

Examining Spatial Patterns of Exhumation in Colorado's Elk Mountains During the Late Miocene Using Apatite (U-Th)/He Thermochronology

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Abstract

Spatial patterns of the magnitude and rate of exhumation occurring during the late Miocene are examined using Apatite (U-Th)/He (AHe) Thermochronology. AHe date-elevation data collected from the Whiterock pluton in the southwest Elk Range suggests that roughly 1 km of rock cooled through the Helium partial retention zone (HePRZ) from 13-8 Ma. The Whiterock AHe data is consistent with previous AHe thermochronology from the Elk Mountains, and suggests that the Elks experienced continuous exhumation from 15-7 Ma. Exhumation rates in the Elk Range are compared to the surrounding region in order to get a spatially integrated sense of the magnitude and rate of erosion in west-central Colorado from the late Miocene to the Present.



Figure 1. Looking north from the summit of White Rock Mountain towards the Maroon Bells.

1. Introduction

1.1 Evolution of the Colorado Rocky Mountains

Colorado's Rocky Mountains encompass some of the highest elevations in the contiguous United States. The southern Rockies make up a lithospheric "welt" of high topography that is centered around western Colorado. Unlike other orogens such as the Andes and Himalaya, the present-day southern Rocky Mountains are a composite range that cannot be explained by a single tectonic process. A significant portion of the southern Rocky Mountain structure was obtained during the Laramide Orogeny (~70 Ma), with Colorado's Front Range being a classic example of a Laramide age uplift. It is generally agreed that sometime after the Laramide Orogeny the mantle beneath Colorado became buoyant. Anomalously low-density mantle underlying Colorado's Rocky Mountains is responsible for the 1-2 km of relief that separate the region from the adjacent Great Plains and Colorado Plateau (Sheehan et al, 1995; Lee and Grand, 1996). However, the timing and mechanism responsible for mantle de-densification remains contested. Some argue for the onset of surface uplift caused by low density mantle sometime in the Eocene/Oligocene, while others evoke more recent uplift during the Miocene/Pliocene. Regardless of the exact timing of epeirogenic processes, the enigmatic geologic evolution of the Colorado Rocky Mountains during the late Cenozoic undoubtedly shaped the dramatic landscape we observe today.

1.2 Significance of the Elk Mountains

The Elk Mountains located in west-central Colorado share a similar enigmatic history as the broader region. The peaks and valleys of the Elk Range are separated by as much as 1200 m

indicating that erosional processes have played a significant role in the geomorphic evolution of the Elk Mountains. Several competing hypotheses exist with regards to the timing and processes that shaped the Elk Range in the late Miocene. Some workers argue that a pronounced transition to a cooler climate occurring 3-5 Ma increased the frequency of storms, and caused the onset of rapid exhumation in the Colorado Rockies (eg. Molnar and England, 1995). Others claim that the integration of the Colorado River basin around 6 Ma led to rapid incision in its headwaters including the Elk Range sometime thereafter (Pederson et al., 2002). Finally, some evoke upward normal stress due to mantle convection as the cause of surface uplift in western Colorado during the late Miocene (Karlstrom et al., 2012). These workers argue that mantle derived surface uplift was marked by the onset of rapid exhumation in west-central Colorado sometime between 8-10 Ma. While the timing and cause is debated, it is obvious that erosion played a key role in shaping the Elk Mountains during the Late Miocene. Thus, constraining the magnitude, rate and extent of exhumation in the Elks will provide valuable information required for a more complete understanding of the geologic evolution of western Colorado during the last 15 m.y..

1.3 Characterizing Exhumation Rates Using Thermochronology

The removal of rock by erosional or tectonic processes is isostatically compensated by the upward movement of rock through the crust (England and Molnar, 1990). As rock is brought to the surface by exhumation it undergoes cooling, which is recorded by temperature sensitive minerals called thermochronometers. When a thermochronometer becomes cool enough, it begins retaining the ratio of radiogenic daughter to parent isotopes produced in the mineral. Thus, it is possible to document the point in time when a mineral transitioned from an open to a closed system, which happens to be a function of its temperature. Characterizing the cooling

history of rocks using thermochronology can provide valuable information regarding the magnitude and rate of rock movement towards the surface. Exhumation by erosional processes is common in regions with high relief, making thermochronology a powerful tool when studying the geomorphic evolution of mountain ranges.

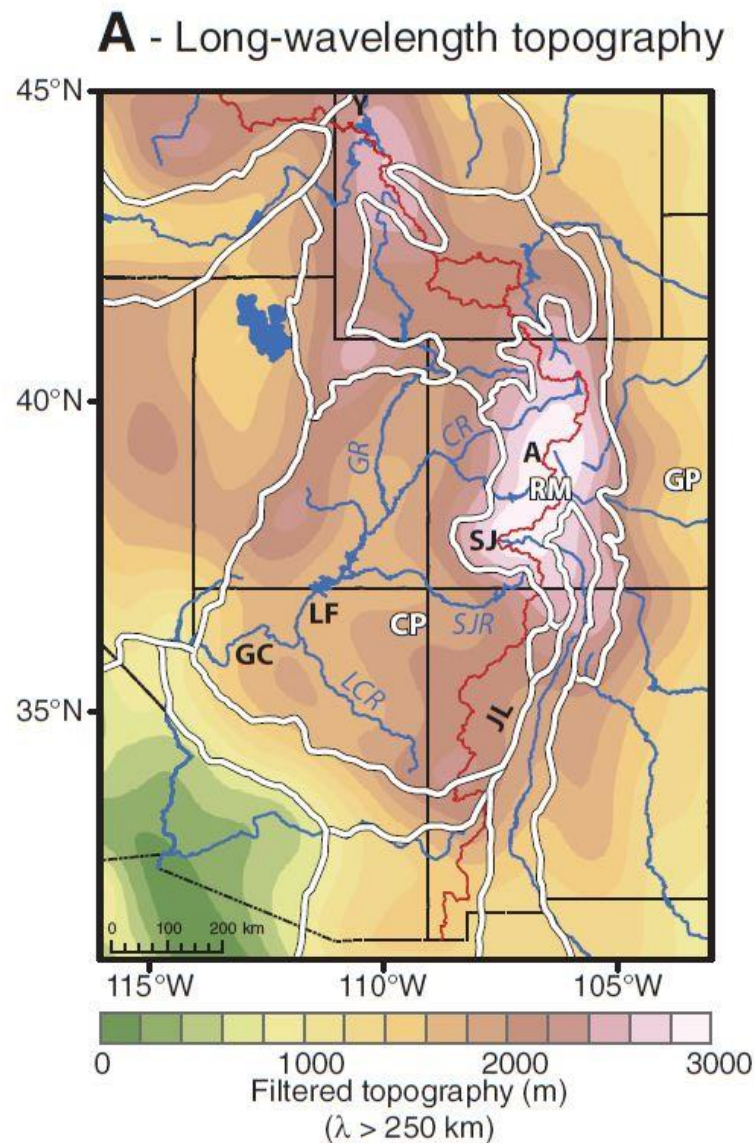


Figure 2. Long wavelength topography of the southern Rocky Mountain Region (RM). Modified from Karlstrom et al. 2012.

1.4 Previous Thermochronology in the Elk Mountains

Garcia (2011) examined the cooling histories of seven mid-Tertiary granitic plutons in the Elk and West Elk mountains using low temperature apatite fission track (AFT) and (U-Th)/He (AHe) thermochronometry. According to the AFT data, northern plutons (Sopris, Snowmass, Ragged and Capitol) record relatively slow cooling rates of ~ 75 m/m.y. immediately after emplacement. Garcia interprets the AHe data to show accelerated exhumation rates beginning ca 6-8 Ma which she attributes to surface uplift via dynamic topography. This uptick is not obvious, and in some transects may not exist at all due to erroneous elevation data. AFT and AHe data from the southern plutons (Gunnison and Beckwith) show rapid cooling immediately after emplacement, which likely reflects shallow emplacement depths into Cretaceous/Tertiary strata.

Hiatt (2017) used AHe thermochronology to constrain the cooling history of the Crystal pluton, located near the western edge of the Elk Range. The Crystal pluton was emplaced ca 12.4 Ma (Obradovich, 1969), and makes up the core of the Treasure Mountain (4123 m). Low temperature AHe data indicate rapid cooling through ~ 60 °C ca 10 Ma. Hiatt interprets rapid cooling to reflect exhumation by the Crystal River, and calculates a minimum exhumation rate of 218 m/m.y using overburden thickness estimates.

The purpose of this research project is to continue the study of exhumation in Colorado's Elk Mountains over the last 15 m.y. using low temperature AHe thermochronology. This will be done by collecting an AHe date- elevation profile from White Rock Mountain located in the south-central Elks. By comparing exhumation rates in the Elk Range to the surrounding regions we hope to get a spatially integrated sense of the extent and magnitude of exhumation in west-central Colorado that occurred during the late Miocene. An additional goal is to add to the

existing Elk Range AHe thermochronometry data set collected by Garcia (2011) and Hiett (2017).

2. Colorado's Elk Mountains: Geologic History and Regional Setting

2.1 Pre-Cenozoic

While the present-day landscape of the Colorado Rocky Mountains is largely a product of tectonic and magmatic processes that took place during the Cenozoic, understanding the “early” geologic evolution of the region is crucial when studying more recent geologic events.

