Long-term tectonothermal history of Laramide basement from zircon-He age-eU correlations

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Abstract

The long-term (> 1 Ga) thermal histories of cratons are enigmatic, with geologic data providing only limited snapshots of their evolution. We use zircon (U-Th)/He (zircon He) thermochronology and age-composition correlations to understand the Proterozoic-Phanerozoic thermal history of Archean Wyoming province rocks exposed in the northern Laramide ranges of western North America. Zircon He ages from the Wind River Range (54 dates) and Bighorn Mountains (32 dates) show negative correlations with effective uranium (eU), a proxy for radiation damage. Zircon dates from the Bighorns are between 960 Ma (low-eU) and 20 Ma (high-eU) whereas samples from the Wind Rivers are between 582 Ma (low-eU) and 33 Ma (high-eU). We applied forward modeling using the zircon radiation damage and annealing model ZrDAAM to understand this highly variable dataset. A long-term t-T path that is consistent with the available geologic constraints successfully reproduced age-eU correlations. The best fit to the Wind Rivers data involves two phases of rapid cooling at 1800-1600 Ma and 900-700 Ma followed by slower cooling until 525 Ma. During the Phanerozoic, these samples were heated to maximum temperatures between 160-125°C prior to Laramide cooling to 50°C between 60-40 Ma. Data from the Bighorn Mountains were successfully reproduced with a similar thermal history involving cooler Phanerozoic temperatures of ~115 °C and earlier Laramide cooling between 85-60 Ma. Our results indicate that age-eU correlations in zircon He datasets can be applied to extract long-term thermal histories that extend beyond the most recent cooling event. In addition, our results constrain the timing, magnitude and rates of cooling experienced by Archean Wyoming Province rocks between recognized deformation events, including the >1 Ga period represented by the regionally-extensive Great Unconformity.

1. Introduction

Basement rocks of the Laramide ranges of northwestern Wyoming experienced a protracted thermal history involving multiple burial and exhumation episodes since their formation during the Archean. Geologic and geochronologic data indicate that prior to
their most recent exhumation in the Cenozoic and burial by several kilometers of sediment in the Paleozoic and Mesozoic, these rocks were affected by multiple Proterozoic tectonic events such as supercontinent assembly and rifting (e.g., Chamberlain et al. 2003; Marshak et al., 2000). However, specific constraints on the time-Temperature ($t$-$T$) history of the region remain enigmatic. Understanding the early Proterozoic-Mesozoic thermal history enables an integrated long-term history that could reveal previously undocumented events, including thermal maturation, cratonal stability, and orogenesis. Apatite fission track (AFT) and (U-Th)/He (apatite He) thermochronology has previously been used to resolve the thermal histories of cratons, typically over $10^8$-year time scales (e.g., Gleadow et al., 2002; Kohn et al., 2005; Flowers, 2009; Ault et al. 2009; 2013). The broad temperature sensitivity of the zircon (U-Th)/He (zircon He) system enables recovery of even longer, billion-year thermal histories. This study utilizes recent advances in our understanding of the influence of radiation-damage on He diffusion in zircon (Guenthner et al., 2013; Guenthner et al. 2014) to elucidate major features of a ~2 Ga thermal history of Laurentian basement rocks in western North America.

Zircon He dating can be combined with radiation damage and annealing modeling to recover long-term thermal histories when varying amounts of radiation damage accumulate over time in grains with different U-Th concentrations from the same sample (Powell et al. 2016; Guenthner et al. 2015). These variations produce a range of He diffusivities and closure temperatures ($T_c$) such that each grain records a different He age. Among grains that experience the same thermal history, differences are proportional to differences in effective uranium ($eU$, $U + 0.235 \times Th$). Correlations between He age and
eU therefore reflect the coevolution of the sample’s thermal history and radiation damage and damage annealing of its zircon grains. More specifically, the retentivity of He in zircon, and therefore the $T_c$, initially increases with progressive damage accumulation to a critical threshold after which retentivity and $T_c$ decrease (Guenthner et al., 2013; Guenthner et al. 2014). Given the initial increase and subsequent decrease in $T_c$, the damage-diffusivity relationship typically manifests as positive (increasing $T_c$ with increasing eU) or negative correlations (decreasing $T_c$ with increasing eU) between single grain ages and their eU concentrations.

In this paper, we present the first zircon He ages from the Wind River Range, which were obtained from a suite of samples collected and analyzed for AFT by Cerveny and Steidtmann (1993). We also present new zircon He data from the Bighorn Range (Fig. 1). Zircon grains from samples in both regions show strong negative age-eU correlations, which we use in combination with the radiation damage-based model for He diffusion in zircon (ZRDAAM) from Guenthner et al. (2013) to resolve distinct $t-T$ relationships. Our new $t-T$ constraints describe not only the most recent phase of exhumation related to Laramide orogenesis, but previous cooling and heating episodes spanning ~2 Ga. In geologic settings where evidence of previous thermal events is overprinted or eroded, low-temperature thermochronology has the ability to reconstruct its long-term thermal history.

