

Using Apatite (U-Th)/He Thermochronology
to Determine Exhumation Rates and the Topographical History
of the Elk Mountains

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Abstract

Low temperature AHe thermochronology shows that Gothic Mountain, at the center of a bull's-eye of exhumation in the Elk Mountains, was rapidly exhumed between 9 and 14 Ma. This is consistent with previous thermochronological studies of the Elk Mountains and supports the idea that the Elk Mountains underwent a centralized exhumation far more intensely than the surrounding areas. This project unexpectedly discovered how Miocene surface elevations in the Elk Mountains were spatially varied and how this can have an influence on thermochronological data.



Figure 1. Looking east of Gothic Mountain within the Elk Mountains, October 12, 2019.

1. INTRODUCTION

The Elk Mountains in the Rocky Mountains have an enigmatic history much like the Rockies as a whole. The Elk Mountains are located in west central Colorado running northwest to southeast and lie roughly between the White River uplift and Grand Hogback monocline to the north, the Gunnison Uplift to the south, Piceance Basin to the west and the Sawatch Range to the east (Tully, 2009). The Elk Mountains consist of Oligocene and Miocene plutons that intrude Paleozoic and Mesozoic sediment. The difference in elevation between peaks and valleys in the Elk Mountain Range can be as high as 1200 m, emphasizing high amounts of erosion have taken place since the emplacement of these plutons (McCorkel, 2017).

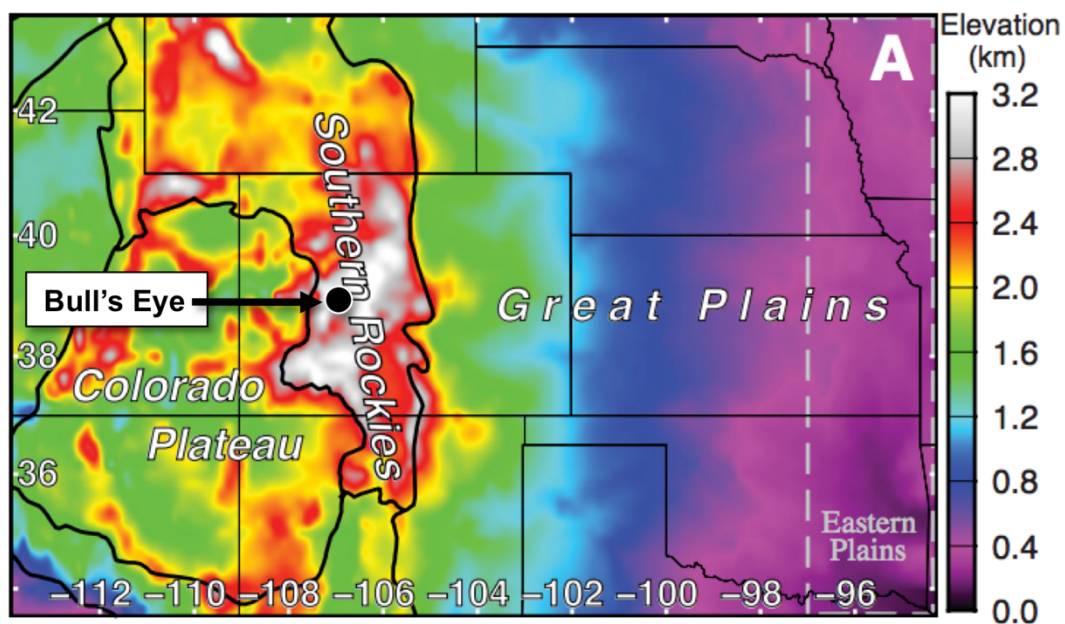


Figure 2. Modified from Levandowski, 2018, showing the bull's-eye of exhumation in the Elk Mountains (Kelleher, 2020).

