Abstract

A reanalysis of apatite fission track (AFT) thermochronology coupled with thermal-kinetic modeling of samples from the Wind River Range document Late Cretaceous to early Eocene episodic cooling and exhumation of one of the largest basement-cored ranges in the western United States. Three vertical transects taken at different latitudes along the length of the 145 km Wind River Range reveal that exhumation is uniform along strike suggesting steady displacement along the Wind River Fault, and significant exhumation and relief in the Wind River Range by the early Eocene. Thermal modeling of AFT ages, lengths, and compositional proxies document rapid exhumation from ~65 to 50 Ma. This rapid exhumation episode matches a period of accelerated subsidence in the adjacent Green River and Wind River basins. At ~50 Ma, exhumation dramatically slowed by an order of magnitude coincident with decreasing subsidence in the adjacent basins. No signal of Oligocene cooling is apparent in either AFT cooling ages or thermal modeling suggesting that a possible later phase of reactivation of structures and uplift, as previously suggested, was limited to less than approximately 1 km of exhumation.

1. Introduction

The Wind River Range in west central Wyoming is a classic example of Laramide-style basement block uplift. The Wind River Range is the highest range in the Laramide region with a maximum elevation of 4207 m at Gannett Peak (Figure 1). The timing of exhumation of the Wind River Range is important for understanding the timing of Laramide-style deformation and to assess proposed mechanisms for Late Cretaceous-Paleogene tectonic deformation within the North American Cordilleran foreland basin [Dickinson and Snyder, 1978; Dickinson et al., 1988; Liu et al., 2010; Fan and Carrapa, 2014].

Several models of Wind River Range exhumation have been proposed using sedimentological, geophysical, and thermochronologic data sets. Early studies modeled Wind River uplift and exhumation using the sedimentary record [e.g., Dickinson et al., 1988; Steidtmann and Middleton, 1991; Keef, 1965b]. The sedimentary record preserved in the Wind River basin indicates the erosion of the Wind River Range started to be recorded in the basin by 53 Ma [Fan et al., 2011]. Studies of conglomerate deposition in early Paleogene basins of the western United States record an introduction of Paleozoic and Precambrian clasts by the beginning of the Eocene [Carroll et al., 2006]. In the Wind River basin northeast of the range (Figure 1), Precambrian clasts appear by the Eocene. However, in the Green River basin south and west of the range, Paleozoic and Precambrian clasts appear in Paleocene stratigraphy [Carroll et al., 2006], which would require tectonic unroofing of the Wind River Range at that time.

Steidtmann and Middleton [1991] propose that Late Cretaceous-Eocene erosion kept pace with uplift, ultimately burying all but the highest peaks of the range and creating a regional erosional surface in the Oligocene [Steidtmann et al., 1989; Steidtmann and Middleton, 1991]. Modern relief was achieved in the crest of the range only by a second Oligocene period of uplift and erosion recorded by deposition of conglomerates in the late Oligocene South Pass Formation [Steidtmann and Middleton, 1986; Shuster and Steidtmann, 1988]. Recent paleoaltimetry data using the δ18O values of bivalve aragonite, calcite cement, and leaf fossils [Fan and Dettman, 2009; Fan et al., 2011; Chamberlain et al., 2012; Davis et al., 2008; Wolfe et al., 1998] suggest that surface elevations >2 km were in place in the Wind River region by circa 53 Ma and that burying all but the highest peaks of the range would have required between 2 and 4 km of sedimentation in some locations [Fan and Carrapa, 2014].

Geophysical data have been used to model the tectonic history of Laramide-style deformation in the western United States. Liu et al. [2010] use inverse convection models to show that Laramide deformation followed a two-phase history triggered by the subhorizontal subduction of the Shatsky Plateau beneath the western U.S.
between 84 and 68 Ma and the eclogitization and subsequent removal of this buoyant feature by the late Paleocene.

Cooling, exhumation, and deformation can result from the flattening of a buoyant slab and regional-scale uplift of basement-cored ranges from the removal of the eclogitized plateau [Liu et al., 2010]. Fan and Carrapa [2014] use paleotopography, subsidence analysis, and thermochronology to identify the Liu et al. [2010] two-phase deformation history in the geologic record throughout Wyoming and suggest a more rapid exhumation signal in the Paleocene–Eocene interpreted to be associated with westward slab rollback following a period of flat slab subduction. In a modification of this model, Smith et al. [2008] use evidence from paleohydrology patterns to propose that regional exhumation precedes the rollback of the flat slab. Alternatively, a more recent study of seismic tomography shows high-velocity mantle beneath the Wyoming craton, which has been interpreted to represent basal depleted oceanic plateau mantle lithosphere of the Shatsky Rise conjugate, which accreted under Wyoming in the early Cenozoic [Humphreys et al., 2015]. In order to test models of Laramide tectonics, it is essential to accurately determine the timing of exhumation.

One of the first applications of low-temperature thermochronology to constrain the timing and exhumation history of the northern basement-cored uplifts was to the Wind River Range [Steidtmann et al., 1989; Cerveny, 1990; Cerveny and Steidtmann, 1993]. Cerveny and Steidtmann [1993] conducted fission track analysis of 80 samples from six traverses and a wellhole that encompass 5 km of relief along the length of the range. Their apatite fission track (AFT) data are significant since they represent the first thermochronological constraints on the timing of exhumation of the Wind River Range. However, these data were produced before the standardization of etching protocols. Samples in this study were etched between 30 and 45 s in 7% nitric acid [Cerveny, 1990]. The effect of nonstandard etching procedures on the cooling age of an AFT sample is
variable, producing both higher and lower cooling ages than standard techniques [Murrell et al., 2009; Fleischer et al., 1975]. Therefore, the original interpretation by Cerveny and Steidtmann [1993] that cooling in the Wind River Range commenced by 85 Ma and was punctuated by rapid events at 62–57 Ma and 40 Ma may not be accurate. Furthermore, AFT data produced by nonstandard procedures cannot be analyzed by more recently developed thermal kinematic modeling techniques [Murrell et al., 2009; Ketcham, 2005].

This study reanalyzes samples collected by Cerveny and Steidtmann [1993] from the Middle Fork Lake (nine samples) and Temple Peak (seven samples) traverses using up-to-date AFT etching methods. Samples analyzed using modern standard etching methods provide more accurate cooling ages [Murrell et al., 2009] that together with track lengths and compositional proxies ($D_{\text{par}}$) can be modeled by thermal-kinetic annealing modeling [Donelick et al., 2005; Ketcham, 2005].

