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The Rise and Fall of Laramide Topography and the Sediment Evacuation From Wyoming

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Key Points:

- Low-T-thermochronological data from type Laramide localities in Wyoming record burial of Laramide ranges and basins between ~40 and 10 Ma
- Regional incision and sediment evacuation after <10 Ma increased relief contributed to the attainment of modern topography
- High-elevation low-relief surfaces in the Wind River Range developed from Laramide erosion and subsequent basin filling and continental-scale basin evacuation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The modern topography within the Laramide region consists of high-relief ranges and high-elevation low-relief (HELR) surfaces separated by intraforeland basins. However, the timing and development of this topography within the type-locality of the Wyoming Laramide province is poorly understood. Previous models suggest that the modern topography is a young feature that was acquired after Laramide tectonism, post-Laramide burial, and basin evacuation; however, evidence of such a progression is sparse. We present low-temperature-thermochronological data from two Laramide uplifts in Wyoming, the Wind River and Bighorn Ranges, which document an early record of Laramide exhumation, subsequent reheating, and significant cooling after 10 Ma. Our results indicate that the Laramide ranges were buried by post-Laramide Cenozoic basin fill, creating a low-relief topography by the early Miocene that was reduced due to late Miocene regional incision and basin evacuation. We suggest that HELR surfaces experienced further relief reduction from Pleistocene glaciation.

Plain Language Summary The Laramide region of Wyoming is characterized by high elevation ranges surrounded by lower relief sedimentary basins and is the result of tectonics and erosional processes. However, the timing and mechanisms responsible for the formation of the modern topography in Wyoming are still debated. We report new age data from key Laramide ranges and basins in the Wyoming Laramide province that indicate the these ranges were exhumed 100–50 Ma and were subsequently buried by Cenozoic basin fill deposited between 50 and 10 Ma. Our results suggest that Wyoming's modern topography began to develop after ~10 Ma due to widespread incision and sediment evacuation along continental-scale river systems such as the paleo-Mississippi.

1. Introduction

The Laramide tectonomorphic region of the western USA is dominated by rugged high elevation ranges bounded by relatively flat basins creating some of the highest relief in North America (N.A.), exceeding 2 km in some areas. The Laramide region extends from Montana to northern Sonora, Mexico and is marked by local magmatism and basement-involved uplifts that disrupted the regional N.A. Cordilleran foreland basin ~1,000 km inboard of the plate margin (Figure 1, Dickinson & Snyder, 1978; Dickinson et al., 1988; Henderson et al., 1984; Jordan, 1981; Jordan & Allmendinger, 1986; Lawton, 2008). Deformation, exhumation, subsidence, and uplift of the Laramide region have been explained by upper and lower plate processes (Bird, 1984, 1998; Carrapa et al., 2019; Coney, 1972; Coney & Reynolds, 1977; Copeland et al., 2017; Cross & Pilger, 1978; Currie & Copeland, 2022; Dickinson, 1989; Dickinson & Snyder, 1978; Henderson et al., 1984; Lipman & Sawyer, 1985; Liu et al., 2010; Saleeby, 2003). The timing of thick-skinned "Laramide" deformation has long been studied using structural, geomorphological, geochemical, sedimentological, geochronological, and thermochronological records which provide constraints for models of Laramide tectonomorphic evolution (Carrapa et al., 2019; Copeland et al., 2017; Currie & Copeland, 2022; Liu et al., 2010). However, post-Laramide basin filling and subsequent sediment evacuation, and their role in establishing the modern topography of the Laramide region in its type locality of Wyoming remain debated. Some workers suggest that these basins were filled with late Eocene–early Miocene sedimentary and volcaniclastic units up to high elevations (>2 km), effectively burying all but the highest peaks of the surrounding Laramide ranges (Mckenna & Love, 1972; Steidtmann & Middleton, 1991; Steidtmann et al., 1989). This model implies that by the mid-Miocene, the Laramide region in Wyoming experienced significant relief reduction by basin filling, creating a subdued topography possibly resembling the Altiplano of Bolivia. Following burial, the modern topography between the Laramide ranges and basins began to