Throughout the early and middle Paleozoic much of Colorado was covered by a shallow sea. This is recorded by an extensive marine sedimentary sequence that is present in south-central Colorado. Marine facies are mostly comprised of limestones, dolomites and some sandstones which span the Ordovician through Mississippian. The late Paleozoic was a period of significant tectonic change marked by the uplift of the Ancestral Rocky Mountains. The Ancestral Rockies were divided into two distinct uplifts, the ancestral Front Range to the northeast and the Uncomahgre Range to the southwest. As the Ancestral Rockies rose, synorogenic sediments were deposited in the lowlands between the two highlands, an area called the “Central Colorado Trough”. This thick clastic sedimentary sequence includes the Maroon Formation which can be as much as 1200 m thick, and makes up a significant portion of the high topography in the Elk Range (Gaskill et al., 1991).

The Mesozoic was characterized by a transition from terrestrial environments of the Triassic and Jurassic to marine environments of the Cretaceous. Terrestrial sedimentary units such as the Morrison and Entrada Formations indicate that the much of Colorado lay above sea

level during the first half of the Mesozoic. The transgression of the Western Interior Seaway into Colorado is marked by a distinct depositional transition to marine sediments. These include the Mancos Shale which has a maximum thickness of about 1300 m, and is widespread throughout much of the Elk Range. Deposition of the Mesa Verde Group; marine sandstone and shales during the late Cretaceous denotes the final transition from marine to terrestrial environments in Colorado, and provides an elevation datum for which to examine subsequent surface uplift.

2.2 The Laramide Orogeny

The early Cenozoic brought renewed tectonism to Colorado. Beginning in the latest Cretaceous and continuing through the early Paleogene (~70-50 Ma), much of western Colorado was affected by an enigmatic mountain building event known as the Laramide Orogeny. One peculiar aspect of the Laramide Orogeny is that it produced thick skinned deformation nearly 1000 km inland from a continental margin (Jones et al, 2011), which does not adhere to conventional tectonic models. Currently, the most widely accepted cause of the Laramide Orogeny is the subduction and subsequent shallowing of oceanic lithosphere beneath the North American Lithosphere. While the geometry of the shallowly subducting slab is contested (Jones et al, 2011; Bird, 1984; Liu et al, 2010), it is generally agreed that Laramide age deformation is the result of stresses imposed by shallow subduction. The Elk Mountains were deformed by Laramide age thrust faults, and represent some of the westernmost effects of the Laramide Orogeny in Colorado (Tully, 2009).

Sedimentation occurred during and after the Laramide Orogeny, which contributed to the filling of the Piceance Basin adjacent to the Elk Range. These sediments include the Ohio Creek conglomerate, Wasatch Formation, Green River Formation, and Uinta Formation (Heller et al.

2012). The thickness and extent of Paleocene/late Eocene sediments likely influenced the erosional history of plutons emplaced in the Elk and West Elk Mountains later in the Cenozoic.

2.3 Mid -Tertiary Magmatism

During the middle Tertiary, a large portion of the western U.S cordillera experienced prolonged magmatism/volcanism (Lipman, 2007). The Colorado Rocky Mountains are no exception, with numerous intermediate composition plutons being intruded into the upper crust from 38-24 Ma. The Mount Princeton Batholith in the Sawatch Range, Never Summer Mountains, and much of the Elk Range are but a few examples of mid-Tertiary magmatism in Colorado. Most workers agree that separation of shallowly subducting oceanic lithosphere from the North American lithosphere allowed upwelling asthenosphere to come in contact with relatively cool/hydrated North American Lithosphere (Humphreys, 2003). This contact would have likely induced partial melting of the North American Lithosphere.

2.4 Regional Geologic Setting

The Elk Mountains are characterized by isolated granitic peaks protruding through a thick Paleozoic/Mesozoic sedimentary cover. The transition to an erosional environment sometime after intense Oligocene magmatism incised the relatively soft sedimentary rock exposing more resistant granitic plutons. The Elk Range runs southeast from the town of Carbondale to Taylor Park. It is bounded by the Grand Hogback Monocline to the north, the Sawatch Monocline to the east, the Gunnison Uplift to the south and the West Elk Volcanic Field to the west. The thickest sedimentary units exposed in the Elk Range are the Pennsylvanian/Permian Maroon and Gothic

formations, as well as the Cretaceous Mancos Shale (Tully, 2009 ; Gaskill et al., 1991). The thick sedimentary cover is intruded by numerous granitic plutons that make up many of the high peaks in the Elk Range. Major plutons in the Elk Mountains can be separated into 3 general groups based on composition and emplacement age. These are: **1)** felsic porphyries near Aspen (73-65 Ma), **2)** relatively large, granodiorite plutons including Sopris, Capitol, Snowmass, and Whiterock (36-28 Ma), and **3)** isolated soda granites such as the Crystal pluton (17-12 Ma) (Obradovich, 1969; Garcia, 2011).



Figure 3. Paleozoic sedimentary roof pendant (background) contrasting the Whiterock granodiorite (foreground). Photo taken by Lon Abbott during the 2017 field campaign to White Rock Mountain.

Structurally, the most noticeable feature in the Elk Mountains is the Elk Range Thrust System, which is a series of Laramide age northwest striking, west vergent thrust faults that run from Redstone southeast of Crested Butte. Tully (2009) interprets the Elk Range Thrust System

as a “transitional deformation zone” between the high angle reverse faults bounding the Sawatch Monocline and fold shortening indicative of the Grand Hogback Monocline. In addition to its effect on regional deformation, The Elk Range Thrust System provided a significant structural control on mid-Tertiary pluton emplacement including Whiterock pluton.

2.5 Whiterock Pluton

The Whiterock Pluton encompasses roughly 100 km² in the southwestern Elk Mountains. It is made up of light and dark gray equigranular granodiorite, ranging from quartz monzonite to quartz diorite in composition (Thomas, 1972a). K/Ar dates provided by Obradovich (1969) suggest that Whiterock Pluton was emplaced 33.9 ± 1 Ma. Garcia (2011) used Ar/Ar biotite dating methods to constrain the emplacement ages of the nearby Snowmass and Capitol plutons at $33.89 \pm .13$ and $33.84 \pm .09$ Ma respectively. These are consistent with Obradovich’s dates for Whiterock Pluton emplacement. In addition, Whiterock pluton was intruded at the stratigraphic level of the Gothic formation, which makes up observable roof pendants throughout the region (fig3).

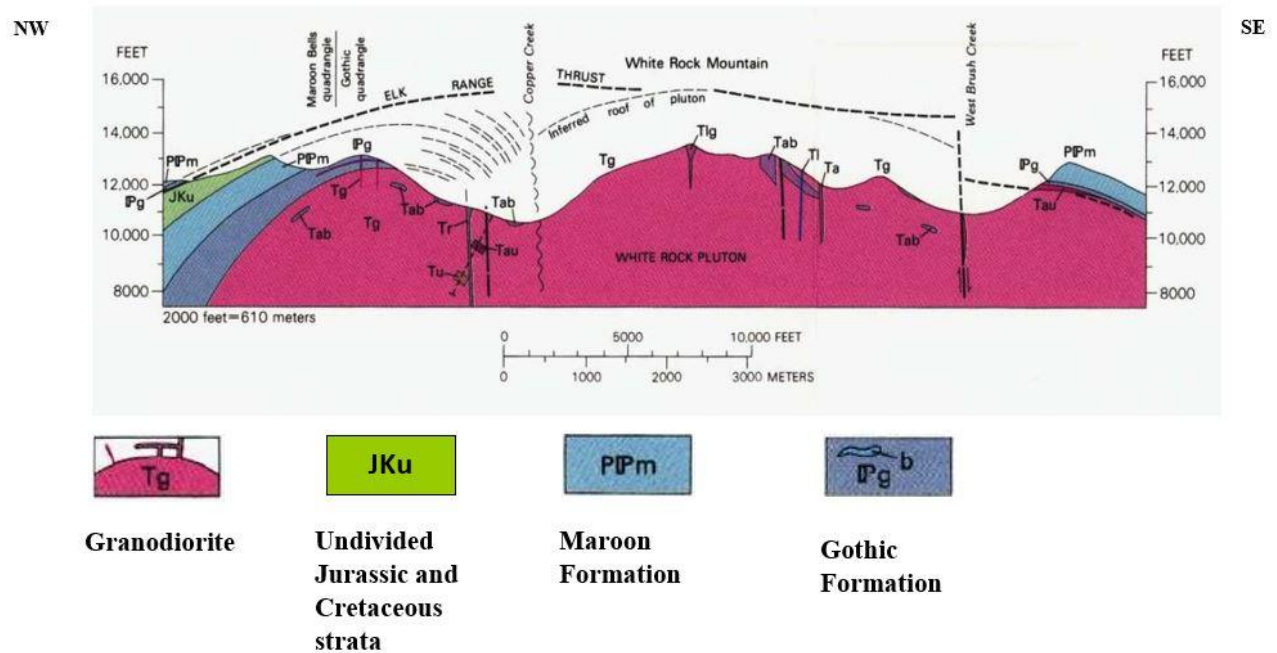


Figure 4. Geologic cross-section through White Rock Mountain. Modified from Gaskill et al., 1991.

