Early Cenozoic exhumation and paleotopography in the Arkansas River valley, southern Rocky Mountains, Colorado

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ABSTRACT

New thermochronometric, geochronologic, and clumped isotope data from the Mosquito Range, Arkansas Hills, and Arkansas River valley (Colorado, USA) constrain the magnitude and timing of Laramide deformation in this region, as well as the development of a low-relief Eocene erosion surface found throughout the southern Rocky Mountains. Apatite (U-Th-Sm)/He thermochronometry from seven vertical transects near the lower Arkansas River valley were collected to assess exhumation histories. New paleomagnetic data from the latest Cretaceous Whitehorn Granodiorite is presented to assess the effect of possible upper crustal tilting on these transects. These data, in combination with new zircon (U-Th)/He thermochronometry and ⁴⁰Ar/³⁹Ar and zircon U-Th-Pb geochronology from the Whitehorn Granodiorite support inverse thermal history models that imply ~3–5 km of differential (west side up) exhumation between the Mosquito Range–Arkansas Hills (5–7 km total exhumation from 80 and 60 Ma) and the Royal Gorge region to the east (<1–2 km exhumation since ca. 120 Ma). Challenges in extracting reliable thermal histories from this data set include samples with significant grain-to-grain age variability, and the observation of upward younging age-elevation relationships in parts of several vertical transects. The former problem is common in Proterozoic crystalline rocks with protracted cooling histories, deriving from complications including helium implantation and radiation damage. We demonstrate, through the application of clumped isotopic data on colocated carbonate samples, that the latter complication likely arises from post-exhumation hydrothermal reheating driven by paleotopography and overlying late Eocene to early Miocene ignimbrite sequences. By comparing multiple closely spaced vertical transects in Proterozoic rocks with those that are not, we demonstrate that reliable thermal histories can be obtained from complex thermochronometric data sets through careful data evaluation and intertransect thermal history comparisons.

Interpreting the thermochronometric data in the context of the spatial distribution of mid-Cenozoic ignimbrites in this region also provides new insights into the development of the low-relief Eocene erosion surface in the Rocky Mountains. We observe rapid and extensive Laramide exhumation while ignimbrite deposition is confined to narrow paleovalleys within a paleosurface of moderate relief in the Arkansas Hills and Mosquito Range. Where Laramide exhumation is minimal, the ignimbrites blanket a low-relief paleoerosion surface. The former paleo-landscape was entirely formed in the Paleocene, based on our low-temperature thermochronometric data, while the latter paleosurface may well record a much longer evolutionary history, possibly partially inheriting an older paleolandscape. The compound nature of the Eocene erosion surface in this region may provide insight into the development of such surfaces throughout the Rocky Mountains.

INTRODUCTION

Significant debate surrounds the timing and cause of present-day elevation and relief generation in the southern Rocky Mountains (Colorado, USA). The physiography of much of the region appears to be young, with assumed recent high-relief generation, high elevations, and local evidence of young cooling and fast exhumation rates (Karlstrom et al., 2012; Landman and Flowers, 2013; Ricketts et al., 2016). However, Late Cretaceous to early Cenozoic low-temperature thermochronologic ages (Kelley and Chapin, 2004; Landman and Flowers, 2013), the demonstration of a well-defined Eocene erosion surface (Epis and Chapin, 1974, 1975), and the preservation of widespread, relatively undeformed mid-Cenozoic volcanic rocks all imply that the exhumation and relief development may have been generated much earlier. These features suggest that the topography of the Rocky Mountains is long lived and possibly inherited from previous orogenic deformation (i.e., the latest Cretaceous to early Cenozoic Laramide orogeny) and that any exhumation or topographic change after the Eocene has been relatively minor.

Distinguishing between ancient and youthful relief is of key importance in our understanding of the topographic evolution of large mountain belts (Pazzaglia and Brandon, 1996). Long-term decay (10⁶ yr) in the topography of orogens is governed by crustal thickness and buoyancy
On shorter time scales (10⁶–10⁷ yr), however, the destruction, preservation, or development of local relief can vary depending on the type of erosional processes that dominate across the landscape (e.g., planation, river incision, glaciation, and mass wasting; Whipple et al., 1999; Baldwin et al., 2003; Babault et al., 2007; Egholm et al., 2009, 2013), making it difficult to ascertain the timing of relief development. Although such challenges are not unique to the southern Rocky Mountains, this region is a prime example of the range of processes and time scales that conceivably could be proposed for uplift and relief generation.

Crustal shortening associated with latest Cretaceous to early Cenozoic Laramide orogenesis is one of the most frequently cited causes for the development of high elevations and relief in the southern Rocky Mountains (e.g., Bird, 1984). Thickening of the lithosphere resulting from crustal shortening (e.g., Brewer et al., 1982; Hamilton, 1988), and buoyancy changes arising from mantle and crustal processes (e.g., Liu et al., 2010; Jones et al., 2015) contributed to regional elevation gain during the Laramide orogeny. Development of a high-elevation mountain range during this time is supported by isotopic and paleobotanical studies of paleoelevation change (e.g., Gregory and Chase, 1992; Sjostrom et al., 2006; Fan et al., 2014) and the generation of topographic relief is indirectly supported by increased exhumation rates observed through the application of low-temperature thermochronometry, specifically apatite fission track (AFT) studies in the Front Range and Sangre de Cristo Mountains (Kelley and Chapin, 1995; 2004).

Crustal shortening within most of the Laramide orogenic belt ceased by the mid-Eocene (e.g., Tweto, 1975). However, an increase in erosion rates across the southern Rocky Mountains and Colorado Plateau in the late Miocene (Murray et al., 2016) and arguments that at least some of the relief in major fluvial drainages traversing this region developed over the same time interval (e.g., Karlstrom et al., 2008; Thomson et al., 2016) have been used as evidence of post–late Miocene regional uplift and postorogenic relief development in the central and southern Rocky Mountains (Rockies). One line of argument arises from eastward tilting of the Miocene Ogallala Formation along the eastern range front of the Rockies (McMillan et al., 2002). This tilting has been attributed to regional doming, associated with Rio Grande rift propagation and possibly augmented by surface erosion and isostatic response (McMillan et al., 2006). The magnitude of differential uplift associated with this regional tilting is ~700 m down to the east determined by a 250 km transect in southern Wyoming from Cheyenne to the western Great Plains in Nebraska (McMillan et al., 2002). Mantle-driven dynamic uplift has also been invoked as a mechanism for generating 500–1000 m of surface uplift across the Rocky Mountains and Colorado Plateau since the late Miocene (Karlstrom et al., 2012; Heller and Liu, 2016), although controversy remains over the magnitude of surface topography that can be generated by dynamic forces (Molnar et al., 2015).

Processes that may continue to drive relief development in the southern Rocky Mountains include ongoing erosional and isostatic response to Rio Grande rift propagation (Leonard, 2002), distal base-level fall (Frankel and Pazzaglia, 2006), and climate change that modulates glacial-interglacial cycles (Small and Anderson, 1998).

Here we focus on the tectonic development of the southern Rocky Mountains in the vicinity of the Arkansas River (Fig. 1). This region exhibits ~1 km of local relief, produced by river incision, exposing profiles of many key geologic relationships such as high-angle faults, extensional grabens, and erosional contacts. Such a setting provides an ideal location to address the time scales and potential driving processes of topographic evolution and relief generation.

**Physiography and Geology of the Lower Arkansas River Valley**

The southern Rocky Mountains in Colorado represent a region of high-elevation peaks and intermontane basins, with an abrupt transition into...
the lower elevation Great Plains expanse to the east, and the relatively undeformed Colorado Plateau to the west (Fig. 1). Within the southern Rocky Mountains, the Arkansas River divides the Mosquito Range from the Sawatch Range, with headwaters near Leadville, Colorado. It flows south until reaching Salida, Colorado, where the river makes an abrupt directional change and flows east (Figs. 2 and 3). The river has two clear physiographic segments. We define the upper Arkansas River (UAR) valley as the southward-flowing section of the river, which flows through a broad normal-fault-bounded valley defined by high-elevation peaks associated with extensional features in the northern Rio Grande rift. The lower Arkansas River (LAR) valley is the eastward flowing section of the river from Salida to Cañon City, Colorado (Fig. 3). The LAR valley, in contrast to the UAR, is defined by a narrow, steep, fluvially incised gorge that exposes rocks spanning ~1.7 b.y. of geologic time.

The oldest rocks within the LAR valley are Proterozoic gneisses and granitoids (Scott, 1975b; Taylor et al., 1975a, 1975b, 1975c; Bryant and Naeser, 1980; Wallace et al., 1997). These Proterozoic crystalline rocks are locally disconformably overlain by relatively thin sequences of lower Paleozoic sedimentary rocks, as well as thicker sequences of upper Paleozoic strata. High-angle, basement-cutting faults record the latest Mississippian to Permian Ancestral Rocky Mountain orogeny (Baars and Stevenson, 1984; Kluth and Coney, 1981; Fig. 2). Paleozoic sediments are sparsely preserved, but remnants of Ordovician to Permian carbon-ate and detrital sedimentary rocks are exposed in and along the LAR canyon (Taylor et al., 1975a, 1975b, 1975c; Wallace et al., 1997; Fig. 2). Middle to upper Mesozoic sediments associated with the Cretaceous Interior Seaway (ca. 72 Ma; Blakey et al., 1996, 2008; DeCelles, 2004) are preserved in the eastern part of the LAR valley (Fig. 2).

Deformation in the form of crustal shortening, high-angle thrust faulting, and local folding of the crystalline basement, all related to the Laramide orogeny, took place during the latest Cretaceous to middle Eocene time (ca. 85–40 Ma; Tweto, 1975; Dickinson et al., 1988; Keller and Baldridge, 1999; Marshak et al., 2000; DeCelles, 2004), eroding and dissecting Paleozoic and Mesozoic strata. Laramide deformation in southern Colorado was also associated with small volume plutonism, including the emplacement of the latest Cretaceous Whitehorn Granodiorite in the Arkansas Hills and Mosquito Range (Wallace et al., 1997; Fridrich et al., 1998; Fig. 3).

Laramide orogenic deformation was followed by the development of a regional low-relief erosion surface across the southern Rocky Mountains (Epis and Chapin, 1974, 1975; McMillan et al., 2002, 2006; Gregory and Chase, 1994). This erosion surface was blanketed in the mid-Cenozoic (ca. 36 to ca. 20 Ma) by volcanic deposits, primarily silicic ignimbrites and andesitic porphyritic flows and lahars, originating from calderas located in the present-day Sawatch Range (Epis and Chapin, 1974, 1975; Taylor et al., 1975a, 1975b, 1975c; Taylor, 1975; Scott, 1975a; Epis et al., 1976; Chapin and Lowell, 1979; Shannon, 1988; Gregory and McIntosh, 1996; Wallace et al., 1997; McIntosh and Chapin, 2004; Fig. 2). Following this phase of volcanic activity, extension associated with the Rio Grande rift initiated in southern Colorado during the early Miocene (Kelleay and Chapin, 1995; Ehlers, 2005), and ZHe records temperatures from ~130 to ~230 °C (Reiners et al., 2002; Reiners, 2005). 40Ar/39Ar thermochronometry records thermal histories between ~100 °C and ~500 °C, depending on the mineral phase analyzed (Farley, 2005), and ZHe records temperatures from ~130 to ~230 °C (Reiners et al., 2002; Reiners, 2005). 40Ar/39Ar thermochronometry records thermal histories between ~100 °C and ~500 °C, depending on the mineral phase analyzed (McDougall and Harrison, 1988), providing constraints on the higher temperature thermal history of a given sample. Together, this suite of thermochronometers affords the ability to resolve thermal histories for the upper 15–20 km of the Earth’s crust, depending on the local geothermal gradient.

Thermochronometric data from the southern Rockies are abundant, but available data are predominantly K-Ar and 40Ar/39Ar age determinations that record higher temperature information (Klein et al., 2010). Extant low-temperature thermochronometric data from the southern Rockies come mostly from AFT analyses (see Klein et al., 2010; much of the data from rocks in the Arkansas River region are from Kelley and Chapin, 2004, 1995), which record pre-Cenozoic cooling ages. Only a few studies incorporating AHe ages have been published for the southern Rocky Mountains (Landman and Flowers, 2013; Ricketts et al., 2016), thus, our suite of AHe and ZHe data from the LAR region provides a more complete picture of the near-surface thermal histories of the rocks in the locality of the LAR valley.