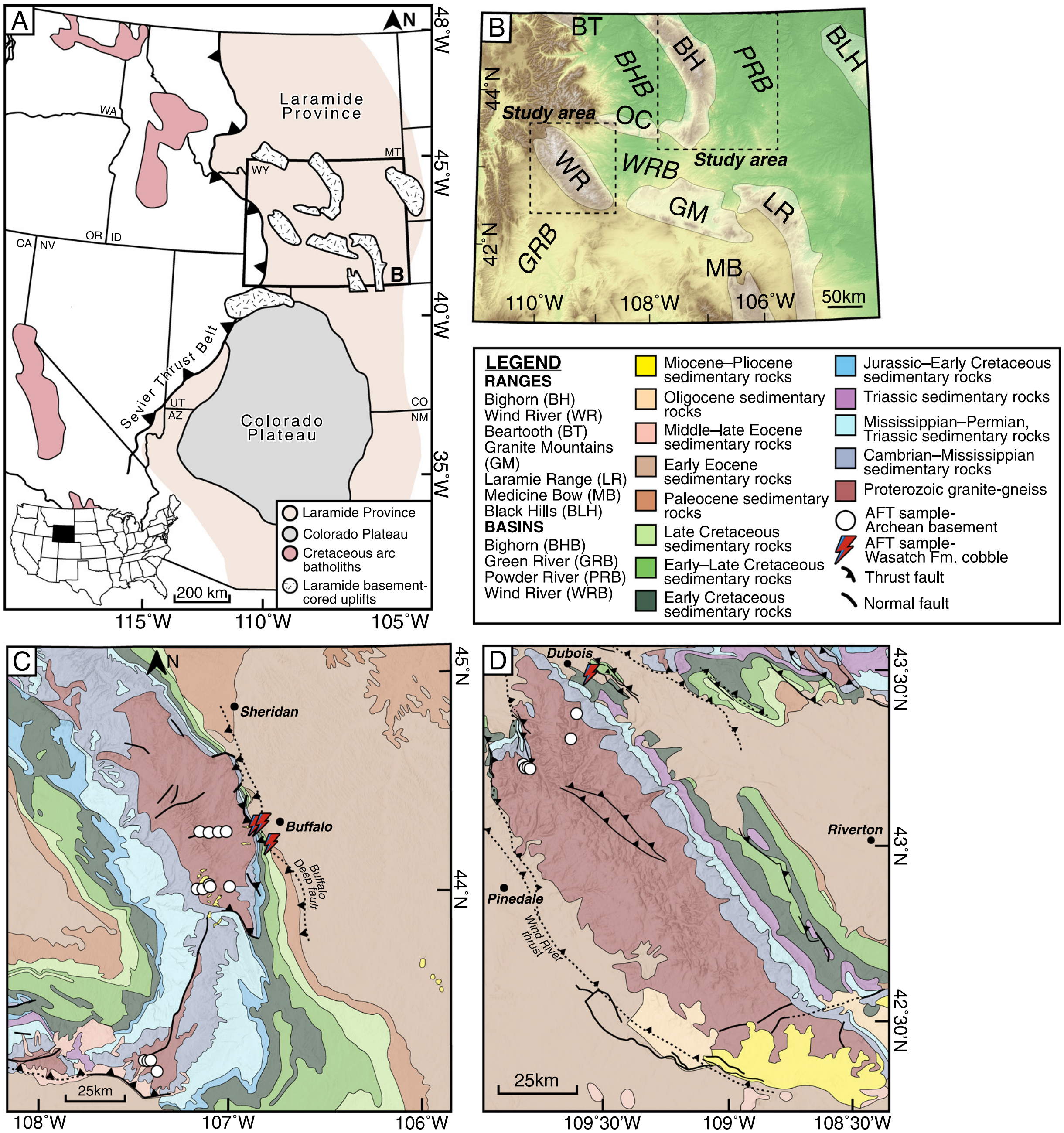

Figure 1. (a) General location and tectonic province map of the western USA (b) Digital elevation model of Wyoming showing Laramide ranges and basins. (c) Inset generalized geological map of the Bighorn Mountains and Powder River Basin showing locations of samples in this study. (d) Inset generalized geological map of the Wind River Range and Wind River Basin showing locations of samples in this study. Geologic map modified after Love and Christiansen (1985) and Ranz (2000).

develop as basins were incised and evacuated after the late Miocene. This model also has implications for the formation of high elevation low relief surfaces (HELR) observed in many of the Laramide ranges. However, clear evidence of such basin filling, incision, and evacuation are lacking from existing thermochronological records.

This study presents new apatite fission track (AFT) results and thermal models from classic localities in the Laramide region of Wyoming including the Bighorn Mountains and Powder River Basin and the Wind River Range and Wind River Basin (Figure 1). Our results address the following questions: (a) When did Laramide erosion initiate in these ranges? and (b) How much basin burial and subsequent incision/erosion did Laramide basins and ranges experience? Understanding the thermal history of the Laramide region is important for understanding tectonomorphic processes associated with the development of the modern Laramide topography. Thus, our study holds important implications for the tectonic and paleotopographic evolution of the Laramide region and other high relief regions on Earth affected by similar tectonic, erosional, and depositional histories.

1.1. Geologic Setting

The Laramide region is characterized by basement-cored uplifts and intervening intraforeland basins that developed by flexural and dynamic subsidence during the Late Cretaceous–early Eocene (Dickinson et al., 1988; Fan & Carrapa, 2014; Heller & Liu, 2016; Painter & Carrapa, 2013). Topography within these ranges is characterized by >4 km-high peaks and broad, low-relief surfaces exposed at high elevations (∼3.5 km). The development and age of HELR surfaces that are observed in many of the Laramide ranges remains uncertain. Some models interpret the HELR surfaces as low-elevation peneplains that were later uplifted during the Laramide (Blackwelder, 1915; Chamberlin, 1919; Davis, 1911). Other models infer that these surfaces are Late Cretaceous–Eocene and formed by erosion during Laramide uplift and subsequent basin filling (Steidtmann & Middleton, 1991). Post-Laramide development models suggest that HELR surfaces are remnants of Oligocene–Miocene erosional surfaces (Mckenna & Love, 1972) or relatively young features that attained high elevations during Laramide uplift and later experienced Pleistocene glacial erosion (e.g., Egholm et al., 2009).

The Bighorn and Wind River Ranges in Wyoming are prominent Laramide uplifts primarily composed of ∼2.9–2.55 Ga Archean basement (Figure 1, Arth et al., 1980; Frost et al., 2000) that was uplifted during the Late Cretaceous–Eocene (∼75–40 Ma). The Bighorn Mountains are bound to the east by east-verging thrusts that placed Archean basement in contact with Paleocene–Eocene synorogenic strata filling the Powder River Basin (Hoy & Ridgway, 1997). The Wind River Range is bound by the southwest-verging Wind River thrust and Green River Basin on its western margin and the Wind River Basin along its northeastern margin (Fan & Carrapa, 2014; Fan et al., 2011; Steidtmann & Middleton, 1991). Thermochronological data from these ranges document rapid cooling at ∼65–50 Ma interpreted to be a minimum temporal estimate of Laramide deformation with the onset of exhumation occurring sometime before the late Paleocene (Peyton et al., 2012; Stevens et al., 2016). Early studies in the Wind River Range combining geologic evidence with AFT thermochronology interpreted cooling to have commenced as early as ∼100 Ma (Steidtmann & Middleton, 1991).

The Powder River and Wind River basins consist of >2 km of Maastrichtian–Eocene synorogenic sedimentary units (Fan & Carrapa, 2014; Hoy & Ridgway, 1997; Steidtmann & Middleton, 1991; Winterfeld & Conrad, 1983). Maastrichtian–early Paleocene deposits in both basins are composed of fine-grained facies that are interpreted to represent initial slow phases of uplift and unroofing of Paleozoic sedimentary cover (Shuster & Steidtmann, 1988). Accelerated Laramide deformation and erosion of Archean basement occurred during the late Paleocene–early Eocene and is recorded by up-section changes in synorogenic conglomerates from predominantly Paleozoic clasts to Archean basement clasts (e.g., the Wasatch Formation, Kingsbury and Moncrief conglomerate units, and the Indian Meadows and Wind River Formations (Fan et al., 2011; Hoy & Ridgway, 1997).

Regional sedimentation in the Laramide basins persisted until Oligocene–Miocene time as evidenced by tuffaceous fluvial and eolian deposits of the White River and Arikaree Groups preserved at high elevations (e.g., ∼2.8 km, Malone et al., 2022; Mckenna & Love, 1972). These deposits show evidence of basin filling and suggest that the Laramide basins and bounding ranges were partially buried by sedimentary deposits that have since been incised and evacuated along major drainage systems (Galloway et al., 2011; McMillan et al., 2006; Steidtmann et al., 1989). Thermochronological data recording such a history have been documented in the Beartooth Range (Carrapa et al., 2019; Omar et al., 1994; Ronemus et al., 2023), although this thermal signature has not been shown in other Laramide ranges and basins. Late Miocene incision of Laramide basins is supported by thermochronological data, albeit sparse, and reconstructions of post-Laramide basin fill surfaces suggesting that >1.5 km of incision has occurred in the Laramide region and western Great Plains since the late Miocene (Cerveny & Steidtmann, 1993; McMillan et al., 2006; Naeser, 1992; Omar et al., 1994; Steidtmann et al., 1989).

2. Methods

We analyzed 11 basement samples from three transects in the Bighorn Mountains and 6 basement samples from two transects in the northern Wind River Range (Figure 1). In the Wind River Range, we targeted vertical profiles that capture significant elevation change (>3 km) and low internal relief (<300 m) surfaces. In addition, we analyzed four orthogneiss clasts, one from the Kingsbury Conglomerate and two from the Moncrief Conglomerate in the Powder River Basin; and one from the Wind River Formation in the Wind River Basin (Figure 1).

