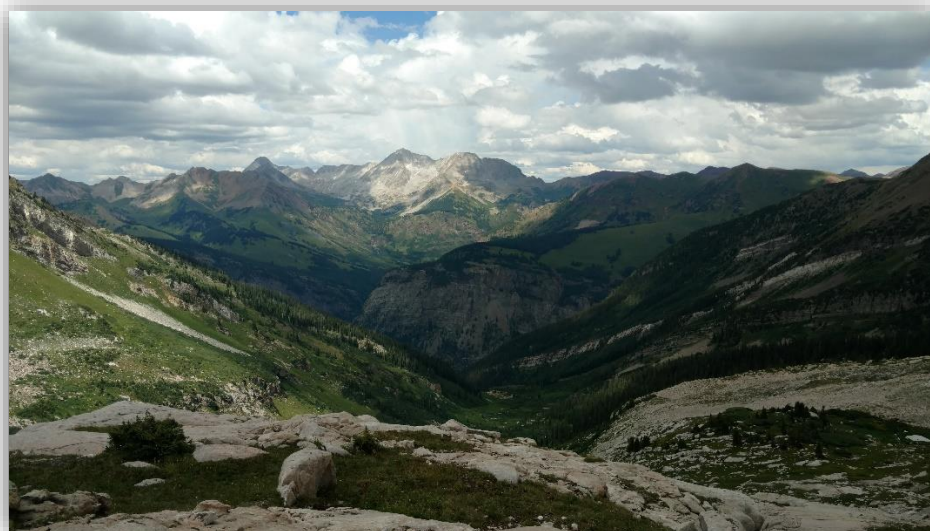


Constraining the Timing of River Incision in the Upper Colorado Drainage Basin Using Apatite (U-Th)/He Thermochronology in the Elk Mountains, Western Colorado

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ABSTRACT

This study utilizes apatite (U-Th)/He, or AHe, to produce a vertical transect of cooling histories along the height of the partially exhumed Crystal Pluton in the Elk Mountains of west/central Colorado. These cooling histories are interpreted to reflect exhumation controlled by the incision of the Crystal River – a tributary of the Colorado River. A period of rapid exhumation is observed from 8 – 11 Ma, likely beginning earlier, that is consistent with previous AHe data taken from nearby exhumed plutons in the Elk and northern West Elk Mountains. This period of exhumation predates the incision of a low relief surface that developed in northwestern Colorado by ca. 10 Ma, and is therefore not believed to have been controlled by the incision of the Colorado River. A review of previously noted incision constraints suggests that post-10 Ma Colorado River incision has become more rapid in the last 1 – 3 Ma, suggesting that climate change, rather than epeirogenic uplift, is the major driver for recent river incision.

1. INTRODUCTION

1.1 Concerns of the Colorado River

For more than a century, geologists have struggled to better understand the geologic evolution of the western United States. Within the American West, the entire region from the Great Plains through the Colorado Plateau sits at anomalously high elevations, with the Southern Rocky Mountains of Colorado being the summit of this massive lithospheric welt (Fig. 1). Given their lack of over-thickened crust, the so-called ‘rootless Rockies’ and Colorado Plateau have commonly been said to be supported by buoyancy in the crust and upper mantle (Karlstrom et al., 2015; Hansen et al., 2013; Humphreys et al., 2003; Sheehan et al., 1995). When and why this lithospheric buoyancy was acquired is still up for debate, with many authors fitting into groups that either favor young uplift (late Miocene/Pliocene) or old uplift (late Eocene/Oligocene). Regardless of the timing of uplift, it is these anomalously high elevations that allow for the spectacular exhibit of geologic history in the high mountains of Colorado and the deep canyons of the Colorado Plateau.

Aside from the high elevations of these regions, one other factor has dominated the evolution of this landscape - the Colorado River. The Colorado River is the master stream that is responsible for draining the majority of the Southwest, and has therefore provided the base level to which its tributaries have responded to (Fig. 2). A large body of research has focused on detailing the evolution of the Colorado River system, knowing that the timing and style of incision might lend clues as to the details of any epeirogenic uplift.

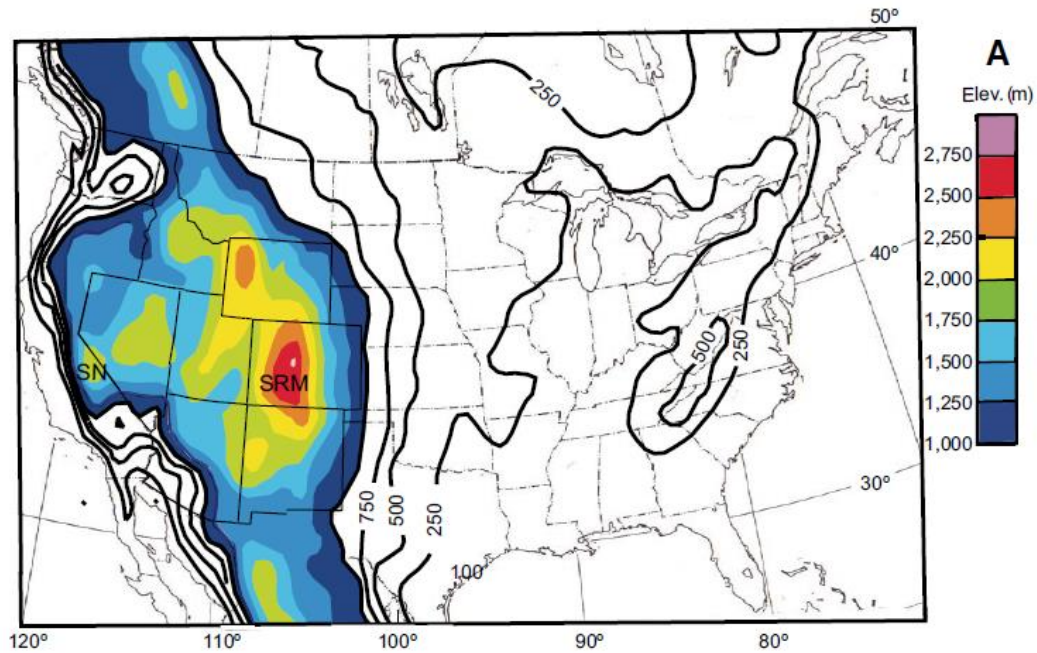


Figure 1: Map showing smoothed topography of the contiguous United States and adjacent parts of Canada and Mexico. Contours and colors are in intervals of 250 m. Elevations below 1,000 m are left uncolored. (Eaton, 2008)



Figure 2: Map of the modern Colorado River drainage basin. The Crystal River is highlighted in red and The Roaring Fork River is highlighted as purple. (Modified from: On the Colorado, 2017)

This work has not yet led to a consensus, however, as the Colorado River system has proven to hold an enigmatic history. In the upper half of its drainage basin, river gravels have been documented that indicate an ancestral Colorado River flowed westward onto the Colorado Plateau near its present course by at least ~11 Ma (Aslan et al., 2010). In contrast, the oldest evidence for a through-flowing Colorado River downstream from the edge of the Colorado Plateau is not seen until ~6 Ma (Faulds et al., 2008; Lucchitta, 1972; Dorsey et al., 2007). It is unclear exactly where the Miocene Colorado River ultimately flowed, though we do know that some form of integration established its present course through the Grand Canyon between 5 – 6 Ma (Lucchitta, 1972).

Since the Late Miocene, average incision rates and magnitudes of the upper Colorado River have been relatively high. Colorado River gravels capped by basalts on Grand Mesa, the oldest record of an ancestral Colorado River at ca. 11 Ma, sit ~1500 m above the current river level, giving a long-term average incision rate of ~140 – 170 m/m.y. (Aslan et al., 2010). When this incision was accomplished, and what drove it is still open ended. One possible driver for incision in the upper Colorado River basin is its integration with the lower river basin at ca. 6 Ma. If this were the case, one could expect the river to have experienced slow incision prior to ca. 6 Ma, with rapid incision sometime thereafter. Another possibility is the influence of global climate change and the onset of cooler and stormier climates at ca. 5 Ma and ca. 2 Ma, which would induce rapid incision at those times (Molnar and England, 1990). The other possible driver for incision, which happens to be the favored hypothesis by many authors, is regional uplift. Incision rates in the Grand Canyon have been interpreted as relatively steady since ca. 6 Ma, causing authors to argue for the beginning of regional uplift at that time (Karlstrom et al., 2008). These authors argue that if the incision did not respond to the influence of climate change, it must have been keeping pace with uplift. The effects of drainage integration at the same time seem to be dismissed. Others have used basalt capped river gravels like those at Grand Mesa to argue for steady incision since ca. 10 Ma, arguing that regional uplift commenced at that time, with similar arguments of incision keeping pace with uplift (Aslan et al., 2010). In all of these cases, interpretations of incision rates rely on similar questionable assumptions; firstly, authors must carefully decide which data actually indicate paleoelevations of the river system, and secondly, authors are forced to interpolate between sparse data points from distant locations. Thus, it is clear that a more spatially exclusive and temporally continuous incision history must be developed in order to better constrain the evolution of the Colorado River throughout the late Cenozoic.

1.2 Direct Measurements of River Incision

Several direct measurements of the Colorado River's relative paleo-elevation have been noted to this point, which have been used in the interpretations introduced above. Grand Mesa represents one of several plateau-capping basalts that were extruded onto the landscape at ca. 10 Ma. Other basalts with similar ages and elevations currently sit on the Flat-Tops, Battlement Mesa, Basalt Mountain, and other locations that have since been deformed by evaporate tectonism (Kirkham et al., 2001). The Flat-Tops, which are the remains of a dissected volcanic plateau on the White River Uplift, exhibit these 10 Ma basalts that are underlain by older basalts up to 24 Ma and locally interfinger with alluvial sediments of the Brown's Park Formation (Larson et al., 1975). The lack of incision between basalt flows at the Flat-Tops, combined with the widespread occurrence of ca. 10 Ma basalt flows that now sit at similar elevations provides evidence that a low relief surface had developed in northwestern Colorado by ca. 10 Ma, suggesting that little incision by the ancestral Colorado River occurred between 24 – 10 Ma (e.g. Larson et al., 1975; Kirkham et al., 2001).