Analytical Methods for Helium and Argon Thermochronometry

Apatite (U-Th-Sm)/He and Zircon (U-Th)/He Procedures

Samples were processed using standard mineral separation practices. Individual apatite and zircon grains were hand-selected and screened for...
Figure 2. (A) Simplified geologic map of the upper and lower Arkansas River valleys. (B) Schematic representation of geologic relationships in the lower Arkansas River valley is shown in cross section. Note vertical exaggeration with actual distances on figure (structure orientations are not exaggerated). Large faults and fault systems represented by black lines with displacement shown by black arrows (Taylor et al., 1975b, 1975c) dissect the Proterozoic, Paleozoic, and Mesozoic rock. Early Cenozoic deformation includes graben formation (i.e., Echo Park Canyon). The regional Eocene erosion surface is indicated with a thick black line overlain by relatively undeformed late Eocene to early Miocene ignimbrite deposits. Blue line at the base of the cross section represents the modern lower Arkansas River.
Early Cenozoic evolution in the southern Rocky Mountains, Colorado

Figure 3. A 90 m digital elevation model (DEM) showing study region and sample localities. (A) Location of the upper and lower Arkansas River (UAR and LAR, respectively) near its headwaters in Colorado. (B) UAR valley marked by black box outline in A, showing apatite helium (AHe) data (colored circles) and clumped isotope sample locations (white squares) for the West Buffalo Peak (WBP) transect. (C) LAR Valley marked by rectangle in A, showing sample locations of clumped isotopes (white squares) and AHe data (colored circles) collected in vertical transects. GM—Green Mountain, CM—Cameron Mountain, BB—Big Baldy, BTM—Burned Timber Mountain, TCBR—Texas Creek–Bull Ridge, FPG—Five Point Gulch, FMT—Fremont Peak. Some apatite fission track (AFT) data for this region have been published (triangles; Kelley and Chapin, 2004). Colors signify sample mean ages. Two additional AHe samples were collected from quarries in the Whitehorn Granodiorite (AFWH). Other analyses (ZHe, U-Th-Pb of zircon, and ⁴⁰Ar/³⁹Ar of biotite, hornblende, and K-feldspar) were performed on many samples in both the GM and WH (Whitehorn) transects shown in D. (D) Gray circles indicate samples with only AHe data while black circles indicate samples analyzed with multiple techniques: ZHe ages (bold font; Table DR1), ⁴⁰Ar/³⁹Ar (italicized; Table DR3), and U-Th-Pb (semibold and underlined; Tables DR5 and DR6).
zoning and inclusions prior to outgassing on an Alphachron Helium Instrument at the University of Michigan. Ages reported are averages based on multiple (3–9) individual replicate analyses from each sample. We only interpret apatite or zircon ages from samples with at least three or two inclusion-free grains, respectively. All grains analyzed were >80 µm in both length and width (Table 1; Table DR1). Additional details of the analytical procedure are described in Appendix 1 and Niemi and Clark (2017). Analyses of U, Th, and Sm from the apatite and zircon grains were performed at the University of Arizona following the methods outlined in Reiners and Nicolescu (2006).

### **Ar**/**Ar Procedures

Mineral separates were obtained using standard mineral separation practices followed by step-heating using a Mo double vacuum resistance furnace at the New Mexico Bureau of Geology and Mineral Resources. Biotite and hornblende crystals were heated in 11 and 10 min increments, respectively, whereas K-feldspar analyses involved a detailed 42-step heating schedule to retrieve data necessary for multiple diffusion domain (MDD) modeling. The **Ar**/**Ar** analytical method follows that of McIntosh and Cather (1994) and Sanders et al. (2006; see Appendix 1 for details). Argon closure in K-feldspar is treated following the MDD method developed by Lovera et al. (1989).

### Thermostratigraphic Data Quality Assessment and Interpretation

Interpretation of low-temperature thermostratigraphic data is complicated in data sets with protracted or nonmonotonous thermal histories (Fitzgerald et al., 2006; Peyton et al., 2012; Stanley et al., 2013). Proterozoic rocks especially may be subject to an array of processes that give rise to scatter in single-grain apatite dates from a given sample. Such processes include radiation damage (Flowers et al., 2009; Shuster et al., 2006), He implantation (Reiners et al., 2008; Spiegel et al., 2009; Kohn et al., 2009), zonation (Hourigan et al., 2005), or U-rich inclusions (House et al., 1997). In some cases, relationships between grain size and date (e.g., Reiners and Farley, 2001) or radiation damage (eU) and date (e.g., Flowers et al., 2009; Gautheron et al., 2009) effectively explain the observed variation in single-grain apatite dates from the same bulk sample. When this is the case, each grain records a specific part of the thermal evolution of the sample, and these variations can be exploited to derive the thermal history of the sample (Flowers et al., 2007). In other cases, the cause of scatter in measured dates cannot be ascribed to any of the processes described here (e.g., Peyton et al., 2012), and limited thermostratigraphic information may be gleaned from such analyses.

In interpreting thermostratigraphic data, determining how much weight to place on samples with significant scatter has historically been a subjective decision (Galbraith and Laslett, 1993; Gallagher, 1995). We describe our statistical approach to assess scatter in our data set. As a general rule, we place limited confidence in the geologic relevance of thermostratigraphic ages derived from samples with mean age standard errors that exceed 15%, and we exclude these samples from thermal modeling (Flowers et al., 2015).

Data quality of individual samples is assessed through a multistep procedure to remove outliers and test for typical causes of data scatter. Samples are assessed for outliers using either the Dean and Dixon (1951) Q-test or the Boddy and Smith (2010) test for two extreme outliers. The Q-test is amenable to small data sets (n ≥ 3), and thus useful for (U-Th-Sm)/He thermochronometry, where individual samples typically include 3–5 replicates. The drawback to this test is that it is conservative in identifying outliers, and can only be used once on each sample. Other tests are available for larger data sets (n ≥ 5) that can identify as many as two outliers (Boddy and Smith, 2010), and we employ these tests for two extreme outliers on samples with five or more replicates. Both tests exclude samples with outliers found at the 95% confidence level.

Once individual grain outliers are identified, date–eU and date–grain-size correlation plots are generated, with outliers flagged (Fig. DR1). These plots are visually inspected for trends in grain date versus eU and grain date versus size. If correlations between these parameters are observed, previously identified outliers may be retained in the data set. If no trends are observed, the outliers are excluded from further analysis, and the sample age and standard error are recalculated from the retained grain dates.

Samples are also inspected for indications of He implantation. Implantation from surrounding U-rich phases can bias date determinations, particularly on apatite grains with low eU (<5 ppm; Table DR1; Spiegel et al., 2009). We observe low-eU grains primarily in samples from the Whitehorn transect (discussed in the following), although these samples did not display high degrees of age scatter (Table 1; Table DR1; Fig. 4). To address concerns of potential He implantation in the low-eU grains from the Whitehorn transect, we acquired whole-rock trace element analyses for three samples that exhibited low eU (14BB-03, 15CM-05, and 15AFWH2; Table DR1). Trace element analyses by inductively coupled plasma–mass spectrometry (ICP-MS) indicate that U concentrations in the whole rocks are no greater than the concentrations observed in individual apatite grains (<5 ppm; Table DR2). Given the low concentration of U in the whole rock, He implantation is unlikely to have an effect on the dates of the apatite grains that we analyzed. Following the data quality procedure outlined here, we define four different stages through which our sample ages are filtered prior to use in interpretations and thermal modeling.

1. Samples with no outliers and exhibiting little scatter (<15% standard errors) are accepted at face value, with high confidence in the mean age calculated from the individual grain dates.
2. Samples for which scatter can be reduced to less than 15% by outlier removal are subject to age recalculation, with high confidence in the mean age calculated from the retained individual grain dates.
3. Samples with high scatter (>15% standard error) after outlier tests, but that exhibit a correlation between date and eU or date and grain size, are retained for thermal modeling, but mean ages for these samples are treated cautiously with respect to geologic interpretations.
4. Samples with high scatter, to which no clear cause can be ascribed, are given little confidence in the mean age calculated and are not used in any thermal modeling.

### Low-Temperature Thermostratigraphic Results

New AHe low-temperature thermostratigraphic data are presented for 39 samples from the LAR valley, in addition to ZHe data for 3 of those samples. These samples were collected from seven vertical transects along the LAR from Salida to Cañon City, as well as along two additional vertical transects located on the eastern side of the UAR valley near Salida and Buena Vista, respectively (Fig. 3; Table 1; Table DR1). Furthermore, AHe data and **Ar**/**Ar** analyses on hornblende, biotite, and K-feldspar are reported for samples from two quarries located in high-elevation exposures of the Whitehorn Granodiorite, northeast of Salida (Fig. 3; Table 2; Tables DR3 and DR4).

All samples were collected from rocks in the hanging wall of the northern Rio Grande rift extensional system (southwest Front Range, Arkansas Hills, and Mosquito Range; Fig. 3), with most transects gathered in
TABLE 1. APATITE AND ZIRCON HELIUM RESULTS

<table>
<thead>
<tr>
<th>Sample name (transsect)</th>
<th>Long Lat Elevation (m)</th>
<th>Rock type</th>
<th>Grains analyzed per sample</th>
<th>Mean age (Ma)</th>
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</thead>
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<tr>
<td>West Buffalo Peak (WBP) transect</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>15WBP-02*</td>
<td>-106.0960 38.96303</td>
<td>Alkali feldspar granite</td>
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<td>260 ± 41</td>
</tr>
<tr>
<td>15WBP-04*</td>
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<td>5†</td>
<td>60 ± 2</td>
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<td>72 ± 10</td>
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<tr>
<td>15WBP-06*</td>
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<td>Granite</td>
<td>3</td>
<td>60 ± 4</td>
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<tr>
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<tr>
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<td>62 ± 3</td>
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<tr>
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<td>Granite</td>
<td>3</td>
<td>115 ± 24**</td>
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<td>Whitehorn (WH) transects and individual samples</td>
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<tr>
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<td>28 ± 3</td>
</tr>
<tr>
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<td>Granite and/or granodiorite</td>
<td>4</td>
<td>30 ± 3</td>
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<tr>
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<td>Intermediate granite</td>
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<td>19 ± 4**</td>
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<td>15AFWH26</td>
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</tr>
<tr>
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<td>4</td>
<td>41 ± 3</td>
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<td>Quartz monzonite</td>
<td>1†</td>
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</tr>
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</table>

Note: Sample EC-03a produced four datable grains; however, they are detrital and cannot be averaged together as a mean age. Individual grain dates reported in Table DR1 (text footnote 1). Dash indicates no data obtained from sample; (2) indicates zircon helium analyses, other data are from apatite helium analyses.

*Used in thermal models (reasoning described in text).
†Four or more grains were included in mean age calculation, but some grains were excluded due to outlier rejection (Table DR1).
‡Fewer than four grains were included in mean age calculation, due to outlier rejection for apatite samples and due to number of grains analyzed for zircon samples (Table DR1).
**Sample mean age has >15% error.
††No apatite in sample.
Figure 4. Apatite helium (AHe) single-grain dates and mean ages plotted against elevation for each transect or grouping of transects. Note the age inversion seen in the Whitehorn, Burned Timber, and Texas Creek plots. Whitehorn Granodiorite graph includes the Big Baldy (BB) and Cameron Mountain (CM) transects and two single samples (AFWH). All other individual graphs are labeled with the specific transects they include. Samples that fail our data quality assessment defined in the text marked by small and large gray circles.