3. Methods

3.1 Location / Sampling

White Rock Mountain is centrally located within the Whiterock Pluton. About 1200 m of vertical relief expose the pluton on the western flanks of White Rock Mountain, making it an ideal location to conduct a vertical sample transect. Seven samples were collected from in-situ outcrops at ~200 m intervals while descending from the summit via the southwest ridge and west face. The transect was collected with the intent of covering as much vertical relief as possible to optimize our ability to study the cooling history of Whiterock pluton. Samples were taken from fresh faces without evidence of significant weathering, faulting or alteration. In general, all samples are coarse grained granodiorites that lighten in color towards the summit of White Rock

Mountain. NM17-5 is noticeably greener in color than the rest of the samples, indicating that it may have undergone chlorite alteration. Garcia (2011) also noted possible chlorite alteration in some of her samples, especially those taken from Mt. Sopris.

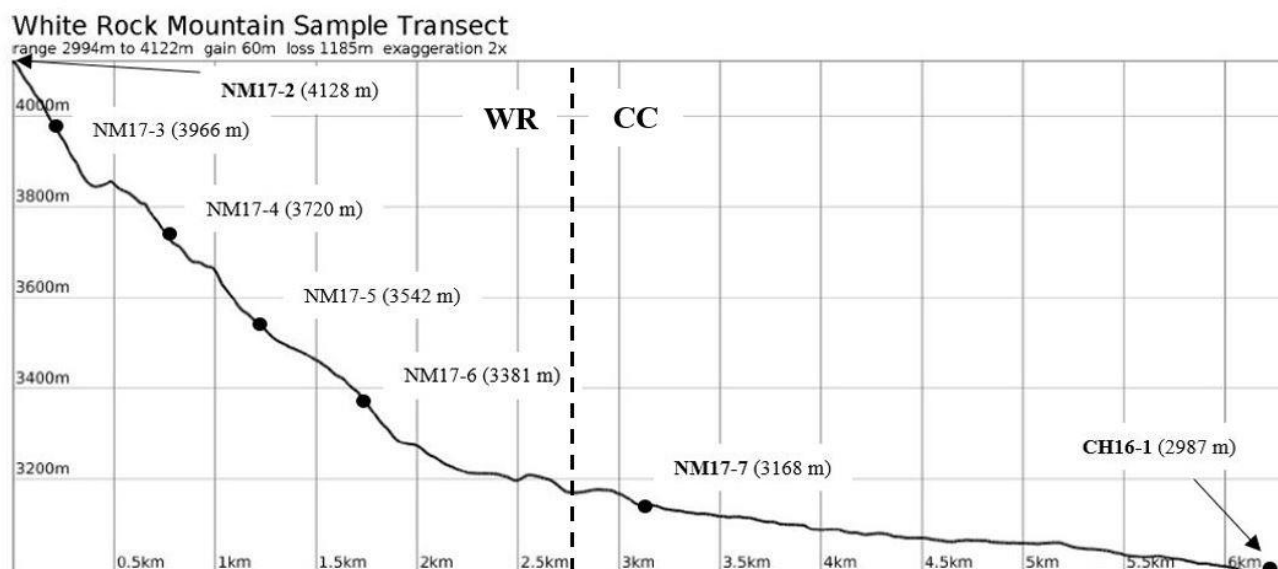
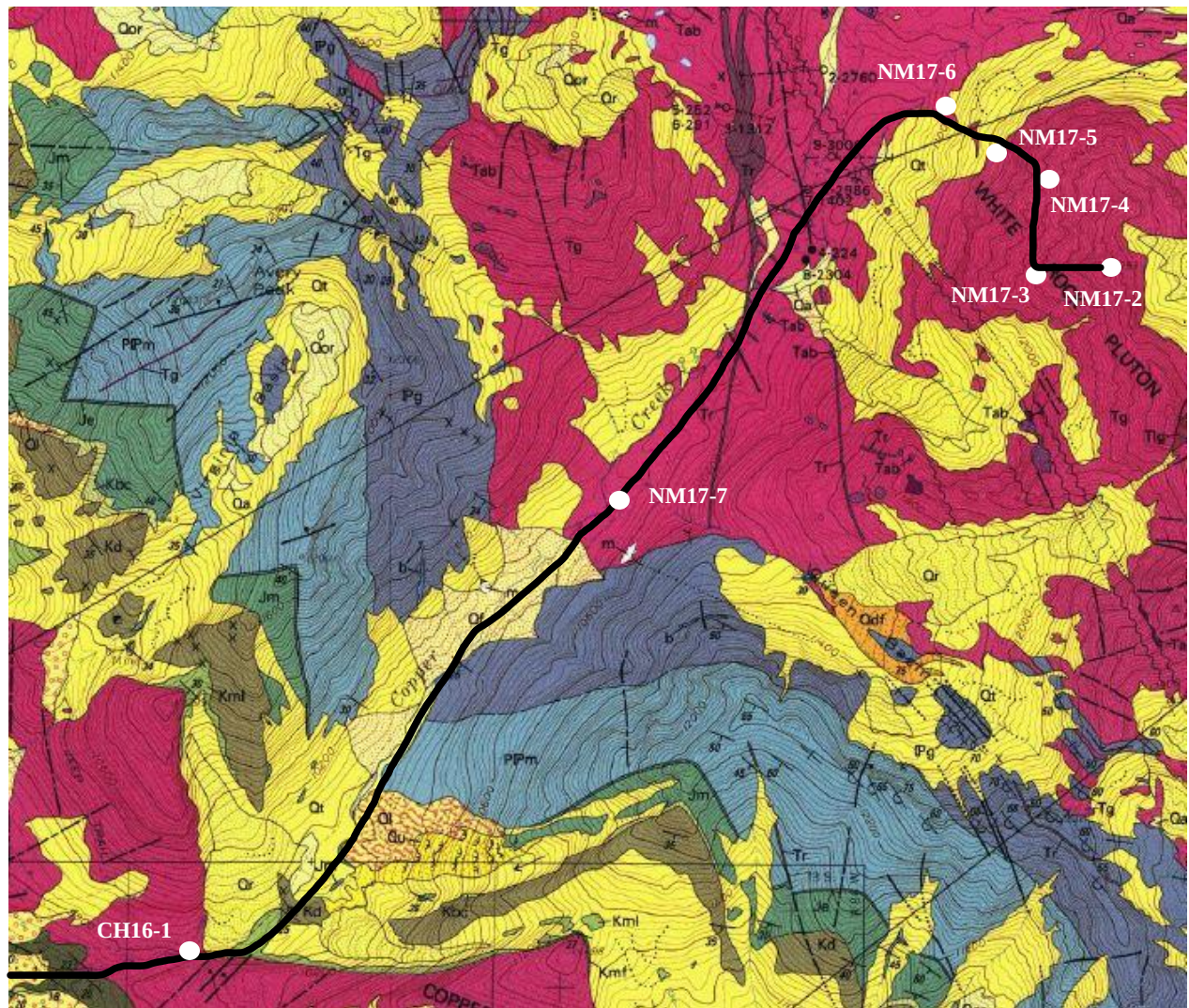


Figure 5. Elevation profile of the vertical sample transect taken from White Rock Mountain. Bold samples were processed for AHe date analyzation. Dashed line denotes the intersection of White Rock Mountain with the Copper Creek drainage.



— ~ 3 km

Figure 6. Geologic map of the Whiterock pluton overlain with the approximate location transect path and samples. Pink color represents the Oligocene granodiorite that makes up the Whiterock pluton. Modified from Gaskill et al., 1991.

3.2 Mineral Separation

Three samples were selected for mineral separation and analysis. NM17-2 was collected just below the summit of White Rock Mountain (4128 m), NM17-7 was collected in the Copper

Creek drainage (3168 m). CH16-1, the lowest elevation sample was collected from the Copper Creek Sill near Judd Falls (2987 m) the previous year, and is thought to be genetically related to the White Rock Pluton (Gaskill et al., 1991). While in the field, samples were broken into pieces that were the correct size for processing by a jaw crusher. The selected samples were crushed using a BICO jaw crusher and disk mill, then sieved to 500 microns. Next, the samples were passed over a Wilfly table in order to concentrate dense apatite grains. A hand magnet and two passes through the Frantz magnetic separator, at 35 and 60 Amps respectively, was used to remove magnetic minerals from the samples. The heavy liquid Lithium Metatungstate (LMT) was used to concentrate apatite grains into high enough quantities to be picked by hand.

3.3 AHe Dating

Apatite grains were analyzed at the University of Colorado Thermochronology Research and Instrumentation Laboratory (TRaIL). Grains were hand selected for analysis using a Leica M165 binocular microscope with a calibrated digital camera. Only large ($>60\text{ }\mu\text{m}$), high quality grains absent of inclusions or cracks were selected for analysis. Apatites from NM17-2 (4128 m) were relatively large ($>100\text{ }\mu\text{m}$), euhedral with well-preserved crystal faces. Grain color ranged from blue/green to purple/brown under polarized light. Apatites from NM17-7 (3168 m) were relatively large ($100\text{-}200\text{ }\mu\text{m}$), equidimensional and blue/green under polarized light. Overall, grains from NM17-7 are significantly less euhedral than NM17-2, and have minor surficial deformities. Unfortunately, CH16-1 did not yield any usable apatite grains.