Estimates of post ca. 10 Ma incision diverge from there, as there are only a handful of marker horizons available from which to derive incision data. The 640 ka Lava Creek B ash overlies Colorado River gravels ~85 m above the current river level in Glenwood Canyon, constraining the most recent incision rates of 132 m/m.y. By including a ~3 Ma basalt flow in Glenwood Canyon that isn't associated with river gravels, Kunk et al. (2002) argue for rapid incision beginning at ca. 3 Ma. Aslan et al. (2010) disregard this ambiguous basalt flow and argue for relatively steady incision since 10 Ma. Basalt-capped river gravels on Triangle Peak in the Roaring Fork River Valley indicate incision rates of 291 m/m.y. since 1.4 Ma, supporting the hypothesis of Kunk et al. (2002). Downstream from Glenwood Canyon, a series of river terraces/ alluvial fans record the position of the Colorado River throughout this time. More research is necessary to determine the incision rates recorded by these terraces/fans, as previous authors have arrived at conflicting conclusions. Thus far, a pediment known as Grass Mesa has been cosmogenically dated to ~1.8 Ma, giving incision rates of 95 – 127 m/m.y. (Berlin et al., 2008; Aslan et al., 2010). A younger (~440 ka) terrace gives average rates of 214 m/m.y., and a ~88 ka pediment near the town of Rifle gives incision rates of 227 m/m.y. (Aslan et al., 2010).

1.3 Previous Thermochronology

Garcia (2011) conducted an extensive study of low temperature thermochronology in the Elk and West Elk Mountains in central/western Colorado. These mountain ranges consist of numerous mid to late Tertiary aged granitic plutons emplaced into Mesozoic and Paleozoic strata. Since their emplacement,

tributaries of the Colorado River have eroded away the country rock leaving the Tertiary plutons as high elevation isolated mountains, making them ideal candidates for age-elevation thermochronology transects. Using both apatite fission track (AFT) and apatite (U-Th)/He (AHe), Garcia interpreted periods of exhumation from 25 – 15 Ma and 12 – 5 Ma, with the onset of rapid incision between 6 – 12 Ma which was attributed to regional uplift. Results from different transects show variation between the timing of rapid incision, and the data can be interpreted not to show this onset at all. Furthermore, several of the plutons in her study might have been reheated during the emplacement of the younger (12.4 Ma) Crystal Pluton, which was not sampled in her study.

It is the goal of this research to continue Garcia's AHe work in the Elk/West Elk Mountains and improve our understanding of the exhumation history there, with the hopes of connecting it to the incision history of the Colorado River. To this end, six samples of Crystal Pluton granite separated by more than a kilometer of elevation were processed and analyzed for cooling histories using the AHe method. The cooling history of the Crystal Pluton is interpreted to reflect exhumation and incision of the Crystal River, which cuts into the pluton. As a tributary of the Colorado River, the incision history of the Crystal River is expected to reflect the behavior of its master stream. Due to its young age, the existence of extant overburden, and its proximity to the Colorado River, the Crystal Pluton is the perfect candidate to improve our understanding of exhumation in western Colorado.

2. GEOLOGIC SETTING

2.1 Elk and West Elk Mountains / Treasure Mountain Dome

The high elevation ranges of the Elk and West Elk mountains are the result of a complex geologic history, with contributions of tectonic deformation, magmatism, epeirogenic uplift and differential incision. The timing of tectonic deformation and magmatism have long been well constrained, while contention remains on the timing and relationship between epeirogenic uplift and incision.

Colorado was at or below sea level throughout most the Paleozoic. Regionally extensive sedimentary sequences dominated by marine limestones and shales accumulated during this time. Marine dominated sedimentation ended during the Pennsylvanian with the onset of tectonic deformation and uplift of the Ancestral Rocky Mountains. The area of the modern Elk and West Elk Mountains lay in between the ancestral Front Range and Uncompahgre Range, a region known as the Central Colorado Trough. Clastic debris shed from nearby mountains accumulated in this trough, as evidenced by the coarse grained red beds of the Pennsylvanian Maroon Formation. During the first half of the Mesozoic

terrestrial environments developed in western North America, depositing formations such as the Entrada and Morrison. The second half of the Mesozoic saw the inundation of the Cretaceous Interior Seaway. The Cretaceous Mancos Shale was laid down during this time, with a thickness of more than 1.3 km in the Elk/West Elk region (Mutschler, 1970). Regression of the seaway is marked by the return of shoreline deposits like the Mesa Verde Group which were deposited at the end of the Cretaceous. These shoreline deposits are the last reliable elevation datum for the region.

With the dawn of the Cenozoic era came the renewed tectonism, deformation, and volcanism of the Laramide Orogeny. In the Elk and West Elk mountains, kilometer scale folding of sedimentary sequences accompanied displacement along discrete fault systems. In the Elk mountains, the most notable fault system is the southwest verging Elk Range Thrust, which is believed to be the up-thrown leading edge of a gravity driven low angle normal fault (Bryant and Martin, 1988). The Elk Range Thrust carried a thick prism of sediments westward from the Sawatch uplift to the Elk Mountains (Bryant and Martin, 1988). A large overturned syncline, known as the Schofield Syncline, developed at the leading edge of this prism of sediments.

Roughly ~15 million years after the end of the Laramide Orogeny, widespread volcanic activity began occurring from Nevada to Colorado. The ignimbrite flare-up, which refers to this protracted (36 – 23 Ma; Lipman, 2007) and spatially extensive event, has had several proposed causal mechanisms but is typically considered to be the result of foundering of the underlying Farallon slab. The North American lithosphere is believed to have been both chilled and hydrated during contact with the Farallon plate (Humphreys et al., 2003; Farmer et al., 2008). Upon removal of the plate, the renewed contact between the North American plate and the hot and dry upwelling asthenosphere likely triggered extensive melting, leading to widespread volcanism across the region. It was during this event that most of the intrusions of the Elk and West Elk Mountains were emplaced. The San Juan, Mogollon-Datil, and Sierra Madre Occidental volcanic fields also developed at this time.

In the Elk Mountains, the first plutons to be emplaced were the large granodiorite stocks of Mount Sopris, Snowmass and Whiterock, all with ages of ~34 Ma (Obradovich, 1969; Garcia, 2011). Emplacement of these larger volume plutons was structurally controlled by the Elk Range Thrust system. The Mount Gunnison stock, which lies in the southern portion of the West Elks, was emplaced at a similar time (~33.8 Ma; Garcia, 2011). Subsequent intrusions of laccoliths, sills and dykes then migrated north from Mount Gunnison and south from Mount Sopris, meeting in the middle near the Ragged Mtn. laccolith (~28.4 Ma; Garcia, 2011). Each of these Oligocene aged intrusions are composed of similar granodiorite (Obradovich, 1969).

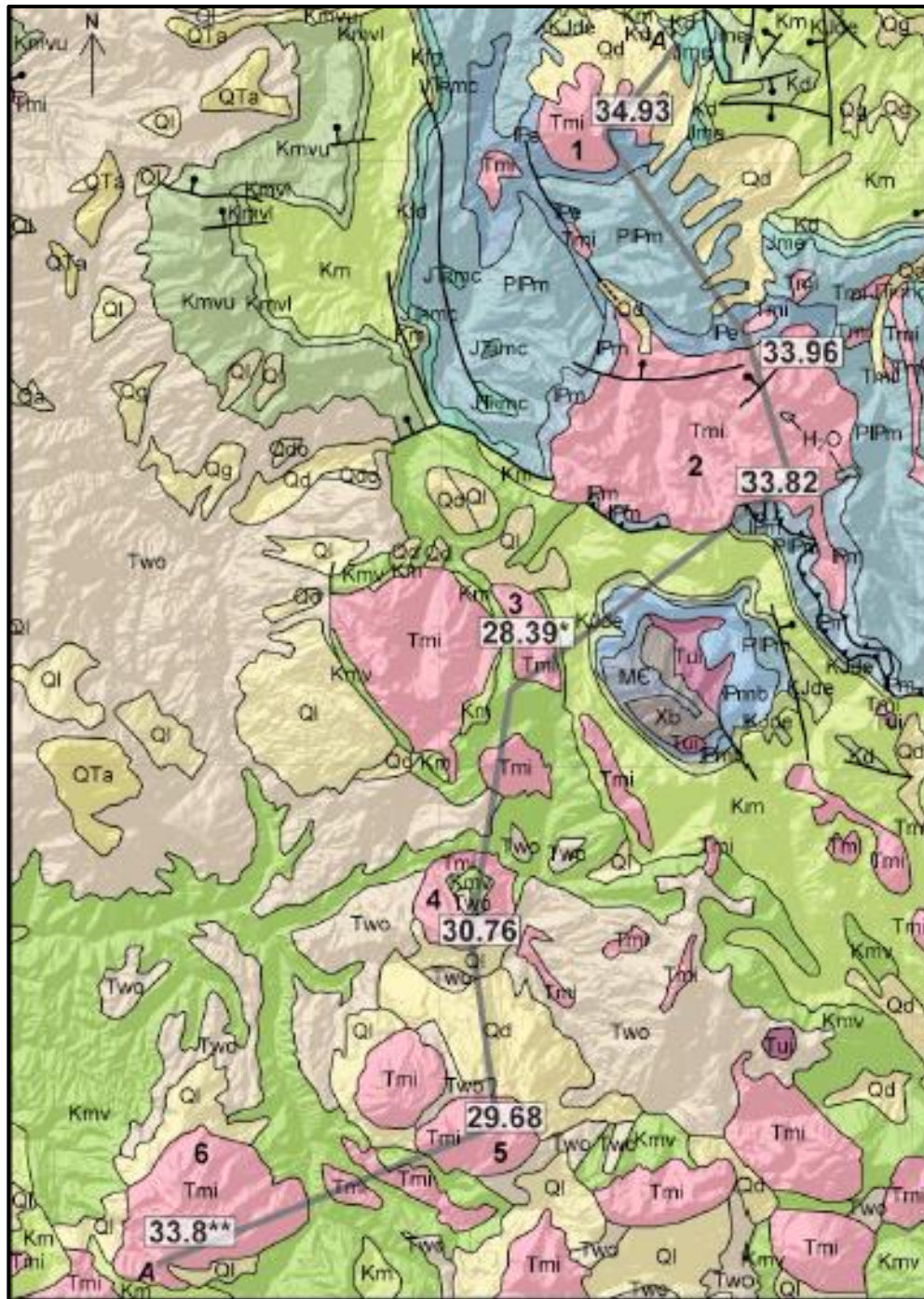


Figure 3: Generalized map of the Treasure Mountain Dome and surrounding area, including plutons of the western Elk Mountains and northern West Elk Mountains. Grey line is line of section for figure 4. Boxed numbers give emplacement age. The intrusion ages are $^{40}\text{Ar}/^{39}\text{Ar}$ biotite ages except for the $^{40}\text{Ar}/^{39}\text{Ar}$ K-feldspar age for Ragged Mountain (*) and the AFT age for Mount Gunnison (**). Legend for map is located in Figure 4. (Garcia, 2011)