<table>
<thead>
<tr>
<th>TABLE 2. ARGON DATA RESULTS</th>
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<tr>
<td>WH-2 hornblende</td>
</tr>
<tr>
<td>WH-2 K-feldspar</td>
</tr>
<tr>
<td>WH-26 K-feldspar</td>
</tr>
</tbody>
</table>

Note: Lab#—lab identifier; Irrad—irradiation package identifier; n—number of steps used to calculate preferred age; %$^{39}$Ar—percent of $^{39}$Ar comprising the preferred age; MSWD—mean square of weighted deviates; ±1σ—1 sigma errors calculated for the age.
Proterozoic granitoids and gneissic basement rocks (Scott, 1975b; Taylor et al., 1975a, 1975b, 1975c; Wallace et al., 1997). Exceptions include two transects that were collected within the Cretaceous Whitehorn Granodiorite (Taylor et al., 1975b), and another in Eocene sedimentary rocks in Echo Canyon (Fig. 2; Wallace et al., 1997). All transects in the LAR valley were collected below the Eocene erosion surface and overlying volcanic rock sequences. The two sample transects in the UAR valley are not covered by these volcanic flow deposits.

AHe and ZHe results from each transect and 40Ar/39Ar data from the Whitehorn Granodiorite are described in the following (Fig. 3); in some cases, geographically proximal transects are described and discussed jointly. Results are presented in downstream order along the Arkansas River (i.e., transects farthest from Calion City are described first).

**West Buffalo Peak Transect**

The West Buffalo Peak (WBP) transect is the northermmost transect (Fig. 3B) spanning ~900 m of elevation. AHe analyses were performed onapatite extracted from Precambrian basement located conformably below Carboniferous strata (Tweto, 1974; Scott, 1975b) and the data record apparent ages of 60 ± 4 Ma, 72 ± 10 Ma, and 60 ± 2 Ma for the three samples collected at the lowest elevations. The highest elevation sample, however, yields a much older age, 260 ± 41 Ma (Table 1; Table DR1; Figs. 3B and 4A).

**Green Mountain Transect**

The Green Mountain (GM) transect is located just north of Salida (Fig. 3C). The vertical transect includes 5 samples that span >830 m of elevation. The transect extends eastward from the river (Fig. 3C) and all collected samples are in Paleoproterozoic granodiorite (Wallace and Lawson, 2008). The AHe ages for all GM samples investigated are Paleocene (oldest: 65 ± 3 Ma, youngest: 55 ± 6 Ma) with no obvious elevation trend (Table 1; Table DR1; Figs. 3C, 4D, and 5). ZHe analyses were performed on the lowest two samples in the transect (GM-04 and GM-05) with three grains analyzed per sample. Dates range from 84 to 144 Ma in GM-04 and from 71 to 155 Ma in GM-05 (Table 1; Table DR1).

**Whitehorn Granodiorite Transects**

We sampled two vertical transects in the Whitehorn Granodiorite (WH). The Big Baldy (BB samples) transect encompasses the south flank of Big Baldy Mountain from 2073 m (river level) to 2932 m (Table 1; Table DR1) and includes samples within the Cretaceous granodiorite as well as adjacent samples in the surrounding Paleoproterozoic basement rock (14BB-03, also analyzed for ZHe). The Cameron Mountain (CM samples) transect extends the elevation range of samples collected in the Whitehorn Granodiorite to 3338 m along the southern ridge of Cameron Mountain (Table 1). Combined, these transects span ~1.3 km of elevation. Two additional samples (AFWH; Table 1; Table DR1) were taken from rock quarries between these two transects, at the localities of previously collected samples for 40Ar/39Ar geochronology and paleomagnetic data (WH; Table 2; Table DR3). AHe data were obtained from BB, CM, and AFWH quarry samples (Table 1; Table DR1), while 40Ar/39Ar data is presented for the WH quarry samples (Table 2).

AHe thermochronometry data show that the lower 3 BB samples progressively decrease in age with decreasing elevation, from 63 ± 3 Ma at 2586 m to 19 ± 4 Ma at 2338 m (Table 1; Figs. 4 and 5). In contrast, all 8 samples at higher elevations yield a range of ages from 27 ± 2 Ma to 51 ± 3 Ma and do not show a correlation with elevation (these samples include sample 14BB-02 and all CM and AFWH samples) (Table 1; Figs. 3C, 4C, and 5). The ZHe data from sample 14BB-03 record an age of 83 ± 1 Ma (Fig. 3D; Table 1; Table DR1).

The 40Ar/39Ar incremental heating data reveal relatively flat spectra for biotite and hornblende from both samples (Fig. 6). Biotite from WH-2 and WH-26 yield plateau spectra for >90% of the 39Ar released and give apparent ages of 69.3 ± 0.2 Ma and 69.8 ± 0.2 Ma, respectively (Figs. 3D and 6; Table 2; Table DR3). The hornblende spectra are somewhat more complex than the biotite spectra and are slightly saddle shaped (Fig. 6). The intermediate steps of WH-26 hornblende yield a plateau age of 70.0 ± 0.4 Ma, while the preferred age of the hornblende from sample WH-2 is 69.1 ± 0.6 Ma, determined from the isochron analysis (Fig. 6; Table 2; Table DR3).

K-feldspar age spectra reveal variable age gradients for the two samples (Fig. 6). K-feldspar from sample WH-2 shows a gradual increase from ca. 66.3 to ca. 70 Ma over the entire spectrum (Fig. 7; Table 2; Table DR4). In contrast, WH-26 yields initial minimum ages of ca. 69.4 Ma over the first 20% of the spectrum, followed by a sharp increase to ca. 82 Ma before falling to ca. 76 Ma during the final 50% of the spectrum (Fig. 7). The shape of the release spectrum for sample WH-26 has been observed in other K-feldspars and is interpreted to be caused by excess argon trapped within large diffusion domains (Foster et al., 1990). Thus, we do not further consider the K-feldspar age data from sample WH-26.

**Burned Timber Mountain Transect**

North of Coaldale, the Burned Timber Mountain (BTM) transect was collected over 600 vertical meters along a traverse that is parallel to the Arkansas River (Fig. 3C). The lowest elevation sample (BTM-06, 2201 m) records a mean age of 41 ± 3 Ma, while two samples at higher elevations (BTM-01, 2318 m and BTM-03, 2597 m) have mean ages of 62 ± 3 Ma and 110 ± 14 Ma, respectively. The highest elevation sample in the transect (BTM-04, 2844 m) yields a younger age of 28 ± 3 Ma (Table 1; Table DR1; Figs. 4D and 5).

**Texas Creek–Bull Ridge and Five Point Gulch Transects**

The Texas Creek–Bull Ridge (TCBR) and Five Point Gulch (FPG) traverses are considered together here, as they are at similar downstream distances along the river (Fig. 3C and 5) and span the same elevation range. The FPG traverse is located south of the Arkansas River and the...
TCBR traverse is on the north side (Fig. 3C). Many of the samples collected in these two transects are at similar elevations (Table 1; Figs. 4E and 5), and the data from them indicate a consistent cooling history both north and south of the LAR valley. The three lowest elevation samples from both transects combined did not yield reproducible data (Table 1), with low apatite yield (only one grain; 48 ± 1 Ma, FPG-01; Table 1; Table DR1) and high percent error (23 ± 6 Ma, TCBR-04 and 320 ± 106, FPG-05; Table 1; Table DR1). The mid-elevation samples within these two transects record late Cretaceous and early Cenozoic ages (FPG-06, 63 ± 5 Ma; TCBR-03, 67 ± 0.3 Ma; FPG-08, 61 ± 5 Ma; Table 1; Fig. 4). The TCBR transect continues to higher elevations than the FPG transect, yielding older AHe dates in the two samples at these higher elevations (135 ± 11 Ma and 101 ± 9 Ma; Table 1; Figs. 4 and 5). In summary, for all samples from these two transects that fit our data quality criteria, the AHe dates are latest Cretaceous to Paleocene in age (Table 1; Table DR1; Figs. 3C, 4E, and 5).

**Echo Canyon**

Five samples were collected in Echo Canyon (EC) from the coarse, unconsolidated sandstone mapped as the Eocene Echo Park Alluvium (Taylor et al., 1975b). Apatite yields from these samples were poor, and thus dates were only obtained from two samples. Of these two, only one

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![Figure 6](https://pubs.geoscienceworld.org/gsa/lithosphere/article-pdf/4098454/239.pdf)
Early Cenozoic evolution in the southern Rocky Mountains, Colorado

RESEARCH

The four dates obtained from sample EC-03a range from 406 ± 4 Ma to 3486 ± 26 Ma (Table 1; Table DR1), while the one AHe date obtained from EC-04 yielded a date of 33 ± 0.3 Ma (Table 1; Table DR1). The Paleozoic and older dates of the individual apatite grains, combined with the geologic age constraints on the unit from which these samples were collected, indicate that these dates reflect the thermal evolution of the source terrain from which they were derived (and not the thermal history of the Echo Park Alluvium). Because we lack any geologic context for this source terrain, and because the detrital nature of these grains prevents us from treating them statistically as an integrated sample, we exclude these dates from further analyses.

Fremont Transect

The Fremont transect (FMT) samples were collected in a vertical transect on Fremont Peak near Royal Gorge, Colorado (Fig. 3C). Only three of the five samples collected yielded apatite (Table 1; Table DR1). The AHe dates for the three samples range from Early Cretaceous to late Paleogene (27 ± 2 Ma, FMT-01; 110 ± 29 Ma, FMT-02; 70 ± 27 Ma, FMT-03; Table 1; Figs. 4F and 5) and show no correlation between age and elevation. All three samples, however, have poor reproducibility (Table 1; Table DR1) and were not incorporated into thermal models or subject to further interpretation.

ASSESSMENT OF REGIONAL DIFFERENCES ON THE INTERPRETATION OF THERMOCRONOMETRIC DATA

Interpretations of low-temperature thermochronometric data from Proterozoic rocks that most likely have complex or protracted thermal histories can be complicated. Often dates from a single sample will have low reproducibility (Fitzgerald et al., 2006; Peyton et al., 2012; Flowers et al., 2009; Shuster et al., 2006; Reiners et al., 2008; Spiegel et al., 2009; Kohn et al., 2009; Hourigan et al., 2005; House et al., 1997), and although samples may be collected along vertical transects, it is not always clear that their present spatial relationships are representative of those at the time of cooling and exhumation (e.g., Reiners and Farley, 2001; Niemi et al., 2013). Interpretations of paleoisotherm geometries from low-temperature thermochronometric data can also be affected by long-wavelength regional tilting (e.g., House et al., 2001; Roy et al., 2004).

Because much of the southern Rocky Mountain region is composed of Paleoproterozoic and Mesoproterozoic crystalline rocks that have undergone significant metamorphic and deformation events, and because these rocks are not typically overlain by sedimentary strata that provide constraints on the orientation of paleohorizontal, accurate information on regional tilting is critical to the valid interpretation of the spatial relationships among our low-temperature thermochronometric samples. Regional deformation and tilting could compromise assumed age-elevation
relationships in our sampling transects, and regional-scale down-to-the-west tilting has been proposed to have affected much of the Front Range of Colorado (Naeser et al., 2002). To assess the degree of tilting that may have been imposed on our sampling transects, we employ a joint geochronologic and paleomagnetic study of the Cretaceous Whitehorn Granodiorite. New U-Th-Pb geochronologic analyses from zircon collected from the Whitehorn Granodiorite define the emplacement age of this pluton. These geochronologic analyses, together with paleomagnetic data, can be used to assess the magnitude of postemplacement tilting of the granodiorite by comparison with expected paleomagnetic directions for the study area based on North American paleomagnetic poles of comparable age. This exercise has potential implications for the effects of post–Late Cretaceous deformation on our low-temperature thermochronometric sampling.

**Emplacement and Tilting of the Cretaceous Whitehorn Granodiorite**

The Whitehorn Granodiorite intruded into the Arkansas Hills (Fig. 3C; Wallace and Lawson, 2008; Wallace et al., 1997) and is ~8 km (east-west) by 25 km (north-south) in surface exposure. The stock is granodioritic in composition (Wrucke, 1974), and was emplaced in the Late Cretaceous (ca. 70 Ma), as initially inferred by K-Ar dates on biotite (cf. Chualaoawanich, 1997, for a summary of new and recalculated K-Ar age determinations on the Whitehorn stock).