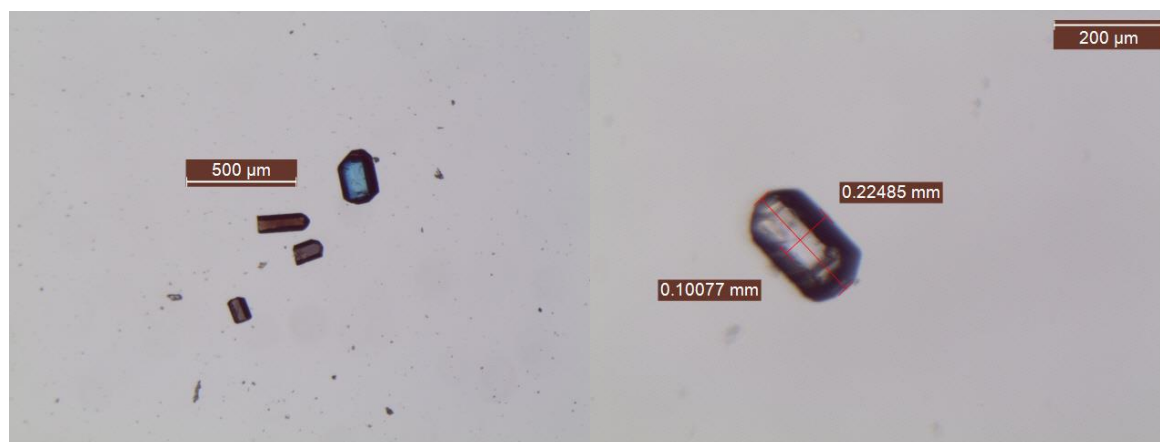


Figure 7. Left: Apatite grains from NM17-2 (4128 m). Note the euhedral grain geometry. Right: Apatite grain from NM17-7 (3168 m). Note the more rounded grain geometry.

Four grains from NM17-7, and five grains from NM17-2 were deemed suitable for AHe analysis. First, grain dimensions were measured using the calibrated digital camera. Each grain was then packed into a ~5mm Nb tube and crimped on each end to secure the grain. Radiogenic ^4He was measured in each of the packed grains using an ASI Alphachron He extraction and measurement line by heating the grain to a temperature range of ~800-1100 °C with a 50W diode laser under UHV conditions (3×10^{-8} torr) for 5-10 minutes. ^4He is spiked with ^3He , then purified via gettering methods and analyzed on a Balzers PrismaPlus QME 220 quadrupole mass spectrometer. This process was repeated at least once to ensure that all ^4He is degassed from the grain. Next, concentrations of U, Th and Sm were determined in each of the degassed apatite grains. This is completed by spiking each grain with ^{235}U , ^{230}Th and ^{145}Nd tracer, dissolving them in HNO_3 and heating the solution to 80 °C for two hours. Finally, a Thermo Element 2 magnetic sector ICP-MS analyzed each sample for U, Th and Sm concentrations. Durango Fluorapatites were used as a standard to ensure consistency from run to run. AHe dates were calculated from radiogenic ^4He , U, Th and Sm concentrations along with grain dimensions using methods described in Ketchum et al (2011).

4. Results

4.1 AHe Dating Results

Unreliable AHe dates were identified and rejected as follows. Low concentrations of ^4He , U, and Th can significantly reduce precision, thus dates were checked to have blank corrected concentrations that were at least five times higher than background values. Next, effective Uranium (eU) concentrations, which is a measurement of radiation damage experienced by the crystal were checked to be higher than 2ppm. eU values lower than 2 ppm increase the risk of possible ^4He diffusion from the surroundings into the crystal. eU concentrations for all grains in both samples ranged from 7-27 ppm. Grains that didn't degas ^4He fully in the first laser extraction ($\text{Re} < 99.9\%$) were excluded due to the possibility of inclusions or low diffusivity zones. During the U-Th decay process, ^4He atoms are ejected $\sim 20\text{ }\mu\text{m}$ from the parent atom, this is known as alpha ejection (Ehlers and Farley, 2009). In small grains, a significant amount of ^4He can be lost to alpha ejection. Thus, the alpha ejection correction (Ft) accounts for this ^4He loss. All grains possessed Ft values $>.55$ indicating alpha ejection was not a significant source of uncertainty in ^4He diffusion. Finally, dates that were older than the emplacement age of Whiterock pluton were excluded due the presence of inclusions with high U or Th concentrations which severely compromised the date. Of the nine grains analyzed two were omitted, one due to a date that was older than emplacement, and the other due to a Re value less than 99.9%. A complete table of AHe data, including grains that were excluded can be found in the appendix.

Four AHe dates from NM17-2 taken near the summit of White Rock Mountain (4128 m) range from 15.00 to 12.30 Ma. Three grains with dates of $13.10 \pm .22\text{ Ma}$, $12.58 \pm .33$ and $12.30 \pm .28\text{ Ma}$ agree within their respective uncertainties. The $15.00 \pm .24\text{ Ma}$ date doesn't agree

within uncertainty, yet the data provide no reason for omission. Three grains from NM17-7, taken in the Copper Creek drainage (3168 m) possess ages that range from $9.11 \pm .14$ to $6.23 \pm .11$ Ma. Although no dates from NM17-7 agree within their respective uncertainties, there is no evidence for omission based on criteria discussed in the previous paragraph.

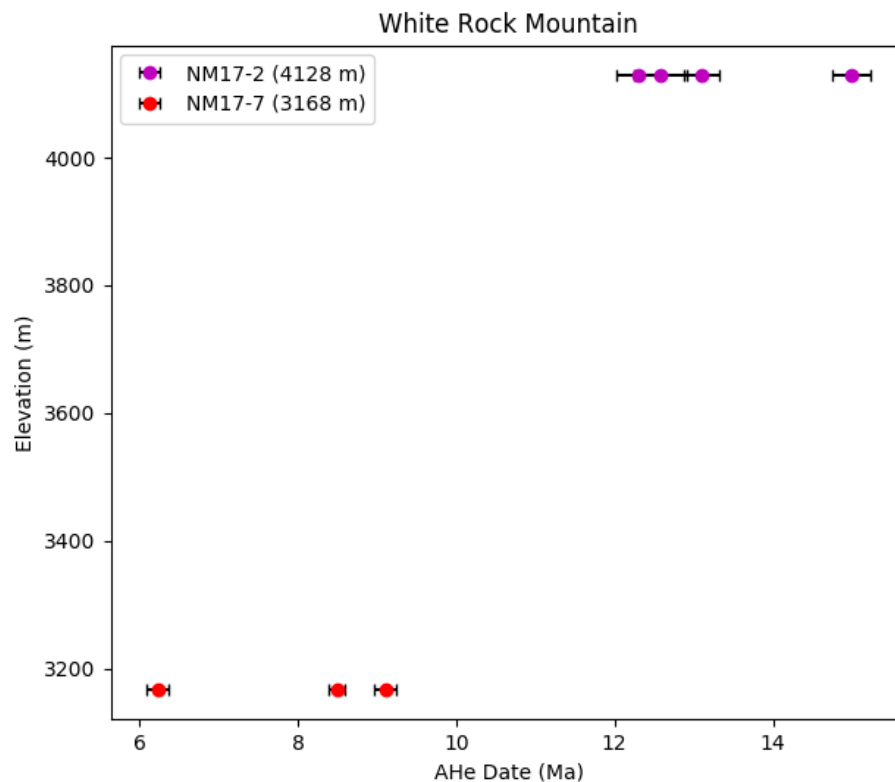


Figure 8. Individual grain AHe date-elevation data from the Whiterock Pluton. Data shown with direct analytical uncertainty.

4.2 Effective Uranium Observations

As U, Th and Sm undergo radioactive decay, apatite grains accumulate radiation damage. Effective Uranium (eU) quantifies radiation damage in a crystal, and is defined as $[U] + .235*[Th]$. (Flowers et al, 2007; Flowers et al 2009) In apatites, radiation damage increases the

closure temperature of a given grain. Thus, apatites with different U concentrations experience different amounts of radiation damage, and develop separate closure temperatures which yield unique dates. Correlations between AHe date and eU can be used as an additional constraint on cooling history. For example, grains that cool quickly through the helium partial retention zone (HePRZ) don't have time to accumulate much radiation damage, which results in similar closure temperatures that yield consistent AHe date regardless of eU (Flowers et al, 2009). Neither sample exhibits an AHe date-eU correlation (fig 9). The absence of date-eU correlation could reflect relatively quick cooling through the HePRZ and/or the small number of data points.