Reanalyses of AFT from the Wind River Range can test the following: (1) the importance of modern etching protocols and thermal-kinetic modeling, (2) variations in exhumation in response to structural deformation along strike of the Wind River Range, (3) the magnitude of late Eocene heating and Oligocene cooling associated with burial and later exhumation and uplift hypothesized by the presence of coarse conglomerate input into the proximal Green River basin in the early Cenozoic [Steidtmann and Middleton, 1986; Shuster and Steidtmann, 1988], (4) the response of the sedimentary system to periods of increasing and decreasing exhumation, and (5) relationships between exhumation of the Wind River Range and subduction-related lithospheric-scale processes. The predicted AFT ages for each of these models are summarized in Table 1.

The authors would like to emphasize the importance of the seminal AFT studies in the Wind River and other ranges in the western U.S. These studies provided initial tectonothermal constraints, but more importantly, they laid the foundation for AFT work that would follow. The standardization of etching protocols in the mid-1990s and the ability to use $D_{\text{par}}$ as a proxy for annealing behavior [Donelick et al., 1999; Ketcham et al., 1999] now requires that we revisit these old studies to update datasets with modern AFT preparation methods and modeling techniques.

2. Geologic History

2.1. Tectonic Evolution of the Laramide Region

The ~6000 km$^2$, northwest-southeast trending Wind River Range is a dominant structure within the Laramide foreland and one of the most prominent basement-cored uplifts in North America (Figure 1). The range core is composed of Proterozoic granites, granitic gneisses, and migmatites of the Archean Wyoming Province [Frost et al., 1998]. Zircon fission track (ZFT) thermochronology indicates that Wind River Range basement rocks have not been heated above the ZFT closure temperature (~200–250°C) [Zaun and Wagner, 1985] since Proterozoic time [Cerveny, 1990; Cerveny and Steidtmann, 1993]. The Archean rocks exposed in the range record four primary thermal events: (1) emplacement and high grade metamorphism between 2.8 and 2.55 Ga [Frost et al., 1998], (2) relatively slow and poorly constrained unroofing in the Proterozoic culminating in exposure at the surface marked by an unconformable relationship with the Cambrian Flathead sandstone [Snoke, 1993], (3) burial throughout the Paleozoic and Mesozoic under 4–6 km of sedimentary cover [Winterfeld and Conard, 1983; Seeland, 1978; Phillips, 1983], and (4) uplift and exhumation in latest Cretaceous to Cenozoic [Fan and Carrapa, 2014; Peyton et al., 2012; Dickinson et al., 1988; Carroll et al., 2006] culminating with exposure of crystalline basement at the surface in the Paleocene. Previous thermochronological studies [e.g., Steidtmann et al., 1989; Cerveny, 1990; Peyton et al., 2012; Fan and Carrapa, 2014; Orme et al., 2015] have shown that the Paleozoic-Mesozoic burial stage resulted in significant heating of basement rocks in the Wind River Range to completely anneal any older fission tracks in apatite prior to exhumation during Laramide deformation. The early thermal history of these crystalline basement blocks is recorded by geochronology and high-temperature thermochronology, whereas the primary cooling signal recorded in low-temperature systems, such as AFT, captures the final thermal event resulting from exhumation and tectonic uplift associated with Laramide and post-Laramide deformation.

During the Early Mesozoic, western Wyoming was a foreland basin, receiving western derived detritus that was deposited on top of Cambrian to Permian carbonate and clastic sedimentary strata [Keffer, 1965a]. To the west, convergence between the subducting Farallon plate and the western margin of North America led to the formation and eastward migration of the thin-skinned Sevier fold and thrust belt [e.g., DeCelles, 2004].
<table>
<thead>
<tr>
<th>Source</th>
<th>Methods Used</th>
<th>Region Studied</th>
<th>Timing of Initial Laramide Deformation</th>
<th>Timing of Exhumation and Burial</th>
<th>Model Predicted AFT Ages in Wind River Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Upper Eocene burial ~4 km</td>
<td>2. Eocene cooling at highest elevation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. Upper Oligocene uplift</td>
<td>3. Oligocene cooling at lower elevation</td>
</tr>
<tr>
<td>Cerveny and Steidtmann [1993]</td>
<td>Apatite Fission Track (old etching method)</td>
<td>Wind River Range</td>
<td>85 Ma</td>
<td>1. Earliest AFT ages suggest initial exhumation as early as 85 Ma</td>
<td>1. Earliest AFT ages suggest initial exhumation as early as 85 Ma</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Rapid cooling ~40 Ma</td>
<td>2. Concentration of 62–57 Ma ages</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. ~40 Ma ages at lowest elevations</td>
<td>3. ~40 Ma ages at lowest elevations</td>
</tr>
<tr>
<td>Liu et al. [2010]</td>
<td>Inverse convection models and plate reconstructions</td>
<td>Laramide region</td>
<td>Late Cretaceous</td>
<td>1. Local shortening and minor uplift ~80 Ma</td>
<td>1. Some Late Cretaceous/Paleocene cooling may be preserved</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Accelerated regional uplift ~65 Ma</td>
<td>2. Major pulse of cooling beginning ~65 Ma</td>
</tr>
<tr>
<td>Fan and Carrapa [2014]</td>
<td>Paleoaltimetry, basin subsidence records, thermochronology, and provenance records</td>
<td>Laramide region</td>
<td>Late Cretaceous</td>
<td>1. Slow exhumation Late Cretaceous to early Paleocene</td>
<td>1. Some cooling Late Cretaceous to early Paleocene</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Rapid exhumation Paleocene to early Eocene</td>
<td>2. Major pulse of cooling Paleocene to early Eocene</td>
</tr>
<tr>
<td>Smith et al. [2014]</td>
<td>Lacustrine stratigraphy of Laramide Basins</td>
<td>Laramide region</td>
<td>NA</td>
<td>1. Creation of lake basins attributed to damming of NE flowing rivers during slab rollback</td>
<td>1. AFT cooling should predate timing of lake ponding when basement cored ranges are exposed</td>
</tr>
</tbody>
</table>
The onset of Laramide deformation, beginning as early as the Late Cretaceous [Steidtmann and Middleton, 1991; Devlin et al., 1993], is characterized by the reorganization of the Sevier foreland basin by activation of thick-skinned structures within Precambrian basement. This is recorded in the structural and stratigraphic history throughout Wyoming, Montana, Colorado, Utah, and South Dakota [e.g., Leary et al., 2014; Steidtmann and Middleton, 1986; Roberts and Kirschbaum, 1995; Painter and Carrapa, 2013; Erslev, 2005]. Shortening of the Precambrian basement is evident, but the mechanism for deformation of brittle basement rocks is controversial. Erslev [1986] uses fault curvature at depth to create a kinematic solution of the Wind River Fault. Stearns [1978] argues that deformation in the Wind River Range must have been driven by nearly vertical faulting that created drape folds on the Eocene surface. Berg [1981] proposes a method of “fold-thrust” uplift that incorporates a horizontal component to deformation along Laramide faults.