**Zircon U-Th-Pb data from the Whitehorn Granodiorite**

We analyzed two samples for zircon U-Th-Pb data, one from the Whitehorn Granodiorite pluton (15CM-05) and one from Proterozoic gneiss in the wall rock adjacent to the pluton (14BB-03; Table 1; Fig. 3D).

**Igneous Zircon U-Th-Pb Analytical Methods**

Analyses were performed using laser ablation–ICP-MS on both the Nu Plasma multicollector ICP-MS (14BB-03) and the Thermo Element 2 single-collector ICP-MS (15CM-05) at the University of Arizona’s LaserChron Center following the procedures outlined in their procedures manuals (Gehrels and Pecha, 2014; Ibanez-Mejia et al., 2015).

**Zircon U-Th-Pb Results**

The sample from the Whitehorn Granodiorite (15CM-05) yields an age of 67.31 ± 0.57/–0.78 Ma (2σ; Table DR5; Fig. 8), confirming the previously inferred Late Cretaceous age for the intrusion of the pluton. The wall-rock sample (14BB-03) yields zircon U-Th-Pb ages of ca. 1.7 Ga (Table DR6), which is consistent with U-Th-Pb ages from basement rocks in the surrounding area (Klein et al., 2010). The zircon U-Th-Pb ages and the biotite and hornblende 40Ar/39Ar ages are analytically indistinguishable and suggest that the Whitehorn Granodiorite was emplaced at, and cooled to, ambient temperatures below ~300 °C by ca. 67 Ma.

**Paleomagnetism of the Whitehorn Granodiorite**

**Paleomagnetic Analytical Methods**

We collected independently oriented samples from more than 50 sites in the Whitehorn Granodiorite and related thin intermediate composition dikes, as well as intrusion host rocks, including Proterozoic metagneous rocks and hornfels developed in Pennsylvanian strata in contact with the pluton. At all sites, sampling involved the use of a portable field drill with a nonmagnetic diamond drill bit that was water-cooled. At most sites, azimuthal orientation of independent cores (samples) was obtained by both magnetic and solar compasses. Core specimens were prepared in the laboratory into 2.5-cm-diameter, 2.25-cm-high right cylinders for anisotropy of magnetic susceptibility (AMS) and all remanence measurements. AMS measurements were made on an AGICO KLY-4A automated susceptibility unit. All remanence measurements were made on a 2G Enterprises Model 760R superconducting rock magnetometer equipped with an online 2G Enterprises alternating field (AF) demagnetization system and automated specimen handler. Thermal demagnetization employed on a Shaw MMMT instrument or an ASC TD48 instrument. Measurements of bulk susceptibility, as a continuous function of heating and cooling, were conducted on an AGICO MFK1-A susceptibility unit equipped with a CS4 furnace attachment. All heating and cooling experiments were conducted in an inert (argon) atmosphere.

**Paleomagnetic Results**

For samples of the Whitehorn Granodiorite that contain a single component of magnetization, as revealed in progressive demagnetization, the intensity of the natural remanent magnetization (NRM) is typically between 0.5 and 5 A/m. Several sites established in the pluton yield NRM intensities that are considerably higher (>10 A/m) and demagnetization results yield highly scattered directions of remanence. We interpret this behavior to be the effect of one or more lightning strikes, resulting in a lightning-induced RM, and the results from these sites are deemed uninterpretable (the results from these sites are omitted from Table DR7). For those sites not affected by lightning, alternating field (AF) demagnetization typically isolates a remanence of north-northwest to northwest declination and moderate to slightly steep positive inclination over a range of peak (AF) fields up to at least 80 mT, if not higher (Fig. 9). A similar magnetization is isolated in thermal demagnetization over a range of laboratory unblocking temperatures between ~450 °C and 580 °C (Fig. 9). Most sites in the Whitehorn Granodiorite that were not affected by lightning yield well-grouped magnetizations at the site level, with a 95% confidence in values of ~7° or less and k values >75 for typical sample populations between 7 and 10 independent samples (Fig. 10; Table DR7). Sites in adjacent Paleozoic sedimentary rocks or Precambrian crystalline rocks that we interpret to have been remagnetized during pluton emplacement typically yield the most dispersed population of directions. On the basis of demagnetization behavior and monitoring bulk susceptibility continuously in heating and cooling (Fig. DR3), we infer that the remanence
Early Cenozoic evolution in the southern Rocky Mountains, Colorado

Figure 9. Representative examples of response to progressive alternating field and thermal demagnetization of specimens from samples from the Whitehorn Granodiorite from selected sampling sites. NRM—natural remanent magnetization. Each orthogonal demagnetization diagram plots the endpoint of the magnetization vector measured after successive demagnetization steps onto the horizontal (filled symbols) and vertical (open symbols) planes. Selected demagnetization steps are indicated along vertical projections. All projections are in geographic coordinates and all projections have the same coordinate scheme.

Figure 10. Equal area projection of estimated site mean directions and associated projected cones at 95% confidence of paleomagnetic data from sites in the Whitehorn Granodiorite and adjacent host rocks. Black squares show sample projections onto the lower hemisphere. Paleomagnetic data from the Whitehorn Granodiorite are compared with examples of expected directions (gray squares) of the locality for latest Cretaceous time. All paleomagnetic data from the Whitehorn Granodiorite are of north to north-northwest declination and moderate positive inclination (normal polarity).
characteristic of the pluton is carried by low-Ti magnetite. Reflected light microscopy and scanning electron microscopy both show that magnetite is typically unoxidized and exhibits textures that are consistent with a primary magmatic origin (Fig. DR4). AMS data from the pluton exhibit a range of fabric orientations and fabric types, as well as a variable dispersion of principal susceptibility axes (Fig. DR5). Consequently, it is difficult to interpret these data in the context of a model of homogeneous magma emplacement; further sampling, at very high spatial resolution, if possible, may result in a refinement of the data set to more fully assess the emplacement mechanism for the pluton. Notably, the degree of anisotropy and magnitude of fabric parameters (e.g., L and F) are acceptably low and do not warrant concern about a strong magnetic fabric influencing the direction of a thermoremanent magnetization blocked in the granodiorite.

**Paleomagnetic Interpretations**

The in situ magnetization characteristic of the Whitehorn Granodiorite, as defined by results from 32 sites in granodiorite and contact host rocks, is of north-northwest declination and moderate positive inclination (Dec. = 324.2°, Inc. = +56.5°, α95 = 4.1°, k = 38.6). All magnetizations resolved from the pluton are exclusively of normal polarity, consistent with the interpreted age of emplacement of the pluton as ca. 67 Ma, with magnetization acquisition during magnetic polarity Chron 31/30 time interval, which is dominated by normal polarity (Gradstein et al., 2012). The direction of the in situ magnetization differs slightly from expected latest Cretaceous (ca. 70–66 Ma) directions (~340/62–347/61) derived from paleomagnetic poles for North America for this time period (Fig. 10). The discordance of principal susceptibility axes (Fig. DR5). Consequently, it is interpreted as the rapid exhumation of samples that cooled quickly through the partial retention zone (PRZ; Fitzgerald and Gleadow, 1990). Sample suites with steep or elevation-invariant ages are interpreted as the rapid exhumation of samples that cooled quickly through the partial retention zone (PRZ; Fitzgerald and Gleadow, 1990). Sample suites with steep age-elevation gradients at lower elevations and shallow age-elevation gradients at higher elevations are inferred to record lesser amounts of total exhumation, for a given thermochronometer, with partial preservation of the PRZ. In such cases, the onset of exhumation is marked by the time of change in slope from a shallow to steep elevation gradient (Fitzgerald and Gleadow, 1990). In all cases of simple cooling histories driven by tectonic or erosional exhumation, thermochronometric ages in vertical transects are predicted to increase monotonically with higher elevation (Fitzgerald and Gleadow, 1990).

We observe aspects of all of these expected behaviors in the vertical transects from the Arkansas River valley; however, there are also some notable deviations from these expectations. In the UAR valley, the WBP transect records elevation invariant ages below ~3200 m (Fig. 4A), indicating rapid cooling ca. 70–60 Ma. The uppermost sample in this transect yields a cooling age that is significantly older than the rest of the transect samples (ca. 260 Ma), implying that the change from Paleozoic ages to Cretaceous–Paleocene ages records the location of the base of the PRZ and places a limit on the amount of exhumation in this region to ~3 km in the Cenozoic.

The GM, WH, and BTM transects also exhibit rapid exhumation ca. 60 Ma. None of these transects preserve older ages at higher elevations (Figs. 4 and 5), suggesting that these transects may have undergone greater total exhumation than the WBP transect, which is farther to the north. Samples at higher elevations in the WH and BTM transects display anomalous behavior, which we discuss in the following.

In the Texas Creek transects (TCBR and FPG), samples collected below ~2600 m display cooling from ca. 135 Ma to ca. 60 Ma at a rate slower than that observed in transects to the west (Fig. 4E). These transects do not display a change in exhumation rate as a function of time or depth, suggesting that they may reflect a fossil PRZ. In addition, the fact that the Echo Canyon (EC) gravel samples show varying ages from the Proterozoic and Paleozoic as well as the mid-Cenozoic (Table DR1) indicates that the samples in the east were never buried deeply enough, after the Cretaceous, to reset the AHe ages. Thus, the eastern part of the LAR valley appears to have undergone less exhumation in comparison to the rocks included in the transects from the western end of the LAR valley.

**Spatial Patterns of Low-Temperature Thermochronometric Data**

In general, the AHe data reveal older ages at the east end of the LAR valley (ca. 135 Ma to ca. 60 Ma) and younger ages to the west (ca. 65 to ca. 40 Ma; Table 1; Figs. 3C and 5). The boundary between the older and younger age domains is approximately located west of Texas Creek (transects TCBR and FPG) and east of Burned Timber Mountain (BTM transect), in the vicinity of Coaldale (Fig. 3C). This spatial pattern of AHe ages is also notable in the vertical relationships of these transects. We discuss these vertical relationships and the hypothesis that there was differential exhumation in the LAR valley during Laramide tectonism, with greater exhumation taking place toward the western end of the LAR valley.

**Vertical Patterns in Low-Temperature Thermochronometric Transects**

In contrast to a fairly clear-cut overall spatial pattern in the AHe ages, vertical age patterns in the individual transects suggest a more complex and nuanced thermal history. Vertical transects are often interpreted to reflect the cooling history of rocks, with the slope of sample data in age-elevation space being proportional to the exhumation rate (Fitzgerald and Gleadow, 1990). Sample suites with steep or elevation-invariant ages are interpreted as the rapid exhumation of samples that cooled quickly through the partial retention zone (PRZ; Fitzgerald and Gleadow, 1990). Sample suites with steep age-elevation gradients at lower elevations and shallow age-elevation gradients at higher elevations are inferred to record lesser amounts of total exhumation, for a given thermochronometer, with partial preservation of the PRZ. In such cases, the onset of exhumation is marked by the time of change in slope from a shallow to steep elevation gradient (Fitzgerald and Gleadow, 1990). In all cases of simple cooling histories driven by tectonic or erosional exhumation, thermochronometric ages in vertical transects are predicted to increase monotonically with higher elevation (Fitzgerald and Gleadow, 1990).

**Whitehorn Granodiorite Emplacement and Tilting Summary**

Based on the paleomagnetic data presented here, which show that analyses from the Whitehorn Granodiorite are not statistically distinguishable from expected directions for the latest Cretaceous time, it is unlikely that tilting occurred southwest of the Front Range in the LAR valley. Given the location of the Whitehorn Granodiorite and immediately surrounding Proterozoic rocks, gentle tilting to the east may be related to the development of the broad Sawatch anticline that developed during Laramide deformation or regional flexure associated with the Rio Grande rift. The sense of tilting is opposite that previously proposed for the Front Range (Naeser et al., 2002) and of magnitude small enough that it should not affect the interpretation of thermochronometric data collected along vertical transects.

**General Spatial Patterns of Thermochronometric Ages**

The paleomagnetic results here show that little tilting has affected the rocks in the LAR valley. In addition, the base of the Wall Mountain Tuff, which is preserved across the LAR region and as much as 130 km east at Castle Rock (just south of Denver), has a regional tilt of <1°. Therefore, we conclude that our sampling transects, with a possible exception for transects west of the Mosquito Range ridgeline (discussed in detail in the following), approximate true vertical profiles and that their respective vertical spatial relationships reflect paleodepth relationships.