2. Geologic Setting

The ~6000 km², northwest-southeast trending Wind River Range and the ~4500 km², north-south trending Bighorn Mountains of Wyoming are two of the most
prominent features in the Laramide Province, which comprises mountain ranges bound by high-angle reverse faults that cut crystalline basement rocks (Fig. 1). The cores of these ranges consist of Archean granite, granitic gneiss, and granodiorite of the Wyoming Province that amalgamated with other Archean cratons to form Laurentia during the Paleoproterozoic (2.0-1.8 Ga) Trans-Hudson orogeny (Hoffman, 1988). Between 1.8-1.7 Ga, juvenile crust accreted to the southeastern margin of Laurentia along the Cheyenne belt of southeastern Wyoming as part of the Yavapai and Mazatzal orogenies (Houston, 1993; Chamberlain, 1998; Whitmeyer and Karlstrom, 2007). Sometime between ~1.7-0.5 Ga, Archean rocks in the core of the Wind River Range and Bighorn Mountains were exhumed to the surface. Later, these rocks were buried under 4-6 km of Paleozoic and Mesozoic passive margin strata. Finally, they were exhumed in the cores of Laramide ranges in the hanging walls of high-angle reverse faults related to Cenozoic orogenesis.

In western North America, the contact between Archean igneous and metamorphic rocks and overlying Paleozoic strata is referred to as the “Great Unconformity”. The ~2 Ga of missing geologic record across this contact represents nearly half of Earth’s history and as such, the thermal and tectonic history is largely unconstrained during this interval. Previous low-temperature thermochronology datasets (apatite He and AFT) were completely reset by the youngest cooling episode, related to slip across Laramide reverse faults. However, high-temperature thermochronology studies have shown limited evidence of prior cooling, including biotite K-Ar ages of ~2.0-1.5 Ga in the Wind River Range (Peterman, 1979). In the Bighorn Mountains, biotite K-Ar ages indicate > 2.5 Ga cooling (Heimlich and Armstrong, 1972).
Regional geologic field investigations data indicate that two phases of extension affected the interior of the Wyoming craton, between 1300-1000 Ma and 900-700 Ma (Chamberlain et al. 2003; Mueller and Frost, 2006). The timing and orientation of extensional structures suggest they are far-field effects of the ~1.2-1.0 Ga Grenville collisional orogen and/or Neoproterozoic-early Paleozoic Iapetan rifting (Timmons et al., 2000). The latter event is evidenced by retrograde metamorphism along Precambrian deformation zones dated at ~900 Ma in the Wind River Range (Mitra and Frost, 1981). Various authors interpret that inherited crustal weak zones related to extensional structures controlled the orientation of Cenozoic reverse faults that bound the Laramide ranges (e.g. Marshak and Paulsen, 1996; Marshak et al. 2000; Timmons et al. 2001), suggesting that these events affected Archean rocks in the Wind River Range and Bighorn Mountains.

3. Previous Low-Temperature Thermochronologic Results

Low-temperature thermochronology of Archean basement is restricted to apatite He and AFT studies sensitive only to the most recent Cenozoic or “Laramide-age” phase of exhumation (Shuster, 1986; Steidtmann et al., 1989; Cerveny, 1990; Crowley et al. 2002; Peyton et al. 2012). Cerveny and Steidtmann (1993) obtained AFT ages from crystalline basement from the Wind River Range, which they interpreted as requiring exhumation through depths of ~4 km as early as 85 Ma, followed by two periods of rapid cooling between 62-57 Ma and 40 Ma. More recent work by Peyton et al. (2012) and Stevens et al. (2016) found AFT ages of 57-54 Ma and 61-42 Ma in samples collected near Gannett, Temple, and Fremont Peaks, respectively. Thermal modeling of track-
length distributions and ages by Stevens et al. (2016) were interpreted to require rapid cooling at ~65-50 Ma. These authors modeled maximum burial temperatures in the 135 to 160 °C range just prior to Laramide cooling.

Apatite He ages from the crystalline core of the Bighorn Mountains are 369-60 Ma, and were interpreted to record a pre-Laramide He partial retention zone (PRZ) exhumed around ~65-70 Ma (Reiners and Farley, 2001; Crowley et al., 2002; Peyton et al., 2012). Subsurface samples from a ~4.5-km deep borehole on the east side of the range are predominantly 60-70 Ma near the surface and as young as 3 Ma at depths about 5 km beneath the Great Unconformity (Peyton et al., 2012). Reiners and Farley (2001) used age-grain-size correlations to infer pre-Laramide burial temperature of ~65-80 °C. Merging a larger data set with previous surface and borehole results, Peyton et al. (2012) found best-fit models for about 50 °C of Laramide cooling beginning by 85 Ma and ending at ~60 Ma. Peyton et al.’s (2012) inverse modeling suggested maximum pre-Laramide temperatures ranging from ~80 to ~115 °C for certain t-T paths but did not consider t-T paths that began before 200 Ma, which may be important for radiation damage effects (e.g., Shuster et al., 2006; Flowers et al., 2009; Gautheron et al., 2009).

We use the approximate timing (~85-60 Ma) and maximum temperature (~80-120 °C) of Laramide exhumation in the Bighorns as a guideline for our interpretations.

4. Zircon He Results

We dated 54 single-crystal aliquots of zircon from 9 samples along the range-perpendicular Middle Fork Transect in the Wind River Range (2567-3534 m above sea level) from the original mineral separates acquired by Cerveny and Steidtmann (1993) (Fig. 1). We followed methods described in Reiners et al. (2004) (Appendix I). Zircon He
ages range from 581±8.1 to 33.2±0.45 Ma and show no correlation with grain size, or, with the exception of WY-100-89 and WY-101-89, elevation (Fig. 2A; Appendix I; Supplementary Material I). However, zircon He ages correlate strongly with eU (Fig. 2A), over an eU range of 270-7200 ppm. The correlation with age is strongly negative at eU values less than ~850 ppm, but younger ages form a long tail of relatively restricted ages between 61-33 Ma across a wide range of higher eU (i.e. 850-7200 ppm).