The change from thin- to thick-skinned deformation that marked the initiation of Laramide-style deformation in the Cretaceous is commonly associated with the decreased subduction angle of the Farallon slab [Dickinson and Snyder, 1978; Constenius, 1996; Saleeby, 2003]. The timing of initial slab flattening and the propagation of this slab flattening under the North American craton can be tracked by an inboard translation of magmatism [Coney and Reynolds, 1977; Constenius, 1996] which coincides with the partitioning of the Sevier foreland and activation of basement structures [Dickinson and Snyder, 1978; Constenius, 1996; Saleeby, 2003]. Widespread magmatism during the early Eocene that extends as far west as the Idaho batholith and as far east as the Black Hills of South Dakota serves as a surface manifestation of the widespread thermal activity associated with slab rollback and delamination [Constenius, 1996; Humphreys, 2009; Humphreys et al., 2003].

2.2. Stratigraphic Record of Sevier Foreland and Laramide Basin Evolution

The stratigraphy preserved in the western U.S. provides a detailed record of sedimentation and subsidence throughout the Mesozoic and early Cenozoic. In the Late Cretaceous there was a continuous marine foreland basin system that connected the Arctic Ocean in Alaska to the Gulf of Mexico [DeCelles, 2004]. The continuous foreland basin system related to the Sevier orogeny was broken by irregularly distributed Laramide block uplifts and their coinciding basins starting in the Upper Cretaceous. Structural relief between basin floors and the crests of adjacent uplifts range from 5 to 10 km [Dickinson et al., 1988]. All of these basins contain nonmarine successions of dominantly uppermost Cretaceous to mid-Eocene age, although some lack nonmarine Cretaceous beds, and others include upper Eocene strata as well. Locally derived alluvium is typical of basin stratigraphy from 70 to 50 Ma, with some sedimentation continuing until as late as 35 Ma [Dickinson et al., 1988]. Postdeformational strata overlie unconformities that extend across tectonic boundaries between adjacent uplifts.

The Wind River basin, located to the northeast of the Wind River Range (Figure 1), comprises ~6000 m of nonmarine clastic strata including the Maastrichtian Lance Formation, Paleocene Fort Union Formation, and Eocene Indian Meadows and Wind River Formations [Keef er, 1965b; Seeland, 1978; Winterfeld and Conard, 1983; Phillips, 1983; Fan et al., 2011]. Sedimentation and subsidence in the Wind River basin was controlled by both uplift of the Wind River Range and the Owl Creek and Washakie Ranges to the northeast (Figure 2). The Green River basin, immediately south of the Wind River Range and bounded on its northern margin by the Wind River Thrust (Figures 1 and 2), comprises just under 3000 m of nonmarine stratigraphy associated with late Cretaceous to early Eocene deformation [Berg, 1962; Curry, 1973, Shuster and Steidtmann, 1988, Bradley and Bruhn, 1988]. The western margin of the Wind River basin is bounded by the Sevier thrust front, active through the early Eocene, possibly affecting basin dynamics [DeCelles, 2004]. The Green River basin also contains the Paleocene Fort Union Formation, which is overlain by the Eocene Wastach, Green River, and Bridger Formations.

Both the Wind River and Green River basins record the initiation of coarse clastic sedimentation in the Maastrichtian [Keef er, 1965a, 1965b; Steidtmann and Middleton, 1991; Shuster and Steidtmann, 1988]. Significant topographic relief of the bounding Laramide ranges led to restriction of both the Wind River and Green River basins and intermittent lacustrine deposition in Paleocene-Eocene time [Carroll et al., 2006; Smith et al., 2014, 2008]. The Indian Meadows and lower to middle Eocene Wind River Formations contain conglomerate clasts derived from Archean basement rocks exposed in the Wind River Range and therefore require that crystalline basement was exposed at the surface and being eroded in the Eocene [Carroll et al., 2006; Fan et al., 2011]. In the Wind River basin the Wind River Formation is supplanted...
3. AFT Thermochronology

3.1. Methods

We acquired 18 of the original mineral separates from surface samples used by Cerveny and Steidtmann [1993] for reanalysis using modern etching and modeling techniques as well as one new granite clast sample from the Wind River Formation in the Wind River basin (Figure 1). The samples used from this study were originally published as the Middle Fork Lake (Bailey Peak) and Temple Peak range-perpendicular transects of the Wind River Range in Cerveny and Steidtmann [1993]. We compare our results with AFT ages and thermal modeling [Peyton et al., 2012; Fan and Carrapa, 2014] from the Gannett Peak age-elevation transect (Figure 1).

Sample separates were mounted in epoxy and irradiated at Oregon State University on glass slides. The apatites were etched in 5.5 M nitric acid for 20 s at 21°C, according to methods outlined by Donelick et al. [1999] in order to allow for optical identification of fission tracks using an Olympus petrographic microscope at 1600 times magnification at the University of Arizona. The mica prints were etched in 49% hydrofluoric acid for 15 min at 23°C following Donelick et al. [2005]. For each sample from the Temple Peak and Middle Fork Lake transects 20 grains were dated using the external detector method. All raw counting data are reported in the supporting information Table S1, following the procedure of Flowers et al. [2015]. Constrained track lengths, when present, were measured in the same grains counted for age determination, or from other grains on the same mount, or a second mount from the same sample. As many track lengths were counted as possible, but typically ~50 track lengths were acquired per sample. The angle between the confined track and the crystallographic axis (C axis projected data) was measured in order to mitigate track measurement bias [Barbarand et al., 2003], because confined tracks anneal anisotropically as a function of orientation [Donelick et al., 1999; Ketcham et al., 1999]. $D_{par}$ a measure of etch pit geometries [Donelick et al., 1999, 2005; Ketcham et al., 1999], was measured in all grains counted for age determination and measured for length data in order to model kinetic characteristics.
3.2. Results

All samples passed the chi-square test indicating homogenous populations [Galbraith, 1981; Green, 1981]; we report the pooled age of each sample with uncertainty reported at 95% confidence intervals [Galbraith, 2005]. Radial plots are provided in the supporting information. The complete AFT data set including age, length, and $D_{par}$ are represented in Table 2 and supporting information Table S1.