**Spatial Patterns of Low-Temperature Thermochronometric Data Along the Arkansas River**

In general, the AHe data reveal older ages at the east end of the LAR valley (ca. 135 Ma to ca. 60 Ma) and younger ages to the west (ca. 65 to ca. 40 Ma; Table 1; Figs. 3C and 5). The boundary between the older and younger age domains is approximately located west of Texas Creek (transects TCBR and FPG) and east of Burned Timber Mountain (BTM transect), in the vicinity of Coaldale (Fig. 3C). This spatial pattern of AHe ages is also notable in the vertical relationships of these transects. We discuss these vertical relationships and the hypothesis that there was differential exhumation in the LAR valley during Laramide tectonism, with greater exhumation taking place toward the western end of the LAR valley.

**Younging of Apatite Helium Ages Below and Adjacent to Igneous Rocks**

At elevations above ~2600 m in multiple transects (WH, BTM, TCBR) we observe that thermochronometric ages no longer monotonically...
increase, but are instead younger than the samples below them (Table 1; Figs. 4 and 5), and in some cases (e.g., BTM) are younger than all other samples in the vertical transect. These highest elevation ages range from ca. 50 to 28 Ma in the WH and BTM samples, while the highest elevation sample in the TCBR transect is ca. 100 Ma (35 m.y. younger than a sample <120 m below it). This inflection in the age-elevation relationship is inconsistent with simple tectonic or erosional exhumation, and requires further exploration.

**EVALUATION AND INTERPRETATION OF LOW-TEMPERATURE THERMOCHEMOMETRIC DATA**

To further refine the thermal histories recorded by our low-temperature thermochronometry data, we wish to understand the age inversion seen in many of our vertical transects and to decide how samples or transects displaying this behavior should be interpreted. Notably, transects that display this age inversion were collected beneath or adjacent to thick exposures of mid-Cenozoic ignimbrites (Fig. 11).

Circulation of hydrothermal fluids has been proposed to partially reset low-temperature thermochronometers to depths of at least several hundred meters (Arne et al., 1990; Foster et al., 1994; Gallagher, 1998; Whipp and Ehlers, 2007; Hickey et al., 2014; Ault et al., 2016), and large-volume ignimbrites are observed to generate short-lived (tens to thousands of years), high-temperature (200–500 °C) hydrothermal systems (Gazis et al., 1996; Holt and Taylor, 1998; Keating, 2005). To assess whether hydrothermal circulation may have been a factor in partially resetting AHe samples collected directly below or adjacent to the nonconformity and overlying ignimbrites, we combine clumped isotope analyses of Paleozoic carbonate rocks (both adjacent to and distal from the ignimbrites) with thermal modeling to evaluate if the temperatures and isotopic signatures they record can be linked to hydrothermal fluid circulation.

**Application of Clumped Isotope Thermometry to Assess Paleohydrothermal Fluid Circulation**

Clumped isotope analysis is a tool that can be used to determine the temperature of formation waters, diagenetic temperatures, metamorphic conditions that range from some combination of original near-surface temperature fluids, the hydrothermal fluid signature should be manifested as diagenetic alteration of carbonate rocks from the LAR valley. Thus, sampling and analysis of carbonate rocks proximal to our AHe sampling transects can potentially quantify the thermal and diagenetic conditions undergone by these rocks.

Carbonate clumped isotope analysis uses the tendency of heavier oxygen and carbon isotopes (16O and 13C) to clump together within the same carbonate molecule at lower temperatures (Schäuble et al., 2006). This method offers a way of measuring carbonate formation temperature without additional assumptions, thereby making possible calculation of the isotopic composition of precipitating waters. Geologically ancient fine-grained carbonates are unlikely to preserve clumped isotope temperatures indicative of original Earth surface conditions (Winkelstern and Lohmann, 2016). Instead, such samples may preserve clumped isotope conditions that range from some combination of original near-surface conditions and temperatures at depth (arising from shallow diagenesis), to extensive resetting by solid-state reordering at temperatures above ~150 °C, to complete recrystallization at a range of burial depths (Passey and Henkes, 2012; Winkelstern and Lohmann, 2016).

Experimental data show that solid-state reordering of carbonate bonds only occurs at temperatures >~150 °C and that the clumped isotope composition preserved in a given sample is a function of both temperature and time (Passey and Henkes, 2012; Stolper and Eiler, 2015). Essentially, the carbonate Δ 47 value of a given rock will equilibrate with ambient conditions more quickly if temperatures are higher. Thus a carbonate rock, if slowly cooled over millions of years, will continually reequilibrate to a final temperature near the ~150 °C blocking threshold, below which the bonds can no longer reorder. Alternatively, the rock can be rapidly cooled to a temperature below 150 °C, in which case the clumped isotope temperature recorded will be hot (at or near the peak burial or heating temperature of the sample; Passey and Henkes, 2012; Henkes et al., 2014; Lloyd et al., 2017). Fundamentally, as soon as solid-state reordering has resulted in a carbonate clumped isotope temperature in excess of the ~150 °C blocking temperature, solid-state reordering during cooling cannot yield a clumped isotope temperature lower than ~150 °C without subsequent recrystallization or diagenetic alteration (cf. Lloyd et al., 2017). We present clumped isotope data from carbonate rocks in the LAR region, including from the contact metamorphic aureole of the Cretaceous Whitehorse Granodiorite. We demonstrate that the clumped isotope Δ 47 values preserved in the contact aureole are cooler than independently determined peak metamorphic temperatures, requiring a postmetamorphic diagenetic alteration of the carbonate samples in post-Cretaceous time.

**Stable Isotope Methods and Analysis**

We analyzed bulk micritic limestone samples from Mississippian carbonates in the LAR region. These samples were taken from localities near several of our vertical transects (Fig. 3). Two samples were collected from the Mississippian Williams Canyon Limestone near the easternmost extent of the Arkansas River gorge and Cañon City (MOX-02 and MOX-03 near the FMT AHe transect; Fig. 3C; Table 3; Table DR7). An additional sample was collected in the Mississippian Leadville Limestone at the base of the Whitehorn Granodiorite east of Salida (14BB-04; Fig. 3; Table 3; Table DR7). Two samples were collected from the Leadville Limestone on West Buffalo Peak (overlying the WBP transect; Fig. 3B; Table 3; Table DR7).

Our analytical methods follow those described in Defliese et al. (2015). Three ~5 mg subsamples of each carbonate sample were measured for their conventional and clumped stable isotopic composition. Following reaction with 75 °C phosphoric acid, evolved CO 2 was cryogenically purified and passed through Porapak resin held at ~10 °C (instead of the colder temperature used by Defliese et al. 2015; see Petersen et al., 2016). The clumped isotope acid fractionation factor and ±75 °C acid temperature calibration of Defliese et al. (2015) were applied to all data. Final clumped isotope measurements are reported as Δ 47 values (Table 3) in the absolute reference frame of Dennis et al. (2011). Carbonate δ 18O and δ 13C values are measured concurrently with clumped isotope analyses. These data are reported relative to the Vienna Pee Dee belemnite (VPDB) standard and are interpreted using the calcite acid fractionation factor of Kim and O’Neil (1997). Calculated δ 18O water values employ the revised calcite-water fractionation factor of Friedman and O’Neil (1977) and are reported relative to Vienna standard mean ocean water (VSMOW).

**Clumped Isotope Δ 47 Temperatures and δ 18O Water Values**

All samples record clumped isotope temperatures in excess of 65 °C (Table 3) and therefore no longer record surface conditions and have been diagenetically altered. The three western samples (BB-04, WBP-03, and WBP-02; Fig. 3) record temperatures in excess of 100 °C (Table 3), significantly warmer than the ~70 °C temperatures recorded by the samples from the east end of the valley (MOX-02 and MOX-03; Fig. 3; Table 3). Calculated water δ 18O values for the fluids from which these carbonates formed also differ substantially. Western samples precipitated from ~3‰ more positive waters than those in the east.
Salida-Waugh Mountain Tuff (36.6 Ma)

Late-Eocene to Oligocene volcanic deposits
(excludes Wall Mtn Tuff)

Mioocene volcanic deposits

AHe ages inconsistent with vertical trends

AHe samples that fit our data quality criteria

Clumped isotope samples with $\Delta_47$ temperatures > 100 °C

Clumped isotope samples with $\Delta_47$ temperatures < 80 °C

High-angle reverse fault

Paleovalley

No Data

Transects with fast exhumation from ~80-60 Ma (Fig. 15)

Transects showing no significant exhumation after ~120 Ma (Fig. 15)

Wall Mountain Tuff (36.6 Ma)

Late-Eocene to Oligocene volcanic deposits
(excludes Wall Mtn Tuff)

Miocene volcanic deposits

Whitehorn Granodiorite

Paleozoic carbonate rocks

Arkansas River

Salida

Buena Vista

East side

West side

Colorado Springs

Cañon City

Gribbles Run

Palisade

Paleovalley

No Data

Figure 11. Prospective ArcGIS Earth view with 3x exaggerated topography. Late Eocene to early Miocene ignimbrites are draped over topography (red—Wall Mountain Tuff, orange—Oligocene, yellow—Miocene). Dashed white lines indicate paleovalleys proposed to have existed prior to ignimbrite deposition (Chapin and Lowell, 1979). On the basis of differential exhumation recorded by the low-temperature thermochronometry and the clumped isotope signatures we propose an east-west boundary in the LAR valley, marked by dotted white line with high-angle reverse fault symbols, we propose that the Salida–Waugh Mountain paleovalleys do not extend as far west as previously mapped and that another paleovalley from Salida to Coaldale may have existed (marked by the white dashed line with question marks) where ignimbrite deposits are still preserved at modern river level. AHe—apatite helium; WH—Whitehorn; TCBR—Texas Creek–Bull Ridge; FPG—Five Point Gulch; BTM—Burned Timber Mountain; GM—Green Mountain.
Constraints on Late-Stage Hydrothermal Circulation from Clumped Isotope Temperatures and δ¹⁸O Values

The clumped isotope temperatures from our samples are all below the ~150 °C blocking threshold, indicating that the samples have either (1) never equilibrated to temperatures in excess of 150 °C, or (2) equilibrated in the past to temperatures above 150 °C but were subsequently altered via dissolution and recrystallization, thereby erasing previous diagenetic or metamorphic temperatures. However, the differences in both clumped isotope Δ⁴⁷ values and calculated water δ¹⁸O values (Table 3; Fig. 12) between the eastern and western samples imply possible different thermal histories, particularly because the sample suite is collected from carbonate rocks of roughly the same age, with presumably similar initial Δ⁴⁷ values. We interpret the clumped isotope temperatures in light of our thermochronometric data and other independent geologic evidence to resolve the genesis of the observed clumped isotope variability.

**Eastern carbonate samples.** The elevated temperatures recorded by samples collected near Cañon City (~70 °C) are consistent with alteration under shallow burial conditions and are consistent with observations from other fine-grained carbonate rocks (e.g., Quade et al., 2013; Winkelman and Lohmann, 2016). Calculated water δ¹⁸O values of ~+7‰ (relative to VSMOW) are also consistent with waters that have partially equilibrated with surrounding rock (e.g., Clayton et al., 1966; Sousa et al., 2016), likely indicating that some recrystallization of these samples has occurred. Together these results are broadly what one would expect for clumped isotope alteration of geologically ancient rocks that have never undergone deep burial or complete solid-state reordering. Their current Δ⁴⁷ and water δ¹⁸O values likely reflect diagenetic background conditions, i.e., the result of partial recrystallization at a range of depths, potentially along with minor solid-state alteration (without reaching equilibrium).