We dated 32 single zircon crystals from the northeastern part of the Bighorn Mountains at Bald Mountain (Samples BaldMtn-1-12 and 5SP-1-12; 2397-2824 m), along Shell Canyon (Samples BH12, BH17, and SC-2-12; 1808-2410 m), and at Burgess Junction (BJ-1-12). Single grain ages range from 956±14.7 to 6.10±0.09 Ma (Fig. 2B) and do not correlate with grain size or elevation. These samples show a similar inverse age-eU correlation as the Wind River samples, but across a lower range of eU, (~200-1000 ppm). These results are similar to those from the BH12 and BH17 samples of Guenthner et al. (2013) (Fig. 2B).

5. Thermal-History Modeling

Thermal-history (t-T) modeling can be used to assess the validity of potential t-T paths (hypotheses) for producing a set of thermochronometric ages. We used this approach to investigate whether our data are compatible with expectations of the geologic history of the region and to constrain specific t-T segments of our sample thermal histories that were not resolved by apatite He and AFT data presented in previous studies (i.e. the Proterozoic thermal history). We used a forward modeling approach to constrain possible t-T paths, using a portion of the relevant code from the program HeFTy (i.e., He diffusion modeling with alpha ejection correction and ZrDAAM; Guenthner et al., 2013).
implemented in Matlab in order to handle a large number of single grain inputs and more
easily output model age-eU correlations. This code was checked against HeFTy outputs
to confirm similarities.

We favored a forward modeling approach as inverse modeling requires averaging
of grain-specific inputs (i.e. grain size, U and Th concentrations) and typically only
displays modeled date-eU correlations for the best-fit t-T paths. This in turn makes it
difficult to visually a specific t-T path date-eU correlation. Visual inspection is important
when dealing with apatite and zircon He data, as the statistical tests employed in inverse
models critically assume that all sources of date variation are well constrained. In reality,
some sources of date variation are better accounted for (e.g. grain size, radiation damage
effects) than others (e.g. U and Th zonation). For these reasons, the forward approach
better demonstrates the extent to which date variation in zircon He datasets can be
explained by ZRDAAM and is thus better suited for our purposes.

For modeling purposes, we combined single grain aliquots from individual
samples into either a single suite of ages (Bighorn dataset) or distinct groups (Wind River
dataset). The Bighorn ages can be interpreted as a single group because: 1) all ages from
a given suite form a single, coherent negative age-eU correlation, suggesting that
radiation damage is the primary source of intra- and intersample age variation, and 2) all
samples were collected within the same approximate depth relative to the Great
Unconformity (and are not separated by major faults), which suggests that samples in a
given dataset share a common thermal history. The Wind River dataset is complicated by
the lack of a single coherent negative trend and differences in sample elevation. In figure
2A, a distinct group of ages from samples WY-96-89 and WY-98-89 has a range of 200-
600 Ma with eU concentrations between ~200 and 300 ppm. This group appears shifted towards lower eU concentrations at a given age relative to the rest of the main negative trend, and should therefore be modeled with a separate thermal history. This observation is strengthened by the age-elevation relationship for the full Wind River dataset (Supplementary Material, Fig. 1). Although no clear correlation between age and elevation is apparent for the majority of the dataset, we note that WY-98-89 and WY-96-89 are two of the lowest elevation samples, positioned closest to the main Wind River thrust (Fig. 1), suggesting that they are more deeply exhumed than the higher elevation samples. Age-elevation relationships also show that samples WY-100-89 and WY-101-89 lie below the Laramide paleo-PRZ and were likely fully reset. Indeed, these samples display nearly flat correlations between age and eU. For modeling purposes, we therefore consider WY-98-89 and WY-96-89 as a separate group and exclude WY-100-89 and WY-101-89.

To interpret age-eU correlations, ZRDAAM combines the damage-diffusivity relationship (Guenthner et al., 2013) with a damage-annealing model defined by a fanning curvilinear fit to the zircon fission track (ZFT) annealing data of Yamada et al. (2007). Annealing kinetics give a ZFT partial annealing zone (PAZ) of 310-223 °C (0.4-0.8 mean length reduction ratio, 10 Ma isothermal hold-time). These kinetics are currently the best available option for describing how the radiation damage that affects He diffusivity anneals over geologic timescales. Although more work is needed to better define damage annealing in zircon, the primary relationships between accumulated damage and He diffusivity provide strong constraints on the thermal histories under the
reasonable assumption (considering sedimentary and tectonic reconstructions) that little
to no damage annealing occurred after Neoproterozoic.

5.1 Model inputs

Our model takes grain size, U and Th concentrations, and $t-T$ paths as inputs
(Appendix II). For grain size, we model three separate age-eU curves for each $t-T$ path
using the mean grain size $\pm$ two standard deviations for each dataset. The resulting output
is an envelope with a central curve that shows the extent to which the combined effects of
grain size and radiation damage explain the observed age variation.