All of the basement samples from this study had AFT cooling ages within a 20 Myr range with a youngest age of 42 ± 4 Ma from the Temple Peak traverse and an oldest age of 61 ± 6 Ma from the Middle Fork Lake transect (Table 2). Of the 22 basement rock samples in both studies, 5 are between 55 and 61 Ma, 14 are between 55 and 50 Ma, and 3 are between 50 and 42 Ma. Samples follow a general age-elevation trend with younger ages at lower elevations and older ages at higher elevations, with some inversion potentially related to structural offset (Figure 2). Average track lengths corrected for $C$ axis orientation range between 13.5 and 14.3 $\mu$m and are unimodal with minor tails toward shorter lengths observed in some samples (Table 1 and Supporting Information S1).

The cobble from the Wind River Formation in the Wind River basin produced a pooled AFT cooling age of 59 ± 5 Ma (Table 2). The absence of a pre-Cenozoic cooling age in the circa 53–51 Ma Wind River Formation [Fan et al., 2011] indicates the complete removal of a paleopartial annealing zone and suggests that rapid cooling may have initiated before ~59 Ma.

3.3. AFT Thermal Modeling

Perhaps the greatest utility of AFT analysis lies in the capability to couple cooling ages with confined AFT track length [Gleadow et al., 1986] and $D_{par}$ measurements. Thermal modeling of AFT ages, track length, and $D_{par}$ measurements reveals trends in cooling histories, distinguishing, for example, between monotonic cooling and rapid cooling followed by slow cooling [Donelick et al., 2005; Ketcham et al., 1999; Ketcham, 2005; Ketcham et al., 2007; Green et al., 1989]. Forward and inverse thermal models based on AFT age and length data were produced using HeFTy modeling software [Ketcham et al., 1999, 2007: Ketcham, 2005].

### Table 2. Sample Names, AFT Ages, Length Distributions, $D_{par}$ and Elevations From This Study and the Correlative Samples From Cerveny and Steidtmann [1993]a

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Elevation (m)</th>
<th>Pooled AFT Age (Ma) This Study</th>
<th>AFT Error ± 2 $\sigma$ (Ma) This Study</th>
<th>Track Lengths Corrected for C Axis This Study</th>
<th>Pooled AFT Age [Cerveny and Steidtmann [1993]]</th>
<th>AFT Error ±2 $\sigma$ (Ma) Cerveny and Steidtmann [1993]</th>
<th>Track Lengths Cerveny and Steidtmann [1993]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gannet Peak [Peyton and Carrapa, 2013]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GP5</td>
<td>3146</td>
<td>54.2</td>
<td>1.6</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>GP2</td>
<td>3298</td>
<td>54.0</td>
<td>1.9</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>GP1</td>
<td>3573</td>
<td>54.4</td>
<td>2.9</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>GP4</td>
<td>3978</td>
<td>54.8</td>
<td>2.0</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>GP3</td>
<td>4208</td>
<td>56.6</td>
<td>1.8</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Middle Fork Lake</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WY 90-89</td>
<td>3534</td>
<td>52.9</td>
<td>4.7</td>
<td>13.90</td>
<td>62.3</td>
<td>5.2</td>
<td>14.4</td>
</tr>
<tr>
<td>WY 91-89</td>
<td>3381</td>
<td>56.8</td>
<td>5.4</td>
<td>13.80</td>
<td>62.7</td>
<td>5.5</td>
<td>14.4</td>
</tr>
<tr>
<td>WY 92-89</td>
<td>3226</td>
<td>50.1</td>
<td>4.6</td>
<td>13.72</td>
<td>67.9</td>
<td>5.8</td>
<td>14.5</td>
</tr>
<tr>
<td>WY 93-89</td>
<td>3161</td>
<td>58.6</td>
<td>5.0</td>
<td>13.57</td>
<td>66.3</td>
<td>5.5</td>
<td>14.2</td>
</tr>
<tr>
<td>WY 96-89</td>
<td>3033</td>
<td>53.6</td>
<td>5.2</td>
<td>14.17</td>
<td>64.8</td>
<td>5.4</td>
<td>14.5</td>
</tr>
<tr>
<td>WY 97-89</td>
<td>2975</td>
<td>58.5</td>
<td>6.1</td>
<td>14.19</td>
<td>69.1</td>
<td>6.8</td>
<td>14.8</td>
</tr>
<tr>
<td>WY 98-89</td>
<td>2934</td>
<td>61.0</td>
<td>5.9</td>
<td>13.91</td>
<td>74.6</td>
<td>6.9</td>
<td>14.3</td>
</tr>
<tr>
<td>WY 99-89</td>
<td>2878</td>
<td>54.8</td>
<td>5.0</td>
<td>13.67</td>
<td>70.8</td>
<td>6.2</td>
<td>14.4</td>
</tr>
<tr>
<td>WY 100-89</td>
<td>2728</td>
<td>44.6</td>
<td>4.1</td>
<td>14.06</td>
<td>67.5</td>
<td>5.7</td>
<td>14.2</td>
</tr>
<tr>
<td>WY 101-89</td>
<td>2567</td>
<td>53.0</td>
<td>5.0</td>
<td>13.77</td>
<td>66.7</td>
<td>5.8</td>
<td>14.1</td>
</tr>
<tr>
<td>Temple Peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WY 45-86</td>
<td>2912</td>
<td>47.8</td>
<td>4.3</td>
<td>14.26</td>
<td>47.1</td>
<td>4.6</td>
<td>13.4</td>
</tr>
<tr>
<td>WY 35-86</td>
<td>3216</td>
<td>42.1</td>
<td>3.9</td>
<td>14.02</td>
<td>54.2</td>
<td>5.0</td>
<td>13.6</td>
</tr>
<tr>
<td>WY 43-86</td>
<td>3369</td>
<td>53.9</td>
<td>5.1</td>
<td>13.66</td>
<td>59.6</td>
<td>5.7</td>
<td>12.1</td>
</tr>
<tr>
<td>WY 40-86</td>
<td>3503</td>
<td>51.3</td>
<td>4.6</td>
<td>13.85</td>
<td>60.3</td>
<td>5.9</td>
<td>13.2</td>
</tr>
<tr>
<td>WY 46-86</td>
<td>3659</td>
<td>51.2</td>
<td>5.0</td>
<td>13.85</td>
<td>72.9</td>
<td>7.4</td>
<td>13.4</td>
</tr>
<tr>
<td>WY 34-86</td>
<td>3826</td>
<td>53.1</td>
<td>4.7</td>
<td>13.61</td>
<td>73.5</td>
<td>5.7</td>
<td>13.7</td>
</tr>
<tr>
<td>WY 44-86</td>
<td>3954</td>
<td>51.1</td>
<td>4.8</td>
<td>13.81</td>
<td>69.0</td>
<td>6.1</td>
<td>13.4</td>
</tr>
<tr>
<td>Detrital Cobble</td>
<td>Wind Riv 1</td>
<td>NA</td>
<td>59.3</td>
<td>4.8</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