Samples were prepared for AFT thermochronology by separating, mounting, and etching in 5.5 M nitric acid for 20 s at 21°C and mica prints were etched in 40% HF for 45 min following protocols of Donelick (2005). For each sample, 20–30 apatite grains were dated using the external detector method and confined fission track lengths and Etch-pit diameter (D_{par}) measurements were collected for thermal modeling (Table S3, Gleadow et al., 1986; Wagner & Van den Haute, 1992).

We used the modeling software QTQt (v. 5.8.0) to generate inverse thermal models based on AFT age, length, and D_{par} measurements (Gallagher, 2012). QTQt applies the Bayesian transdimensional Markov chain Monte Carlo inversion scheme to determine the time-temperature cooling pathway of a given sample. Fifteen basement and four cobble samples were suitable for thermal modeling. Models were initially run unconstrained to explore statistical space and allow the maximum degree of freedom; then model parameters were adjusted to consider geological constraints (Table S2). Modeling results presented in this study were generated based on time–temperature paths for ≥200,000 runs. Samples from the Squaretop Mountain transect were modeled together as a vertical profile to reduce uncertainties in the model results. Individual sample data and model parameters and outputs are available in Supporting Information S1.

3. Results

3.1. Bighorn Mountains–Powder River Basin

Basement samples from the Bighorn Mountains were collected along the Bighorn South, Hazelton Peak, and Lake Angeline transects (Figure 1). Three samples produced central ages ranging from ∼155 to ∼85 Ma (B2, HP1, HP3), six samples produced ages ranging from ∼85 to ∼60 Ma (HP2, HP4, HP5, LA1, LA6, LA7), and two samples produced ages ranging from ∼60 to ∼50 Ma (B1, B4). Cobble samples from the Kingsbury (KB1) and Moncrief (C2, D1) Conglomerates produced ages of ∼384, ∼224, and ∼143 Ma, respectively (Table S1).

Thermal modeling results for these samples show cooling between ∼130 and ∼50 Ma with most samples showing rapid cooling between ∼75 and 50 Ma (Figure 2a). Four basement samples show continued and slow cooling after 50 Ma. The remaining five samples show a consistent period of reheating between ∼50 and ∼10 Ma followed by cooling after 10 Ma. Models for cobble samples from the Kingsbury and Moncrief Conglomerates were run with and without deposition of the Wasatch Formation at ∼50–45 Ma (Hoy & Ridgway, 1997) and indicate relatively slow cooling between ∼800 and ∼50 Ma, followed by post-depositional reheating between ∼50 and ∼10 Ma and cooling after 10 Ma (Figure 2b). We note that inverse modeling results from the Kingsbury and Moncrief cobble samples document long thermal histories prior to 200 Ma, outside of the scope of this study, and are therefore not discussed in this paper (Figures S12, S13, and S14).

3.2. Wind River Range

Basement samples from the Wind River Range were collected along the Squaretop Mountain and Goat Flat transects (Figure 1). These samples produced one AFT age at ∼94 Ma (GRSM-02), three ages ranging from ∼85 to ∼60 Ma (GRSM-01, GRSM-03, GRSM-04), and two ages between ∼60 and ∼50 Ma (GF1, GF5). The cobble sample from the Wind River Formation (2DIB) produced an AFT age of ∼59 Ma.

Samples from the Squaretop Mountain transect follow a near-vertical profile over a total relief of ∼600 m (Figure 2). Results from this thermal model show cooling at ∼100–80 Ma. Samples from the Goat Flat transect were modeled individually as these samples were collected too far apart to be considered a true vertical profile (Figures 2b and 2d). Sample GF1 collected from the highest elevation shows cooling at ∼70 Ma and sample GF5 from the lowest elevation shows cooling at ∼55 Ma. Both transects show reheating between ∼30 and 10 Ma followed by cooling to surface temperatures after 5 Ma.

The thermal model for the Wind River Formation cobble sample (2DBI) was run with and without deposition of the Wind River Formation at ∼52 Ma (Clyde et al., 1997; Robinson et al., 2004; Smith et al., 2008). These models are similar to basement samples from the Goat Flat transect showing cooling between ∼70 and ∼50 Ma, followed by post-depositional reheating between ∼50 and ∼10 Ma, and cooling after 3 Ma (Figure 2d).

4. Discussion

Combined AFT ages and thermal modeling results reveal a multi-phase thermal history of the Laramide region in Wyoming during the Mesozoic–Cenozoic. We focus on the Late Cretaceous–modern thermal record, pertinent

