithson et al., 1979). The ranges are usually bounded on one or both sides by listric thrust faults that carried the basement up and over the sedimentary fill of the adjacent asymmetrical foreland basin.

This project examined the Bighorn Mountains (Fig. 1), one of the eastern most of the Laramide ranges in order to better constrain the timing and style of deformation along the range margin and role of fluid in development of the Laramide structural style.

BIGHORN MOUNTAINS

Starting with the mapping of Darton (1906), the Bighorn Mountains have been the subject of numerous geological studies. Precambrian crystalline rocks crop out over much of the core of the range; the northern part of the range core is characterized by younger Archean granitoids and the southern part by older Archean gneissic lithologies. The basement rocks are overlain by Cambrian through Tertiary sedimentary rocks. There are approximately 1.4 km of Cambrian through Jurassic shallow marine and terrestrial strata. Sedimentation rate apparently increased in the Cretaceous when more than 2.5 km of marine to terrestrial strata were deposited. Beginning in the Paleocene, the sedimentation pattern changed and thick sequences of coarse terrestrial clastics were deposited near the margins of the range. Adjacent to the Bighorn Mountains, terrestrial clastic sedimentation continued in the Powder River Basin through Middle Eocene.

The eastern flank of the Bighorns is bounded by a moderate-angle, west dipping thrust system that places the crystalline rocks of the Bighorns on the strata of the Powder River Basin. This thrust system accommodated approximately 10 km of shortening and produced nearly 10 km of structural relief (Hoy and Ridgeway, 1997). The western flank of the range is largely a gentle west-dipping homocline in which the crystalline rocks of the Bighorns dip beneath the Paleozoic to Eocene strata of the Bighorn basin. However, in the northern Bighorns (the Five Springs region of Wise and Obi, 1992), the western margin of the range is marked by a moderate angle thrust fault that accommodates <2 km of shortening and produces < 2 km of structural relief. The displacement on this thrust dies out to the south. The displacement is transferred to a fold (the Shell Canyon monocline) before dying out all together.

Timing of deformation in the Bighorn Mountains should be well constrained by the sedimentary rocks in the Powder River and Bighorn basins. Late Cretaceous isopachs (Lewis and Hotchkiss, 1981), sedimentary facies and paleocurrent determinations (Belt, 1993) do not indicate the presence of Bighorn Mountains as either a sediment source or as a flexural load. However, beginning in the early Paleocene (Puercan time), the depocenter of the Power River basin (Lewis and Hotchkiss, 1981) moved towards the Bighorn Mountains suggesting the emergence of the range as a flexural load at that time. Similarly, changes in both the sedimentary facies and paleocurrent directions (Belt et al.,1992) indicate the creation of the Bighorn as a clastic sedimentary source. However, Eocene orogenic clastics (the Kingsbury and Moncrief conglomerates) are associated with the thrust system on the eastern side of the Bighorns. This indicates an Eocene age for at least some of the deformation (Hoy and Ridgeway, 1997).