In choosing our input $t-T$ paths, we considered the geologic observations and
previously published thermochronometric results described in previous sections. Few
constraints on the geologic history of these rocks are available between their formation in
the Archean and deposition of basal Cambrian strata (i.e. the Great Unconformity). As
discussed above, a few K-Ar ages from the southernmost Wind Rivers hint at cooling
below $\sim$300 °C at approximately 1500 Ma. The next nearest constraints are Rb/Sr data
from the Laramie Range in southeastern Wyoming, which suggest an $\sim$1.78 Ga
metamorphic cooling event (Patel et al., 1999). Similarly, K-Ar hornblende and U-Pb
apatite ages within the Laramie Peak shear zone and Cheyenne Belt are interpreted to
record rapid uplift during Cheyenne belt deformation between 1.8-1.6 Ga (Chamberlain
et al., 1993). However, no thermochronologic data are available that describe the
subsequent 1.2 b.y. of geologic history. As such, our $t-T$ inputs are primarily designed to
examine when major Proterozoic cooling (exhumation) initiated in each range, how much
cooling occurred, and how long-lived the Proterozoic cooling episode was. We have also
designed our specific paths to be consistent with previously published constraints for the
timing of Laramide exhumation, although this is not our main focus. For the Wind River Range, we use the approximate timing of 60—40 Ma, in agreement with the constraints discussed above. Fan and Carrapa (2014) modeled Laramide-related cooling to ~50 °C, and we used this as the temperature at the end of Laramide cooling. For the Bighorn Mountains, we again used the inverse model results from Peyton et al. (2012) to define the timing of Laramide-related exhumation—85 to 60 Ma—as well as the temperatures at the end of Laramide exhumation event—50 °C. We considered the maximum Phanerozoic burial temperatures achieved just prior to Laramide cooling as a variable and a more detailed investigation of these temperatures for both datasets is discussed in subsequent sections.

Our forward modeling follows an iterative process in which we continually narrow our search of Proterozoic \( t-T \) space, and the discussion of specific \( t-T \) tests and model results in this section reflects that approach. We first model “end-member” thermal histories, followed by “representative” and then “refined” thermal histories. With each subsequent iteration, our objective was to bracket the observed data to arrive at the most acceptable solution. Model \( t-T \) paths are as parsimonious as possible given principal geologic constraints outlined above, and, given the lack of constraints on the Proterozoic thermal history of our samples, this simplifying approach does not over interpret the data or lead overly complex and unwarranted models. Additional complexities, such as considering the precise burial history from unit thickness-age variations in the stratigraphic record, would likely have only a minor effect on the model age-eU correlations (e.g. Guenthner et al., 2015).
5.2 End member scenario and results

Our most extreme end-member $t$-$T$ path forward models (Fig. 3A) are focused on distinguishing whether earliest or latest Proterozoic cooling can reproduce the basic features of the age-eU correlation. The two end-member thermal histories assume rapid cooling from well above zircon He PRZ temperatures from either 2600 to 2500 Ma (corresponding to the approximate age of high-grade, granulite-facies metamorphism in both ranges (Frost and Frost, 1993)), and or from 700 Ma to the mid-Cambrian, simulating Neoproterozoic formation of the Great Unconformity. The Phanerozoic portion of the thermal history that involves relatively well-constrained burial and Laramide exhumation is kept constant in this set of models; details of this portion of the path have little effect on the results. In both cases, cooling starts at 350 °C to allow our samples to cool fully through the ZFT partial annealing zone (PAZ) and ends at surface temperatures of 20 °C (Fig. 3A). These end-member scenarios represent roughly the maximum and minimum amount of time that our datasets could have spent at near-surface temperatures in the Proterozoic.

The Phanerozoic portions for these and all subsequent “representative” paths begin with the middle Cambrian (525 Ma) deposition of the Flathead Sandstone, followed by the Laramide constraints described above with reheating to 160 °C for the Wind River dataset and 120 °C for the Bighorn dataset. We chose 120 and 160 °C in part because these are the maximum burial temperatures modeled by Peyton et al. (2012) and Fan and Carrapa (2014), respectively, but they also simulate intermediate temperatures while keeping the model grains below the conventional zircon He $T_c$ of ~180 °C. Models with these temperatures closer to 180 °C lead to nearly flat age-eU curves as all of the
grains are reset to ages much younger than those observed in either dataset at both low
and high eU concentrations. For these initial tests, we did not attempt to refine the late-
stage portions of the thermal history most relevant to Laramide exhumation, but expand
upon these particular inputs in our “refined” thermal history models.

Model outputs for the two end-member \( t-T \) paths are shown in figure 3B. In both
datasets, the model age-eU correlations cross-over and bracket the observed age-eU
trends. Rapid Paleoproterozoic cooling (path 1 in fig. 3A) produces model correlations at
much lower eU values than the observations, whereas much younger Neoproterozoic
cooling leads to ages that are far too young at low eU to explain the Bighorn age-eU
trends, or too old at intermediate eU to explain the Wind River trends. These results
indicate that major cooling events in either the earliest or latest Proterozoic do not satisfy
the observations but their crossover bracketing of the data suggest an intermediate
solution may be a better solution.