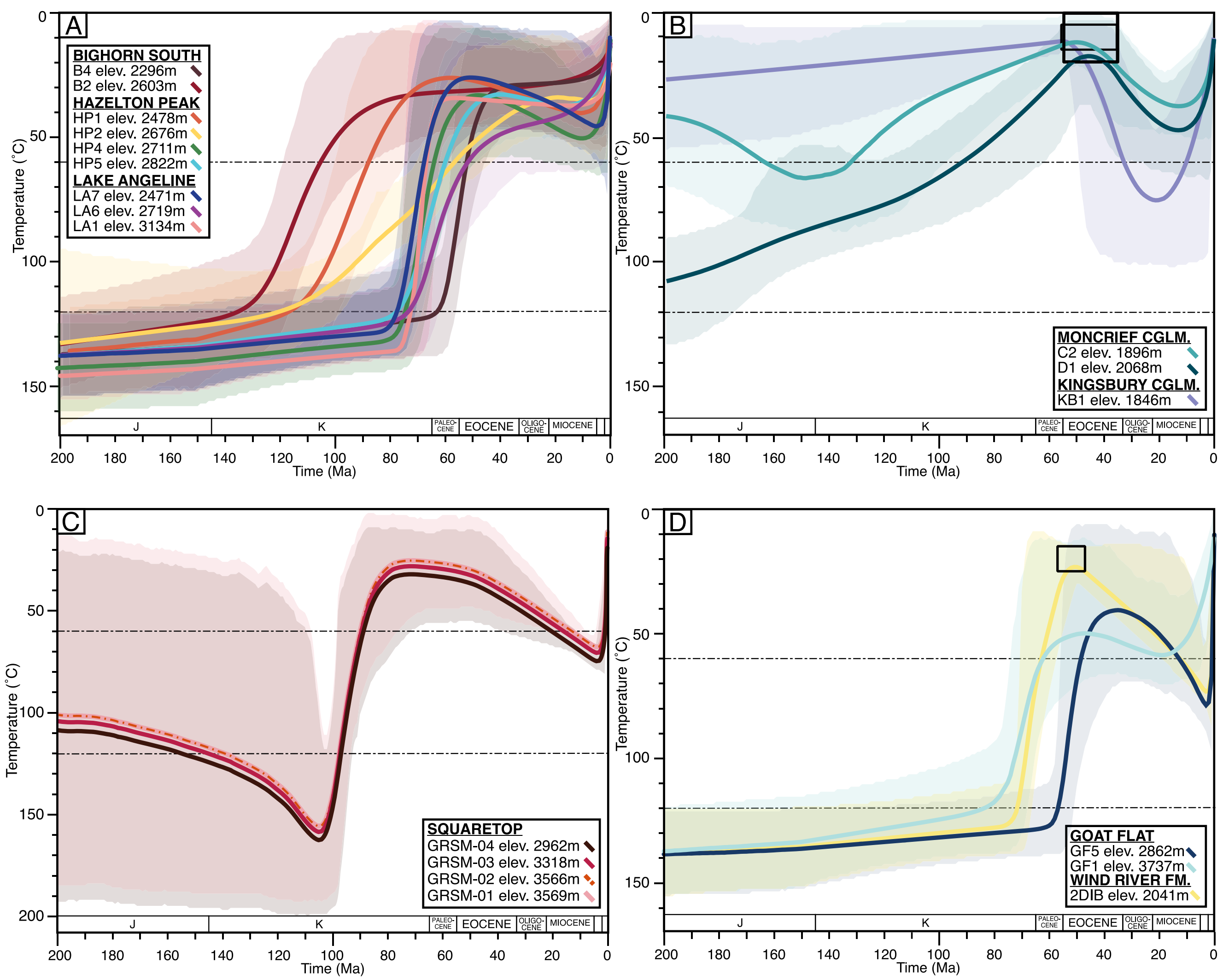

Figure 2. Inverse thermal models for samples in this study (0–200 Ma). Bold lines represent best-fit time-temperature path, transparent areas correspond with good fit envelopes. (a) Basement samples from the Bighorn Mountains, (b) cobble samples from the Kingsbury and Moncrief Conglomerates in Powder River Basin, (c) vertical profile basement samples from the Squaretop Mountain transect in the northern Wind River Range, and (d) basement samples from the Goat Flat transect in the Wind River Range and cobble sample from the Wind River Formation in the Wind River Basin.

to the development of the topographic relief between Laramide ranges and intervening Laramide basins, and the physiographic development of HELR surfaces within these ranges. Thermal models from cobble samples in the Powder River Basin document thermal histories prior to 200 Ma outside of the scope of this study (Figures S12, S13, and S14).

4.1. Thermal Record and Implications for Erosion and Basin Burial

The earliest record of rapid cooling is identified during the Late Cretaceous (∼100–80 Ma) by three basement samples from the Bighorn Mountains and samples from the Squaretop Mountain transect in the Wind River Range (Figure 2). Previous thermochronological studies in the Wind River Range document rapid cooling ∼66–50 Ma and suggest that these results provide only a minimum age of Laramide deformation-driven exhumation (Peyton et al., 2012; Steidtmann & Middleton, 1991; Stevens et al., 2016). Several additional lines of evidence support mid-Late Cretaceous cooling in the Wind River Range. First, Upper Cretaceous–lower Paleocene strata in the Green River Basin record a shift in paleocurrent direction from southeastward to southward-flowing systems accompanied by a change in sandstone composition from lithic-rich units derived from Paleozoic–Mesozoic cover strata to feldspar-rich units derived from Precambrian basement. This suggests that by early Paleocene time,

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Paleozoic–Mesozoic cover strata had been stripped away to expose Precambrian basement in the Wind River Range (Shuster & Steidtmann, 1988; Steidtmann & Middleton, 1991). Moreover, Late Cretaceous cooling is consistent with studies in southwestern Montana that document cooling at ~100–90 Ma, interpreted as evidence for early Laramide exhumation (Carrapa et al., 2019; Ronemus et al., 2023). Our results from Squaretop Mountain combined with previous evidence support an early phase of cooling and erosion during the Late Cretaceous, although the exact mechanism is not well understood. We note the difference in cooling ages between our samples along the Squaretop Mountain transect (~100–80 Ma) and samples from previous transects in the Wind River Range (~65–50 Ma, Peyton et al., 2012; Stevens et al., 2016). We speculate that samples from the previous studies were collected in areas from which the rocks containing the earlier (Cretaceous) record of cooling and erosion have been erosionally removed.

By the Late Cretaceous–Paleocene, Laramide-style deformation and range exhumation were well underway throughout the Wyoming Laramide Province, with the peak magnitude of exhumation occurring between the late Paleocene and early Eocene (~65–50 Ma). The timing of cooling indicated by our model results (~75–50 Ma) is supported by existing thermochronological data, stratigraphic, provenance, paleoaltimetry, and basin subsidence data (DeCelles et al., 1991; Fan & Carrapa, 2014; Fan et al., 2011; Gries, 1983; Hoy & Ridgway, 1997; Peyton et al., 2012; Stevens et al., 2016). This signal is consistent with an erosional response to Late Cretaceous–Paleocene Laramide flat slab subduction and subsequent Paleocene-Eocene slab rollback (Fan & Carrapa, 2014).

Thermal models of basement samples from the Bighorn and Wind River Ranges and cobble samples from Eocene synorogenic deposits from the Powder River and Wind River basins show similar Cenozoic thermal histories indicating these regions experienced Eocene–Miocene (~50–10 Ma) reheating to temperatures of ~35–80°C (Figure 2). Reheating can be attributed to either: (a) an elevated regional geothermal gradient during late Eocene–early Miocene magmatism, or (b) burial by late Eocene–early Miocene basin filling units, that is, the White River and Arikaree Groups and their correlative units. In the Bighorn Mountains, reheating via sediment burial is supported by remnant exposures of basin fill at high elevations (~2.8 km) along the flanks of the Bighorn Mountains, approximately ~1.2 km above the average Wyoming Laramide basin level of ~1.5 km (Fan & Carrapa, 2014; Fan et al., 2011; Malone et al., 2022; Mckenna & Love, 1972; McMillan et al., 2006). We note that there are no exposures of Oligocene–Miocene basin fill units along the northern flanks of the Wind River Range where our samples were collected. However, these deposits are preserved along the southern flanks of the range (Steidtmann & Middleton, 1991). Although it is possible that Cenozoic reheating may be associated with Late Eocene–Oligocene magmatism in Wyoming, the reconstructed thickness and distribution of basin-fill remnants (McMillan et al., 2006) along with the magnitude of reheating indicated by our data can explain partial reheating caused by a period of sustained sedimentation within the Laramide basins, burying the flanks of the Laramide ranges. We note that a thermochronological signature of post-Laramide burial may not be preserved everywhere in the Laramide region due to different magnitudes of exhumation and burial; nevertheless, this signature has also been documented by studies in the Beartooth Range (Carrapa et al., 2019; Omar et al., 1994; Ronemus et al., 2023).