Causes of exhumation in the Rockies as a whole is keenly contested. Karlstrom et al. (2012) argue that surface uplift of the range increased the levels of erosion and exhumation and was caused by the mantle's dynamic convection. England and Molnar (1990) suggest that cooling climates caused an increase in the amount of storms creating greater levels of erosion; one such example may be: the formation of the Colorado river basin and its tributaries lead to

greater levels of erosion and exhumation (Pederson et al., 2002). These hypotheses are not mutually exclusive and do provide reasons for widespread exhumation in the Rocky Mountains but do not explain how exhumation is spatially restricted in the Elk Mountains.

Centralized plutons in the Elk Mountains have been exhumed from 1-2 km in the last 8-16 Ma. Outside the perimeter, exhumation of that magnitude occurred much earlier (greater than 40 Ma). It is important to confine properly this perimeter to better determine valuable information as to the rates and causes of erosion in The Elk Mountains. The further collection of data added will help develop the understanding of the geological evolution of this bull's-eye and western Colorado as a whole.

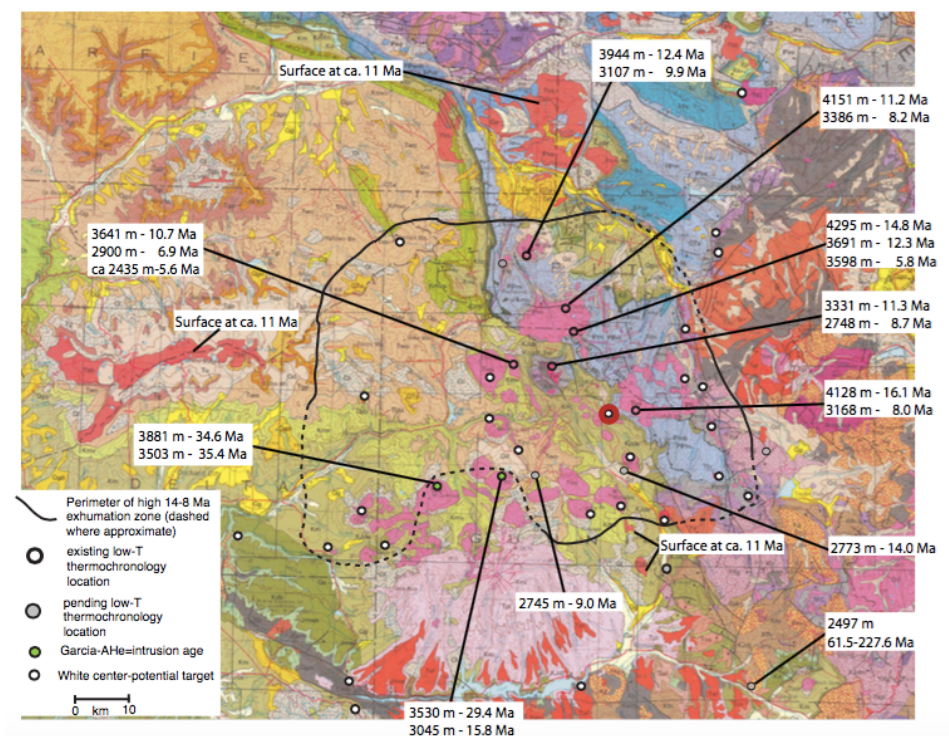


Figure 3. Elk and West Elk Range Bull's Eye of exhumation; Gothic Mountain site is circled red (Abbott, 2020).

This thesis is adding to the work currently being undertaken by Dr. Lon Abbott, Dr. Rebecca Flowers, and Dr. James Metcalf of the University of Colorado, Boulder, which is

building upon Garcia's 2011 Master's thesis.

The project raised one primary hypothesis, that Gothic Mountain was one of the most recently exhumed plutons within the bull's-eye and the erosion rate at Gothic Mountain is one of the fastest within the bull's-eye (Figures 1,2, 3).