5.3 Representative scenarios and results

With the end member results in mind, we constructed a series of different
representative paths that further tested the Proterozoic \( t-T \) space, while exploring the
specific hypotheses of Proterozoic tectonism previously discussed. These geologic events
include: 1) the 1800-1600 Ma Yavapai-Mazatazal orogenic event as expressed in the
crustal suturing along the Cheyenne Belt of southeastern Wyoming (Houston, 1993;
Chamberlain, 1998), 2) two episodes of rifting related extension at 1300-1000 Ma and
900-700 Ma (Marshak et al., 2000; Timmons et al., 2001), and 3) Neoproterozoic erosion
(~700 Ma to 542 Ma) associated with the creation of the Great Unconformity.
In figures 4A and 5A we show $t$-$T$ paths that represent these proposed events and consist of either initial rapid cooling to surficial temperatures over a given time (Fig. 4A), or a two-stage monotonic cooling with prolonged residence at intermediate temperatures (Fig. 5A). We also considered a $t$-$T$ path with linear cooling beginning at 1800 Ma (Fig. 5A) as described below. For the Proterozoic intermediate temperatures, we initially chose 170 °C because it simulates long term residence at the low temperature boundary of the conventional PRZ and therefore would not fully reset ages during the Proterozoic. Higher intermediate temperatures from 1600 Ma to 900 Ma, for example, would more fully reset zircon He ages and in effect produce model age-eU curves similar to rapid cooling at 900 Ma, which partially defeats the purpose of exploring representative thermal histories. We further tested this intermediate temperature with our refined thermal histories. The results from these representative $t$-$T$ paths are compared to the observed Wind River and Bighorn datasets (Fig. 4B and 5B). In all three rapid cooling scenarios for the Bighorn data (Figs. 4Bi, 4Biii, and 4Bv), the model curves are too young at most eU concentrations. Furthermore, no combination of model curves brackets the observed ages, which suggests that a $t$-$T$ path with rapid cooling from high temperature to near surface temperatures in the Proterozoic is not a viable solution. In contrast, for the Wind River data, scenarios 1 (1800-1600 Ma cooling, Fig. 4Bii) and 3 (900-700 Ma cooling, Fig. 4Bvi) yield model curves that bracket almost all of the observed ages, with scenario 3 capturing 33 of the 43 single grain ages (77%). The “intermediate” scenario 2 (1300-1000 Ma rapid cooling, Fig. 4Biv) appears to split the other two scenarios and also reproduces 77% of the observed ages. Importantly though, both scenarios 2 and 3 miss the distinctive cluster of young ages at low eU, and model age-eU curves remain too old
for this cluster even with further modification of maximum Phanerozoic temperatures (see next section for more details). For these reasons, we do not consider \( t-T \) paths for either the Bighorns or Wind Rivers from figure 4 in our refined scenarios.

Our two-stage or linear cooling paths (Fig. 5) help to refine our search for viable \( t-T \) hypotheses. For the Bighorns dataset, only thermal scenario 2 (two stages of major cooling at 1800-1600 Ma and 900-525 Ma) replicates a high number of observed ages, as well as the overall form of the observed age-eU correlation (age plateau at low eU, steeply negative correlation, age pediment at high eU) (Fig. 5Biii). All other scenarios give ages that are too young at most eU concentrations. Results are more ambiguous for the Wind River dataset. All three two-stage models give roughly the same model curves: they reproduce the group of ~200-600 Ma grains at approximately 150-300 ppm eU, but are too young at a given eU concentration for the majority of the ages (Figs. 5Bii, 5Biv, and 5Bvi). A \( t-T \) path with linear cooling from 1800 to 525 Ma (scenario 4) appears to yield model curves that shift slightly towards older ages, but still captures relatively few ages (19 out of 43, Fig. 5Bviii).

Altering the intermediate Proterozoic and maximum Phanerozoic temperatures in these Wind River scenarios (Figs. 5Bii, 5Biv, and 5Bvi) could result in model curves that encompass more ages. We consider \( t-T \) paths that both increase and decrease these temperatures. Because the Wind River models tend to give ages that are too young at most eU concentrations, none of these three model outputs are significantly changed by increasing the Phanerozoic maximum burial temperature. That is, higher maximum burial temperatures cause flatter age-eU correlations and a further shift towards younger ages and the fit to the observed data is not improved. Decreasing these temperatures, however,
produces model curves with a broader age range and older results that could better model the observed data. Decreasing the maximum Phanerozoic burial temperatures also provides some leverage on achieving better model results. These segments of the \( t-T \) path are partially constrained by the previous apatite He and AFT modeling efforts, but the previous thermal models give a range of burial temperatures, and it is important to consider this entire range.

### 5.4 Refined scenarios and results

Our refined tests explored one representative \( t-T \) path for the Bighorn dataset (scenario 2 in Fig. 5Biii) and three representative \( t-T \) paths for the Wind River (scenarios 1, 2, and 3 in Fig. 5Bii, 5Biv, and 5Bvi). These tests involved varying the two remaining parameters that are least well known: the intermediate temperature to which rocks initially cooled in the Proterozoic, and the maximum temperature to which rocks were reheated by pre-Laramide burial. For the former we examined \( t-T \) paths across a wide range of intermediate Proterozoic temperatures (100 °C to 300 °C) in increments of 5 °C. For the latter, in the Bighorns, we tested the previously modeled range of Phanerozoic maximum temperatures between 80 and 120 °C (Peyton et al., 2012), and in the Wind Rivers, we tested between 120 and 160 °C (Fan and Carrapa, 2014).

Two model scenarios for the refined Bighorn thermal histories are shown in figure 6. The first (scenario 1) consists of a Proterozoic intermediate temperature of 155 °C and a Phanerozoic maximum burial temperature of 110 °C. A slightly higher intermediate temperature of 160 °C and burial temperature of 110 °C yield the model ages shown in scenario 2 from this figure. Intermediate temperatures less than ~145 °C and greater than ~180 °C shift the low eU portions of the model curve to older and younger ages,
respectively, and miss the observed ages at lowest eU. In all scenarios that we tested, the cluster of 20-40 Ma ages at high eU was never fully encompassed by the 2-sigma envelope, but some tested $t$-$T$ paths do capture the average trend of this cluster. We emphasize, however, that regardless of the precise intermediate Proterozoic or maximum Phanerozoic temperatures, the data appear to require two major phases of Precambrian cooling, one in the Paleoproterozoic (1800-1600 Ma) and a later one to near-surface temperatures in the Neoproterozoic (900-525 Ma).