The final phase of cooling, recorded by basement and cobble samples in both study regions, began after 10 Ma and is consistent with the timing of widespread incision across the Rocky Mountain region (McMillan et al., 2006). The late Miocene regional shift from basin filling to basin incision is indicated by the reconstructed minimum basin fill surface based on the elevation and age of sedimentary and volcanic basin fill remnants (Mckenna & Love, 1972; McMillan et al., 2006 and reference therein; Pelletier, 2009), and thermochronological data from Laramide uplifts (Cerveny, 1990; Cerveny & Steidtmann, 1993; Omar et al., 1994; Peyton et al., 2012; this study). Basin incision and sediment evacuation are suggested to have occurred via major fluvial systems draining the Wyoming Laramide region, that is, the paleo-Mississippi, paleo-Red, and paleo-Platte river systems (Galloway et al., 2011). Since the Middle Miocene, these rivers served as major sediment routing systems to the Gulf of Mexico Basin as indicated by significant proportions of detrital zircon populations derived from western Cordilleran sources found in Early–Middle Miocene sedimentary units of the Gulf of Mexico Basin (Xu et al., 2022) and paleogeographic reconstructions from industry well and seismic databases (Galloway, 2008).

4.2. Regional Post-Laramide Topography

By the Eocene, relief between the Laramide ranges and basins was comparable to the modern relief in the Wyoming Laramide Province (~2.3 km, Fan et al., 2011). Regional erosion of highlands and sedimentation within the Laramide basins persisted through the Oligocene–Early Miocene resulting in thick accumulations of sedimentary to

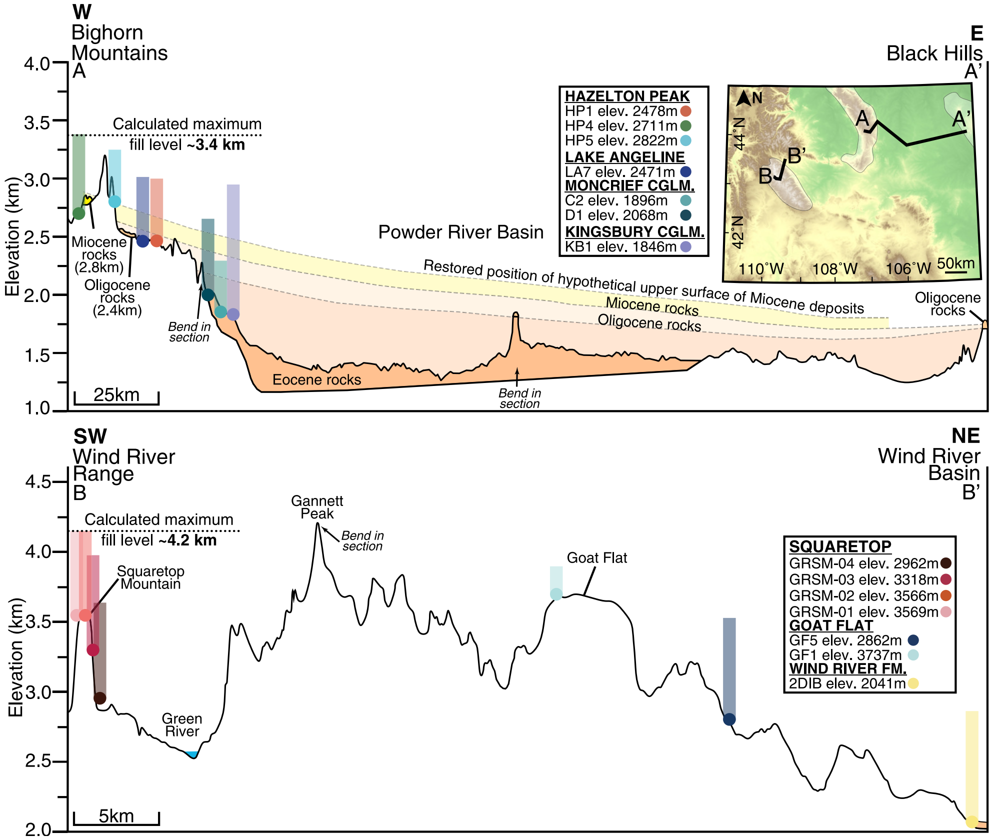

Figure 3. Cross sections of study sites in the (a) Bighorn Mountains and Powder River Basin and (b) Wind River Range and Wind River Basin showing exposures of Eocene sedimentary rocks and erosional remnants of Oligocene–Early Miocene sedimentary rocks where present. Reheated samples (circles) are superimposed on the profile at their respective elevation with a color bar on top of them indicating the calculated amount of burial to reheat each sample. Panel (a) modified after Mckenna and Love (1972).

volcanic basin fill (i.e., the White River and Arikaree Groups) and relief reduction between Laramide ranges and basins (Mckenna & Love, 1972; McMillan et al., 2006). The magnitude of basin filling remains contentious with some workers suggesting a minimum ~1 km of burial (Stevens et al., 2016) while others suggest ~4 km of burial, sufficient to obscure all but the highest peaks of the Laramide ranges (Steidtmann & Middleton, 1991). To estimate the depth of burial, we divided the maximum temperature during reheating indicated by our models by 60°C/km, a geothermal gradient appropriate for the volcanic setting at the time (Coney & Reynolds, 1977).

Our calculations indicate that reheated samples in the Bighorn Mountains were buried to depths of 0.4–1.1 km and suggest that the sedimentary fill in the Powder River Basin reached elevations of ~3.4 km along the eastern flank of the Bighorn Mountains (Figure 3a). Samples from the Wind River Range and Wind River Basin show similar magnitudes of burial between 0.2 and 0.8 km and suggest that basin fill reached elevations of ~4.2 km in some areas of the Wind River Range (Figure 3b). Our calculated basin fill elevations are comparable with the highest modern peaks in Wyoming that do not show partial reheating during the Late Eocene–Early Miocene, for example, Gannett Peak (~4.21 km) and Freemont Peak (~4.19 km), suggesting that by the Miocene, only the highest peaks were exposed (Peyton et al., 2012; Steidtmann & Middleton, 1991). Our results provide estimates of maximum burial and the establishment of a subdued low internal-relief topography in the Wyoming Laramide region during Early Miocene time and are comparable with minimum elevations reconstructed from basin-fill elevations predicted by McMillan et al. (2006).