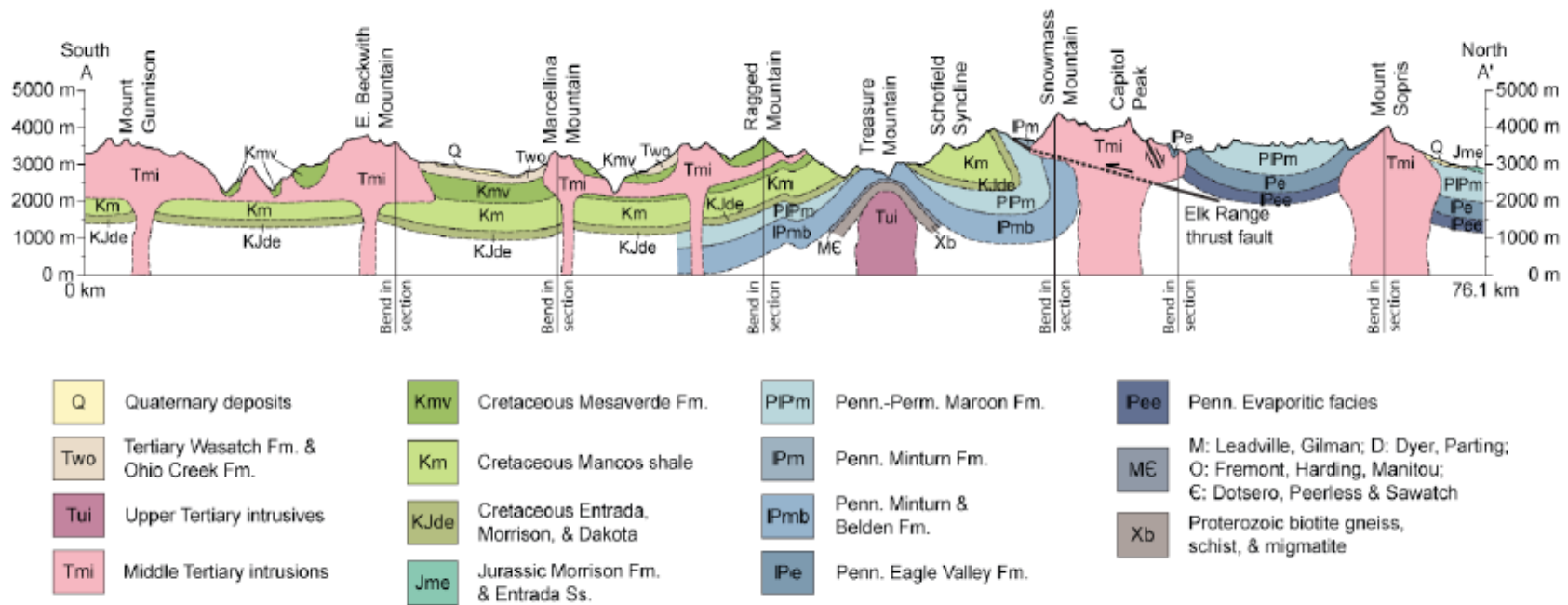


Figure 4: Generalized cross-section of the Treasure Mountain Dome and surrounding area, including plutons of the western Elk Mountains and northern West Elk Mountains. (Modified from Garcia, 2011)

After this wave of Oligocene magmatism, igneous activity did not return to the region until the mid-Miocene when the Redwell stock and Crystal Pluton were emplaced. The Redwell stock is a molybdenum-bearing granite located just west of Crested Butte in the West Elks and has an emplacement age of ~17 Ma (Garcia, 2011; Thomas and Galey, 1982). This intrusion remains largely in the subsurface, and has been identified mainly by drilling operations. The soda granite of the Crystal Pluton was emplaced further north near the plutons of the Elk Mountains, just east of Marble, and has an age of 12.4 ± 0.6 Ma using biotite K-Ar (Obradovich, 1969). During emplacement, the Crystal Pluton domed up the overlying strata creating the Treasure Mountain Dome. Stratigraphically, the pluton was emplaced near the level of the great unconformity; in its southwestern portion the pluton is in contact with Precambrian basement, and to the northeast, the pluton is in contact with Paleozoic strata, the youngest of which is the Pennsylvanian-aged Belden Formation. Extensive contact metamorphism accompanied emplacement of the Crystal Pluton, metamorphosing the surrounding Precambrian basement and Paleozoic strata. The Leadville limestone, for example, was metamorphosed into the famed Yule Creek marble, which is mined from the western flank of the dome. The Treasure Mountain dome has since been partially exhumed and incised by the Crystal River, which now flows into the Roaring fork at Carbondale and continues to the Colorado River at Glenwood Springs (Fig. 5).

2.2 Regional Elevation Trends/ Geophysical Observations

Today the Treasure Mountain Dome sits at an average elevation of roughly 3,000 m. Authors have used various methods to produce maps of long-wavelength filtered topography to deduce the regional elevation trends, yielding average elevations ranging from 2,500 m to >2,800 m in the central Southern Rocky Mountains (e.g. Eaton, 2008; Karlstrom et al., 2012). These regionally averaged topographic analyses reveal that the high topography in Colorado forms the summit of a broad N-S elongated topographic dome, with the Colorado Plateau, northern Basin and Range and the Great Plains flanking the dome at intermediate elevations (~1.5-2 km; Eaton, 2008) (Fig. 1). Estimates derived from seismic receiver function analyses show that the crustal thickness below the Colorado Rockies is roughly the same, if not slightly less, than the adjacent Colorado Plateau and Great Plains, indicating the absence of an Airy-style crustal root below the Southern Rockies (Hansen et al., 2013; Sheehan et al., 1995). Integrated studies of mantle tomography throughout the region also indicate the presence of low-velocity zones in the upper mantle below some of the highest topography in Colorado (Schmandt and Humphreys, 2010; Humphreys et al., 2003; Dueker et al., 2001; Lee and Grand, 1996). The Elk and West Elk Mountains sit above one of these low velocity anomalies – referred to as the Aspen anomaly by Dueker et al., 2001. Other geophysical studies have shown that the high topography of Colorado is also coincident

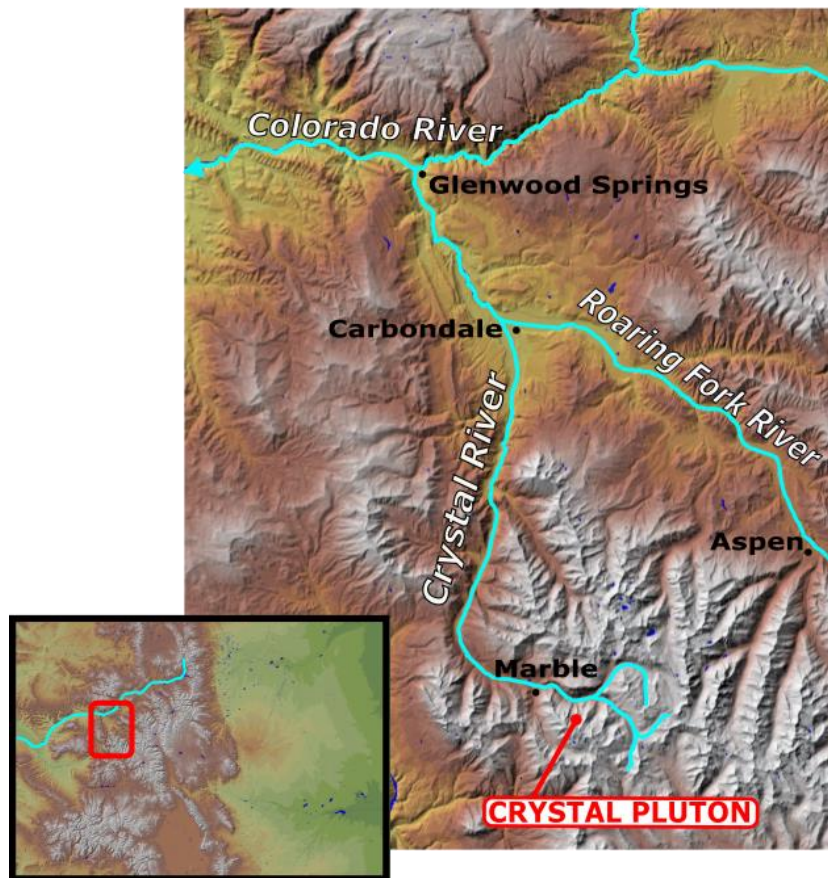


Figure 5: Shows the location of the Crystal Pluton and Crystal River in relation to the Roaring Fork and Colorado River. Inset shows the area of detail with respect to the rest of Colorado. Base map from USGS EROS digital image gallery, 2010.

with relatively large crustal seismic attenuation values and a 5-10 m positive geoid anomaly relative to the Colorado Plateau (Karlstrom et al., 2012). By combining these various geophysical observations, many authors have come to similar conclusions that the elevated topography below the Southern Rocky Mountains is currently at least partially supported by low-density crust and/or upper-mantle (Karlstrom et al., 2012; Humphreys et al., 2003; Sheehan et al., 1995; Hansen et al., 2013). It remains unclear, however, exactly when and how the upper-mantle and/or crust obtained these lower densities. It is possible that the incision history of the Colorado River and its tributaries holds clues to help solve this enigma.

3. METHODS

3.1 Sampling

To develop a complete incision record of the Crystal Pluton, I collected a vertical transect of six samples along the more than 1200 m of exposed granite in the Treasure Mountain Dome. Each of the six samples was spaced ~200 vertical meters apart, with the highest sample from 3668 m and the lowest from

2656 m. The four highest elevation samples were all taken from a small valley on the south flank of the Crystal River known as Bear Basin. The two lowest elevation samples were taken from the north side of the main river valley roughly 2 and 4 km downstream from Bear Basin (Fig. 6 and 7). A ~400 m gap in the vertical transect exists between CH16-9 and CH16-10 due to a lack of accessible exposure. Samples were taken from pristine granite outcrops away from any signs of prolonged weathering, fluid alteration or faulting. All six samples were composed of relatively similar soda granite seriate porphyry.

3.2 Mineral Separation

Either back at the lab or during collection in the field, samples were broken into pieces small enough to be pulverized by a Bico jaw crusher and disc mill. After pulverization, samples were sieved through a 500 μm mesh to ensure that grains were the proper size. The samples were then passed over a Wilfley water table to concentrate heavier minerals like apatite and zircon. After drying, samples were then run through a Frantz magnetic separator to remove unwanted magnetic minerals. Samples were finally separated by heavy liquids, specifically lithium metatungstate, in order to further concentrate the heaviest minerals. After this final separation, most accessory minerals such as apatite and zircon are at sufficient concentrations to be picked. Equipment and materials for mineral separation were provided by the University of Colorado's Thermochemistry and Instrumentation Laboratory (CU TRaIL).