The refined thermal history models for the Wind River dataset do not produce a single preferred solution for all samples. Instead, we considered the Wind River data as comprising two groups of samples with slightly different thermal histories. This is consistent with the two sample groups being collected at different elevations with one group at lower elevations (samples WY-98-89 and WY-96-89) likely experiencing higher maximum temperatures. To reflect differences in elevation, we constrained the two refined best-fit $t$-$T$ paths to have the same general form with two stages of cooling, one at 1800-1600, and another at either 1300-1100, 900-525, or 700-525 Ma (Figs. 5Bii, 5Biv, and 5Bvi), but slightly different maximum Phanerozoic temperatures and different intermediate temperatures between the two Proterozoic stages of cooling. These $t$-$T$ tests therefore consisted of a matrix of 320 individual $t$-$T$ paths (see above, 100 to 300 °C for Proterozoic intermediate, and 120 to 160 °C for Phanerozoic maximum temperatures, both tested in increments of 5 °C) applied to each two-stage cooling scenario (Figs. 5Bii, 5Biv, and 5Bvi) and each distinct sample group.

Following this approach, a range of refined $t$-$T$ paths provides the best results for either distinct sample group (Fig. 7A). Specific $t$-$T$ paths within the temperature ranges
discussed below are shown as solid blue and red paths in figure 7A, and their corresponding model age-eU curves (Fig. 7B) are indicative of the range of age-eU curves that result from our refined scenarios. These specific temperatures for the lower elevation sample group include: 200 °C for the Proterozoic intermediate and 160 °C for the Phanerozoic maximum, and, for the higher elevation group, 170 °C for the Proterozoic intermediate and 130 °C for the Phanerozoic maximum.

Both sample group thermal histories consist of initial cooling from 1800-1600 Ma followed by a second stage of cooling beginning at either 900 or 700 Ma with a wide range of potential intermediate temperatures (shown as the red and blue dashed-line t-T segments between 1800 and 525 Ma in Fig. 7A). This range of Proterozoic intermediate temperatures extends from 135 to 220 °C for the lower elevation samples (transparent red t-T segments) and from 140 to 220 °C for the higher elevation samples (transparent blue t-T segments). These temperature ranges yield age-eU results similar to those shown in figure 7B for a given sample group, provided that the same maximum Phanerozoic temperatures are used as described below. Model age-eU curves are also similar for the second cooling stage at either 900 or 700 Ma and it is difficult to distinguish between the two options for Neoproterozoic cooling. Importantly though, paths with two-stage cooling from 1800-1600 Ma and 1300-1000 Ma capture fewer ages than the two-stage 900 or 700 Ma paths at any given combination of tested temperatures. The 1800-1600 Ma, 1300-1000 Ma paths yield a narrower range of model ages at low burial temperatures, which reproduce fewer of the observed ages from the high elevation sample group.
The range of subsequent maximum Phanerozoic burial temperatures are 155 to 160 °C for the lower elevation group of samples, and 120 to 140 °C for the higher elevation group (shaded red and blue t-T segments between 525 and 0 Ma in Fig. 7A). Again, temperatures in either of these ranges yield age-eU curves similar to those in figure 7B when paired with their counterpart intermediate Proterozoic temperatures listed above. A minimum 15 °C difference between the two sample groups is therefore required just prior to Laramide cooling. If the offset between these two t-T paths is at least 15 °C during the Laramide, then the offset should be roughly the same throughout both thermal histories, which reduces the lower-bound of potential intermediate Proterozoic temperatures for the higher elevation samples from 220 to 205 °C, and the upper-bound for the lower elevation samples from 135 °C to 155 °C. In figure 7A, this tighter region of t-T space is shown by the transparent red and blue shading between 1800 and 525 Ma.

As a further condition of the 15 °C offset, the lower elevation samples were also likely at higher temperatures during deposition of the middle Cambrian Flathead Sandstone than the higher elevation samples, which is reflected in the t-T paths in figure 7A.

The observations from figure 7, combined with the results from our representative t-T path tests, suggests that the Wind River age-eU correlations are less sensitive to precise intermediate Proterozoic temperatures, but the overall shape of the path (single versus two-stage Precambrian cooling paths) and the timing of cooling are required. The maximum burial temperatures achieved prior to Laramide cooling are also important, as figure 7 demonstrates, with a 15-40 °C difference between the higher and lower elevation sample groups giving markedly different age-eU curves. Only ~600 m of topographic elevation separates the lowest low elevation sample (WY-98-89) from the highest high
6. Discussion

Given the lack of Proterozoic $t$-$T$ constraints from the region, our results provide the first robust thermochronologic constraints on the thermal history of the Archean cores of these Laramide ranges. Our thermal modeling yields a best-fit $t$-$T$ history for Bighorn Mountains consisting of two stages of Proterozoic cooling (1800-1600 Ma and 900-525 Ma), followed by reburial to 110-115 °C just prior to a final phase of “Laramide” cooling between 85-60 Ma (Fig. 6). The histories that best agree with the observed ages for the Wind Rivers consist of the same two stages of Proterozoic cooling as the Bighorn data, with Phanerozoic burial of the structurally deepest samples (WY-98-89 and WY-96-89) to a maximum temperature of 155-160 °C and the remaining samples buried to 120-140 °C prior to all samples experiencing “Laramide” cooling between 60-40 Ma to 50 °C. The maximum Phanerozoic burial temperatures in the Wind River Range therefore exceeded those of the Bighorn Mountains. The best-fit $t$-$T$ constraints for both ranges do not capture several of the youngest ages at high (>1000 ppm) eU values. In addition, the eU concentrations for these zircons suggest that they should be metamict and possess zero ages. Because the observed ages are not zero, this suggests that some zone of
crystallinity remains in these highly damaged grains that ZRDAAM is currently unable to account for. Nevertheless, we emphasize that our best-fit paths capture the dominate trend of the data, supporting our interpretation that radiation damage is the primary control on age variability.