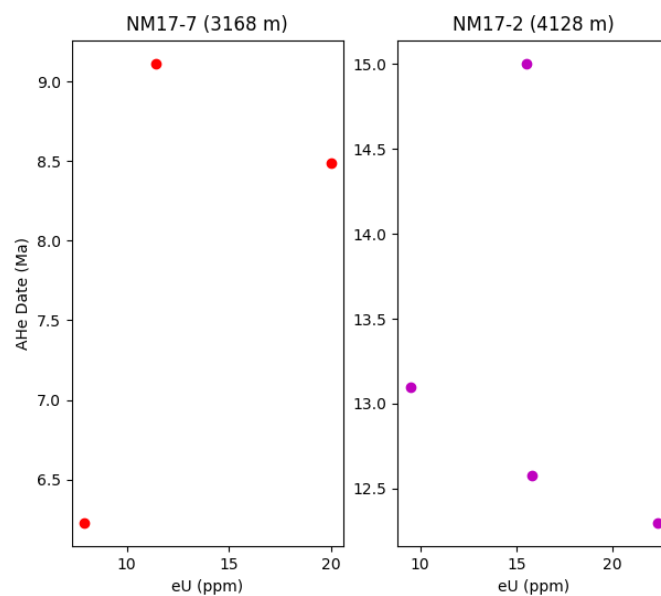


Figure 9. AHe date-eU plots for NM17-7 (3168 m) taken in the Copper Creek drainage, and NM17-2 (4128 m) taken near the summit of White Rock Mountain. Neither sample exhibits a date-eU correlation.

4.3 Thermal History Modeling Using HeFTy

AHe dates are inherently non-unique, meaning that a given date can be satisfied by a wide range of time-temperature paths (Wolfe et al, 1998). Thus, inverse modeling of a cooling history is required to constrain the most likely time-temperature paths. HeFTy, which is a forward/inverse modeling program developed by Ketcham (2005, 2007) uses AHe dates as well as known geologic constraints to determine the most likely cooling histories of a given sample.

In order to assess the cooling histories of samples taken near the summit and base of White Rock Mountain (NM17-2 and NM17-7 respectively), a simple HeFTy cooling model was constructed where the pluton cooled from ~ 300 °C at the time of emplacement (34 Ma) to a surface temperature of ~ 15 °C today, only constrained by the AHe dates. Average AHe age $\pm 1\sigma$, radius and U-Th-Sm concentrations were then entered into HeFTy as standard model input parameters. In addition, the radiation damage and annealing model (RDAAM) developed by Flowers (2009) was used to quantify the closure temperature of each grain based on calculated radiation damage. HeFTy then computed 10,000 random time temperature paths and compared them with the calculated AHe ages and known geologic constraints to determine the most likely time temperature paths.

Given the small number of AHe dates for each sample and lack of other thermochronometers, HeFTy models cannot constrain the entire cooling history of Whiterock pluton. This is evident by the wide range of potential time-temperature paths present before ~ 15 Ma. However, the models do provide reasonable constraints on cooling history from 15-7 Ma. None of the good fitting (purple) time-temperature paths for NM17-2 (4128 m) cross the 40 °C isotherm before ~ 16 Ma indicating that the pluton did not cool below ~ 40 °C until after 15 Ma. Similarly, the good fit time temperature paths for NM17-7 (3168 m) suggest that the base of

White Rock Mountain did not cool below $\sim 40^\circ\text{C}$ before 9 Ma. Many good fit time-temperature paths require Whiterock to be at higher temperatures at the respective dates, therefore 40°C should be regarded as a minimum temperature for NM17-2 and NM17-7 at 15 and 9 Ma respectively.

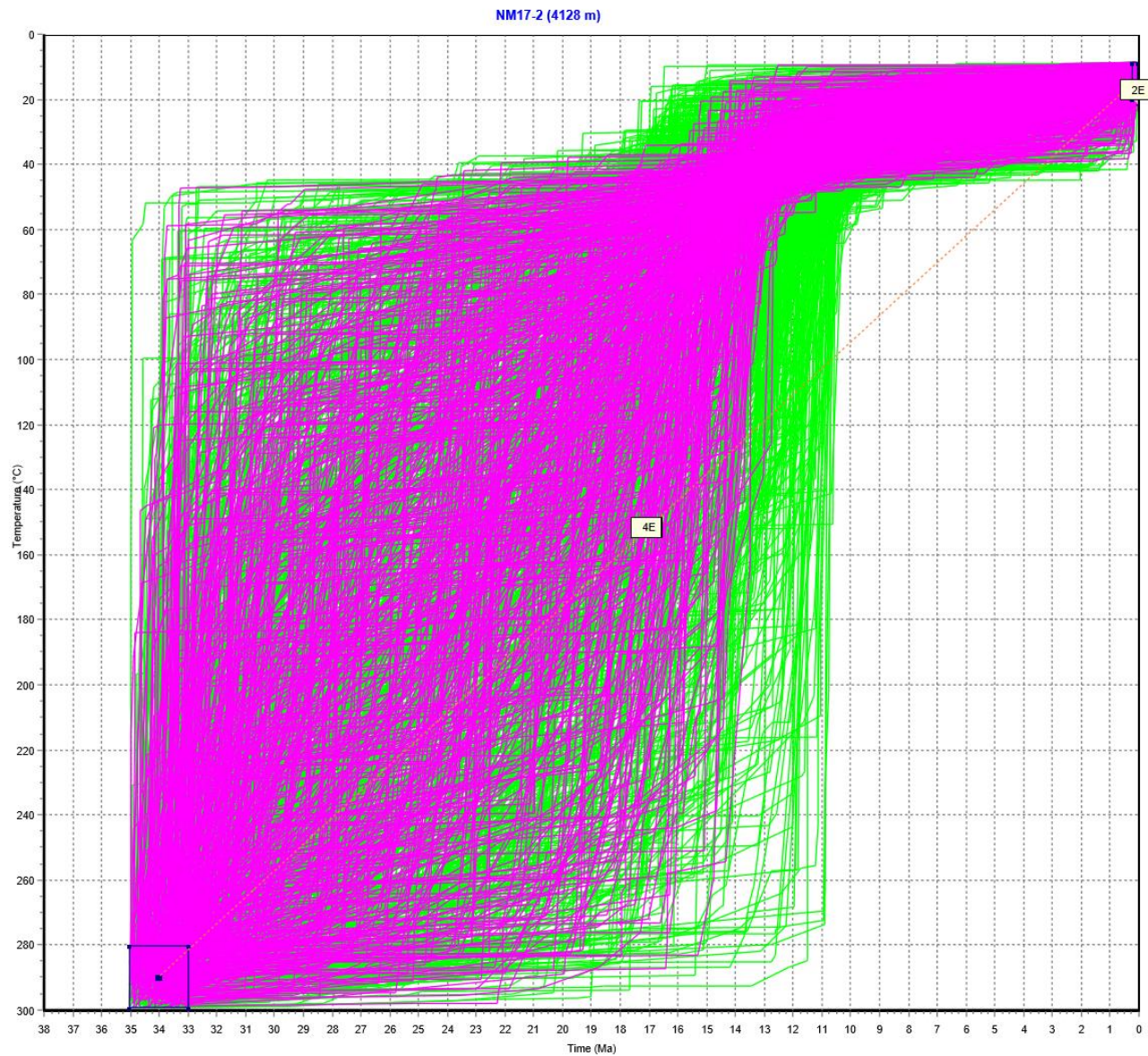


Figure 10. Modeled thermal history for NM17-2 (4128 m) taken near the summit of White Rock Mountain. Green lines represent acceptable time-temperature fits. Purple lines represent good time-temperature fits. See text for discussion.