3.3 AHe Dating

Individual apatite grains were handpicked using a Leica M165 binocular microscope equipped with a calibrated digital camera. Only the highest quality apatites were selected to be analyzed; this includes proper size, shape and the absence of inclusions. Grain dimensions were measured with the calibrated digital camera. After selection and characterization, grains were placed into small Nb tubes that were then crimped on both ends. These Nb packets were loaded into an ASI Alphachron He extraction and measurement line at the CU TRaIL. Radiogenic ^4He is extracted by heating the crystals to ~800-1100°C with a 25W diode laser under UHV conditions ($\sim 3 \times 10^{-8}$ torr) for five to ten minutes. Gas is spiked with ^3He , purified using gettering methods, and analyzed on a Balzers PrismaPlus QME 220 quadrupole mass spectrometer. This process is repeated at least once to ensure all gas is removed from the crystal. Degassed apatites were then retrieved and dissolved in preparation for analysis of U, Th and Sm.

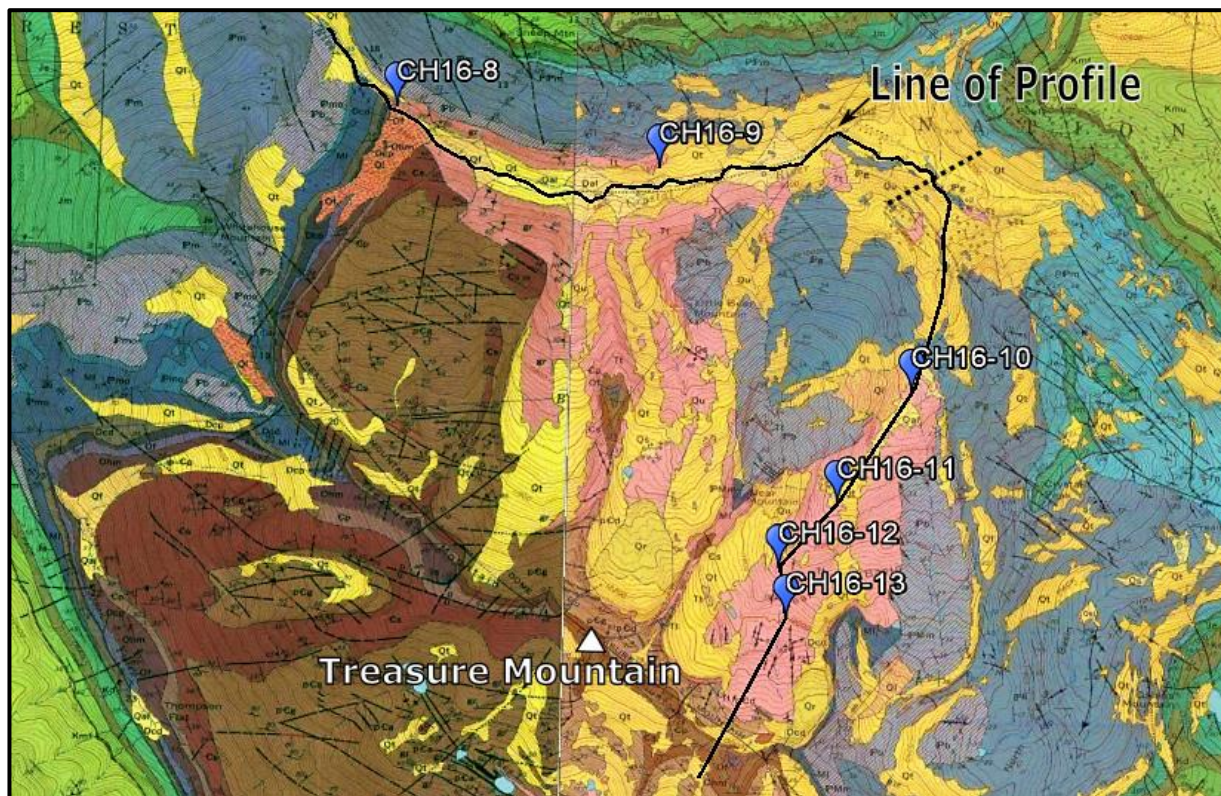


Figure 6: Geologic map of the Treasure Mountain Dome including sample locations. Pink color indicates Tertiary granite of the Crystal Pluton. Line of vertical profile for fig. 7 is shown in black. Dashed line marks boundary between Bear Basin and the main Crystal River valley. Geologic base maps by Gaskill and Godwin, (1966), and Mutschler, (1970).

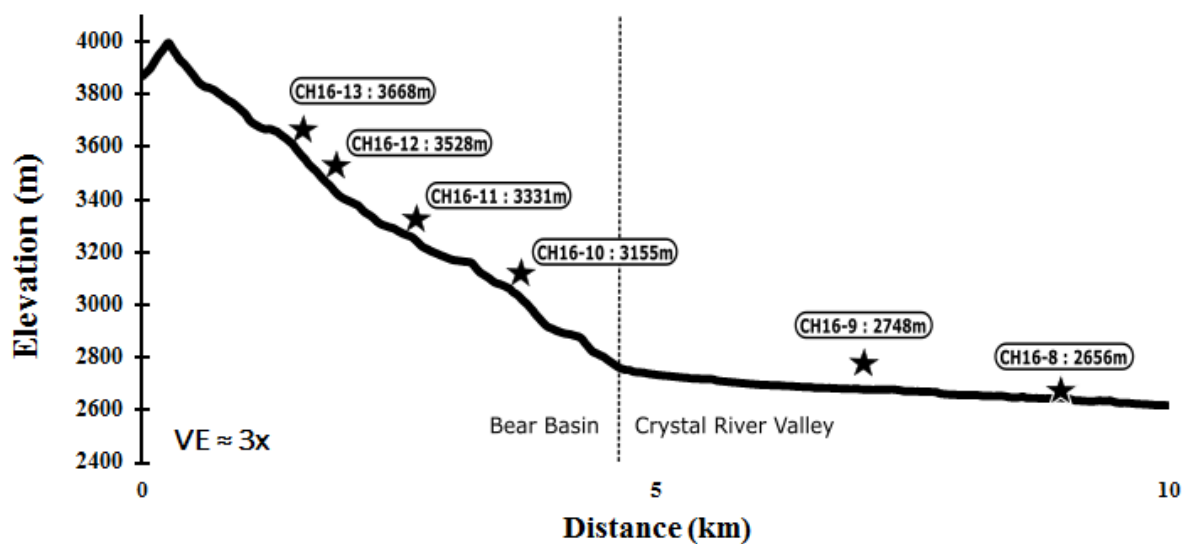


Figure 7: Shows a vertical profile along the Crystal River valley and up Bear Basin. The confluence of Bear Basin with the Crystal River is indicated by the vertical dashed line. Stars indicate sampling locations. Line of profile shown on fig. 3.

Apatites, still in their Nb tubes, were spiked with a ^{235}U , ^{230}Th , and ^{145}Nd tracer, placed in HNO_3 , and baked at 80°C for two hours. Dissolved samples were then analyzed for U, Th, and Sm content on a Thermo Element 2 magnetic sector ICP-MS located at CU's Institute of Arctic and Alpine Research (INSTAAR). Grain dimensions, concentrations of radiogenic ^4He and measurements of U, Th, and Sm were used to calculate He dates using the methods described in Ketchum et al., (2011).

4. RESULTS

4.1 AHe Dating Results

A total of 26 apatite grains were selected and analyzed for temperature histories (see table 2). Three samples (CH16-8, CH16-9, and CH16-11) yielded significant quantities of large ($\geq 50\ \mu\text{m}$ wide), euhedral apatites. The other three samples (CH16-10, CH16-12, and CH16-13) did not contain many large euhedral apatites, and instead yielded significant quantities of somewhat rounded apatite grains that existed as inclusions in either quartz or feldspar. In either case, only inclusionless apatites with appropriate size were analyzed.

Once the apatite grains were measured and analyzed, and apparent cooling ages calculated, all resulting data was filtered for reliability. Individual apatite grains, along with their associated cooling ages, were excluded from the data on a grain by grain basis according to specific compositional properties. Grains with low eU values (< 2 ppm; a weighted combination of U and Th) were excluded due to their increased sensitivity to possible ^4He implantation from surrounding minerals. Grains with anomalously low ^4He content (blank corrected measurements less than 5 times background levels) were excluded due to the technique's lack of precision at such low levels. Apatites that did not fully degas during the initial laser extraction were rejected due to the possible presence of inclusions or low-diffusivity zones. Lastly, smaller apatites with low alpha ejection corrections (< 0.55 ; a function of surface area and volume described by Ketchum et al., 2011) were excluded due to large uncertainties regarding the retention of produced ^4He . After these exclusions were performed, one apatite with an associated age older than the pluton remained, and was subsequently excluded. This process narrowed the dataset to five apatite grains considered to yield the most reliable cooling ages. Of these five grains, all were of the well-developed euhedral variety. Interestingly, each apatite with rounded form, those that likely grew as inclusions in quartz or feldspar, exhibited low ^4He concentrations, low eU values, or both. The observed segregation of apatite forms (euhedral or rounded) between samples, as well as the associated chemical

differences among the apatites, are suggestive of a chemically heterogeneous magma during crystallization of the pluton.

The resulting AHe dates indicate that samples separated by 780 vertical meters experienced contemporaneous rapid cooling below $\sim 60^{\circ}\text{C}$ between 8-11 Ma (Fig.8). Five apatite grains from three samples exhibited sufficient chemical characteristics to be considered for discussion, yielding dates ranging from 7.18 ± 0.51 Ma to 11.75 ± 0.85 Ma. AHe dates do not show a younging pattern with decreasing elevation, but rather all fall near the same age, with the middle sample (CH16-11; 3331 m) giving slightly older dates than the sample below (CH16-9; 2748 m) and above (CH16-12; 3528 m). The two grains from CH16-11 show close agreement in AHe ages (10.90 ± 1.36 Ma, 11.75 ± 0.85 Ma), while the two grains from CH16-9 are not quite within error of each other (7.18 ± 0.51 Ma, 10.20 ± 0.73 Ma). Only one grain from CH16-12 was used. A complete list of dating parameters and results is shown in Table 2, including grains that were excluded from consideration.