Major cooling events in the best-fit thermal histories for both datasets coincide with major tectonic events that affected Laurentia during the Paleoproterozoic-Mesozoic (Fig. 2). Initiation of cooling ca. 1800-1600 Ma in both ranges coincides with Yavapai-Mazatzal tectonic activity (~ 1760-1600 Ma) (Whitmeyer and Karlstrom, 2007). Evidence for cratonic cooling during orogenesis is found to the south of our study region along the Laramie Peak shear zone (Chamberlain, 1998), but our thermochronologic data is the first evidence that the interior of the Wyoming craton also experienced cooling during this time. The Neoproterozoic cooling event required by these data also coincides with documented rifting in the midcontinent, the Rocky Mountains, the southern limit of the Wyoming craton, and the west-central U.S. (Utah, Idaho, Nevada) (van Schmus, 1992; Marshak and Paulsen, 1996; Timmons et al. 2001; Yonkee et al., 2014). Our results suggest that this cooling may have extended much farther into the craton than previously documented.

Although our thermal modeling is an overall good fit to the geologic record in western Laurentia, slight differences exist between the Bighorn and Wind River samples that allow us to make more detailed interpretations. We highlight two important differences between the Bighorn and Wind River age-eU correlations: 1) the Bighorns' continuously negative age-eU correlation begins at ~960 Ma (much older than the oldest Wind River age of 582 Ma), and 2) the Bighorn’s age-eU correlation has a young cluster
of ages (~30-7 Ma) at ~1500 eU instead of an age-eU pediment. Negative age-eU correlations require that the highest eU and therefore most damaged grains have higher diffusivities than their lower eU counterparts. The transition from low to high diffusivity occurs when grains have accumulated an alpha dose in excess of $\sim 5 \times 10^{17} \alpha / g$, and if all grains in a sample compose a single negative correlation, then all grains have at least more accumulated damage than $\sim 5 \times 10^{17} \alpha / g$ (Guenthner et al. 2013). Importantly, the oldest age in a negative age-eU correlation represents the minimum amount of time over which this damage accumulation must have occurred. If the annealing kinetics of the damage that affects He diffusion are the same as those for fission tracks, then all of the grains in the Bighorn dataset have been cooler than $\sim 220 ^\circ C$ (lower temperature bound for the ZFT PAZ) since at least $\sim 950$ Ma.

The cluster of young ages at $\sim 1500$ ppm eU in the Bighorn dataset contrasts with the age-eU tail at similar eU concentrations in the Wind River dataset. Guenthner et al. (2014) showed that age-invariant samples across a wide range of eU require relatively rapid cooling through the wide range of $T_c$’s associated with the wide range of accumulated damage. The ages of the tail correspond to the timing of this cooling event, which for the Wind Rivers, is at $\sim 60$ Ma. In contrast, the Bighorn’s age-eU correlation shows no age-eU tail, and instead is continuously negative from old (957 Ma) to young (7 Ma) ages. In our best-fit model $t-T$ paths (Fig. 7), the Wind River dataset cools from between 160-125 °C to 50 °C between 60 and 40 Ma, whereas the Bighorn dataset cools from 115-110 to 50 °C between 85 and 60 Ma. Because the Wind Rivers experienced higher Phanerozoic burial temperatures, and cooling from higher to lower temperatures over a shorter time period than the Bighorns, a wider range of eU grains were fully reset
and that same wide range of grains “closed” at roughly the same time to yield the same
ages and form a tail.

Differences in the outcrop position of the samples with respect to the Great
Unconformity suggest that contrasting structural depths within Archean basement could
explain the different maximum burial temperatures in the \( t-T \) histories from each range.
The majority of samples from the Bighorn Mountains are from locations relatively close
to the outcrop exposure of the Archean-Cambrian unconformity, whereas the samples
from the Wind River Range were collected from locations likely significantly below this
structural depth. We speculate that the Bighorn samples were located closer to the paleo-
surface than the Wind River Range samples prior to the onset of Cambrian passive
margin sedimentation. Differences in the structural depth of samples across the Wind
River Range transect yield two distinct thermal histories. In contrast, samples from the
Bighorn Mountains yield one best-fit thermal history, likely because the structural relief
across the sample transect is significantly less than that in the Wind River Range. The
characteristics of each range’s age-eU correlation therefore serve as examples of how
contrasting thermal histories can produce different and decipherable age-eU correlations.

This dataset of variable, but systematically correlated, zircon He ages provides
additional information that lower temperature thermochronometers (apatite He and AFT)
cannot resolve. Recognition of the effects of radiation damage on He diffusivity allow for
thermal modeling of samples which show large variation in single grain ages, while not
excluding any replicates. Using the distribution of ages correlated with eU, the modeling
here shows evidence for previously unrecognized cooling events within the Wyoming
craton and constraints on previously documented burial heating events in the Proterozoic
and Phanerozoic, respectively. The addition of significantly older parts of the region’s thermal history to existing models on the most recent exhumation event furthers our understanding of the thermal history of Laurentian basement in the northern Rocky Mountain region and poses potential for understanding ancient tectonic and thermal histories in other regions of exposed basement terranes.