4.3. Laramide High-Elevation Low-Relief Surfaces

Thermal models for basement samples collected along HELR surfaces in the Wind River Range (i.e., Squaretop Mountain and Goat Flat transects) provide thermal histories for these surfaces and test proposed models of

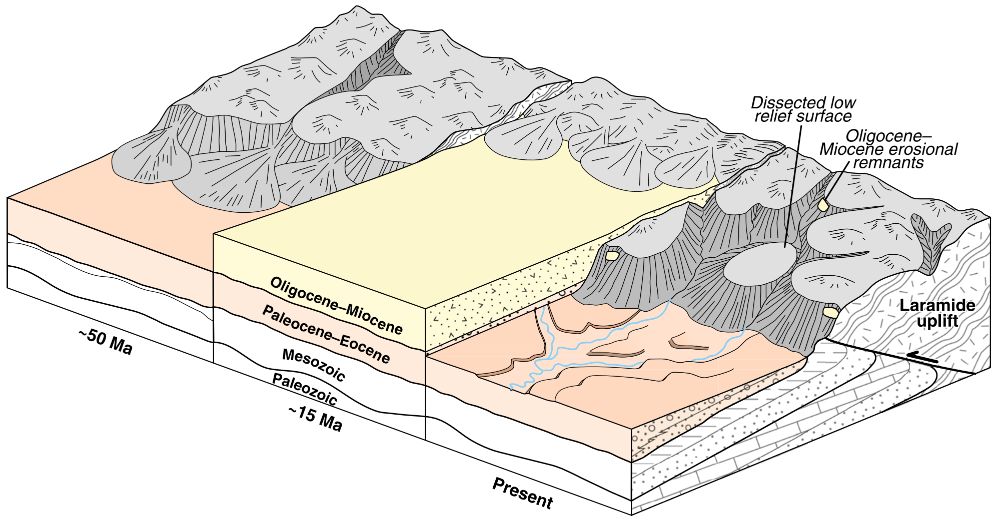

Figure 4. Schematic block diagram showing the post-Laramide topographic evolution of Laramide uplifts and basins. Panels from left to right show high topographic relief by the Eocene (~50 Ma), relief reduction and maximum basin filling during the Early Miocene (~20 Ma), and the modern high relief configuration including Oligocene–Miocene basin fill remnants exposed at high elevations. Modified after Blackwelder (1915).

their origin. Thermal models from both transects show cooling during Late Cretaceous-Paleocene time (~100–80 and 75–55 Ma), minor reheating via basin burial heating (~50–10 Ma), and subsequent cooling to surface temperatures during the Late Miocene (<10 Ma). These results are not consistent with models suggesting that HELR surfaces are remnants of low-relief surfaces that initially formed at low elevations before being uplifted during the Laramide tectonic event, which would require cooling ages before Laramide deformation commenced. Whether HELR surfaces were beveled during or after Laramide uplift remains unresolved by the AFT system alone due to the temperature sensitivity of this system. However, the abundance of Pleistocene glacial features in the Laramide ranges (i.e., glacial lakes, moraines, glacial valleys; Gosse et al., 1995; Leopold, 1980), suggests that glaciation may have played an important role in creating low relief surfaces at high elevations in these ranges (Figure 4). Additionally, paleoaltimetry records suggest that by the end of the Laramide orogenic event, the Wind River Range had already been uplifted to 3–4 km near the Pleistocene equilibrium-line altitude of >3.05 km (Davies, 2011; Fan et al., 2011). We therefore suggest that HELR surfaces in the Laramide ranges are remnants of a more extensive high-elevation paleolandscape that was shallowly buried during the Late Eocene–Early Miocene and then incised by fluvial systems after the Late Miocene, producing isolated surfaces that experienced local relief reduction by glacial erosion. Similar models that support glaciation as a mechanism for production and preservation of HELR surfaces have been proposed in other high-elevation regions such as the Himalaya (Sherpa et al., 2022).

5. Conclusions

Our study indicates that the Bighorn Mountains and Wind River Range experienced multi-stage Laramide cooling and erosion, as early as ~100–80 Ma with rapid cooling at ~75–50 Ma, followed by significant sediment burial and reheating between ~50 and 10 Ma. We estimate that basin fill in the Powder River and Wind River Basins reached elevations of ~3.4 km along the eastern flank of the Bighorn Mountains and ~4.2 km in the northern Wind River Range. Isolated remnants of Oligocene–Early Miocene (~34–15 Ma) post-Laramide basin fill at high elevations throughout Wyoming provide further evidence of post-Laramide regional relief reduction and the establishment of low internal-relief topography by the Early Miocene. Our study supports Late Miocene incision of the Powder River Basin and regional evacuation of basin fill that resulted in the modern topography characterized by >2.5 km of local relief. HELR surfaces within the Wind River Range (Squaretop Mountain and Goat Flat) are consistent with this history and record cooling and erosion during Laramide deformation and reheating-burial by Late Eocene–Early Miocene. This suggests that the Laramide basins were completely filled, partially covering their bounding ranges, possibly across a more extensive high elevation paleolandscape that was later dissected during Late Miocene regional incision and sediment evacuation. Our thermochronological data, combined with Pleistocene glacial features in the Wind River Range, suggest that the Squaretop Mountain and Goat Flat surfaces are isolated remnants of this dissected paleolandscape that experienced further relief reduction due to glacial erosion.

Data Availability Statement

Data archiving of the results and figures supporting the conclusions presented in this study are available through the University of Arizona's Research Data Repository: https://doi.org/10.25422/azu.data.22068719.

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References

Arth, J. G., Barker, F., & Stern, T. W. (1980). Geochronology of Archean gneisses in the Lake Helen area, southwestern Bighorn Mountains, Wyoming. *Precambrian Research*, *11*(1), 11–22. https://doi.org/10.1016/0301-9268(80)90078-9

Bird, P. (1984). Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains. *Tectonics*, *3*(7), 741–758. https://doi.org/10.1029/TC003i007p00741

Bird, P. (1998). Kinematic history of the Laramide orogeny in latitudes 35°-49°N, western United States. *Tectonics*, *17*(5), 780–801. https://doi.org/10.1029/98TC02698

Blackwelder, E. (1915). Post-Cretaceous history of the mountains of central western Wyoming. *The Journal of Geology*, *23*(3), 193–217. https://doi.org/10.1086/622226

Carrapa, B., DeCelles, P. G., & Romero, M. (2019). Early inception of the Laramide orogeny in southwestern Montana and northern Wyoming: Implications for models of flat-slab subduction. *Journal of Geophysical Research: Solid Earth*, *124*(2), 2102–2123. https://doi.org/10.1029/2018JB016888

Cerveny, P. F. (1990). *Fission-track thermochronology of the Wind River Range and other basement cored uplifts in the Rocky Mountain foreland*. University of Wyoming.