Two secondary hypothesis be tested a) the tilting of the Gothic Mountain laccolith happened before exhumation and b) the glacial cutaway on the north eastern side of Gothic Mountain had more of an effect on the exhumation ages than standard vertical erosion.

2. BACKGROUND

2.1 Geologic History

The Colorado Rocky Mountains contain complex structures, profitable mineral deposits, and expansive magmatism due to a dynamic formation. The main Phanerozoic events that culminated in the formation of the Rocky Mountains were, the mid-Cretaceous Western Interior Sea Way, the Late-Cretaceous to Paleocene Laramide orogeny, the Eocene to Miocene ignimbrite flare up, and the Rio Grande rift, which began about 29 Ma and continues today (Chapin and Cather, 1994).

The Ancestral Rockies were uplifted in the Pennsylvanian, later during the late Cretaceous period the Western Interior Seaway (WIS) was formed. The sea would constantly undergo transgressions and regressions depositing multiple formations such as The Mancos Formation, the upper member of which encases the Gothic Mountain laccolith (Gaskill et al., 1967). In the Gothic Mountain area, The Mancos Shale is at its thickest of about 1300 m. The WIS had subsided by 71 Ma (Bryant, 1988).

The Laramide orogeny is the mountain building event that is responsible for most of the formation of the Rockies we see today, it took place 73 Ma to 43 Ma (Abbott and Cook, 2012). In subduction zones, it is rare to find the subsequent continental uplift so far inland from the plate boundary; this conflicts conventional tectonic models (Jones et al., 2011). The widely regarded theory to explain it is the shallow subduction of the Farallon plate, where it caused uplift 1000 km inland and created Elk Range thrust and the Castle Creek fault. Figure 4 illustrates how the Farallon plate subducted shallowly to create