**Western carbonate samples.** The temperatures recorded by all three of the western samples are significantly warmer than the eastern samples, although all are still distinctly lower than the blocking temperature (~150 °C) for calcite (Table 3). We can further divide discussion of the western samples into northern and southern samples. The southern samples, typified by sample BB-04, we collected in close proximity (tens of meters) to the intrusive contact of the Whitehorn Granodiorite. Sedimentary rocks in the contact metamorphic aureole of the Whitehorn Granodiorite are inferred to have undergone peak metamorphic temperatures of ~600 °C (Wofford, 1986). This observation, combined with our ⁴⁰Ar/³⁹Ar biotite, hornblende, and K-feldspar data, as well as our ZHe data, imply that the Whitehorn Granodiorite and its associated metamorphic aureole cooled rapidly (from ~600 °C to ambient temperatures of <200 °C in ~2 m.y.). Such a cooling history should preserve clumped isotope Δ⁴⁷ temperatures at or near peak metamorphic conditions (Passey and Henkes 2012; Lloyd et al., 2017). Therefore, the relatively cold temperatures from BB-04 (~50 °C below the blocking temperature for solid-state reordering of clumped isotope bonds) necessitate postmetamorphic alteration or recrystallization to overprint the metamorphic clumped isotope temperature. The more positive water δ¹⁸O values involved in precipitating this carbonate, relative to the eastern samples, are also consistent with more extensive recrystallization via waters equilibrated with (isotopically heavy) rock δ¹⁸O.

The carbonate samples collected farther north from West Buffalo Peak also exhibit Δ⁴⁷ temperatures of ~100 °C and heavy water δ¹⁸O values, but were collected from an area devoid of post-Mississippian intrusions. There is also no evidence that these samples were ever deeply buried, as AHe sample WBP-02 (collected from Pretrozoic basement rock that underlies the carbonate samples) has individual grain ages as old as Late Mississippian (Table DR1), suggesting that regional burial has not attained temperatures hot enough to reset AHe ages (~60 °C) since the late Paleozoic. We would therefore expect the northern carbonate samples to reflect roughly the same background diagenetic temperatures as the eastern samples. However, the elevated Δ⁴⁷ temperatures and heavier oxygen isotope values of precipitating waters indicate alteration under conditions similar to those of sample BB-04 (Fig. 12).

From these observations, we infer that carbonate samples in the western LAR region record a late-stage (post-Cretaceous Whitehorn Granodiorite emplacement) clumped isotope signal that overprints earlier values. From the similarity of clumped isotope temperatures recorded by all the western samples, we infer that the present-day signal was post-Cretaceous.
AHe ages arising from the emplacement of hot ignimbrites (~750 °C) on AHe ages recorded in a given sample. Thus, taking these data into account we infer that hydrothermal systems in the upper hundreds of meters of Proterozoic basement were driven during emplacement and cooling of the ignimbrite sheets (Fig. 13), partially resetting the AHe ages in samples adjacent to the ignimbrite base (Figs. 11 and 14). Therefore, the data from these samples cannot be used for interpretations related to cooling from exhumation.

Selection of Low-Temperature Thermochronometric Data for Thermal Modeling

To extract thermal histories related to the tectonic evolution in our study area, it is critical to identify samples from our data set that have thermochronometric ages that may reflect heating associated with the hydrothermal processes described here. The clumped carbonate thermometry data (Table 3; Fig. 12), age inversions observed in our vertical transects (Figs. 4 and 5; Table 1), and numerical modeling of pulse heating events (Fig. 13) raise concerns that samples collected in proximity to the regionally extensive ignimbrite deposits (Chapin et al., 2004; McIntosh and Chapin, 2004) may have been subject to resetting by hydrothermal fluid circulation, as proposed here.

We first note that there are two AHe transects where we observe no evidence of anomalous behavior or potential resetting. Samples from the Green Mountain (GM) and West Buffalo Peak (WBP) transects (Figs. 4 and 5) both display typical age-elevation relationships, and are spatially removed from the confined paleovalleys that appear to have captured much of the deposition of ignimbrites in the western part of our study area (although the view in Fig. 11 seems to display a close proximity between the base of the GM transect and the ignimbrite deposits in the UAR valley north of Salida, they are in fact separated by nearly 2 km; Epis et al., 1976; Chapin and Lowell, 1979). In the case of the WBP transect, hydrothermal fluid circulation appears to have altered clumped isotope temperatures in late Paleozoic carbonate rocks overlying this transect. However, given the late Paleozoic AHe age for the highest elevation sample in the WBP transect (older than 260 Ma; Table 1; Fig. 4), either such fluids did not penetrate into the Proterozoic igneous rock in this region, or they had minimal effect on the thermochronometric ages (Fig. 14). In either case, the potential effects on the highest elevation sample in this transect, if any, will not alter the thermal modeling of the Late Cretaceous to recent thermal history.

Each of the other transects, however, show an indication of hydrothermal resetting, as evidenced by an age inversion pattern, with relatively younger ages observed in the closest proximity to the regional Eocene erosion surface, blanketed by late Eocene to early Miocene ignimbrites (Fig. 11). To exclude the potential biasing of our thermal models by hydrothermally mediated reheating, we exclude the results from the highest elevation samples of these transects.

In addition to concerns about samples in close proximity to the erosion surface and ignimbrite base, we are also wary of samples collected along the walls of regional paleovalleys (Fig. 11; Chapin and Lowell, 1979), which are currently filled by hundreds of meters of ignimbrite deposits. Samples collected along the flanks of these paleovalleys, particularly the samples to the north and south of the preserved ignimbrite valley fill in the Salida–Wauh Mountain paleovalley (Fig. 11; McIntosh and Chapin, 2004), also appear to have been subjected to hydrothermal resetting, based on their position relative to ignimbrite deposition and the inverse age-elevation relationship that they preserve. Thus, samples collected along paleovalley walls should also be excluded from thermal modeling. These criteria potentially exclude a number of samples collected along the north side of the Arkansas River between Salida and Coaldale, where remnants of ignimbrite deposits mantle the canyon wall from summit to river level.

Effects of Short-Lived, Top-Down Heating and Hydrothermal Circulation

The effect of advective heat transport by topography-driven fluid flow has been found to modify the crustal thermal field (Whipp and Ehlers, 2007). In such scenarios, ages from low-temperature thermochronometers could be biased toward younger cooling ages by being reset or partially reset by the influx of heat from circulating fluids rather than by conductive cooling arising from exhumation. In the models of Whipp and Ehlers (2007), fluid circulation was driven by significant topographic relief, and transported heat that was advected toward the surface by rapid exhumation in an active orogenic belt. Near-surface hydrothermal circulation, however, can also be established by other processes. Volcanic eruptive centers and large-volume ignimbrites can both generate short-lived (10 yr to 10 k.y.) hydrothermal systems, with temperatures from 70 to 150 °C, depending on local meteoric water temperatures (Keith, 1991; Keith et al., 1992; Gazis et al., 1996; Holt and Taylor, 1998; Keating, 2005). Even short-lived modest temperature perturbations can alter low-temperature thermochronometers and partially, or completely, reset AHe ages (Hickey et al., 2014; Ault et al., 2016).

Late Eocene to early Miocene volcanism and ignimbrite emplacement are prevalent, and voluminous, throughout the Mosquito Range and the LAR (Eps and Chapin, 1975; Gregory and McIntosh, 1996), and these eruptive products are deposited on highly dissected and fractured Proterozoic basement rocks, which may form copious pathways for fluid penetration and circulation. Such hydrothermal systems have previously been invoked to explain regional mineralization and, to a lesser extent, local remagnetization (e.g., DeVoto, 1990; Geissman and Harlan, 2002).

We explore the impact of potential hydrothermal fluid circulation on AHe ages arising from the emplacement of hot ignimbrites (~750 °C) on cold (~7 °C; modern mean annual surface temperature at Salida) basement rock. We employ a forward thermal model, implemented in QTQt (version 6R54.4.6; Gallagher, 2012), to explore the effects of short-lived thermal pulses on AHe ages. The thermal models initiate with instantaneous cooling from temperatures >200 °C to 0 °C at 100 Ma, which establishes a baseline thermochronometric age of 100 Ma. This cooling is followed by thermal perturbations beginning at 35.6 Ma of varying duration (10–100 yr) and magnitude (40 to 200 °C), after which the AHe age is recalculated. The results of these experiments (Fig. 13) show that short-lived (100 °C) thermal pulses >100 °C could measurably reset the AHe ages recorded in a given sample. Thus, taking these data into account we infer that hydrothermal systems in the upper hundreds of meters of Proterozoic basement were driven during emplacement and cooling of the
AFT data (Kelley and Chapin, 2004) to extract Cretaceous to present thermal histories. We describe the results in the following, with a focus first on the two transects that display no data quality issues or hydrothermal resetting signatures (WBP and GM), and compare these models to those derived from the complex thermochronometric data sets that characterize the remaining transects.

QTQt Thermal Modeling

Thermal modeling was undertaken in QTQt Macintosh version 64R5.4.6 (Gallagher, 2012). One advantage of this software is the ability to simultaneously solve for the thermal histories of multiple samples collected along a vertical transect. Model inputs include raw age information, grain size, and concentrations of He, U, Th, and Sm. In all model runs we implemented the Flowers et al. (2009) model for radiation damage in apatite and no radiation damage model for zircon. Model parameters that we define include the present-day surface temperature of 7 °C ± 3 °C (mean annual surface temperature at Salida), and a 30 °C/km geothermal gradient (a reasonable estimate for continental regions that are tectonically active but not undergoing igneous activity or extension; Bryant and Naeser, 1980; and similar to the present-day mean geothermal gradient for the southern Rockies; Nathenson and Guffanti, 1988). Models were run with a burn-in of 20,000 iterations then sampled over 80,000 iterations with a thinning of 1.

Thermal Modeling Results and Summary

Two transects from the westernmost part of our study area (WBP and GM) do not show evidence of the hydrothermal resetting signature in samples from other transects (Figs. 3–5; Table 1), and are spatially removed from the emplacement of ignimbrites. Ages along these two transects display expected age-elevation relationships, and we assume that the thermal histories derived from these samples will be the most representative of the tectonic exhumation of the region. Inverse thermal modeling of data from these two transects reveals rapid cooling from ca. 80 to 60 Ma (Fig. 15). After this rapid exhumation event both regions remained at near-surface temperatures from the Paleocene to the present (Fig. 15), recording no younger thermal perturbations.

The preservation of Paleozoic ages at the highest elevations in transect WBP and the existence of partially reset ZHe ages at the base of transect GM reflect differential exhumation from north to south along the western
flank of the Mosquito Range. Transect WBP records cooling since ca. 80 Ma from temperatures as high as ~100 °C, while transect GM records cooling from temperatures in excess of 160 °C over the same time period. For a 30 °C/km geothermal gradient, this implies a southward increase in the depth of exhumation from ~3 km at WBP to ~5 km at GM.

The above interpretation assumes that the present-day vertical relationships in the GM transect reflect paleodepth relationships. Previously we discussed evidence that supports this assumption; however, others have proposed that the southern Mosquito Range–Arkansas Hills may have undergone tilting or step faulting related to Rio Grande rift extension (Chapin and Lowell, 1979; Keller and Baldrige, 1999; McIntosh and Chapin, 2004; Kelley, 2012). Such deformation could decrease the paleodepth range sampled along the GM transect. However, basement contacts are not mapped as offset by faults (Van Alstine and Cox, 1969; Wallace et al., 1997; Wallace and Lawson, 2008), and although we cannot definitively rule out regional folding and/or tilting, both AHe and ZHe data from the second-lowest elevation sample on the GM transect (GM-04) indicate the need for exhumation from depths >4 km from ca. 80–60 Ma, regardless of the spatial relationship to other samples within the transect (Fig. DR6). Thus, both the interpretation of differential exhumation between the eastern and western LAR valley and the timing of that exhumation are not dependent on the assumption of a vertical sample transect. If paleodepth relationships along the transect are not preserved, then our preferred interpretation overestimates the magnitude of differential exhumation by ~1 km (Fig. 15; Fig. DR6).