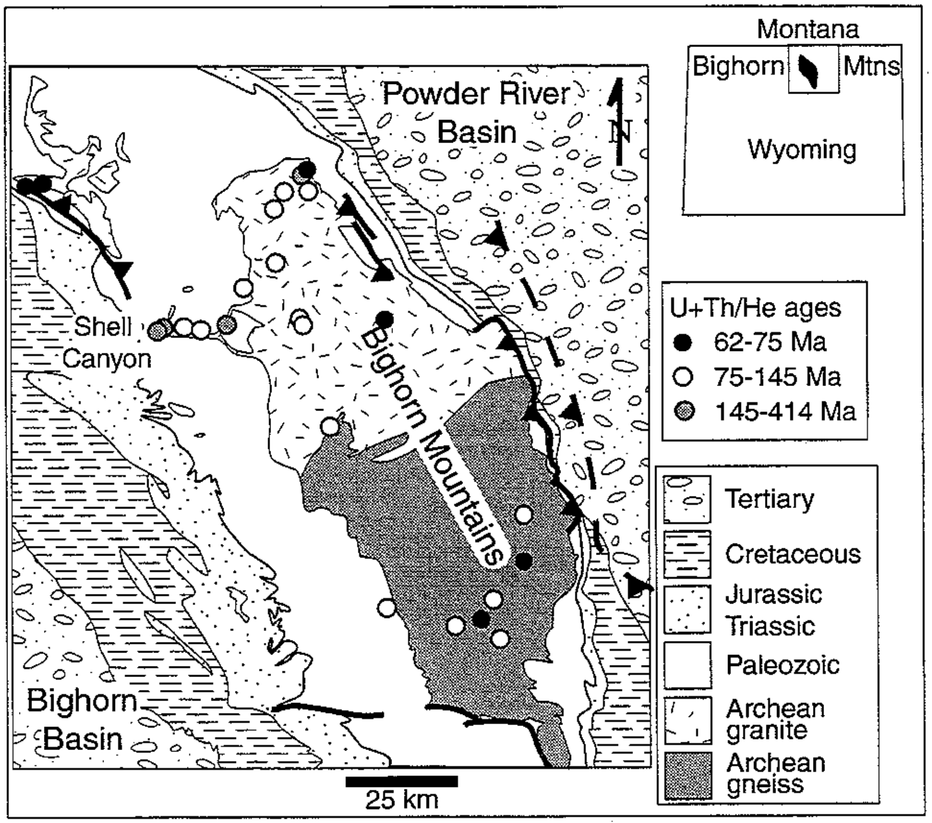

Figure 1: U-Th/He ages from the Bighorn Mountains range from 62 to 141 Ma. The youngest ages are intepreted to represent the time of Laramine deformation and unroofing. After Love and Christiansen, 1985)

U-TH/HE DATING

Alpha particles (^{4}He nuclei) are produced during the decay of both uranium and thorium to lead. The decays of ^{238}U to ^{206}Pb, ^{235}U to ^{207}Pb, ^{232}Th to ^{208}Pb produce 8, 7 and 6 He atoms respectively. The magnitude of helium production from the decay of uranium and thorium make it a potentially powerful geochronometer in uranium and thorium-bearing minerals. In fact, helium geochronology goes back to the earliest investigations of the ages of rocks (Rutherford, 1905). However, after the very early studies helium geochronology fell out of favor (e.g., Hurley, 1954) because it generally gave what were then considered to be unreasonably young ages when compared with the results from other geochronological methods. The modern era of helium geochronology began with the suggestion by Zeitler et al. (1987) that "too-young" apatite helium ages could be geologically significant, and represent the age of cooling through very low temperatures.

In principle, U-Th/He cooling ages could be determined for any U of Th bearing mineral. However, because of the potential thermochronometric power associated with its very low closure temperature, apatite has received the most attention as a (U-Th)/He chronometer (e.g., House et al, 1997; 1998; Wolf et al., 1997).

The diffusion kinetics of apatite have been thoroughly studied (Zeitler et al., 1987; Wolf et al., 1996, Farley, 2000). Apatite completely retains radiogenic helium at temperatures below approximately 40 °C. Helium is only partially retained at temperatures between approximately 40 °C and 75 °C (the partial retention zone [PRZ]), whereas at temperatures above 80 °C radiogenic helium is lost as fast as it is produced. U-Th/He ages from modern boreholes (Warnock et al., 1997; House et al., 1999) show this effect. The oldest ages are recorded near the surface; below approximately 1 km ages progressively decrease with increasing depth with near zero ages recorded below depths of approximately 2 km. For rocks that cool relatively rapidly (~10 °C/Ma) through the PRZ, U-Th/He ages record the time of cooling through approximately 70 °C. For rocks that cool significantly more slowly and spend a long time at PRZ temperatures, interpretation of U-Th/He ages is more difficult.

Low temperature thermochronology (apatite U-Th/He and fission track geochronology) can be a powerful tool to determine the time and rate of unroofing of a mountain range. In these studies, samples are collected from elevation transects (e.g., Cerveny & Steidtmann, 1993; Omar et al., 1994; Wolf et al., 1997). In a simple case of very rapid rock exhumation, the oldest ages are recorded at the highest elevations with ages decreasing with decreasing elevation, becoming invariant below a critical elevation. In such a case, the older ages represent a fossil PRZ and the age at which the ages become elevation-invariant represents the time at which unroofing occurred. For cases in which the slope of the age-elevation trend is not infinite (i.e., slower cooling), the unroofing rate is the slope of the age-elevation trend below the fossil PRZ. With these potential scenarios in mind, U-Th/He elevation transects were sampled in several locations throughout the Bighorns, in an attempt to constrain the timing, magnitude and rate of uplift of the range (Fig. 2).