aGannet Peak transect was analyzed by Peyton et al. [2012] and modeled in Fan and Carrapa [2014]. NA = not applicable.
Forward models are a useful first step to test potential time-temperature histories of a data set. All forward models were run using an initial temperature constraint that accounts for the 4–6 km of burial throughout the Paleozoic to Early Mesozoic. This constraint is consistent with the known geologic history of the Wind River Range as summarized in the geologic setting. Although the Wyoming province has experienced a long and complicated history, we found that changing the rate or duration of Paleozoic and Early Mesozoic burial history has no effect on any model that could fit the age and length distribution; because of this, we assume steady heating coinciding with burial and complete resetting of AFT samples throughout the Paleozoic and Early Mesozoic, although any number of paths would be possible during this time.

To forward model the cooling history beginning in the Late Mesozoic, we used three representative samples from the Temple Peak and Middle Fork Lake transects: WY99-89, WY91-89, and WY43-86. Forward models were fit to the age and length data generated in this study (Figure 3). The AFT system does not record the cooling history at temperatures hotter than 120°C; however, we assume that all samples have reached ~160–135°C by the Late Cretaceous/Paleocene consistent with preliminary results using the (U-Th)/He system on zircon (ZHe) [Orme et al., 2015]. We then tested three separate cooling scenarios proposed by previous models and compared the goodness of fit statistics for the age and length data produced by HeFTy [Ketcham et al., 1999; Ketcham, 2005]. The goodness of fit statistic compares the fit of the model data with the measured data. For the age statistic this is a comparison of the model age to the measured age. For the AFT length distributions, this study analyzed goodness of fit using Kuiper’s statistic which is sensitive to extreme values as well as average values [Ketcham, 2005].

The first cooling scenario modeled rapid exhumation from passage through the closure temperature to ~50 Ma followed by drastically reduced exhumation following 50 Ma. These forward models were designed to maximize the goodness of fit statistics for each sample while matching exhumation models derived from the sedimentary record [Dickinson et al., 1988]. All three models fit age data at or above the 97th percentile for each sample and fit length data at or above the 65th percentile (Figure 3). This suggests that the Temple Peak and Middle Fork Lake transects experienced similar cooling and exhumation histories passing through the closure temperature as early as 65 Ma and ceasing rapid exhumation by ~50 Ma (Figures 3a and 3b).

The second forward model (Figure 3c) tests the possibility of nearly constant, protracted cooling following the passage of the sample through the closure temperature. For each of these forward models, we removed the change in rate from the first scenario and assumed constant exhumation from 160 to 135°C since the Late Cretaceous/Paleocene as suggested by the ZHe system [Orme et al., 2015]. These data produced poor goodness of fit statistics for all age data scoring less than the 1st percentile for each sample. Goodness of fit statistics for length data ranged from 1 to 87%.

The third forward model (Figure 3d) tests the hypothesis of late Eocene to Oligocene burial followed by rapid exhumation by 23 Ma [Steidtmann and Middleton, 1991]. These thermal models contained the same
rapid exhumation until ~50 Ma followed by ~2 km of burial required to nearly eliminate topography (Figure 3) [Fan and Carrapa, 2014; Steidtmann and Middleton, 1991]. Age data produced goodness of fit statistics for the three samples ranging from 17% to <1%. Length distributions ranged from 14% to <1%. This model also predicts biomodal AFT track length distributions, a result not observed in any of the samples.

Next, inverse models were run using constraints consistent with the geologic history of the Wind River Range. HeFTy results presented in this paper allowed up to three inflection points in the model. Models with additional inflection points did not improve model results. We adopt the calculation for a geothermal gradient of ~20°C/km from Peyton et al. [2012] made using borehole temperatures from well logs. We assume that present surface temperatures are between 0 and 20°C and that at least 4 km of sedimentary strata covered the region [Winterfeld and Conard, 1983; Seeland, 1978; Phillips, 1983]. The amount of crystalline basement that once covered the samples is unknown. For this reason samples must have been exposed to minimum temperatures of 100°C at the beginning of the Late Cretaceous. However, for inverse modeling we constrained only that samples must be at temperatures between 200 and 100°C between 100 and 90 Ma and that samples must reach surface temperatures by the present time. Modeling parameters were left intentionally broad, to allow for a wider variety of t-T paths, with upper temperature bounds at 200°C even though it is geologically unlikely that samples ever reached that temperature, based on the known thickness of overburden and geothermal gradient estimates [Peyton et al., 2012]. This strategy allowed modeling data to test the maximum variety of potential cooling paths and constrain the best results. The AFT system alone cannot resolve the time-temperature history at temperatures higher than 120°C. While we present inverse models with cooling paths with temperatures higher than 120°C, we do not attempt to interpret tectonic significance to cooling paths at these higher temperatures. Inverse models are only run from 100 Ma to present because the samples were completely annealed before cooling in the Cenozoic.