The other western LAR transects (WH and BTM) are below or in close proximity to the thickest volcanic deposits and deepest paleovalleys. As a result, many of the samples in these two transects have been omitted from inverse thermal modeling based on the likelihood that they were affected by hydrothermal fluid circulation. Thermal modeling for these two transects, therefore, only includes unaffected samples. The Whitehorn model contains AHe and ZHe from 14BB-03, and the BTM model incorporates our AHe data as well as AFT data from six nearby samples reported by Kelley and Chapin (2004; Figs. 3 and 5). To include the AFT data in the thermal models generated by QTQt, we performed a resampling of the published track count data to generate synthetic spontaneous and induced track length data with statistics that match the reported data. The WH and BTM transects reveal thermal histories similar to those observed at WBP and GM, with rapid cooling from ca. 80 to 60 Ma (Fig. 15). Both the WH and BTM transects were exhumed from temperatures of at least ~120–150 °C, implying between 4 and 5 km of Laramide-age exhumation.

Modeling the easternmost transects (TCBR and FPG) together, we observe that all of the samples in these vertical transects were near the surface (above the PRZ) from at least ca. 120 Ma to the present (Fig. 15). Because these samples all resided below the closure temperature of the AHe system (~70 °C) we have limited resolution on the thermal histories of these samples. However, it appears that these samples have undergone <2 km of exhumation (and perhaps <1 km in some cases) since the Late Cretaceous.

All thermal models, except for those from the easternmost transects, show that the most likely thermal history for these transects involves rapid exhumation between ca. 80 and 60 Ma. Along the western reach of the LAR, 3 transects record 4–6 km of exhumation over this time interval. The magnitude of exhumation appears to diminish northward toward West Buffalo Peak, where Laramide-age exhumation is limited to no more than ~3 km. In contrast, the eastern samples show <2 km of exhumation. Together the thermal models imply ~2–5 km of differential exhumation from ca. 80 to 60 Ma between the western and eastern parts of the LAR region.

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Figure 14. Summary of clumped isotope results, thermochronometry data (T is temperature), and geologic relationships seen in three regions from the study area. East-west boundary shown in upper right box separates regions in the east (C) recording pre-Laramide apatite helium (AHe) and apatite fission track (AFT) ages as well as a background diagenesis signal in the clumped isotopes from western regions (in A and B), which record thermochronometry ages related to the Laramide orogeny and clumped isotope temperatures and δ⁸O signatures indicative of hydrothermal fluid alteration. (A) The region near West Buffalo Peak (WBP) in the upper Arkansas River valley (UAR). (B) The Whitehorn Granodiorite transect in the western lower Arkansas River valley (LAR). (C) The eastern LAR, west of Cañon City.
TECTONIC AND TOPOGRAPHIC EVOLUTION OF THE LOWER ARKANSAS RIVER VALLEY

We discuss the implications that our new low-temperature thermochronometry data set has for improving our quantitative understanding of the timing and magnitude of exhumation related to Laramide tectonism beginning in the latest Cretaceous. We are also able to examine the formation of the Eocene erosion surface and the general paleotopography of the southern Rocky Mountains prior to mid-Cenozoic ignimbrite deposition and their relation to Laramide tectonism.

Laramide Tectonism in the Lower Arkansas River Valley

Low-temperature thermochronometers provide a way to assess exhumation magnitudes and rates through the upper crust and also have the ability to quantify differential exhumation, which may reflect structural offsets that are not recorded by obvious structural or stratigraphic piercing points. Such differential exhumation is observed along the LAR where the magnitude and rate of crustal cooling differ significantly between the eastern and western parts of the valley (Figs. 3, 4, 11, and 15). Three transects in the southern part of the western LAR (GM, WH, and BTM) show rapid cooling from 80 to 60 Ma from peak temperatures of ~130 to ~180 °C to temperatures <~60 °C (Fig. 15). For an assumed geothermal gradient of ~30 °C/km, this equates to exhumation from depths of 4–6 km. The northernmost transect in the western LAR (WBP) shows similar timing and rates of exhumation, but from a lower initial temperature (~100 °C), reflecting a smaller total magnitude of exhumation (~3 km).

In contrast, the eastern LAR valley transects (TCBR, FPG) show no rapid cooling during the latest Cretaceous to early Cenozoic (Fig. 15). AFT ages from this region are principally older than Early Cretaceous (Figs. 3 and 4), indicating that the samples were cooled below the AFT closure temperature before Laramide deformation. Thermal modeling of the AHe ages from the eastern part of the valley defines a cooling history from <60 °C ca. 120 Ma to present-day surface temperatures, which is equivalent to <1 to no more than 2 km of exhumation throughout the Cenozoic (Fig. 15). The magnitude of exhumation inferred from the AHe thermal models is consistent with the lack of burial indicated by carbonate clumped isotope temperatures measured in this region. Thus, the magnitude of differential exhumation between the eastern and western parts of the LAR valley is at least 2 to possibly 5 km.

We can further constrain the magnitude of differential exhumation between the eastern and western transects by using our geochronologic and thermochronologic data to refine estimates of the emplacement depth of the Whitehorn Granodiorite. Thermal models for the WH transect permit cooling from peak temperatures >150 °C. Such temperatures are potentially compatible with a range of proposed geobarometry estimates for the Cretaceous Whitehorn Granodiorite, which vary from ~3.7 kbar (indicating ~10 km of overlying rock; Workman, 1997) to ~1.4 kbar (indicating ~4 km of overlying rock; Wofford, 1986). The closure temperature of existing K-Ar ages on the Whitehorn Granodiorite does not constrain the emplacement depth (or temperature) of the pluton, because these results could be interpreted as either emplacement or cooling ages. Our zircon U-Th-Pb dates from the Whitehorn Granodiorite record a mean age of ca. 67 Ma (Table DR5; Fig. 8), which is unambiguously interpreted as the timing of emplacement. In combination with our new 40Ar/39Ar ages from the Whitehorn Granodiorite, which are indistinguishable from the zircon U-Th-Pb ages, we can infer that the 40Ar/39Ar ages also represent the timing of emplacement, and imply that this emplacement occurred at ambient temperatures below the closure temperature of K-feldspar (~190–350 °C; Table 2; Figs. 6 and 7). This inference is supported by our ZHe ages.

Figure 15. Inverse thermal models run in QTQt version 64R5.4.6 (Gallagher, 2012). Pathways indicate the best-fit thermal history for each transect or set of transects as a whole (only modeled samples fitting data quality criteria and unmodified by hydrothermal fluids). All the thermal histories except for the Texas Creek group show rapid exhumation from temperatures >80 °C occurring between ca. 80 and 60 Ma. The West Buffalo Peak (WBP) model has data adding information to the thermal histories (older AHe samples) so the model can make predictions farther back in time (inset at top). AHe—apatite helium; ZHe—zircon helium; AFT—apatite fission track; elev.—elevation.
from Proterozoic basement samples collected adjacent to the pluton that record a cooling age of ca. 83 Ma, older than the emplacement age of the Whitehorn Granodiorite (Table 1; Table DR1; Fig. 14). This suggests that prior to pluton emplacement, the Proterozoic host rock was cooler than the ZHe closure temperature (150–180 °C) or at ~5–6 km depth. Thus, our thermochronometric data are consistent with geobarometric pressures closer to the lower end of previously proposed values (e.g., Wofford, 1986). These data also appear to define an upper limit to the peak exhumation temperatures of the WH transects to not be significantly greater than 180 °C, and imply that maximum depths of exhumation are likely in the 5–6 km range. Therefore, our preferred estimate of the magnitude of differential exhumation between the eastern and western transects is between ~3 and 5 km. Such a magnitude of differential exhumation over a relatively short lateral distance is indicative of structural displacement between the western and eastern regions, and should be accommodated by reverse faulting. Identifying a discrete structure on which this deformation was accommodated is hampered by the lack of preserved exposures of overlying Phanerozoic strata in the LAR valley and the difficulty of tracing structures through crystalline basement rock (Brady et al., 2000), but we hypothesize that the structure is somewhere east of transect BTM (Fig. 11).

The timing of exhumation in the western region indicates that this differential exhumation was accommodated by displacement along reverse faults active during Laramide shortening (Fig. 16). Data from the AHe transects and the spatial distribution of ignimbrite filled paleovalleys (Fig. 11) imply that the structures responsible for this differential exhumation are located near the longitude of Coaldale (Fig. 11). West of Coaldale, rapid Cretaceous exhumation is observed in all thermochronometry transects, and mid-Cenozoic ignimbrites are primarily confined to narrow paleovalleys. East of Coaldale, AHe data show minimal Cretaceous exhumation and mid-Cenozoic ignimbrites are distributed broadly across the presumed Eocene erosion surface.

In combination, these data suggest differential uplift of the western LAR region relative to the east, with the magnitude of this differential uplift dissipating northward (Figs. 14 and 15). Such a pattern of deformation is consistent with the south to north transfer of strain between known Laramide structural systems. South of the LAR, east-directed, Laramide-aged high-angle reverse faults bound both the Wet Mountains and northern Sangre de Cristo Range (Lindsey et al., 1984; Jacob and Albertus, 1985; Bedford, 1994; Lindsey, 2010; Rasmussen, 2016). Conversely, to the north of the LAR valley, Laramide-aged deformation is accommodated on the west-directed Elkhorn and Elk-Sawatch thrust systems (Bryant, 1966; Bryant and Naeser, 1980; Bedford, 1994). The structural link between these two systems has long been a topic of debate (e.g., Bedford, 1994) and the transfer or linking is suggested to be in the vicinity of the LAR (Bedford, 1994). We propose that the west-side-up differential exhumation observed in the LAR (Fig. 11) is a continuation of the well-defined east-directed thrust systems to the south in the Sangre de Cristo Mountains, and that this deformation dies out to the north of West Buffalo Peak as strain is transferred to the west-directed Elkhorn and Elk-Sawatch thrust systems. Our interpretation is consistent with the observed structural style in the region arising from Laramide tectonism and provides a new solution to the question of fault linkage between Laramide structures in the Sangre de Cristo Mountains and the Front Range.

Formation of Late Eocene Erosion Surface

There are many low-relief surfaces documented throughout the southern Rocky Mountains that have been assigned an Eocene age (Eips and Chapin, 1974; Eips and Chapin, 1975; Gregory and Chase, 1994; Chapin and Kelley, 1997; Leonard, 2002; McMillan et al., 2002, 2006; Landman and Flowers, 2013). These surfaces often are lumped together as one large surface throughout the entire southern Rockies, i.e., the late Eocene erosion surface (Eips and Chapin, 1974, 1975). However, debate is ongoing regarding the synchrony and mechanistic similarity in the development of these surfaces (Gregory and Chase, 1994; Leonard, 2002; McMillan et al., 2002, 2006). In the LAR region, mid-Cenozoic ignimbrites blanket and preserve an erosion surface of low to moderate relief (e.g., Eips and Chapin, 1974). The combination of this ignimbrite cover and our new low-temperature thermochronometry data afford an opportunity to estimate the timing and duration of this paleosurface formation.

Development of the distinctive paleotopography preserved in and near the LAR valley appears to have a nonsynchronous evolution. Our low-temperature thermochronometry data imply rapid erosion from ca. 80 to 60 Ma (Fig. 15) in the western LAR valley and little contemporaneous erosion in the eastern part. The distribution and geometry of the western LAR volcanic deposits define a surface of moderate local relief (hundreds of meters) established by the incision of numerous paleovalleys (Chapin and Lowell, 1979). Modeling of our thermochronometry data requires the removal of several kilometers of rock in the western LAR since the time of emplacement of the Whitehorn Granodiorite (ca. 67 Ma). However, these models also place many of the higher elevation samples from the western LAR below the AHe closure temperature (60 °C or even cooler; ~30 °C or less) by ca. 60 Ma (Fig. 15), thus minimizing additional exhumation after that time. These constraints, combined with the modest paleorelief preserved in the paleovalleys, suggest that the simplest explanation for the timing of formation of the preserved paleolandscape is coeval with cessation of rapid exhumation. Because there is minimal exhumation after ca. 60 Ma, we infer that landscape evolution slowed following Laramide deformation and the western surface largely stabilized for ~20 m.y., until the inception of ignimbrite deposition and surface preservation ca. 37 Ma. Thus, the western paleosurface is a preserved remnant of the late Eocene, post-Laramide landscape.