4.2 Thermal History Modelling

Any given AHe date can be satisfied by a large number of thermal histories, so the inverse modelling software HeFTy (Ketcham et al., 2011) was used to determine the possible thermal histories that each sample could have experienced in order to replicate the data and all geologic constraints. Within this software, geologic constraints were added to each sample in the model such as high temperatures at the time of emplacement and surface temperatures today. HeFTy then produced 10,000 random time-temperature (tT) paths that fit the geologic constraints, and depending on the associated AHe date, eU and equivalent spherical radius, the tT paths are either thrown out, considered “acceptable fits” or “good fits” depending on how well they reproduce the data. Each sample with multiple grains was modelled with HeFTy (CH16-9 and CH16-11); modelling results are shown in Fig. 9. For both samples, tT paths were forced to start at 200°C between 12-13 Ma and end at surface temperatures at present ($10\text{-}20^{\circ}\text{C}$).

For sample CH16-11, all acceptable tT paths show that the sample must have cooled below $\sim 60^{\circ}\text{C}$ by 9 Ma, with the “good fitting” tT paths suggesting cooling below that temperature even earlier by ~ 11 Ma. For the lowest sample, CH16-9, acceptable tT paths suggest that this sample must have cooled below $\sim 60^{\circ}\text{C}$ by at least 8 Ma. HeFTy was unable to produce any “good fitting” tT paths for CH16-9, likely due to the wider spread between the two AHe dates from that sample. The lack of “good fitting” tT paths for this sample suggests that the model results should not be taken as entirely robust indications of cooling past $\sim 60^{\circ}\text{C}$ by 8 Ma, and that more data is needed to reconcile the AHe dates.

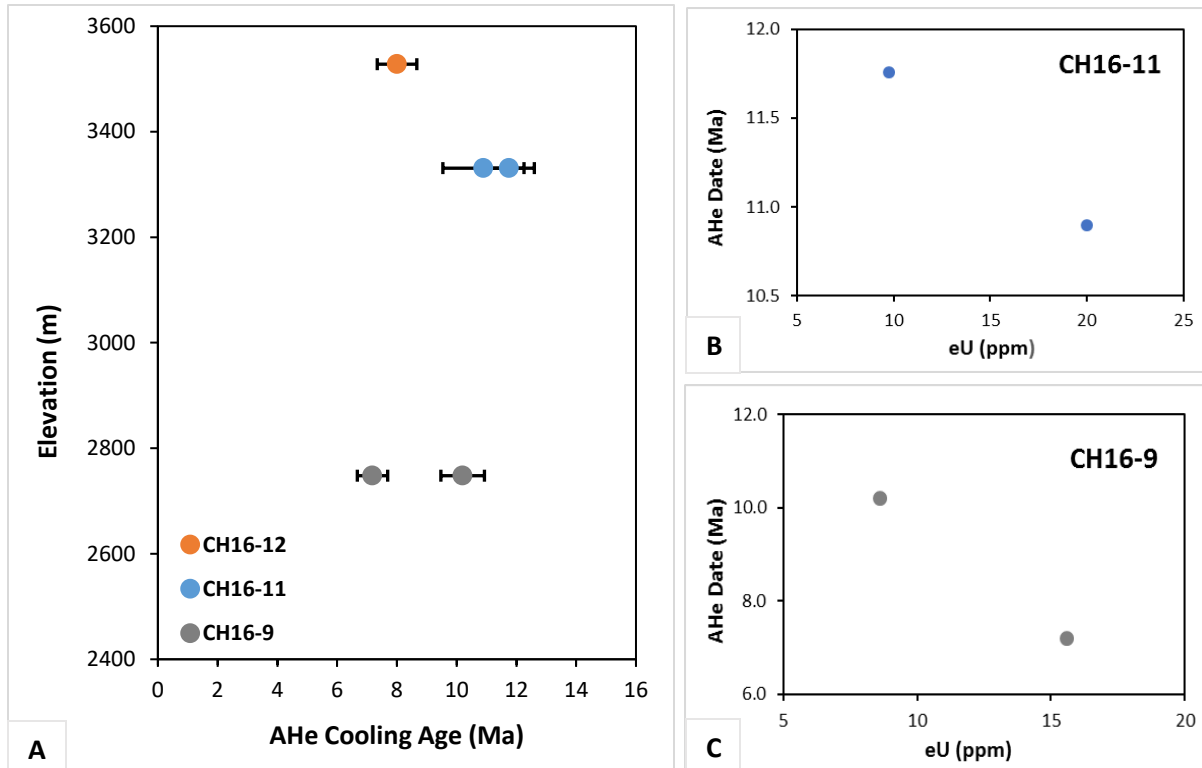


Figure 8: AHe data after excluding unreliable grains. A) Age-elevation plot of AHe data, errors are shown to 1σ . B) Date-eU plot for CH16-11. C) Date-eU plot for CH16-9. Negative trends on date eU plots indicate rapid cooling through the partial annealing zone.

Another model was run on sample CH16-9 to see if the observed AHe dates allow for recent incision in the past ~ 1.5 Ma as suggested by a basalt capped terrace in the nearby Roaring Fork River valley. This terrace (Triangle Peak), as discussed above, provides evidence of 396 m of Roaring Fork River incision in the past 1.4 Ma (Kunk et al., 2002). With their proximity to each other, one can assume similar incision was experienced at the location of CH16-9 in the Crystal River valley at the same time. The location of this sample, however, is roughly 20 km further from the confluence of the two rivers than Triangle peak, and therefore might have experienced less recent incision, perhaps only ~ 300 m. Sample CH16-9 was taken from the hillside ~ 70 m above the modern Crystal River, suggesting that this sample was at a depth of ~ 230 m before the onset of rapid incision at ~ 1.4 Ma. This depth would translate to approximately 7°C above mean annual surface temperature ($\sim 27^\circ\text{C}$), so this constraint was added to the original HeFTy model of sample CH16-9. The results (Fig. 9c) demonstrated that this more recent episode of incision is in-fact permissible with the AHe data, although no “good fitting” tT path was found for the same reasons as in the initial CH16-9 model.

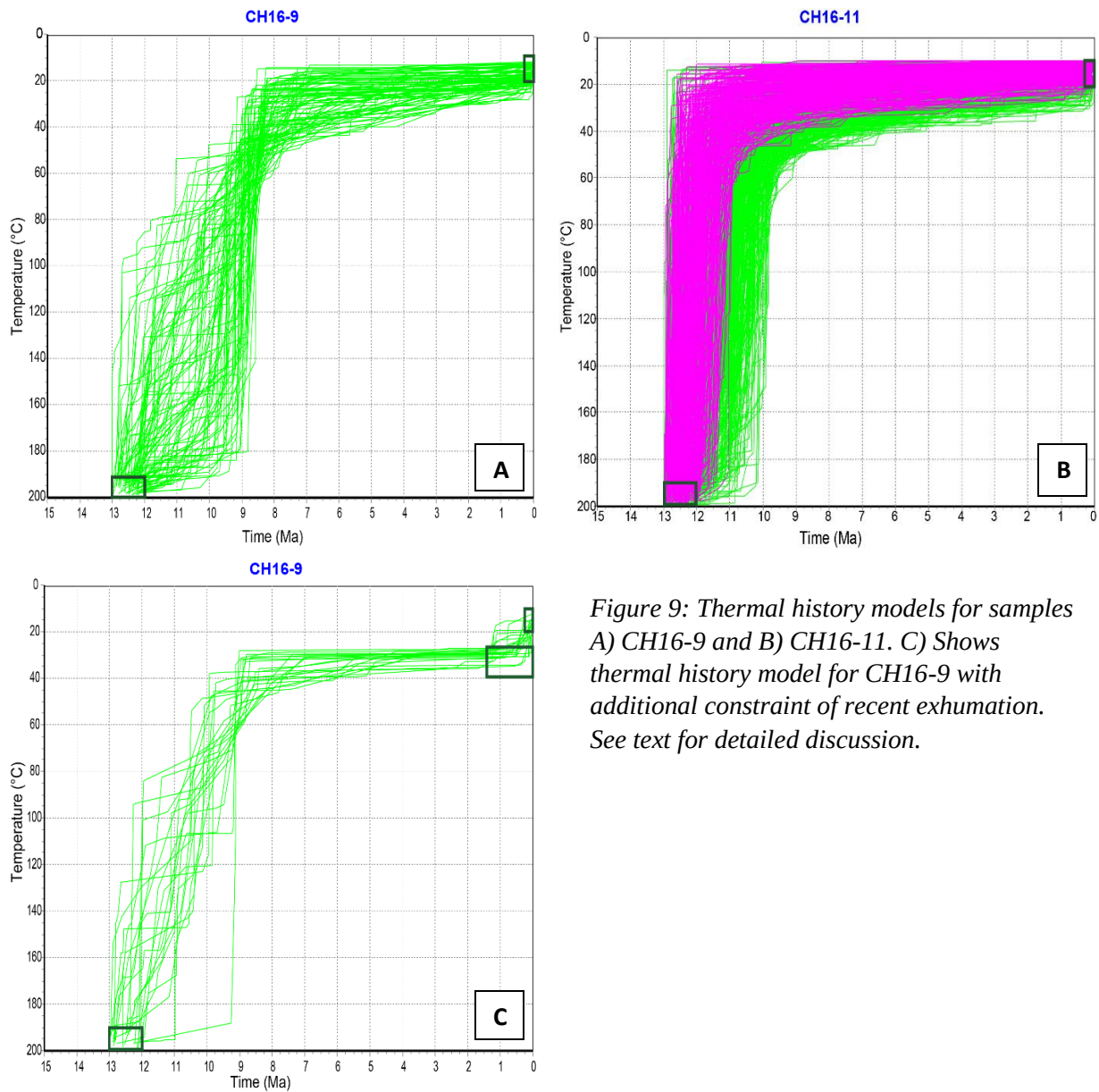


Figure 9: Thermal history models for samples A) CH16-9 and B) CH16-11. C) Shows thermal history model for CH16-9 with additional constraint of recent exhumation. See text for detailed discussion.

5. DISCUSSION

Given the limited data and its associated scatter, both the exact pattern of cooling between these three samples and their exact AHe dates should be accepted with a degree of caution. What can be said, however, is that these three samples, which are separated by 780 vertical meters, experienced relatively coeval cooling below $\sim 60^{\circ}\text{C}$ at some time between 8-11 Ma. (For the sake of the discussion below, I will refer to this coeval cooling between 8-11 Ma as occurring at ca. 10 Ma. This simplification also means that the calculated incision rates below should not be regarded with high precision.) With the wide range

in elevations between samples, there are only two reasonable scenarios that would result in the thermal histories observed in the data; either the Crystal pluton was emplaced at depth, with rapid and extensive incision unroofing the pluton to cooler than $\sim 60^{\circ}\text{C}$ at ca. 10 Ma (sometime between 8-11 Ma), or the pluton was emplaced at more shallow depths, and by the time the pluton had thermally equilibrated to the country rock at ca. 10 Ma, it was structurally above the $\sim 60^{\circ}\text{C}$ isotherm.