Apatite helium data from the Wind River Range was reported in Peyton et al. [2012] for transects in Gannet Peak and Fremont Lake. Samples from both transects have significant data scatter that could not be resolved by correlations between age and eU (effective uranium concentration) or age and grain size thus precluding the application of thermal diffusion models to these data sets. Peyton et al. [2012] suggested that He

Figure 4. Compiled best fit time-temperature paths from inverse models from sections of the (a) Middle Fork Lake traverse and (b) Temple Peak traverse. Modeling parameters (black box) are left intentionally broad to allow a higher degree of freedom for sample time-temperature paths. Inverse models were run in HeFTy based on AFT age, length, and Dpar measurements. Three inflection points were allowed in forward modeling. Allowing additional inflection points did not improve model results. Colored lines show individual, nonunique best fit paths for each sample. Dashed colored lines indicate time-temperature paths below the closure temperature of the AFT system. Grey semiopaque outlines represent the good fit envelopes for individual samples. Black arrows show our interpretation of the average time-temperature exhumation path for each transect. The relative overlap of the good fit envelopes from samples collected at different elevations highlights the rapid exhumation of the entire Wind River Range. Complete results for inverse models including good and acceptable path envelopes for each sample are provided in the data repository.
implantation compromised the integrity of the cooling ages in these apatite grains. While this technical explanation is sufficient to exclude this data set from our thermal modeling, a geologic explanation would also suffice. The AHe data suggest cooling via exhumation of the Wind River Range beginning in the middle to late Cretaceous. However, this time was actually marked by sediment accumulation and burial [Roberts and Kirschbaum, 1995; Keefer, 1965a, 1965b; Winterfeld and Conard, 1983].

Inverse models using HeFTy record time-temperature paths for 10,000 model runs. Each run is scored as good or acceptable based on the degree of fit from both AFT age and length data [Ketcham, 2005]. Results from inverse modeling suggest a temperature-time history with rapid exhumation from passage through the closure temperature as early as 65 Ma that continues until ~50 Ma followed by decreased exhumation that agrees with the AFT data from both Middle Fork Lake and Temple Peak transects (Figure 4). The best fit inverse models should not be treated as unique solutions; instead, they represent the best possible fit without excluding other potential good fit solutions. Inverse models for each sample are compiled in the supporting information with envelopes that show other good or acceptable time-temperature histories. Both the best fit paths and good fit envelopes for each sample support a decrease in exhumation rate by ~50 Ma in both the Middle Fork Lake and the Temple Peak transects (Figure 4).

Figure 4a depicts the best fit paths and good fit envelopes generated using inverse modeling for the Middle Fork Lake Transect. While individual potential cooling paths vary, inverse modeling highlights a significant decrease in exhumation at ~50 Ma. We calculate the exhumation rate in the Middle Fork Lake transect assuming a geothermal gradient of ~20°C/km [Peyton et al., 2012] from passage through the closure temperature, which varies depending upon the sample, until 50 Ma. Using this method, the exhumation rates for individual samples range from 0.11 mm/yr to 0.51 mm/yr with an average of 0.24 mm/yr (σ = ±0.13 mm/yr). We expect that this method of calculation provides minimum estimates of exhumation because it is limited to values above the closure temperature of the AFT system, 120°C. Exhumation rates from 50 to 15 Ma are an order of magnitude lower ranging from 0.09 to 0.01 mm/yr with an average of 0.03 mm/yr (σ = ±0.3 mm/yr).

Inverse modeling of the Temple Peak transect records similar trends. Exhumation rates until 50 Ma range from 0.07 mm/yr to 0.34 mm/yr with an average of 0.18 mm/yr (σ = ±0.10). From 50 Ma to 15 Ma, exhumation slows to rates ranging from 0.001 mm/yr to 0.09 mm/yr with an average of 0.04 mm/yr (σ = ±0.03). An alternative exhumation history is possible in the Temple Peak region. Inverse modeling shows that some samples contain good fit paths that favor steady cooling until ~35 Ma followed by very slow exhumation from ~35 to 5 Ma. Although we cannot eliminate this solution, each sample with a best fit path that supports this alternative hypothesis also contains good or acceptable fit time-temperature paths that support decelerated cooling at ~50 Ma. Results from forward modeling also suggest the alternative interpretation is a less likely scenario (Figure 3).

Exhumation rates obtained in this study are consistent with rates determined by other studies [Peyton et al., 2012] and with erosion rates recorded in other thick-skinned settings such as the Andes [e.g., Deeken et al., 2006; Carrapa et al., 2013]. Modeling of AFT samples from Gannet Peak suggests faster exhumation rates at that location (~0.38 mm/yr) [Fan and Carrapa, 2014; Peyton et al., 2012; Peyton and Carrapa, 2013], this rate is typical of block-style uplifts, with large vertical displacement on relatively high angle faults [e.g., Ehlers, 2005].

4. Discussion

4.1. AFT Comparison

The majority of samples from this study (all but one) are younger than the Cerveny and Steidtmann [1993] by up to 22 Ma (Table 2). Only 7 out of 17 samples analyzed in this study are within error of the ages produced by Cerveny and Steidtmann [1993]. This result is consistent with etching experiments performed by Murrell et al. [2009], who show that nonstandardized etching techniques generally lead to varying results. Overetching due dominantly to exposure to stronger acids for longer time periods exposes more track lengths on the surface of the grain [Fleischer et al., 1975] producing older ages. Cerveny and Steidtmann, 1993 also report longer track lengths and a larger Dpar (etch pit size), which may result from etching variability [Fleischer et al., 1975; Murrell et al., 2009]. There do not seem to be any first-order correlations between mismatched ages and U concentration (supporting information Table S1). A simple correction factor produced by subtracting a uniform age is impossible to apply in this case.
Systematic differences in etching should be removed by zeta calibration on AFT standards. However, variation of etching times that change as much as 30–45 s between samples, a procedure commonly used to obtain uniform length and etch pit diameters, produces inconsistent variations between samples, including AFT standards. Variability between AFT standards and unknown samples in this case would not be corrected by the zeta calibration method. Standardized etching procedures across samples likely contributed to more robust cooling ages produced in this study; Cerveny and Steidtmann [1993] identified a range of 27.5 Myr between samples, whereas we identified a range of 19 Myr. However, a combination of factors may conceivably contribute to the discrepancy in the data spread between studies. The dosimeter glass, SRM 963, with a low uranium concentration [Hurford, 1998] was originally used in the analysis by Cerveny and Steidtmann [1993]. This glass is subject to fission of isotopes other than $^{235}$U if the reactor facility is not well thermalized which may result in spurious results [Wagner and Van den Haute, 1992]. This study instead uses a Corning CN-5 dosimeter glass with a uranium concentration of $\sim$12 ppm [Hurford, 1998]. Additionally, Cerveny and Steidtmann [1993] analyzed only 8 grains per sample, while this study analyzes 20 grains per sample which is more likely to capture the natural Poisson variation and produces more precise results given the natural data dispersion of AFT data (supporting information Figure S1).