The erosion surface across the eastern LAR, however, does not have a thermochronometric record of significant exhumation in the past 120 m.y., and may in fact record the evolution of a much older, more slowly evolving surface that is also preserved by mid-Cenozoic ignimbrite deposition. The evolution of this surface is less well determined with the available thermochronometric data, due to the minimal exhumation in Cretaceous and Cenozoic time. Mesozoic strata are deposited on Proterozoic basement throughout much of the eastern LAR, and the magnitude of exhumation implied by our thermochronometric data is consistent with the removal of these strata (Taylor, 1975). Thus, one plausible interpretation of the eastern LAR erosion surface is that it reoccupies the pre-Mesozoic depositional surface, a paleolandscape presumably the age of the Ancestral Rockies. Stripping of this Mesozoic cover during the Laramide orogeny would be consistent with stratigraphic records of Late Cretaceous to Paleocene erosion recorded both north and south of the LAR (Johnson, 1959; Cole et al., 2010). Although localized post-Laramide deformation can be seen in the form of extensional graben formation (i.e., Echo Park Canyon; Fig. 2), the thermochronometric data from the eastern LAR valley suggest these phases of deformation had minimal extent and did not amount to major landscape evolution during the Eocene. The differences in the rates of formation and erosional magnitudes represented by the western and eastern LAR erosion surfaces suggest that they may in fact be two separate surfaces, characterized by different timing and rates of formation, as well as possible different formation mechanisms.

The question arises as to how this composite paleosurface was preserved between the cessation of Laramide tectonism and the inception of late Eocene to Oligocene ignimbrite eruptions. Debate about the formation of planation surfaces, whether such low-relief surfaces can be long lived and
Early Cenozoic evolution in the southern Rocky Mountains, Colorado

Figure 16. Schematic representation of lower Arkansas River (LAR) valley evolution from the Late Cretaceous to present. Time moves forward from top to bottom. AHe—apatite helium. (A) The region is covered by the interior seaway (light blue) until ca. 72 Ma and has already undergone Ancestral Rockies deformation seen in the Paleozoic deposits while the Mesozoic sediments are still flat lying. PRZ—partial retention zone. (B) Middle of the Laramide orogeny. The Cretaceous Whitehorn Granodiorite has been emplaced and major erosion begins to strip off the overlying sediments with large amounts of exhumation occurring in the western half of the LAR valley while only minimal amounts are recorded in the east. (C) By the end of Laramide deformation significant erosion has taken place, forming most of the Eocene erosion surface and incising many paleovalleys in the western LAR valley. (D) Ignimbrites blanket the surface in large eruptive events from ca. 36 to 29 Ma (Thirtynine Mile volcanic field) and continue with smaller events until ca. 20 Ma. Although not extremely thick (a few hundred meters at most), high temperatures from these deposits and the existing topography drive hydrothermal fluid circulation causing resetting and alteration of the samples nearby (red dots). (E) General present-day setting showing that a small amount of regional erosion occurs post mid-Cenozoic volcanism while the major erosion is taken up by the Arkansas River, which cuts >1 km down into the basement rock.
how they might remain low relief over long time periods, is not new or unique to the Rockies (Jolivet et al., 2007; Landis et al., 2008). A recent hypothesis for the long-term stabilization of a paleosurface in an active mountain range has been proposed for the southern Sierra Nevada, USA, where a low-relief surface is argued to have been maintained for more than 20 m.y. (Sousa et al., 2016). This preservation is attributed to a perpetual, but thin, layer of sediment being continually deposited on and stripped off the erosion surface, armoring it and preventing erosion of the underlying paleosurface topography (Sousa et al., 2016). A similar mechanism may have played a role in stabilizing the Laramide topography of the LAR region, as supported by exposures of thin Eocene to Oligocene fluvial deposits found in the South Park basin just north of the Arkansas Hills (Ruleman and Bohannon, 2008; Kirkham et al., 2006), and even preserved between ignimbrites as fluvial conglomerates in the LAR region (Hon, 1984).

The excellent preservation of the regional paleosurface beneath the mid-Cenozoic ignimbrites, as well as the present-day distribution of these ignimbrites, suggests minimal landscape evolution since Oligocene time (Fig. 11). The two major topographic features that appear to disrupt the erosion surface and overlying volcanic rocks are the Rio Grande rift valley north of Salida and the >1 km incision of the modern LAR canyon between Salida and Cañon City. Remarkably, deposits and eruptive products related to the mid-Cenozoic volcanic rocks that overlie the Eocene erosion surface are also exposed as remnants on the walls of the Arkansas River canyon down to present-day river level between Salida and Coaldale (Fig. 11). The east-west orientation of this segment of the Arkansas River, along with the presence of ignimbrite valley fill, are characteristics that it shares in common with many other preserved paleosurfaces in other regions of the world, including the mid-Cenozoic volcanic rocks of the western United States and the mid-Cenozoic volcanic rocks of the western United States.

In summary, the late Eocene topography in the eastern LAR valley, as preserved by the mid-Cenozoic volcanic rocks, shows the signature of a low- to moderate-relief erosion surface, similar to those documented in other parts of the southern Rockies. The western Eocene surface is characterized by numerous paleovalleys of not insignificant relief and most likely developed rapidly near the end of the Laramide orogeny, ca. 60 Ma in this area, and was preserved by ignimbrite deposition beginning ca. 37 Ma. The eastern low-relief surface may have developed over a much longer period of time, or may even have been inherited from an earlier history of landscape development. The late Eocene erosion surface of the LAR valley thus appears to be two possibly distinct paleosurfaces that formed at different times and rates, and suggests that the many late Eocene erosion surfaces found within the Rocky Mountains could have different evolutionary histories in terms of both formation mechanisms and timing. The only major landscape development that has occurred from the mid-Cenozoic to present in the LAR valley region is the >1 km of modern river incision, which may have been accelerated by a combination of re-incising a paleovalley through headward erosion from east to west and stream capture aided by Rio Grande rifting to the west.

CONCLUSIONS

New geochronologic, thermochronometric, and stable isotope data from the Mosquito Range, Arkansas Hills, and lower Arkansas River valley in the southern Colorado Rocky Mountains provide further clarification on timing of exhumation and paleotopography development in a complex region of the Rocky Mountains. The thermochronometric data we present here suggest that Laramide orogenic deformation was the main driver of rapid exhumation in the LAR valley by the early Cenozoic (ca. 60 Ma). Throughout the rest of the Cenozoic, the LAR valley underwent only small perturbations of burial and re-exhumation that are not recorded in our low-temperature thermochronometric data. There is a significant difference between the exhumation histories of the west part of the LAR compared to the east part. Based on our AHe data and the AFT data of Kelley and Chapin (2004), we estimate that the amount of exhumation could not have been more than ~1–2 km in the eastern segment of the LAR (east of Coaldale). Considering the AHe, ZHe, and 40Ar/39Ar presented here, along with geobarometry estimates from the Whitehorn Granodiorite (Wofford, 1986), we estimate that ~5–6 km of exhumation occurred in the western segment. Thus, we estimate that ~3–5 km of differential exhumation between the east and west of the LAR valley occurred during the Laramide orogeny.

This east-west differentiation is also seen in the paleotopographic surface preserved beneath mid-Cenozoic ignimbrite deposits. Moderate relief, in the form of east-flowing paleovalleys, characterizes the western part of the LAR, while the eastern part displays much lower relief topography. We infer that rapid topographic evolution of the western paleosurface took place near the end of the Laramide, driven by rapid uplift and exhumation, and formation of the eastern paleosurface may have been an older, more slowly and more completely evolving topographic surface.

The conclusions here are drawn from complex low-temperature thermochronometric data sets. However, by comparing samples and transects that have not undergone complex thermal perturbations, and by comparing transects in both older (Proterozoic) and younger (Cretaceous) rocks, we can disentangle the series of events and complex heating histories that may have affected our samples, and develop an approach to extract meaningful thermal histories. The LAR valley reveals this kind of complex system. Mid-Cenozoic ignimbrites perfectly preserve paleotopography, yet they also caused significant thermal modification of near-surface rocks, and Proterozoic basement rocks yield poorly reproducible samples that likely reflect radiation damage and protracted cooling histories. Our findings that ignimbrites act as a heat source for fluids circulating in the near-surface crust (particularly below the erosion surface and adjacent to the paleovalleys), resulting in resetting of AHe ages, builds on several studies concerned with the potential impact of top-down heating on recorded thermochronometric ages. The incorporation of clumped isotopic analyses in our study reveals its potential as a tool to test for such an effect, and to then identify and omit from further analysis data from possibly altered samples.

High-density vertical sampling for thermochronometric data was critical for unraveling the tectonic history of the LAR, and such an approach may be necessary in other regions of complex thermal histories. From 7 different transects in the LAR valley, spanning ~80 km distance, we identify multiple thermal histories, which record information on rapid exhumation, differential exhumation over relatively small spatial scales, and local near-surface thermal perturbations. These diverse thermal signatures would most likely not have been revealed with a sparse sampling strategy.

Acknowledgments

Jesse Fenno and Forrest Gilfoy assisted in sample collection. Megan Hendrick and Amanda Maslyn assisted with sample processing and analysis. S. Nehring, S. Muggleton, and C. Porreca assisted with sampling of the Whitehorn Granodiorite for paleomagnetic study, and Nehring and Muggleton assisted with laboratory measurements. This work was partially supported by National Science Foundation grant EAR-1151247 (Niemi), as well as a GSA Student Research Award, a Rackham graduate student research grant, and a Turner Award from the Department of Earth and Environmental Sciences at the University of Michigan (Abbey).
APPENDIX 1. SAMPLE PREPARATION AND ANALYSIS

Apatite (U-Th-Sm)/He and Zircon (U-Th)/He

Samples were crushed and sieved to small (<300 μm) size fractions, followed by water density separation (2 g/l paraffin oil) to remove any light minerals and lighter fractions of 4 single crystals. The grains were removed with the use of a Frantz magnetic separator and apatite was separated using the high-density liquid lithium metatungstate (LMT) (2.8 g/mL). Using a Leica MZ61 stereo zoom microscope, at least 3 inclusion free apatite grains, >80 μm in length and width along a-axis, with little to no shadowing were picked for each sample (note that in this process grains were difficult to find, so many grains of apatite had 1 or 2 terminations). Individual grains were prepared in Pt tubes for He extraction, which was conducted at the University of Michigan’s thermochronometry lab using an Alphachron Helium Instrument. Each grain underwent extraction through heating to 900 °C for 5 min using a diode laser with tempera-
tures monitored via a 4-color optical pyrometer. A second heating step under the same con-
ditions was conducted to make sure all the He released from the grain. In this process we spike the Alphachron with an internal He standard for measuring (He) ratios on a Pfeiffer quadrupole mass spectrometer. Durango apatite age standards were run with each batch of unbroken grains to ensure age measurement accuracy.

\[ \text{Ar}/\text{Ar} \]

Minerals were separated by standard heavy liquid, magnetic, and hand-picking tech-
niques. Separates were loaded into a machined Al disk and irradiated for 6 h in L67 position at the Ford Reactor, University of Michigan. Field Canyon Tuff sanidine (FC-1) with an assigned age of 28.8 ± 0.2 Ma (Samson and Alexander, 1987), was used as a neutron flux monitor. Samples were step heated in a Mo resistance furnace with heating times of 10 min for biotite and hornblende analyses and 5–235 min for K-feldspars. Electron multiplier sensitivity averaged 1.9 × 10−16 mol/μA and J-factors were determined to a precision of ±0.1% by CO2 laser fusion of 4 single crystals (along c-axis), with little to no discoloring were picked for each sample (note that unbroken grains were difficult to find, so many grains of apatite had 1 or 2 terminations). Individual grains were prepared in Pt tubes for He extraction, which was conducted at the University of Michigan’s thermochronometry lab using an Alphachron Helium Instrument. Each grain underwent extraction through heating to 900 °C for 5 min using a diode laser with tempera-
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MANUSCRIPT RECEIVED 20 APRIL 2017
REVISED MANUSCRIPT RECEIVED 27 SEPTEMBER 2017
MANUSCRIPT ACCEPTED 15 NOVEMBER 2017