The first scenario certainly implies a large amount of rapid incision at ca. 10 Ma, but what implications does the thermal relaxation scenario give with regards to incision? During the thermal relaxation of a large intrusive body, the contact with the country rock should remain at a steady temperature until the pluton and country rock have equilibrated, at which point the temperatures will start to fall in a synchronous fashion. This process should occur somewhat simultaneously around the perimeter of the pluton, which would explain why samples separated by 780 vertical meters experienced contemporaneous cooling (all three samples are within ~ 80 m to ~ 200 m of the contact). This hypothesis would also suggest that thermal relaxation took a lengthy ~ 2 m.y. to take place. However, in order for the lowest sample to demonstrate similar AHe dates as the highest sample, the entire upper portion of the pluton (at least what is exposed today) must have been structurally above the ambient $\sim 60^{\circ}\text{C}$ isotherm before thermal relaxation was complete. In order to estimate any exhumation that took place before thermal relaxation, then, we must be able to estimate the minimum depth of the pluton at the time of emplacement.

Overlying parts of the Crystal Pluton is an extant sequence of sedimentary units with a total thickness up to ~ 1.8 km (Fig. 10). This thick sedimentary pile, preserving the Pennsylvanian Belden Shale through the Cretaceous Mancos Shale, is present on the northeast flank of the dome near Bear Basin. This sedimentary thickness was only measured to the axis of the overturned Schofield Syncline, which may have doubled this overlying thickness (Fig. 10). Elsewhere on the Treasure Mountain Dome, thinner sedimentary sequences are still preserved as well, such as $\sim 1,220$ m on Sheep Mountain above the lowest sample, and ~ 800 m on Crystal Peak above Bear Basin. Each of these sedimentary sequences have likely experienced extensive erosion since the formation of the Treasure Mountain Dome, so the 1,830 m preserved northeast of Bear Basin should represent a minimum thickness of sedimentary cover at 12.4 Ma.

Given that the lowest elevation sample, CH16-9, is currently ~ 1130 m below the top of the pluton, it must have been at a minimum depth of 2,960 m below the surface at 12.4 Ma. Without the occurrence of any exhumation between emplacement and thermal relaxation, this sample would have therefore been at ambient temperatures of 84°C if geothermal gradients were similar to today ($\sim 25^{\circ}\text{C}/\text{km}$; Decker et al., 1988) or at even higher temperatures of 114°C with a steeper geothermal gradient of

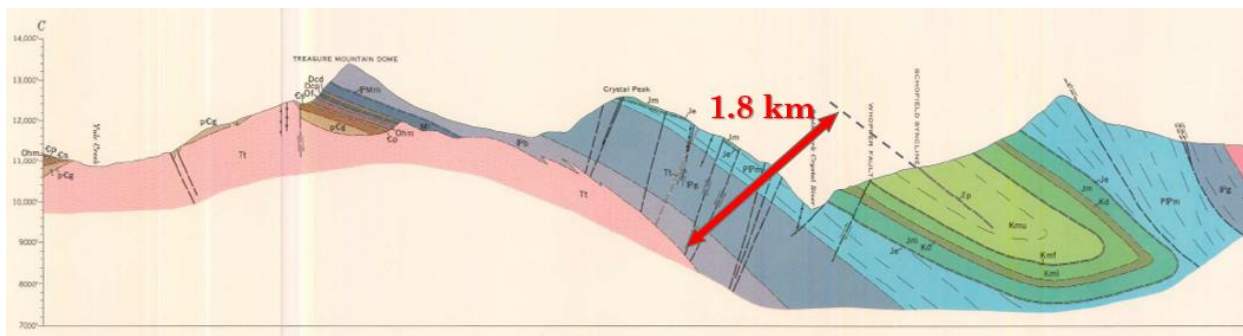


Figure 10: Cross-section of the Treasure Mountain Dome and adjacent Schofield Syncline and Elk Range Thrust. Cross-section from Mutschler, 1970.

35°C/km. If this is the case, then at least 960 m of exhumation would have had to occurred in the ~2 m.y. prior to thermal relaxation. If a higher geothermal gradient of 35°C/km is called upon, it would indicate that 1.54 km of exhumation must have occurred before thermal relaxation. Therefore, 960 m represents the absolute minimum amount of necessary incision/exhumation between 12.4 Ma and ca. 10 Ma (minimum rates of ~218 m/m.y. between 12.4 – 8 Ma). In the case that the signal we see is not one of thermal relaxation, this would simply imply a similar magnitude of incision/exhumation but over a shorter time scale (sometime between 8 - 11 Ma), suggesting even higher incision rates.

These calculations are representative of absolute minimum incision rates and magnitudes, as the sedimentary cover was likely thicker at 12.4 Ma. This is due to the proximity of the overturned Schofield Syncline and Elk Range Thrust, as well as the presence of Laramide age sediments of the Ohio Creek and Wasatch Formations preserved just south of the Elk Mountains near Crested Butte, and to the northwest in the Piceance Basin. By including these additional Laramide sediments, F.E. Mutschler, who wrote his 1968 PhD thesis on the geology of the Treasure Mountain Dome, suggested that the top of the Crystal Pluton was likely 3.5 – 4.8 km below the surface at the time of its emplacement. If these greater depths were indeed the case, up to ~4.5 km of exhumation would be necessary to cool the lowest sample below ~60°C between 12.4 Ma and ca. 10 Ma (using max depth and 35°C/km gradient). This would call for astonishing incision rates of ~1.9 km/m.y. The contact metamorphosed sedimentary units near the pluton would likely present possibilities for thermo-barometric studies, helping to further constrain the magnitudes and rates of incision.

Due to the nature of the technique, my data is unable to resolve the magnitudes and rates of incision since the cooling of my lowest sample (CH16-9) below ~60°C. With this sample currently 71 m above the modern Crystal river, anywhere between 2 km and 1.4 km of incision has occurred in the last ~10 Ma (using geothermal gradients of 25°C/km and 35°C/km respectively). The timing and duration of

this later incision has been debated, and is only constrained by previous attempts to detail incision of the Roaring Fork and Colorado Rivers.

5.2 Comparison with Existing Thermochronology Data

As mentioned earlier, Garcia (2011) collected similar low temperature thermochronology transects on six other exhumed plutons in the Elk and West Elk Mountains. Garcia's AHe and AFT data are given below in Figure 11. Garcia used the data collected in these transects to argue for two periods of exhumation in the area – the first from 25 – 15 Ma, and a second from 12 – 5 Ma. Several of the transects, namely from Ragged Mountain and Mount Sopris, were interpreted as indicating the onset of rapid exhumation between 6 – 12 Ma. Here I reinterpret Garcia's data to indicate a similar exhumation history seen at the Crystal Pluton with no need to call upon accelerated exhumation at 6 – 12 Ma.

Using the original AHe data, I have replotted the age-elevation patterns with three differences: 1) AHe dates are plotted on a grain-by-grain basis rather than as an average of the sample, 2) AHe dates are reported with $\pm 6\%$ error rather than the $\pm 3\%$ that was originally reported (which Garcia intended), and 3) the elevation of the lowest sample for Ragged Mountain is adjusted to match the location reported in her study. This new representation of Garcia's AHe data is shown in Figure 11. Similar to the Crystal Pluton, a period of relatively rapid exhumation is seen centered around 8 – 11 Ma, possibly extending before and after that time (7 – 13 Ma). This data cannot resolve when this exhumation event began or ended, as we are limited by the exposure of exhumed granite. When combined with my data from the Crystal Pluton, it is clear that relatively rapid exhumation between 8 – 11 Ma is not restricted to the Treasure Mountain Dome, but is instead a phenomenon seen throughout the Elk and northern West Elk Mountains. Plutons in the southern portion of the West Elk Mountains such as Mount Gunnison and East Beckwith Mountain were exhumed earlier in the Oligocene/early Miocene, likely due to their shallower emplacement stratigraphically (Fig. 4). When represented in this manner, the AHe data does not call for an increase in exhumation rates from 6 – 12 Ma.

5.3 Post-10 Ma River Incision

The low temperature thermochronology presented in Garcia's 2011 study and this study is unable to resolve the last 1 – 2 km of river incision of the Colorado River and its tributaries. To constrain the timing and pace of this most recent incision, we must refer to previous studies. Of interest are studies

utilizing basalt and associated river gravels in western Colorado, as well as those detailing alluvial fans and strath terraces near Rifle, Colorado.