AFT ages produced by Cerveny and Steidtmann [1993] included Late Cretaceous to early Eocene cooling ages and identified a pulse of rapid cooling between 62 and 57 Ma. These results have guided subsequent interpretations for the onset of Laramide deformation. Our thermal modeling shows that while cooling may have started in the Late Cretaceous, rapid cooling recorded in the earliest Paleocene lasted until at least the early Eocene.

4.2. Structural Record

Identifying age-elevation relationships, which are key to quantifying exhumation rates, may be complicated by structural offset. However, structural deformation, including local faults and folds, is difficult to identify in basement block uplifts which naturally lack bedding indicators. Fault movement may create minor discrepancies in a positive age-elevation relationship in the Temple Peak and Middle Fork Lake transects. Here samples offset by large horizontal distances, such as in the Middle Fork Lake transect, show a greater variability in ages and tend to not show expected age-elevation relationships, which we interpret to indicate minor offset along secondary faults (Figure 2). Faults would be indicated by offset of regional cooling ages at similar elevations or the inversion of cooling ages in a vertical transect [Gleadow and Fitzgerald, 1987]. However, the general displacement profile across the Wind River Range is surprisingly uniform. The spatial uniformity of exhumation implies a similar magnitude and timing of exhumation along the entire 145 km length of the range. This supports the deformation model proposed by Berg [1981] that Laramide faults included a significant horizontal component and is also consistent with cylindrical fault surfaces that reach shallower angles at depth [Erslev, 1986]. AFT data produced in this study are inconsistent with the idea that offset in the Wind River Range, among other Laramide basement block uplifts, is almost entirely vertical [Stearns, 1978].

It is important to note that if faults throughout the Wind River Range are crustal scale, it is possible that movement along these faults would shift the isotherms as the rocks were transported to the surface [Gleadow, 1987]. This would result in a slower calculated cooling rate using the AFT record.

4.3. Late Eocene-Oligocene Burial and Exhumation

Steidtmann et al. [1989] and Steidtmann and Middleton [1991] use the presence of Oligocene conglomerates deposited to the south of the Wind River Range, observations of modern Wind River topographic profiles, and early Eocene AFT cooling ages to suggest that by the end of the Eocene, the Wind River Range was almost entirely buried by its own sediments, and modern elevation of the Wind River Range was achieved in the Oligocene. Paleovaltimetry records indicate $>2$ km elevation by circa 54 Ma and would require burial of at least 2 km, but probably closer to 4 km if only the peaks of the Wind River Range remained exposed [Fan and Carrapa, 2014; Fan and Dettman, 2009]. Assuming a geothermal gradient of $\sim$20°C as suggested by Peyton et al. [2012], the AFT system should record 4 km of burial by the late Eocene. Only 3 of the 22 samples for the Temple Peak, Gannet Peak, and Middle Fork Lake transects record ages younger than 50 Ma and the youngest of these three ages, 42 Ma, does not record an Oligocene cooling event. Forward and inverse thermal modeling is also inconsistent with late Eocene burial greater than $\sim$1 km (Figures 3 and 4). Major faults near this transect may have experienced Oligocene activity which reactivated local Precambrian shear zones
Surrounding regions is identified and Green River basins appears to be during the early Paleogene. A major pulse of coarse clastic sedimentation is much less than the 4 km required to bury most of the range. The presence of the detrital granite cobbles in the Wind River Formation, within the Wind River basin, with an age of 59 Ma suggests that by Eocene time the crystalline basement was exposed and eroded into adjacent sedimentary basins and that the exposure of less erodible granite probably slowed sedimentation by the Eocene [Sklar and Dietrich, 2001; Carroll et al., 2006].

4.4. Exhumation and Sedimentation

Using the relatively low geothermal gradient of 20°C/km, inferred from studies applying multiple thermochronometers [Peyton et al., 2012], ~100–120°C cooling observed at both Middle Fork Lake and Temple Peak from the earliest Paleocene until 50 Ma (Figure 4) represents about 4–6 km of exhumation. Four kilometers of Paleozoic to Mesozoic stratigraphy of the Wind River basin that likely once covered the range are preserved dipping off the east side of the Wind River Range (Figure 2) [Winterfeld and Conard, 1983; Seeland, 1978; Phillips, 1983]. Thermal modeling suggests that this 4 km of sedimentary strata plus 1–2 km of basement rocks were removed since the Late Cretaceous. This magnitude of exhumation is consistent with the ~4–6 km of sedimentary cover documented in the preserved sections of syntectonic Cretaceous-Eocene stratigraphy of the Wind River basin dipping off the east side of the Wind River Range [Keef er, 1965a].

The sedimentary record coupled with the thermochronological record suggests that erosion in the Wind River Range began in the Late Cretaceous and climaxed in the Paleocene-Eocene as shallow marine shales of the Fort Union Formation were supplanted by coarse clastic material of the Indian Meadows Formation derived from the exposed crystalline core of the Wind River and Washakie Ranges [Keef er, 1965b; Seeland, 1978; Winterfeld and Conard, 1983; Fan et al., 2011].

On the west side of the Wind River Range, the Green River basin contains over 4 km of Late Cretaceous through Eocene sedimentary rocks [Steidtmann and Middleton, 1986; Roberts and Kirschbaum, 1995; Smith et al., 2003; Painter and Carrapa, 2013]. The timing of Wind River Range exhumation determined in this study is corroborated by the proximal basin record. The Cathedral Bluffs Tongue of the Green River Formation contains coarse early Eocene conglomerates suggestive of movement along the nearby Wind River Thrust [Steidtmann and Middleton, 1986; Carroll et al., 2006]. The Cathedral Bluffs Tongue is interfingered with the less proximal, but penecontemporaneous Tipton Shale Member of the Green River Formation [Steidtmann and Middleton, 1986] dated using 40Ar/39Ar on volcaniclastic sandstones at ~51.5 Ma [Smith et al., 2008, 2003] indicating fault activity through this time.

The record of sedimentation in the adjacent Wind River and Green River basins was likely influenced by changes in the eroding lithology of the Wind River Range [Carroll et al., 2006; Smith et al., 2014]. Mudstones and sandstones erode at rates 2 to 3 orders of magnitude greater than granites [Sklar and Dietrich, 2001]. Carroll et al. [2006] propose that the change from mudstones and sandstones to granite had a first-order control on the sediment supply in the Laramide basins. The presence of granite clasts in both the Wind River and Green River basins by the early Eocene suggests that Paleozoic and Mesozoic sedimentary cover had been unroofed and sediment supply consisted primarily of Precambrian granites from the core of the basement block uplifts [Carroll et al., 2006].