Cerveny, P. F., & Steidtmann, J. R. (1993). Fission track thermochronology of the Wind River Range, Wyoming: Evidence for timing and magnitude of Laramide exhumation. *Tectonics*, *12*(1), 77–91. https://doi.org/10.1029/92TC01567

Chamberlin, R. T. (1919). The building of the Colorado rockies. *The Journal of Geology*, *27*(145–164), 225–261. https://doi.org/10.1086/622651

Clyde, W. C., Zonneveld, J., Stamatakos, J., Gunnell, G. F., & Bartels, W. S. (1997). Magnetostratigraphy across the Wasatchian/Bridgerian NALMA boundary (early to Middle Eocene) in the western Green River Basin, Wyoming. *The Journal of Geology*, *105*(6), 657–670. https://doi.org/10.1086/515970

Coney, P. J. (1972). Cordilleran tectonics and North America plate motion. *American Journal of Science*, *272*(7), 603–628. https://doi.org/10.2475/ajs.272.7.603

Coney, P. J., & Reynolds, S. J. (1977). Cordilleran Benioff zones. *Nature*, *270*(5636), 403–406. https://doi.org/10.1038/270403a0

Copeland, P., Currie, C. A., Lawton, T. F., & Murphy, M. A. (2017). Location, location, location: The variable lifespan of the Laramide orogeny. *Geology*, *45*(3), 223–226. https://doi.org/10.1130/G38810.1

Cross, T. A., & Pilger, R. H. (1978). Tectonic controls of late Cretaceous sedimentation, western interior, USA. *Nature*, *274*(5672), 653–657. https://doi.org/10.1038/274653a0

Currie, C. A., & Copeland, P. (2022). Numerical models of Farallon plate subduction: Creating and removing a flat slab. *Geosphere*, *18*(2), 476–502. https://doi.org/10.1130/GES02393.1

Davies, N. (2011). *Holocene glaciation of the Green River drainage*. Wind River Range.

Davis, W. M. (1911). The Colorado front range: A study in physiographic presentation. *Annals of the Association of American Geographers*, *1*, 21. https://doi.org/10.2307/2560844

DeCelles, P. G., Gray, M. B., Ridgway, K. D., Cole, R. B., Pivnik, D. A., Pequera, N., & Srivastava, P. (1991). Controls on synorogenic alluvial-fan architecture, Beartooth conglomerate (palaeocene), Wyoming and Montana. *Sedimentology*, *38*(4), 567–590. https://doi.org/10.1111/j.1365-3091.1991.tb01009.x

Dickinson, W. R. (1989). Tectonic setting of Arizona through geologic time. *Arizona Geological Society Digest*, *17*, 1–16.

Dickinson, W. R., Klute, M. A., Hayes, M. J., Janecke, S. U., Lundin, E. R., Mckittrick, M. A., & Olivares, M. D. (1988). Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region. *Geological Society of America Bulletin*, *100*(7), 1023–1039. https://doi.org/10.1130/0016-7606(1988)100<1023:PAPSOL>2.3.CO;2

Dickinson, W. R., & Snyder, W. S. (1978). Plate tectonics of the Laramide orogeny. In *Geological society of America memoirs* (Vol. 151, pp. 355–366). Geological Society of America. https://doi.org/10.1130/MEM151-p355

Donelick, R. A. (2005). Apatite fission-track analysis. *Reviews in Mineralogy and Geochemistry*, *58*(1), 49–94. https://doi.org/10.2138/rmg.2005.58.3

Egholm, D. L., Nielsen, S. B., Pedersen, V. K., & Lesemann, J.-E. (2009). Glacial effects limiting mountain height. *Nature*, *460*(7257), 884–887. https://doi.org/10.1038/nature08263

Fan, M., & Carrapa, B. (2014). Late Cretaceous-early Eocene Laramide uplift, exhumation, and basin subsidence in Wyoming: Crustal responses to flat slab subduction: Laramide uplift and exhumation. *Tectonics*, *33*(4), 509–529. https://doi.org/10.1002/2012TC003221

Fan, M., DeCelles, P. G., Gehrels, G. E., Dettman, D. L., Quade, J., & Peyton, S. L. (2011). Sedimentology, detrital zircon geochronology, and stable isotope geochemistry of the lower Eocene strata in the Wind River Basin, central Wyoming. *Geological Society of America Bulletin*, *123*(5–6), 979–996. https://doi.org/10.1130/B30235.1

Frost, B. R., Chamberlain, K. R., Swapp, S., Frost, C. D., & Hulsebosch, T. P. (2000). Late Archean structural and metamorphic history of the Wind River Range: Evidence for a long-lived active margin on the Archean Wyoming craton. *Geological Society of America Bulletin*, *112*(4), 564–578. https://doi.org/10.1130/0016-7606(2000)112<564:LASAMH>2.0.CO;2

Gallagher, K. (2012). Transdimensional inverse thermal history modeling for quantitative thermochronology. *Journal of Geophysical Research*, *117*(B2), 1–16. https://doi.org/10.1029/2011JB008825

Galloway, W. E. (2008). Chapter 15 depositional evolution of the Gulf of Mexico sedimentary basin. In *Sedimentary basins of the world* (Vol. 5, pp. 505–549). Elsevier. https://doi.org/10.1016/S1874-5997(08)00015-4

Galloway, W. E., Whiteaker, T. L., & Ganey-Curry, P. (2011). History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin. *Geosphere*, *7*(4), 938–973. https://doi.org/10.1130/GES00647.1

Gleadow, A. J. W., Duddy, I. R., Green, P. F., & Lovering, J. F. (1986). Confined fission track lengths in apatite: A diagnostic tool for thermal history analysis. *Contributions to Mineralogy and Petrology*, *94*(4), 405–415. https://doi.org/10.1007/BF00376334

Gosse, J. C., Klein, J., Lawn, B., Middleton, R., & Evenson, E. B. (1995). Beryllium-10 dating of the duration and retreat of the last pinedale glacial sequence. *Science*, *268*(5215), 1329–1333. https://doi.org/10.1126/science.268.5215.1329

Gries, R. (1983). Oil and gas prospecting beneath precambrian of foreland thrust plates in Rocky Mountains. *AAPG Bulletin*, *67*, 1–28. https://doi.org/10.1306/03B5ACB4-16D1-11D7-8645000102C1865D

Heller, P. L., & Liu, L. (2016). Dynamic topography and vertical motion of the U.S. Rocky Mountain region prior to and during the Laramide orogeny. *Geological Society of America Bulletin*, *128*(5–6), 973–988. https://doi.org/10.1130/B31431.1

Henderson, L. J., Gordon, R. G., & Engebretson, D. C. (1984). Mesozoic aseismic ridges on the Farallon Plate and southward migration of shallow subduction during the Laramide Orogeny. *Tectonics*, *3*(2), 121–132. https://doi.org/10.1029/TC003i002p00121

Hoy, R. G., & Ridgway, K. D. (1997). Structural and sedimentological development of footwall growth synclines along an intraforeland uplift, east-central Bighorn Mountains, Wyoming. *Geological Society of America Bulletin*, *109*(8), 915–935. https://doi.org/10.1130/0016-7606(1997)109<0915:SASDOF>2.3.CO;2

Jordan, T. E. (1981). Thrust loads and foreland basin evolution, Cretaceous, western United States. *American Association of Petroleum Geologists Bulletin*, *65*, 2506–2520.