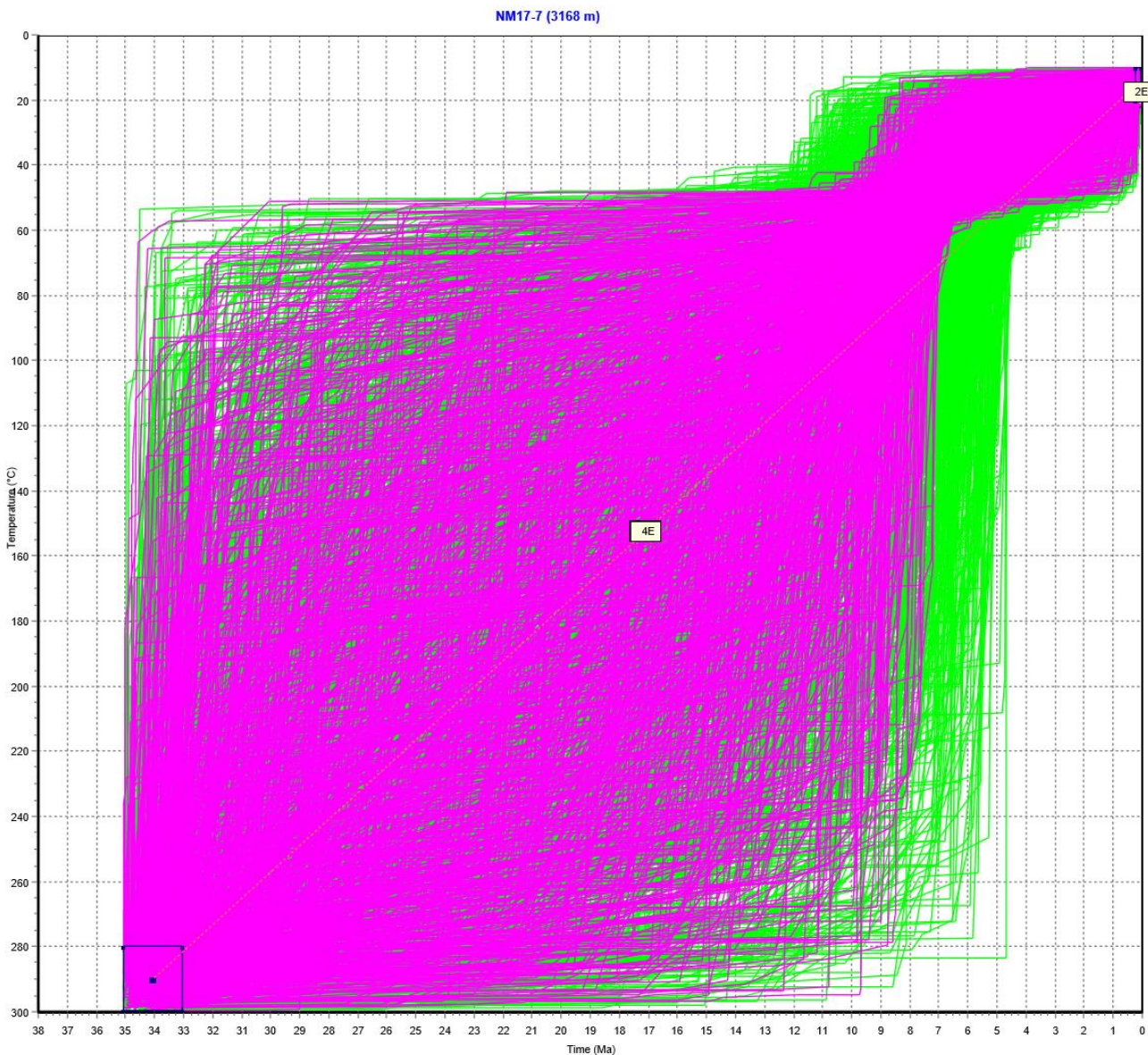


Figure 12. Modeled thermal history for NM17-7 (3168 m) taken in the Copper Creek drainage. Green lines represent acceptable time-temperature fits. Purple lines represent good time-temperature fits. See text for discussion.

5. Discussion

5.1 Exhumation of Whiterock Pluton

While various time-temperature paths can describe a single AHe date, collecting a vertical sample profile can help constrain cooling histories by correlating an AHe date to a specific point in space. As a pluton is exhumed, regions closest to the surface will cool quicker than those at depth producing AHe dates that increase with elevation. Thus, an date-elevation relationship can be used to characterize the magnitude and rate of exhumation in a given location. Different AHe dates can be produced by radiation damage accumulation during slow cooling through the HePRZ, and a trend in dates may not reflect cooling due to exhumation at all! However, the date-elevation data presented in the previous section *do* reflect cooling caused by the exhumation of Whiterock pluton and not differences in apatite closure temperature due to a prolonged period in the HePRZ. This conclusion is validated by **1)** examining the magnitude of thickness of crust moved through the HePRZ from ~13-8 Ma not the timing or change in cooling rate **2)** the lack of any age-eU correlations **3)** the relatively close spacing of AHe dates and relatively large vertical distance separating them.

Samples taken near the summit of White Rock Mountain (NM17-2) and the Copper Creek drainage (NM17-7) are separated by 960 m of vertical relief, and yield average AHe dates of 13.25 ± 1.05 (1 σ) Ma and 7.94 ± 1.24 Ma respectively. Because there are only two data points, nothing can be said about changes in cooling rate caused by variations in exhumation. What can be said though, is that roughly 1 km of the Whiterock pluton cooled through the Helium partial retention zone in ~5 m.y.. Due to the relatively large amount of time between emplacement and the oldest AHe date (~21 m.y.), exhumation rather than thermal relaxation is

the likely cause of cooling. Because of this it is possible to calculate an average exhumation rate of 181 m/Ma from 13-8 Ma (fig 13).

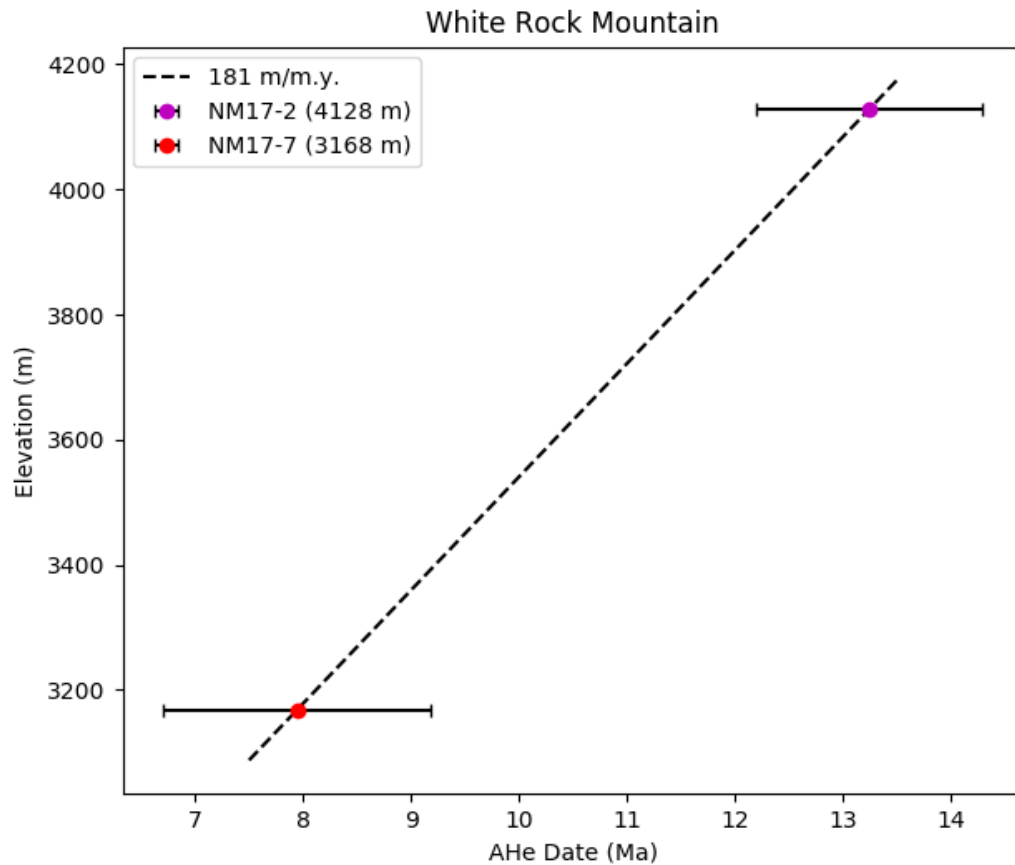


Figure 13. Grain averaged AHe date-elevation data from the Whiterock pluton. The average exhumation rate from 13.25 ± 1.05 Ma to 7.94 ± 1.24 Ma is 181 m/m.y.. Uncertainty is reported at 1σ .

The average geothermal gradient in Gothic Colorado (5 km south of White Rock Mountain) is 38.23 °C /km (Decker et al, 1988; Reiter et al, 1975). This produces an average cooling rate of 6.9 °C /m.y. during the 5 Ma interval for which data is available.

5.2 Continuous Exhumation in the Elk Range (15-7 Ma)

AHe dates from the Sopris, Capitol, Snowmass, Ragged and Crystal plutons collected by Garcia (2011) and Hiatt (2017) range in age from 15-5 Ma. These dates are consistent with AHe dates from the Whiterock pluton, which range in age from (15-8 Ma). When the AHe data from Garcia (2011), Hiatt (2017) and this study are compared a regional trend of exhumation in the Elk Mountains occurring from 15-7 Ma becomes evident. Although Garcia (2011) interprets the AHe data to show an uptick in exhumation rates during this period, the interpreted data contain erroneous dates and elevations that affect Garcia's interpretation. For example, the plotted elevation of the lowest sample in the Ragged pluton transect is almost 600 m lower than the reported elevation in the appendix. The exhumation rate calculated from the inaccurate elevation is an order of magnitude larger (876 m/m.y.) than the exhumation rate calculated for the rest of the Ragged pluton samples (86 m/m.y.). Garcia (2011) interprets this incorrect change in slope as the onset of rapid exhumation in the Elk Range, which she attributes to dynamic topography. In addition, it is likely that the lowest elevation samples from the Ragged pluton were partially reset by the intrusion of the Crystal Pluton ca 12 Ma. When the anomalous data are discarded, and all available AHe date-elevation data from the Elk Range is presented on one plot it becomes clear that the Elk Range experienced continuous exhumation from 15-7 Ma at a rate of 100-200 m/m.y. (fig 14). While the AHe data doesn't provide any information regarding the onset or termination of exhumation in the Elk Range, it does provide a valuable insight into the magnitude of exhumation occurring in the late Miocene.