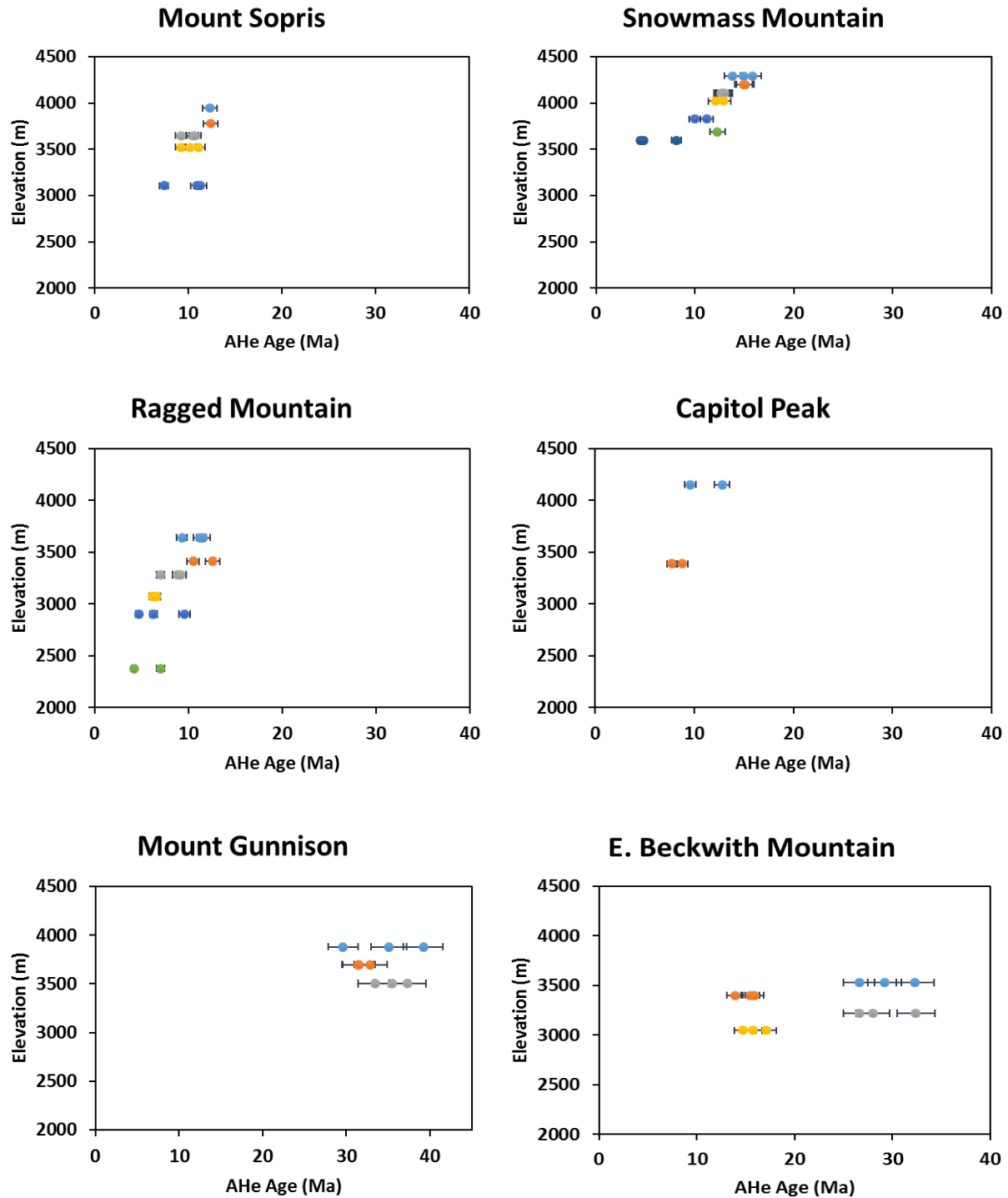


Figure 11: Re-plotting of AHe data from Garcia (2011). See text for discussion.

5.3.1 Data from Basalt Flows

To the north and west of the Elk/West Elk Mountains are several Miocene aged basalts that record the surface topography at the time of their extrusion. Many of these basalts have been locally deformed and lowered by evaporate tectonism associated with the Carbondale and Eagle Valley collapse centers (Fig.12). Several basalt flows lie outside of these collapse areas, however, and have been used to reconstruct paleo-topography. Of particular interest is the dissected volcanic plateau that constitutes the summit of the Flat-Tops mountains north of the town of Glenwood Springs. Here, 24 – 20 Ma basalts are interfingering with fluvial sediments of the Brown's Park Formation, indicating that these basalts were extruded into the lowest part of the paleo-landscape. These basalts are directly overlain by younger, 14 – 9 Ma basalts, suggesting that little incision had taken place between the two phases of volcanism (Larson et al.,1975). A series of similar basalt remnants are preserved nearby in areas such as Grand Mesa, Battlement Mesa, and Basalt Mountain. These basalts all have similar ages (ca. 10 Ma) and elevations (~3,000 – 3,300 m). When combined with the field relations seen at the Flat-Tops, these widespread basalts give evidence that a low relief surface had developed in northwestern Colorado by at least ca. 10 Ma – the so-called Steamboat Basin of Larson et al., (1975). It is clear that an ancestral Colorado River flowed through this low relief landscape by ~11 Ma, as evidenced by Colorado River gravels preserved below the ca. 11 Ma basalt flows of Grand Mesa. River gravels above the Grand Mesa basalts indicate that the Colorado River likely re-established its course on top of those basalts by ~ 9 Ma (Aslan et al., 2010).

Subsequent basalt flows have been noted in Glenwood Canyon that record incision into this low relief surface. On the south rim of Glenwood Canyon are the ca. 8-7 Ma basalt flows of Little Grand Mesa, which have a basal elevation of ~2650 m (Aslan et al.,2010). These basalt flows do not directly overly any Colorado River gravels, but their elevation could reflect several hundred meters of erosion between 10 and 8 Ma. Slightly below the base of the Little Grand Mesa flows is Spruce Ridge, which is capped by Colorado River gravels at an elevation of ~2605 m (Kunk et al., 2002). Basalt boulders on top and adjacent to the river gravels give ages of 7.8 Ma, indicating the Little Grand Mesa basalt as a source and providing a maximum age for the Colorado River gravels. Just east of Spruce Ridge on the south side of the canyon is Gobbler Knob, a remnant of a 3.0 Ma basalt flow at an elevation of 2524 m. These flows are not associated with any river gravels, and therefore do not definitively indicate the lowest point in the paleo-canyon. Within Glenwood Canyon, the next data point for the river's elevation is the ca. 640 ka Lava Creek B ash that overlies Colorado River Gravels near Dotsero. These river gravels now sit ~85 m above the current river level (Aslan et al., 2010; Kunk et al., 2002).

The basalt or ash capped river gravels preserved at Basalt Mountain, Spruce Ridge and Dotsero provide time constraints for the incision of the Colorado River. The basalt flow of Gobbler Knob, however, does not necessarily mark the bottom of the canyon at 3 Ma. Excluding Gobbler Knob as an incision datum, authors have suggested that the Colorado River has been incising at a steady rate of ~ 100 m/m.y. for the last 10 Ma (Aslan et al., 2010). If Gobbler Knob is included as a data point, however, it appears that the Colorado River went through a period of slow canyon cutting (24 m/m.y.) prior to 3 Ma, with accelerated incision (242 m/m.y.) since that time (Kirkham et al., 2001; Kunk et al., 2002). Whether the 3 Ma basalt flow was extruded on or close to the bottom of the paleo-canyon is up for interpretation. Upstream from Glenwood Springs on the Roaring Fork River, the ca. 1.4 Ma basalt flow on Triangle Mountain overlies Roaring Fork river gravels at an elevation of 2560 m, 396 m above the current river level (Kunk et al, 2002; Larson et al., 1975). The existence of these gravels necessitates an average incision rate of 291 m/m.y. in the last ~ 1.4 Ma, and therefore supports the proposed increase in incision rates at 1.5 – 3 Ma.

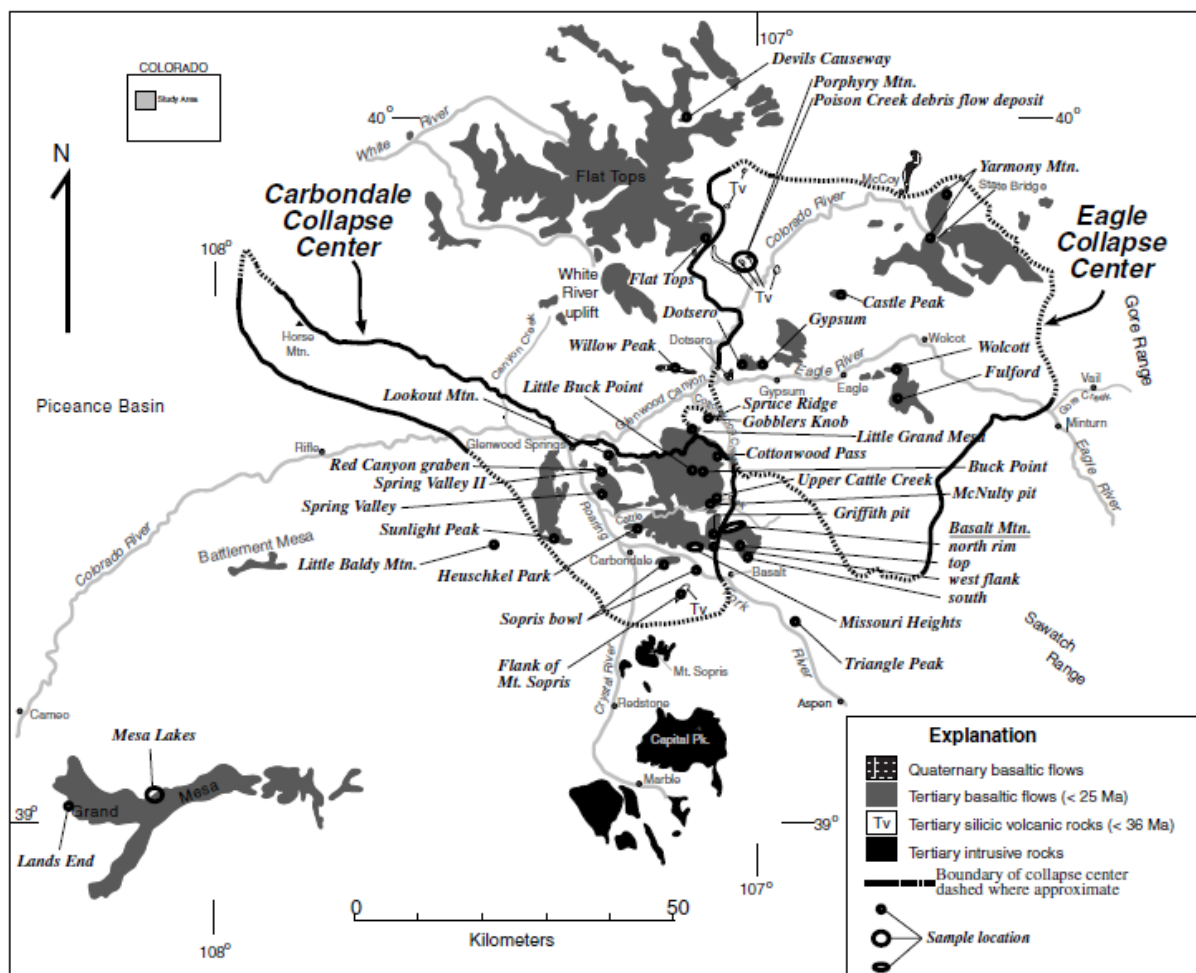


Figure 12: Regional map of basalt flows used in river incision studies. Intrusive plutons of the Elk Mountains can be seen in black at the bottom/center of the map. (Kunk et al., 2002)