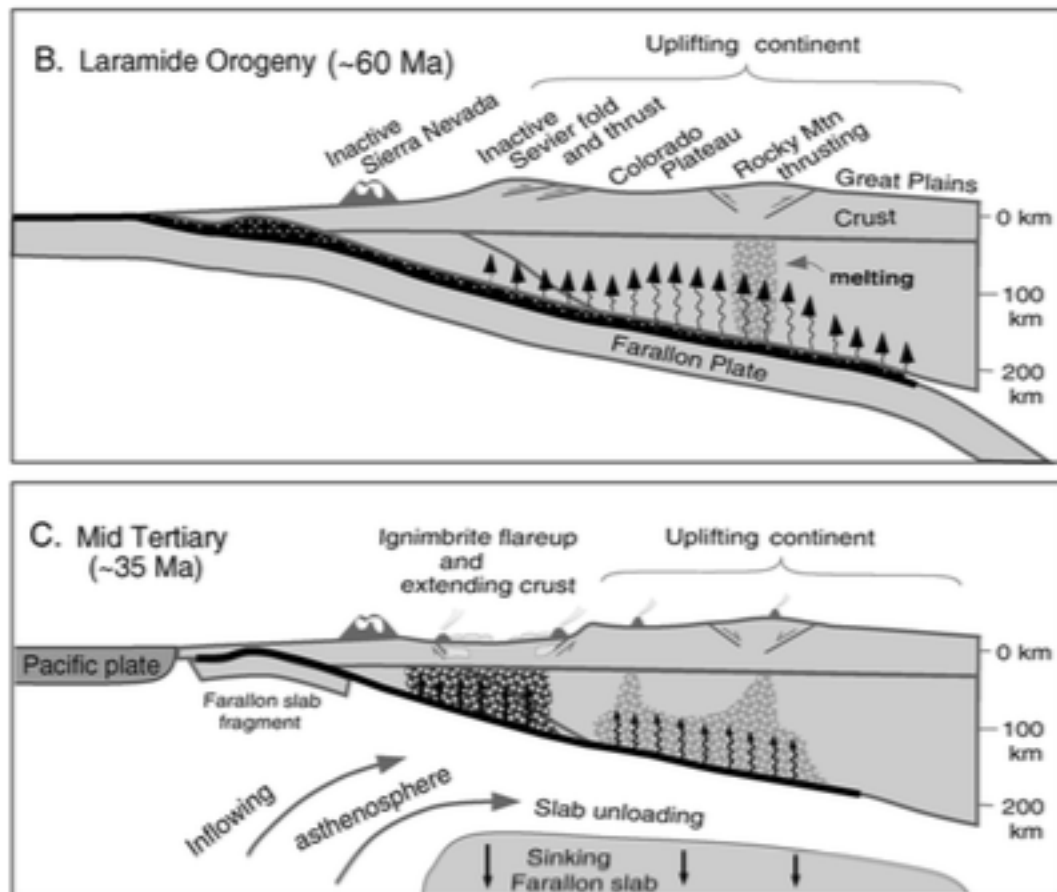


Figure 4. Showing process of shallow subduction of the Farallon Plate and subsequent Ignimbrite flare-up (Humphreys et al. 2003).

After the Laramide orogeny ended, 43Ma, the subsidence of the Farallon plate gave rise to one of Earth's most dramatic periods of magmatism, the ignimbrite flare-up (Figure 4). As the

underlying Farallon plate became cooler and sank into the asthenosphere below the North American Plate, warmer material from the asthenosphere rose and mixed with the hydrated lithospheric material above. This interaction caused much of the lithospheric material to melt and large volumes of magma rose to create extensive Oligocene intrusions in The Elk and West Elk Mountains as well as the volcanic fields in San Juan Mountains (Farmer et al., 2008). This event caused the intrusion of The Elk Mountains' plutons between 38-24 Ma (Humphreys et al., 2003).

The Rio Grande rift, has been thinning the continental crust under the Elk Mountains for the past 29 million years (Keller, 1999). This created Miocene mafic magmatism 18-9 Ma and has maintained high levels of geothermal heat in the Rockies.

2.2 Previous Thermochronological Work

In 2011, Garcia tested the cooling histories of seven plutons in the Elk and West Elk Mountains using various thermochronological methods (Figure 5). Garcia found that the northern plutons as shown in figure, were emplaced (~29 Ma) more than 2 km below the surface. The southern plutons cooled very quickly after emplacement, this shows that they were emplaced at a shallow depth <1.5 km. Garcia also found that the northern plutons underwent a more recent rapid exhumation 12-5 Ma (Figure 6). These northern plutons lead to the idea that there is a bull's-eye of rapid exhumation in the Elk Mountains. This period of rapid exhumation in the Elk Mountains was also supported by two honors theses at CU Boulder by Hiatt (2017) and McCorkel (2017). Hiatt calculated the exhumation rate caused by the Crystal River (~ 10 km northwest of Gothic Mountain) to be a minimum of 218 m/m.y. McCorkel determined that the exhumation rate of the White Rock pluton (~8 km east of Gothic Mountain) to be 181 m/m.y.