Acknowledgements: We thank James R. Steidtmann at the University of Wyoming for providing the separates from his seminal work in the Wind River Range to Barbara Carrapa. We thank Barbara Carrapa for use of these separates and scientific input on this manuscript. We thank Uttam Chowdhury for analytical support. We acknowledge support from ExxonMobil to W.R. Guenthner, EAR-0910577 to P.W. Reiners and ChevronTexaco Fellowships awarded to D.A. Orme and A.K. Laskowski.

Appendix I: Zircon (U/Th)/He Data Table
Appendix II: Thermal history model input table

Supplementary Material:
Figure 1: age-elevation plot of Wind River Range and Bighorn dataset

References


**Figure Captions**

**Figure 1:** Geologic sketch map of the Wind River Range, Bighorn Mountains and surrounding areas showing Zircon (U-Th)/He sample localities. The base map is a shaded, colored ASTER digital elevation model created using GeoMapApp (geomapapp.org). Map unit pCg demarcates the aerial extent of Precambrian crystalline basement rocks. Geology adapted from Schruben et al., (1997). Inset tectonic map adapted from Peyton and Carrapa (2013).

**Figure 2:** Major tectonic events affecting the Archean Wyoming Province from ca. 3.0 Ga to the present. Black vertical boxes denote thermochronologic constraints currently available for Archean basement. Constraints from Hoffman (1988), Chamberlain et al. (2003), Peterman and Hildreth (1978), and Peyton et al. (2012).

**Figure 3:** Zircon (U-Th)/He age-effective Uranium (eU) correlations for the (A) Wind River Range (54 ages) and (B) Bighorn mountains (32 ages). Samples BH12 and BH17 include data from Guenther et al. (2013).

**Figure 4:** (A) End-member $t$-$T$ histories tested for the Wind River Range (red) and Bighorn Mountains (blue). Scenario 1 rapidly cools from 350 to 20 °C between 2600-2500 Ma, reflecting cooling from high-grade metamorphism associated with the Trans-Hudson orogeny. In Scenario 2, cooling initiates between 700-525 Ma, reflecting the formation of the Great Unconformity. Phanerozoic thermal histories are held constant. (B) Resulting envelopes which show how well the combined effects of grain size and radiation damage capture the observed ages Modeled grain sizes for the Wind River and Bighorn datasets average 75 ± 39 μm and 57 ± 26 μm, respectively. The output consists of a central curve (mean grain size) encompassed by a shaded envelop (±2 grain size standard deviations).

**Figure 5:** (A) Representative $t$-$T$ paths testing rapid cooling associated with four Proterozoic tectonic events between 1800-900 Ma as discussed in the text. (B) Model output for thermal histories and observed data for the Bighorn and Wind River datasets. Numbered $t$-$T$ paths in panel insets correspond to the $t$-$T$ paths shown in Part A. For the Bighorns, none of the modeled curves are a good fit to the observed data. For the Wind Rivers, scenarios 2 (inset iv) and 3 (inset vi) capture 77% of the observed dataset, but both fail to capture young ages at low eU values.

**Figure 6:** (A) Representative $t$-$T$ paths testing two-stage monotonic cooling with prolonged residence at intermediate temperatures. (B) Scenario 2 (inset iii), rapid cooling at 1800-1600 Ma and 900-525 Ma, best captures the negative age-eU trend of the dataset. Scenarios 1-3 yield roughly the same fits to the Wind Rivers dataset and fail to capture ages at eU values greater than ~300 ppm.

**Figure 7:** Refined, best-fit $t$-$T$ solutions for the Bighorn Mountains. (A) Scenario 1 has a Proterozoic temperature of 160 °C and Mesozoic burial to 115 °C. Scenario 2 cools to 155 °C in the Proterozoic and 110 °C in the Mesozoic. (B) Best-fit envelopes for the $t$-$T$ paths of Part A.
Figure 8: Refined, best-fit $t$-$T$ solutions for the Wind River Range. (A) $t$-$T$ paths with a range of Proterozoic intermediate temperatures extending from 135-220 °C for low-elevation samples (red envelope) and from 140-220 °C for higher elevation samples (blue envelope). Maximum Phanerozoic burial temperatures are 155 to 160 °C for the lower elevation group of samples, and 120 to 140 °C for the higher elevation group. (B) Best-fit envelopes for low-elevation (red) and high-elevation (blue) samples which best captures the data and the long-tail at high eU values.
Figure 1
Click here to download Figure: figure 1 Geologic Setting copy.pdf
Tectonic History and Constraints on Forward Models

Cratonization
Accretion
Trans-Hudson
Yavapai-Mazatzal
Grenville
Laramide exhumation

Great Unconformity

Extension: K-Ar ages Wind River Range

Figure 2
Click here to download Figure: figure 2 Geologic Constraints Figure.pdf
Figure 3
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A. Wind River Range

B. Bighorn Mountains

Figure 2:
Phanerozoic thermal histories vary based on apatite He and AFT data.

Blue = Bighorns

Red = Wind Rivers
Phanerozoic thermal histories vary based on apatite He and AFT data.

Blue = Bighorns
Red = Wind Rivers
Phanerozoic thermal histories vary based on apatite He and AFT data.

Blue = Bighorns
Red = Wind Rivers
Figure 7

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Figure 8
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