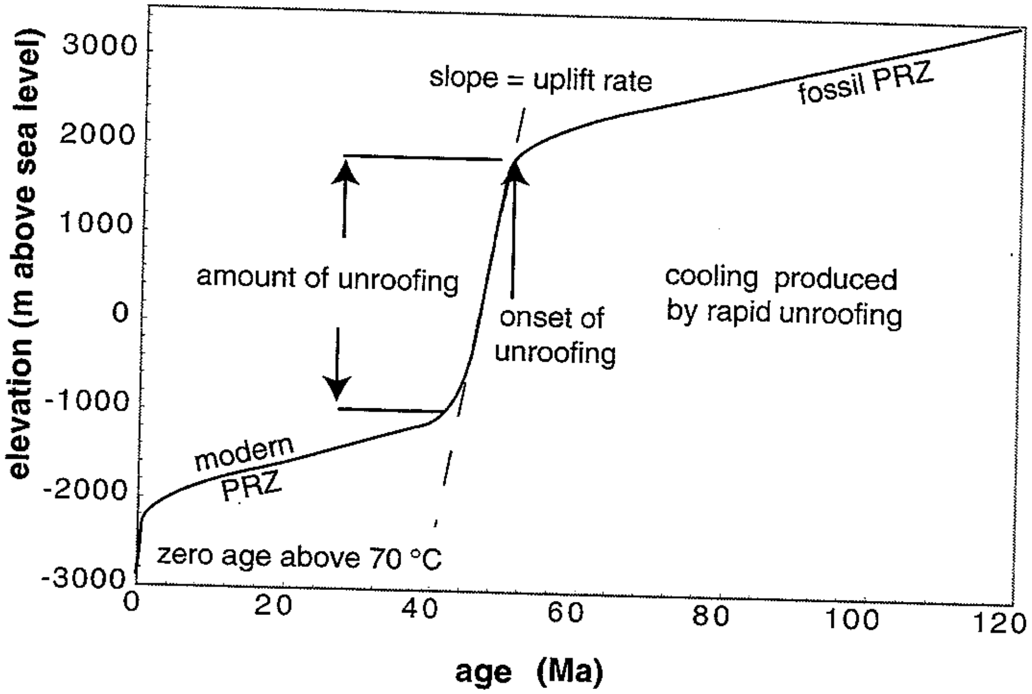

Figure 2: The timing, amount of tectonic unroofing and unroofing rate can be estimated from U-Th/He age-elevation transects.

^{4}He nuclei produced from decay of U and Th have relatively high kinetic energies that propel them a significant distance from their parent atoms before stopping. In an apatite crystal this stopping distance is approximately 15-20 µm. As a result of this long stopping distance, a fraction of the radiogenic helium produced by decay is lost from the crystal. The fraction lost depends on grain size and grain shape but is in the range of 15-30% for common apatite grain sizes. U-Th/He ages must be corrected for this loss using the alpha-ejection correction procedure of Farley et al. (1996). While this correction is large relative to age of the crystals, stopping distances are known, and grain dimensions can be measured quite precisely. Nonetheless, given uncertainties in other part of (U-Th)/He age determinations, uncertainties associated with alpha-ejection correction are probably the largest source of error in U-Th/He ages.

OXYGEN ISOTOPES

Laramide deformation was the result of plate convergence along western North America (Bird, 1998), but why did indvidual faults form where they did? Why were these locations particularly weak? One possibility is that the faults formed along zones of high fluid pressure or pervasive fluid flow. This possibility is suggested by hydrous mineralization associated with the Five Springs thrust in the Bighorn Mountains (Wise and Obi, 1992). Supporting evidence also comes from the anomalously young apatite fission track ages at the Beartooth thrust in the Beartooth Mountains (Omar et al., 1994). Oxygen isotopes offer the possibility of placing constraints on the temperature, relative volume and provenance of fluids that interacted with rocks near a fault zone (Morrison and Anderson, 1998). We collected samples along the faulted western margin of the Bighorns to assess the importance and nature of fluid interaction for this fault.

THE PROJECT

The project was comprised of two distinct components. It began with 10 days of field work in the Bighorn Mountains and ended with three weeks in the isotope labs at the Caltech. While in the Bighorns we stayed at the Iowa State University Geology Field Station near Shell Wyoming. Three students chose to work on projects that would involve U-Th/He dating. While we were in the Bighorns, these students collected samples of apatite bearing rocks (granitoids and their gneissic equivalents) from as wide a range of elevations and structural levels as possible. Two of the projects took advantage of the oxygen isotope lab at Caltech. These projects examined rocks that had been brittlely deformed along west-directed Laramide thrusts. While in the field the orientations and slip directions of minor faults were measured and samples that had been altered by fluids that were associated with the faults were collected. At Caltech, our initial efforts were directed at preparing mineral separates for isotopic analysis. After this initial flurry, we settled in to a routine, collecting data in the ICP-MS, noble gas isotope and oxygen isotope labs.