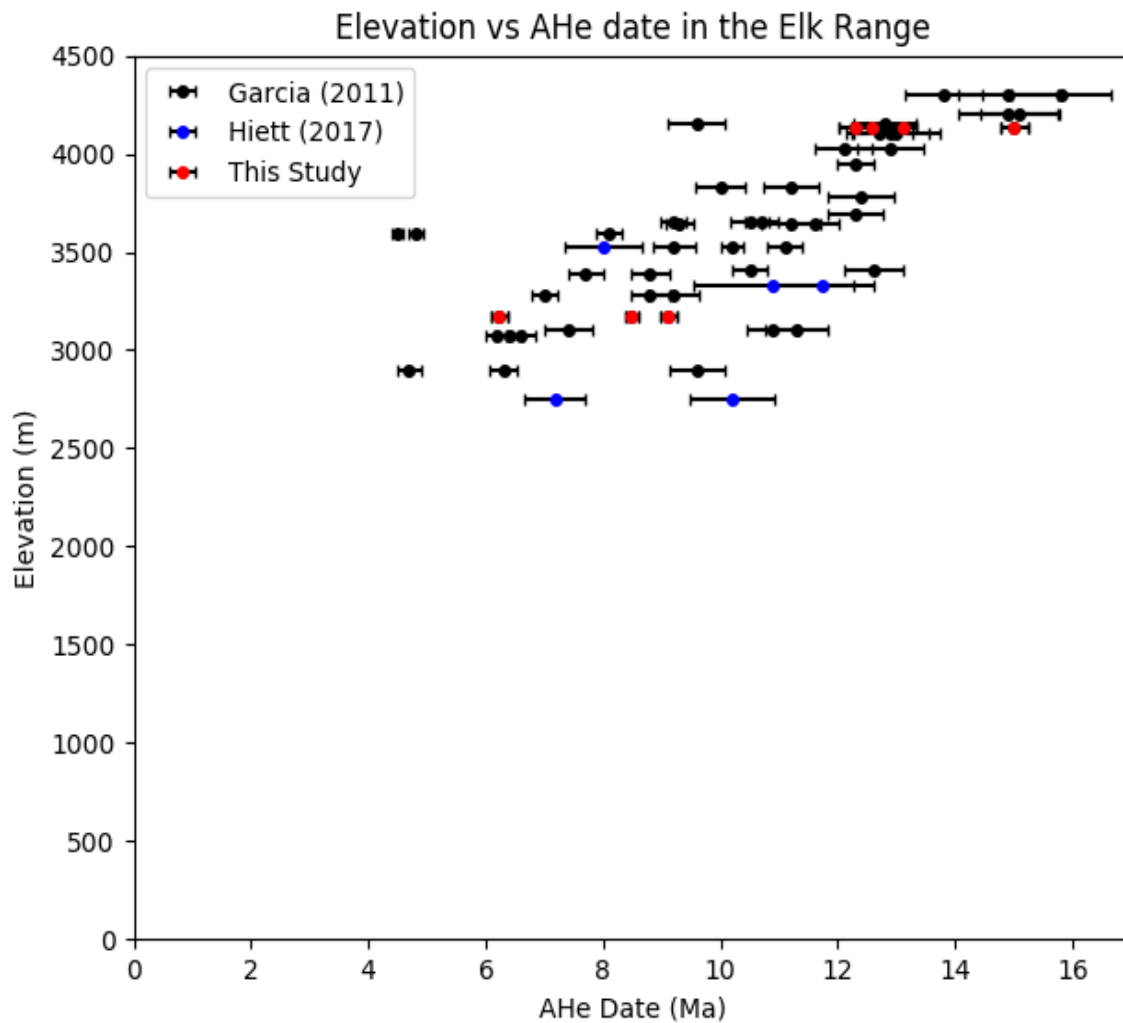


Figure 14. AHe date-elevation data from the Sopris, Snowmass, Capitol, Ragged, Whiterock and Crystal plutons. Note the lack of any obvious inflection point ca 10 Ma suggesting that exhumation rates in the Elks remained relatively constant from 15-7 Ma.

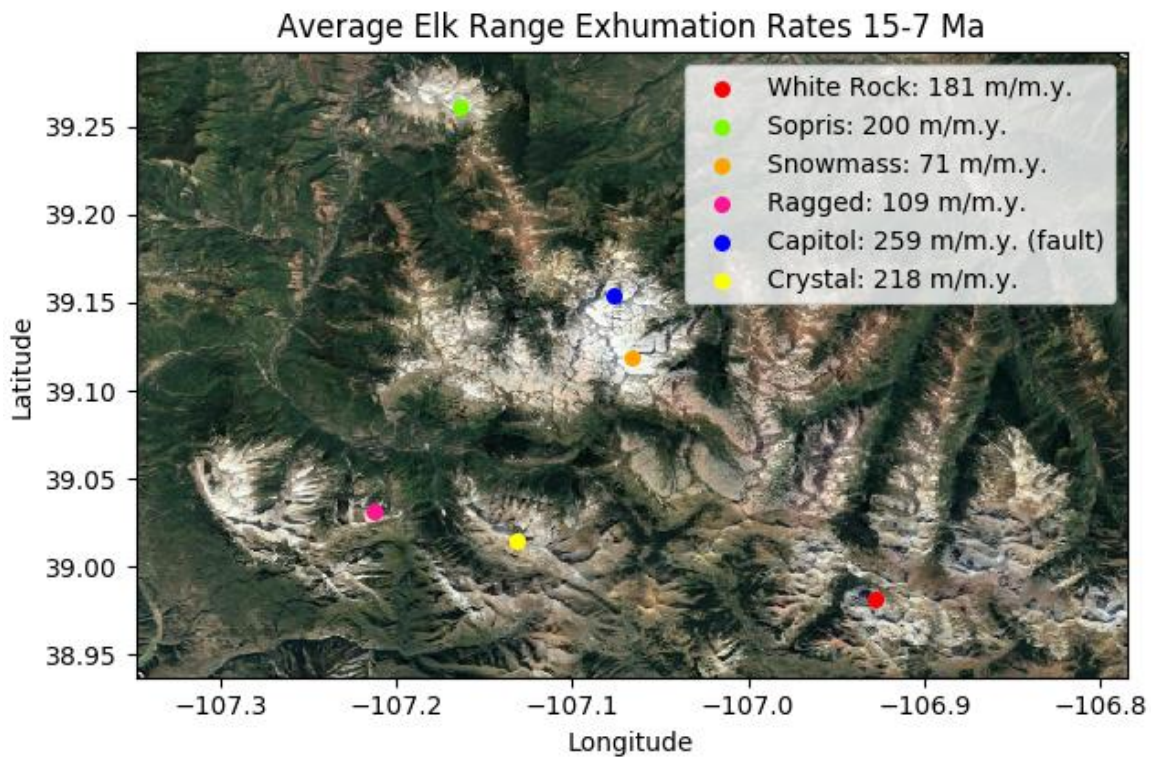


Figure 15. Google Earth image overlain with Elk Range pluton locations. Exhumation rates are calculated from Garcia's (2011) data and reported by Hiatt (2017). Note, the exhumation rate reported for Capitol Peak was likely affected by a fault observed in the field area.

5.3 Spatial Variability of Exhumation in West-Central Colorado 10 Ma-Present

The geomorphic evolution of west-central Colorado during the late Miocene becomes increasingly interesting when the exhumation history of the Elk Mountains is compared to that of the surrounding region. Numerous basalt flows including the Flat Tops, Grand Mesa and Red Mountain bound the Elk Range to the north, west and south (fig 16). Ar/Ar dating of these basalts indicate that they were extruded on to the surface ca 10 Ma (Kunk et al, 2002; Aslan et al, 2010). These basalt flows record the land surface at the time of extrusion suggesting that areas capped by basalt possessed relatively low relief, and experienced little to no exhumation from 10 Ma to the present.