Jordan, T. E., & Allmendinger, R. W. (1986). The sierras pampeanas of Argentina: A modern analogue of Laramide deformation. *American Journal of Science*, *286*(10), 737–764. https://doi.org/10.2475/ajs.286.10.737

Lawton, T. F. (2008). Chapter 12 Laramide sedimentary basins. In *Sedimentary basins of the world* (Vol. 5, pp. 429–450). Elsevier. https://doi.org/10.1016/S1874-5997(08)00012-9

Leopold, L. B. (1980). Bathymetry and temperature of some glacial lakes in Wyoming. *Proceedings of the National Academy of Sciences of the United States of America*, *77*(4), 1754–1758. https://doi.org/10.1073/pnas.77.4.1754

Lipman, P. W., & Sawyer, D. A. (1985). Mesozoic ash-flow caldera fragments in southeastern Arizona and their relation to porphyry copper deposits. *Geology*, *13*(9), 652. https://doi.org/10.1130/0091-7613(1985)13<652:MACFIS>2.0.CO;2

Liu, L., Gurnis, M., Seton, M., Saleeby, J., Müller, R. D., & Jackson, J. M. (2010). The role of oceanic plateau subduction in the Laramide orogeny. *Nature Geoscience*, *3*(5), 353–357. https://doi.org/10.1038/ngeo829

Love, J. D., & Christiansen, A. C. (1985). *Geologic map of Wyoming*. U.S. Geological Survey.

Malone, J. R., Malone, D. H., & Craddock, J. P. (2022). Sediment provenance and stratigraphic correlations of the paleogene White River group in the Bighorn Mountains, Wyoming, (Vol. *59*, No. (4), p. 21).

Mckenna, M. C., & Love, J. D. (1972). High-level strata containing early Miocene mammals on the Bighorn Mountains (p. 32).

McMillan, M. E., Heller, P. L., & Wing, S. L. (2006). History and causes of post-Laramide relief in the Rocky Mountain orogenic plateau. *Geological Society of America Bulletin*, *118*(3–4), 393–405. https://doi.org/10.1130/B25712.1

Naeser, N. D. (1992). Miocene cooling in the southwestern Powder River basin, Wyoming: Preliminary evidence from apatite fission-track analysis (No. (1917)). https://doi.org/10.3133/b1917O

Omar, G. I., Lutz, T. M., & Giegengack, R. (1994). Apatite fission-track evidence for Laramide and post-Laramide uplift and anomalous thermal regime at the Beartooth overthrust, Montana-Wyoming. *Geological Society of America Bulletin*, *106*(1), 74–85. https://doi.org/10.1130/0016-7606(1994)106<0074:AFTEFL>2.3.CO;2

Painter, C. S., & Carrapa, B. (2013). Flexural versus dynamic processes of subsidence in the North American cordillera foreland basin: Flexural versus dynamic processes. *Geophysical Research Letters*, *40*(16), 4249–4253. https://doi.org/10.1002/grl.50831

Pelletier, J. (2009). The impact of snowmelt on the late Cenozoic landscape of the southern Rocky Mountains, USA. *Geological Society of America Today*, *19*(7), 4–11. https://doi.org/10.1130/GSATG44A.1

Peyton, S. L., Reiners, P. W., Carrapa, B., & DeCelles, P. G. (2012). Low-temperature thermochronology of the northern Rocky Mountains, western U.S.A. *American Journal of Science*, *312*(2), 145–212. https://doi.org/10.2475/02.2012.04

Ranz, P. A. (2000). *Generalized geologic map of Wyoming*. Wyoming State Geological Survey.

Robinson, P., Gunnell, G. F., Walsh, S. L., Clyde, W. C., Storer, J. E., Stucky, R. K., et al. (2004). Wasatchian through Duchesnean biochronology. In *Late cretaceous and cenozoic mammals of North America: Biostratigraphy and geochronology*. Columbia University Press. https://doi.org/10.7312/wood13040.10

Ronemus, C. B., Orme, D. A., Guenthner, W. R., Cox, S. E., & Kussmaul, C. A. L. (2023). Orogens of big sky country: Reconstructing the deep-time tectonothermal history of the Beartooth Mountains, Montana and Wyoming, USA. *Tectonics*, *42*(1), e2022TC007541. https://doi.org/10.1029/2022tc007541

Saleeby, J. (2003). Segmentation of the Laramide slab—Evidence from the southern Sierra Nevada region. *Geological Society of America Bulletin*, *115*, 655–668. https://doi.org/10.1130/0016-7606(2003)115<0655:SOTLSF>2.0.CO;2

Sherpa, T. Z. L., DeCelles, P. G., Carrapa, B., Schoenbohm, L. M., & Wolpert, J. (2022). Bhumichula plateau: A remnant high-elevation low-relief surface in the Himalayan thrust belt of western Nepal. *GSA Bulletin*. https://doi.org/10.1130/B36481.1

Shuster, M. W., & Steidtmann, J. R. (1988). Tectonic and sedimentary evolution of the northern Green River basin, western Wyoming. In *Geological society of America memoirs* (Vol. 171, pp. 515–530). Geological Society of America. https://doi.org/10.1130/MEM171-p515

Smith, M. E., Carroll, A. R., & Singer, B. S. (2008). Synoptic reconstruction of a major ancient lake system: Eocene Green River Formation, western United States. *Geological Society of America Bulletin*, *120*(1–2), 54–84. https://doi.org/10.1130/B26073.1

Steidtmann, J. R., & Middleton, L. T. (1991). Fault chronology and uplift history of the southern Wind River Range, Wyoming: Implications for Laramide and post-Laramide deformation in the Rocky Mountain foreland. *Geological Society of America Bulletin*, *103*(4), 472–485. https://doi.org/10.1130/0016-7606(1991)103<0472:FCAUHO>2.3.CO;2

Steidtmann, J. R., Middleton, L. T., & Shuster, M. W. (1989). Post-Laramide (Oligocene) uplift in the Wind River Range, Wyoming. *Geology*, *17*(1), 38. https://doi.org/10.1130/0091-7613(1989)017<0038:PLOUIT>2.3.CO;2

Stevens, A. L., Balgord, E. A., & Carrapa, B. (2016). Revised exhumation history of the Wind River Range, WY, and implications for Laramide tectonics: Wind River Range exhumation history. *Tectonics*, *35*(5), 1121–1136. https://doi.org/10.1002/2016TC004126

Wagner, G. A., & Van den Haute, P. (1992). *Fission track dating*. Kluwer Academic Publishers.

Winterfeld, G. F., & Conrad, J. B. (1983). *Laramide tectonics and deposition, Washakie range and northwestern Wind River Basin, Wyoming* (pp. 137–148). Rocky Mountain Foreland Basins and Uplifts.

Xu, J., Snedden, J. W., Fulthorpe, C. S., Stockli, D. F., Galloway, W. E., & Sickmann, Z. T. (2022). Quantifying the relative contributions of Miocene rivers to the deep Gulf of Mexico using detrital zircon geochronology: Implications for the evolution of Gulf Basin circulation and regional drainage. *Basin Research*, *34*(3), 1143–1163. https://doi.org/10.1111/bre.12653