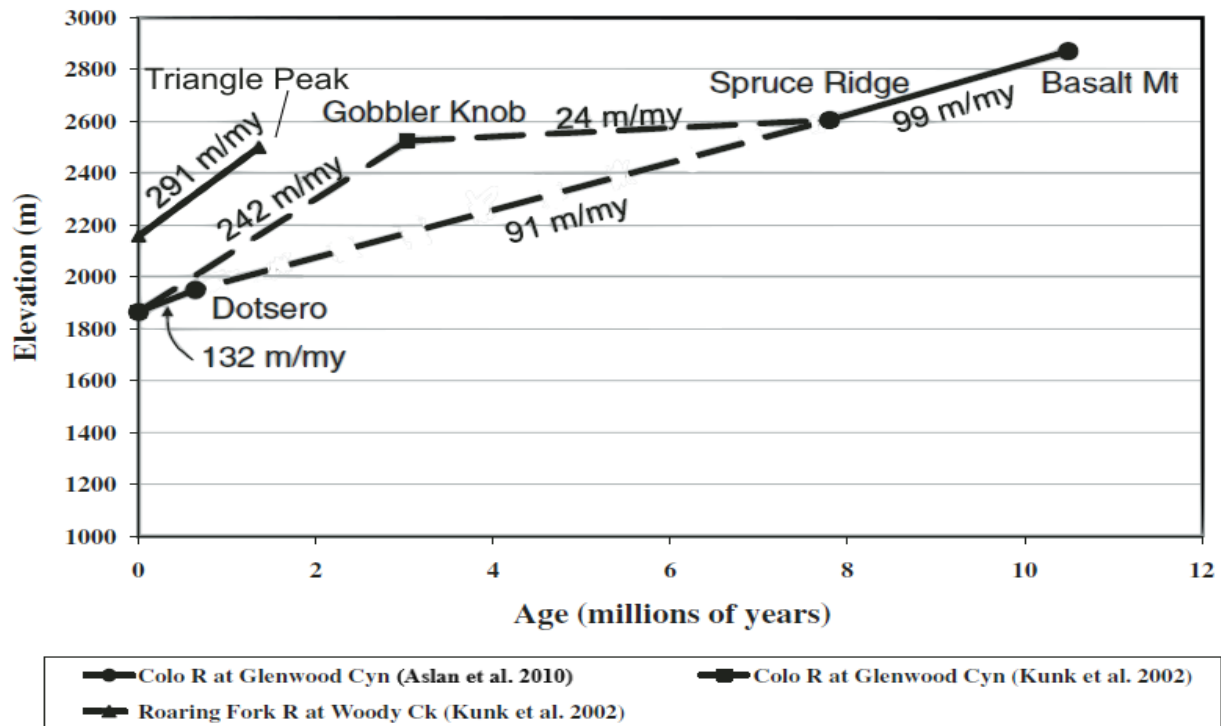


Figure 13: Illustrates the apparent rates of Colorado River incision through Glenwood Canyon using the basalt flows discussed in the text. Dashed lines show the two diverging hypothesis derived from including or excluding Gobbler Knob as an incision datum. (Modified from Aslan et al., 2010)

5.3.2 Colorado River Terraces & Alluvial Fans at Battlement Mesa

A spectacular series of strath terraces and alluvial fans are preserved just south of Rifle, Colorado, on the north flanks of Battlement Mesa. Colorado River gravels were laid down and subsequently buried by alluvial fans from Battlement Mesa, preserving the level of the Colorado River at the time of deposition (Berlin et al., 2008). Based on common heights above the modern river, six levels of strath terraces & alluvial fans have been recognized, as well as a 20 m high terrace north of the river near Rifle. Three of these strath terraces have been dated to produce incision rates. The Grass Mesa terrace, which sits 225 m above the modern river level, gives a cosmogenic $^{26}\text{Al}/^{10}\text{Be}$ age of $1.77 \pm 0.71/-0.51$ Ma (Berlin et al., 2008). This gives an average incision rate of 127 m/m.y. since that time. Subsequent authors have suggested that the terrace should be measured from a lower datum 169 m above the modern river, resulting in more moderate rates of 95 m/m.y. (Aslan et al., 2010). Marrisania Mesa, which sits lower at 94 m above the modern river, has a cosmogenic radionuclide date of $440 \text{ ka} \pm 300 \text{ ka}$, which gives an average incision rate of 214 m/m.y. (Aslan et al., 2010). The unnamed 20 m terrace near Rifle has an optically stimulated luminescence (OSL) age of $>88 \text{ ka}$, lending to recent incision rates of

227 m/m.y. (Aslan et al., 2010). The incision rates calculated from these terraces do not appear to be steady over the last ~10 Ma. Instead, it appears that more rapid incision has taken place in the last million years or so. Future work on these terraces could certainly improve our understanding of recent Colorado River incision.

6. CONCLUSION

The AHe data presented in this paper suggest that the Treasure Mountain Dome, cored by the Miocene Crystal Pluton, experienced extensive exhumation and incision by the Crystal River between 12.4 Ma and ca. 10 Ma. Exhumation related to river incision had a minimum magnitude of 960 m in that timeframe, with minimum rates of at least 218 m/m.y. Exhumation and incision rates were likely much higher, and could have been as much as ~2 km/m.y. depending on the amount of overburden at the time of the Crystal Pluton's emplacement. Agreement with previous AHe data in the Elk and West Elk Mountains taken by Garcia (2011) shows that this period of rapid exhumation was experienced throughout the Elk and northern West Elk Mountains. The onset of this exhumation is not well constrained, and could have initiated much earlier in the lower Miocene or Upper Oligocene. This episode of exhumation and incision could have been enhanced by the uplift induced by isostatic unloading.

Field relations of basalt flows and alluvial sediments in northwestern Colorado indicate that the Colorado River did not undergo extensive incision until 9 – 10 Ma. This observation suggests that the exhumation and incision seen in the Elk and West Elk Mountains was not driven by incision of the Colorado River. Instead, I suggest that the Elk and West Elk Mountains were topographically much higher than the low relief landscape to the northwest, and that the exhumation seen in my data was driven by the leveling-off of that high topography. Sediments brought in by the Elk Range Thrust and associated Schofield syncline, as well as extensive Oligocene volcanism, would have contributed to this high topography.

The last 1 – 2 km of incision in the Elk and West Elk mountains could have been driven by the incision of the Colorado River, as it has experienced ~1.5 km of incision over the past 9 – 10 Ma. Although more work needs to be done to constrain the timing of this incision, previous work suggests that incision of the Colorado River has increased in the past 1 – 3 Ma. Since incision has not been steady for the past 9 – 10 Ma, there is no need to call upon mantle-driven epeirogenic uplift as an explanation. Rather, it seems more realistic that climate change has been a major driver for recent incision.

ACKNOWLEDGMENTS

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APPENDIX

Table 1. Sample collection information

Sample	Rock Type	Location		
		Latitude	Longitude	Elevation (m)
CH16-8	Soda granite porphyry	39.0602°	-107.1399°	2656
CH16-9	Soda granite porphyry	39.0565°	-107.1188°	2748
CH16-10	Soda granite porphyry	39.0421°	-107.0982°	3155
CH16-11	Soda granite porphyry	39.0348°	-107.1040°	3331
CH16-12	Soda granite porphyry	39.0305°	-107.1086°	3528
CH16-13	Soda granite porphyry	39.0273°	-107.1079°	3668

Table 2: Apatite (U-Th)/He data from Crystal Pluton

Sample	Grain	Mass	r ^a	He	U	Th	Sm	eU ^b	Raw Date	Ft ^c	Date	1σ ^d
		(μg)	(μm)	(nmol/g)	(ppm)	(ppm)	(ppm)	(ppm)	(Ma)		(Ma)	(Ma)
CH16-8	a1	0.74	33.27	0.228	11.75	6.16	0.83	13.2	3.20	0.597	5.37	0.80
	a2	0.68	28.65	1.896	7.78	32.78	27.16	15.5	22.27	0.502	43.82	9.64
	a3	0.52	28.30	0.220	7.66	1.99	0.79	8.1	5.02	0.527	9.52	2.75
CH16-9	a1	7.97	67.01	0.398	2.84	26.06	44.87	9.0	7.85	0.769	10.12	0.72
	a2	4.31	50.95	0.444	5.60	42.48	60.37	15.6	5.09	0.702	7.18	0.51
	a3	2.73	44.53	0.341	4.00	19.63	54.20	8.6	6.96	0.670	10.20	0.73
	a4	2.36	45.48	0.661	0.00	0.00	0.00	0.0	0.00	0.694	0.00	0.00
	a5	2.62	41.48	0.810	11.17	82.51	79.68	30.6	4.79	0.632	7.51	0.91
CH16-10	a1	7.58	67.98	0.017	1.12	6.29	0.08	2.6	1.20	0.778	1.55	0.16
	a2	7.71	77.34	0.014	0.20	6.95	0.11	1.8	1.38	0.794	1.73	0.23
	a3	5.15	63.73	0.086	6.98	53.71	0.00	19.6	0.81	0.763	1.06	0.08
	a4	2.22	48.44	0.083	0.28	10.22	1.44	2.7	5.68	0.679	8.34	0.95
	a5	2.78	55.14	0.075	1.07	3.83	0.11	2.0	6.99	0.733	9.53	1.17
CH16-11	a1	2.36	49.19	0.469	1.25	36.41	81.03	9.8	8.25	0.687	11.75	0.85
	a2	1.58	39.26	0.940	5.41	34.60	63.94	13.5	12.32	0.624	19.41	2.03
	a3	1.00	33.14	0.729	11.53	36.19	119.88	20.0	6.41	0.574	10.90	1.36
CH16-12	a1	1.73	43.94	0.978	0.77	141.89	72.73	34.1	5.18	0.642	8.00	0.66
	a2	4.39	63.88	0.096	0.22	1.54	0.12	0.6	30.13	0.762	39.48	5.84
	a3	0.69	34.61	0.651	0.34	5.81	0.15	1.7	69.96	0.564	123.72	29.40
	a4	1.44	44.09	0.085	1.52	8.22	0.50	3.5	4.52	0.663	6.80	0.92
	a5	3.80	65.03	0.066	0.04	2.05	0.14	0.5	23.18	0.749	30.94	5.15
CH16-13	a1	12.27	91.47	0.002	0.30	3.76	0.07	1.2	0.32	0.829	0.39	0.30
	a2	12.22	85.30	0.004	0.08	3.69	0.03	1.0	0.82	0.813	1.01	0.39
	a3	10.43	80.85	0.002	0.20	1.97	0.00	0.7	0.69	0.809	0.85	0.62
	a4	10.46	79.91	0.003	0.13	1.05	0.01	0.4	1.65	0.808	2.05	0.75
	a5	1.93	48.63	0.036	0.22	2.08	0.00	0.7	9.33	0.688	13.56	4.02

^a equivalent spherical radius^beU - effective uranium concentration, weights U and Th for their alpha productivity, computed as [U] + 0.235 * [Th]^cFt is alpha-ejection correction of Ketcham et al., (2011)^dAnalytical uncertainty based on U, Th, He, and grain length measurements**Bold samples and data indicate use in analysis and discussion**

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