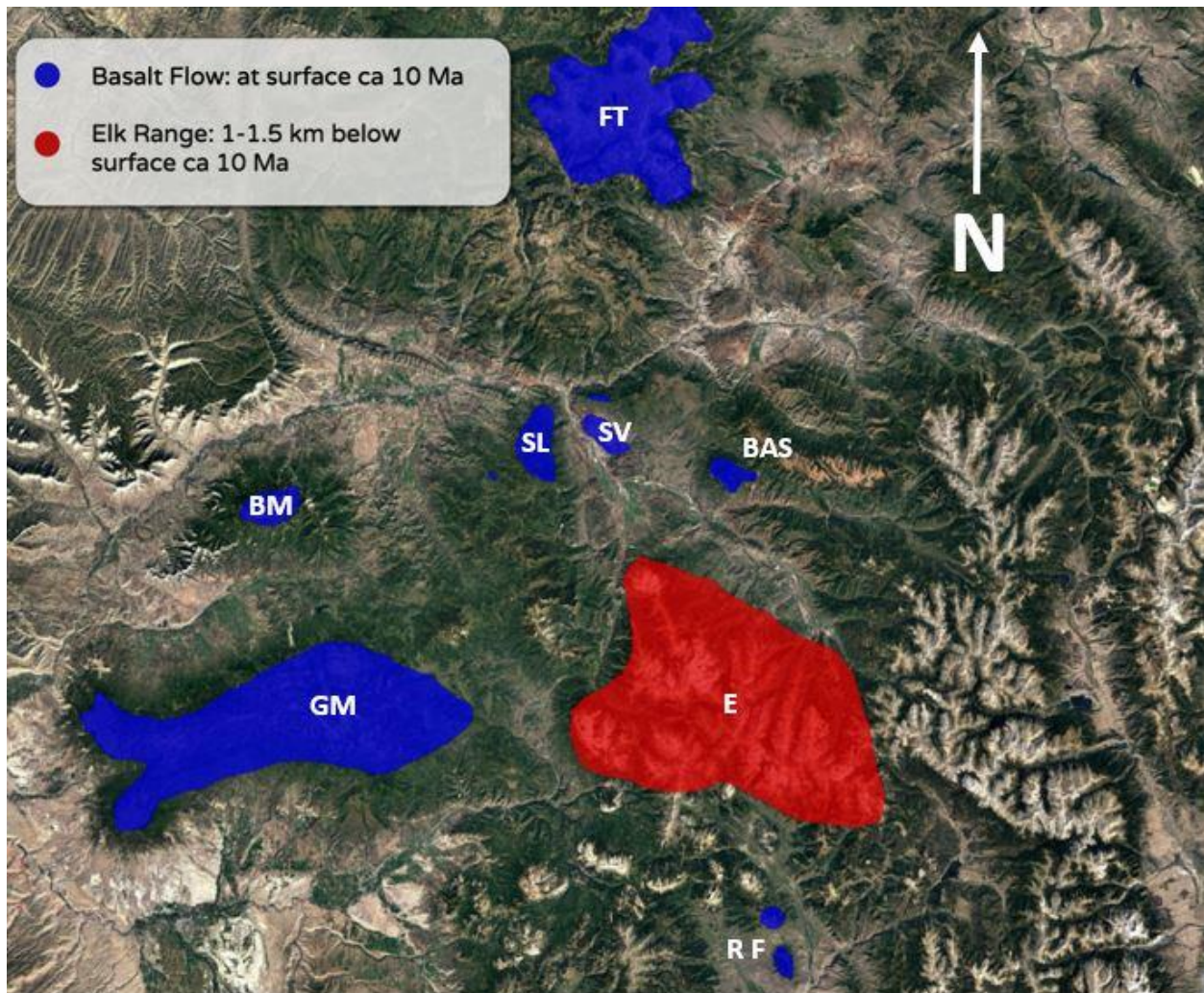


Figure 16. Google Earth image of the Elk Range (E) and surrounding 10 Ma basalt flows: Grand Mesa (GM), Battlement Mesa (BM), Sunlight Peak (SL), Spring Valley (SV), Flat Tops (FT), Basalt Mountain (BAS), Red Mountain and Flat Top Mountain (R F).

Thanks to the available AHe data discussed previously it is now clear that the Elk Mountains experienced continuous exhumation at a rate of 100-200 m/m.y. from 15-7 Ma. Also, simple thermal history models (HeFTy) from samples taken at ~3100 m in the Whiterock and Ragged plutons suggest that at 10 Ma the samples were no cooler than 50 °C. If we assume a paleo geothermal gradient of 35 °C /km, then the region must have been ~1.5 km below the present surface. This means that ~1.5 km of rock must have been removed from the Elk Range in the last

10 Ma, which translates to an average exhumation rate of 150 m/m.y.. Conversely, the East River has incised ~650 m below Flat Top Mountain (basalt) in the last 10 Ma producing an average exhumation rate of 65 m/m.y. White Rock Mountain is only 30 km north of Flat Top Mountain, yet the average exhumation rate of the Whiterock pluton over the last 10 Ma is more than double that of Flat Top. Thus, it becomes clear that the exhumation of the present topography in west-central Colorado over the past 10 Ma varied spatially throughout the region. At 10 Ma the Elk Mountains represent an epicenter of exhumation bounded by non-eroding regions.

6. Conclusion

Apatite (U-Th)/He date-elevation relationships and simple thermal history models indicate that roughly 1 vertical km of the Whiterock pluton located in the south-west Elk Mountains cooled below the HePRZ in ~5 million years. White Rock Mountain was likely exhumed at an average rate of ~181 m/m.y. from 13-8 Ma. My data is consistent with existing AHe data from 5 additional Elk Range plutons collected by Garcia (2011) and Hiatt (2017). AHe date-elevation relationships suggest that from 15-7 Ma the Elk Mountains underwent continuous exhumation that ranged in magnitude from 100-200 m/m.y.. The exhumation of the Elks sharply contrasts with the negligible exhumation experienced by surrounding regions to the north, west and south during the same time.

AHe data and geologic field relations show that the Elk Range was likely a “bullseye” of exhumation in the last 15 Ma. Unfortunately for geoscientists, exhumation can be influenced by a range of variables making interpretations of erosional histories difficult. One possible cause of the relatively high exhumation rates observed in the Elks during the Miocene is the presence of a topographic gradient between the Elk Range and the surrounding region. In the simplest sense,

exhumation acts to diffuse the topographic gradient between low and high elevations. Thus, topographically higher regions will experience greater rates of exhumation than the adjacent low-lying regions until the difference in relief is equilibrated. Based on the relatively high exhumation rates observed in the Elk Range ca 15-7 Ma compared with regions to the north, west and south, it is likely that the region was topographically higher than its surroundings. The question remains, why were the Elks high? Several possible explanations exist. One possibility is that the convection of anomalously hot mantle beneath the Elks described by (Karlstrom et al., 2012) provided enough outward normal stress to induce surface uplift and subsequent exhumation. Karlstrom (2012) argues that an uptick in exhumation across western Colorado ca 8-10 Ma records the onset of surface uplift. While slow P and S wave velocities observed below western Colorado indicate that the mantle is anomalously warm (Schmandt and Humphreys, 2010), the AHe date-elevation data from the Elk Range record no observable increase in exhumation rate from 15-7 Ma (fig 14). Thus, it appears unlikely that the onset of mantle derived surface uplift in west-central Colorado and the erosional response occurred ca 8-10 Ma. However, the AHe data cannot discount the possibility that mantle driven surface uplift was initiated outside of the AHe date range. Another possibility is that thermal expansion of the crust caused by the intrusion of Miocene plutons such as the Crystal affected the topography in the Elk Mountains. The relatively high exhumation rates observed in the Elk Range from 15-7 Ma might reflect erosion of relief created by Miocene plutonism.

It is also possible that the lithologic characteristics of the sedimentary overburden contributed to the relatively high exhumation rates observed in the Elk Range during the Miocene. The thick Paleozoic/Mesozoic sedimentary sequence that overlies much of the Elks is significantly less resistant than the granitic plutons in the region. These “soft” sediments were

likely exhumed at relatively quick rate, which could be reflected by the cooling histories of the Elk range plutons. Thus, it stands to reason that exhumation rates in the Elk Mountains ca 15-7 Ma were partially a function of the lithology being exhumed.

Both the presence of topographic relief and the erodibility of the different lithologies that make up the Elk Range could have affected Miocene exhumation rates. However, this study does not constrain the degree to which each individual process influenced exhumation rates.

Additional low temperature thermochronology data is required to determine the onset, termination and cause of the relatively high exhumation rates in the Elk Range. Erosion in the late Miocene (15-7 Ma) significantly affected the morphology of the modern Elks evident by the removal of ~ 1km of rock during that period. This study indicates that exhumation in west-central Colorado varied spatially, with the Elk Mountains representing a regional epicenter.

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Appendix

Table 1. Sample information

Sample ID	Rock Type	Latitude (DMS)	Longitude (DMS)	Elevation (m)
NM17-2	Granodiorite	38 58 50.0	106 55 40.3	4128
NM17-3	Granodiorite	38 58 46.7	106 55 48.4	3966
NM17-4	Granodiorite	38 58 58.6	106 56 1.5	3720
NM17-5	Granodiorite	38 58 57.6	106 56 17	3542
NM17-6	Granodiorite	38 59 0.3	106 56 33.3	3381
NM17-7	Granodiorite	38 58 43.1	106 57 10.8	3168

Table 2. Apatite (U-Th)/He data from the Whiterock pluton

Sample Name	Dim Mass (mg)	rs (mm)	4He (nmol/g)	U (ppm)	Th (ppm)	Sm (ppm)	eU	Raw Date It (Ma)	Ft	Corrected Date (It) (Ma)	Full Unc. (Ma)	Analytic Unc. (Ma)
NM17-2	1.99	49.99	0.482	5.26	18.01	9.64	9.5	9.30	0.707	13.10	0.96	0.22
	0.67	33.94	0.885	14.71	32.41	32.28	22.3	7.25	0.585	12.30	1.62	0.28
	1.97	36.03	0.766	10.44	21.57	17.95	15.5	9.05	0.600	15.00	1.90	0.24
	5.73	66.48	2.552	12.11	41.86	31.08	21.9	21.21	0.776	27.25	1.96	0.40
	1.20	35.16	0.653	10.16	23.78	24.45	15.8	7.57	0.597	12.58	1.35	0.33
NM17-7	4.37	59.66	0.697	8.20	50.01	34.96	20.0	6.35	0.745	8.49	0.62	0.14
	3.31	52.98	10.236	13.24	58.09	73.30	26.9	68.49	0.720	94.32	6.48	0.77
	3.84	56.70	0.203	3.69	17.82	27.23	7.9	4.63	0.738	6.23	0.44	0.11
	3.32	49.73	0.409	5.00	27.34	28.49	11.4	6.47	0.706	9.11	0.63	0.14

Data in boldface was omitted due to unreliability

rs grain radius

eU effective uranium, $[U] + .235[Th]$

Ft alpha ejection correction

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