Although sedimentation and evidence of thick-skinned Laramide deformation spans from as early as 85 Ma to as late as 35 Ma, an increase of Laramide deformation as determined by stratigraphic relationships in the Wind and Green River basins appears to be during the early Paleogene. A major pulse of coarse clastic sedimentation is identified between 55 and 50 Ma both in the Green and Wind River basins in Wyoming and throughout the surrounding regions [Dickinson et al., 1988]. This is consistent with the exhumation history proposed in this study, particularly accelerated exhumation from ~65 to 50, followed by continued, but significantly less cooling and erosion (only a few samples very close to the Wind River Thrust, Figure 2) after that time.

4.5. AFT as a Record of Lithospheric-Scale Processes

This study combined with analysis of Gannet peak samples published by Peyton et al. [2012] and modeled in Fan and Carrapa [2014] includes 22 samples from the Wind River Range spanning 2 km of elevation. Despite
this major elevation difference, thermal modeling of these samples suggests accelerated exhumation for all samples between ~65 and 50 Ma. While we have identified positive age-elevation relationships in our vertical transects, the difference in ages in these transects is minimal. This is best exhibited in the Gannet Peak transect which identifies a difference of less than 2 Myr in a transect ranging over 1 km [Peyton et al., 2012; Fan and Carrapa, 2014]. Even in transects where a positive age-elevation relationship is disrupted by structural offset, the difference between the ages is minimal.

A cooling age of 59 ± 5 Ma from the conglomerate clast from the Wind River basin suggests part of the early Paleogene exhumation record is no longer preserved in the Wind River Range itself but has been partially eroded and now preserved in the adjacent basin. This cobble, collected from the 53–51 Ma Wind River Formation [Fan et al., 2011] must have passed through the closure temperature of the AFT system at 4–5 km depth, been exposed and eroded from the range surface, and been deposited in the Wind River basin by the mid-Eocene. The chronicle of this single clast supports the rapid exhumation between 65 and 50 Ma identified by thermal modeling.

The timing of exhumation determined by thermokinetic modeling is consistent with timing of accretion of Shatsky Rise depleted mantle lithosphere under Wyoming and associated upper crustal deformation [Humphreys et al., 2015]. Alternatively, our data could be interpreted to represent a tectonothermal response to plateau removal [Liu et al., 2010; Liu and Gurnis, 2010].

The highest rates of exhumation also correspond directly with the attainment of high elevation which paleoaltimetry data indicate occurred by circa 54 Ma [Fan and Carrapa, 2014]. The coincidence of these events suggests that a regional mechanism drove this uplift event from ~65 to 50 Ma.

The rapid exhumation until ~50 Ma proposed in this study is consistent with significant relief formation by early Eocene time as supported by paleoaltimetry proxies [Fan and Carrapa, 2014]. The lower Eocene exhumation signal is similar to the one recorded by surface AFT ages produced using modern protocols from samples from the Beartooth Range of southern Montana and northern Wyoming [Peyton et al., 2012] but is slightly younger than ages recorded in the Front Range and the Bighorn Mountains [Kelley and Chapin, 2004; Peyton et al., 2012; Peyton and Carrapa, 2013]. This temporal relationship, if real, suggests a westward migration of exhumation and inferred deformation. However, other available fission track data from the Laramide ranges preceded modern etching protocol and should be interpreted with caution.

Figure 5. The AFT system records rapid exhumation from the latest Cretaceous/Paleocene through the early Eocene. Exhumation of the Wind River Range is shown here relative to surface elevation gain as well as subsidence and ponding in the adjacent Green River and Wind River basins.
5. Conclusions

New AFT ages in the Wind River Range indicate the importance of the use of current, consistent methodology when using apatite fission track thermochronology and thermal modeling. In this study, the reanalysis of AFT samples from the Wind River Range suggests exhumation of the Wind River Range occurred rapidly between circa 65–50 Ma and is concomitant with surface uplift and relief formation. Our data are consistent with other AFT studies using the same current methodology [Peyton and Carrapa, 2013; Fan and Carrapa, 2014]. No obvious changes in exhumation are observed along strike suggesting uniform displacement along the Wind River Fault, at least along the ~60 km section sampled in this study in the central Wind River Range. Although the relief in the Wind River Range may have been subdued by some sediment burial in the Eocene-Oligocene, thermal modeling limits this burial to ~1 km [Steidtmann et al., 1989; Steidtmann and Middleton, 1991]. While exhumation likely initiates in the Cretaceous, the AFT system records rapid exhumation from ~65 Ma until ~50 Ma (Figure 5). This is consistent with timing of rapid sedimentation in nearby basins [Dickinson et al., 1988]. The timing of exhumation recorded by AFT data in the Wind River Range is consistent with both accretion of Shatsky Rise depleted mantle lithosphere under Wyoming [Humphreys et al., 2015] and with inverse convection model of Laramide deformation presented by Liu et al. [2010] but does not distinguish between these models. Regionally, these results constrain the timing and rate of exhumation during Laramide deformation.

Our data set, when coupled with the sedimentary record, shows an immediate response of the sedimentary system to increased exhumation and erosion after 65 Ma [Dickinson et al., 1988]. It also reflects the decrease in sedimentation observed at ~50 Ma [Carroll et al., 2006]. More studies using up-to-date analytical procedures and thermal modeling of AFT ages and lengths are necessary to test the proposed westward younging of exhumation predicted by the sweeping southwestward rollback of the Farallon slab.

Acknowledgments

The AFT data for this paper are available in Table 2 and in supporting information Table S1. The samples used in this paper were originally collected by Philip Cerveny at the University of Wyoming. We thank Jim Steidtmann for making these samples available to us. This paper originated as a class project in a graduate Thermochronology class taught by Barbara Carrapa. We thank the participants of that class including Andrew Laskowski, Kate Metcalf, Devon Orme, and Jamie Worthington for helpf ul discussion throughout preparation of this manuscript. Alexis Ault provided guidance for thermal modeling. We thank Mariah Romero for counting the detrital cobble sample. Jim Steidtmann provided feedback on early versions of this manuscript. Reviews by Michael Elliot Smith and three anonymous reviewers significantly improved the manuscript.

References