STUDENT PROJECTS

Rashmi Becker examined minor faults associated with the Shell Canyon monocline. She related these faults to the deformation that produced the monocline in the overlying sedimentary rocks. Hillary Brown was part of the helium group and determined ages for an elevation transect on the eastern side of the range. Valerie Esser analyzed oxygen isotopes from quartz, feldspar and epidote associated with minor faults related to the Five Springs thrust. She estimated temperatures of fluid flow (and faulting?) from this. Grant Kaye concentrated on He ages from an elevation transect along the western margin of the range. This transect yielded surprisingly old ages. Joanna Reuters determined He ages from near the crest of the range. She created a series of thermal models to help explain the range of ages determined there. Brian Zeiger explored more conventional U/Pb geochronology using the less conventional method of analysis by inductively coupled plasma mass spectrometry (ICP/MS). His results illustrate both the benefits and pitfalls of this method.

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Structure and oxygen isotope analysis of Precambrian basement in the Cottonwood Creek Area, Black Mountain Quadrangle, Bighorn Mountains, Wyoming

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INTRODUCTION

The Cottonwood Creek study area lies north of Shell Canyon, in the Black Mountain Quadrangle on the western flank of the Bighorn range and the eastern edge of the Bighorn Basin (Fig. 1). Shell Canyon represents a structural boundary between the north-central and south-central Bighorn lineaments, marking the shift in orientation and character of the mountain front (Finley, 1982). Shell Creek and Trapper Creek Monoclines, oriented approximately 45° apart (Finley, 1982), represent the two major structural features of this region (Fig.1). Finley (1982) mapped two intersecting faults in the Cottonwood Creek area. The NW-trending Cottonwood fault roughly parallels the fold axis of Shell Creek Monocline (N60W), and offsets Precambrian basement by 100 meters. It appears to be an extension of the larger structure. A second, poorly exposed N-S trending fault along Cottonwood creek exhibits relatively minor displacement of Cambrian rocks, and separates two different granites.

This study emphasizes analysis of joints and minor faults associated with the NW-trending basement fault in order to determine fault geometry and regional stresses. Movement along faulted basement blocks is believed to have produced the overlying Shell Creek Monocline (Fig.2) (Finley, 1982), and is evidence of the Precambrian basement control of Laramide-generated folds seen throughout the Wyoming Foreland.

Samples of Precambrian granite were collected from mineralized portions of minor faults in the hanging wall for both optical and oxygen isotope analysis. Oxygen isotope data provides information on the fluid origin and temperature of the granite in the fault zone.

RESULTS/OSERVATIONS

Nature of the granite. Hanging wall rocks on either side of Cottonwood Creek display notable textural and compositional differences. Variations in east and west granite types across the creek, as well as extent of mineralization, suggest the possibility of movement along the N-trending fault proposed by Finley (1982). Rocks east of the fault have a medium grained texture, are somewhat alkalic (45-50% K-spar), and contain relatively little quartz (≤ 8%). They are cut by many minor mineralized and slickensided faults. Oligoclase (25-30%) twins are kinked,

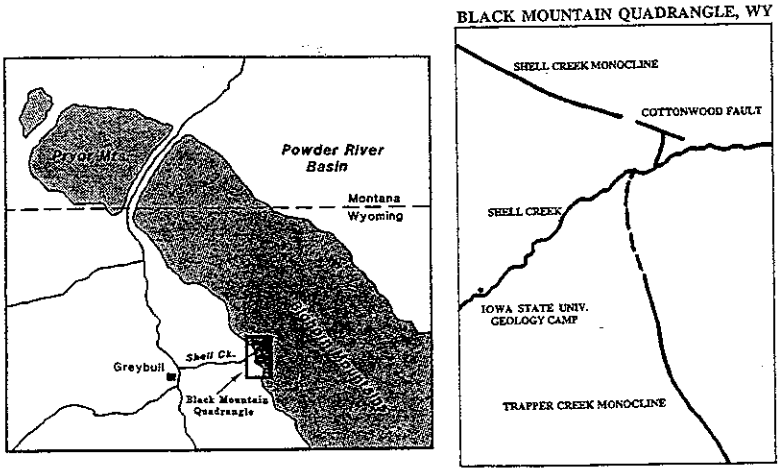

Figure 1: Map of Black Mountain Quadrangle and major structures (modified after Finley, 1982).