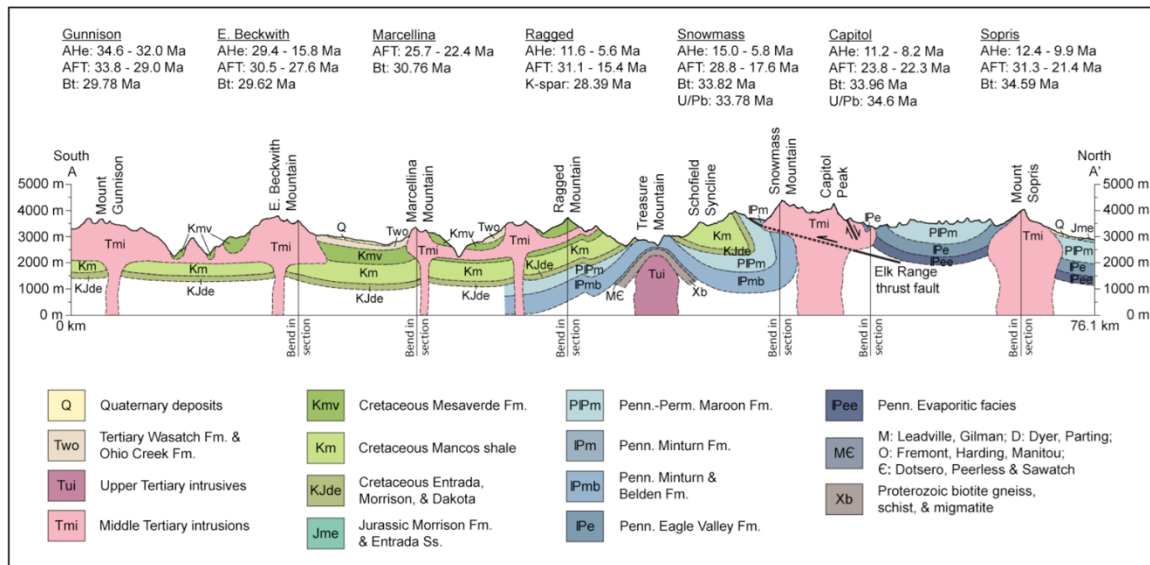


Figure 5. Taken from Garcia, 2011, showing seven transects measured. Note the young exhumation dates of the northern sample sites in the Elk Mountains.

2.3 Gothic Mountain

Gothic Mountain is a Tertiary laccolith found at the heart of this bull's-eye of exhumation. It was formed by intrusion of granitic magma from the lower crust into the uppermost member of The Mancos Shale 29 Ma (Garcia, 2011). Gothic, its encapsulating sills, and sedimentary beds are tilted westwards. Its centralized location will provide much needed evidence on the homogeneity of exhumation throughout the bull's-eye. It will be interesting to contrast the data from the samples found in the sills above and below Gothic Mountain to the samples from the laccolith itself; this provides for some interesting hypotheses.

Gothic Mountain was chosen as the study site for this thesis as it would provide valuable insight to the extent of exhumation and the erosion rate at the center of the bull's-eye.

Previous data north, east, south and west of Gothic Mountain all have middle Miocene AHe ages which are much younger than the emplacement ages for each pluton. This means that the rock which gave these data was emplaced where the geothermal temperature was above

70°C. The geothermal gradient at Gothic Mountain has been tested to be about 40°C/km (Table 1) assuming that the geothermal gradient was constant over time, this would mean the 70°C geothermal region would be roughly 1.75km deep. Using AHe thermochronology we can determine how long ago the samples from Gothic Mountain crossed below this temperature region and if this is consistent with the other AHe data from within the bull's-eye. By comparing each samples elevation and the age of cooling the erosion rate can be calculated. If we compared this data with the other plutons in the area, it will show how central Gothic Mountain is in this bull's-eye.

Gothic Mountain is tilted to the west and this thesis is looking to test if the laccolith was tilted before exhumation or not (Figure 6). This can be determined by comparing how AHe ages change stratigraphic and vertically. If tilting happened after exhumation then the highest elevation sample will be the oldest and the lowest elevation sample will be the youngest. If tilting happened before exhumation then the stratigraphically highest but lower sample in topographic comparison (CH16-3) would be older than the stratigraphically lower but topographically highest sample (LA19-23). Thermochronological studies normally do not take tilting into account (Abbott, pers. comm., 2020). Testing this could show how influential tilting can be on thermochronological data.

The Rockies are filled with U-shaped valley's which are a result of glaciation. It is undetermined whether or not glacial erosion influences the thermochronology of samples by the lateral retreat of a glacial cirque headwall. The northern and eastern slopes of Gothic Mountain have glacial cutaways meaning the influence of glaciers on exhumation ages can be tested (Figure 7).

Gothic Mountain also is a useful study site as the modern geothermal gradient is known unlike at many of the other testing sites in the bull's-eye.

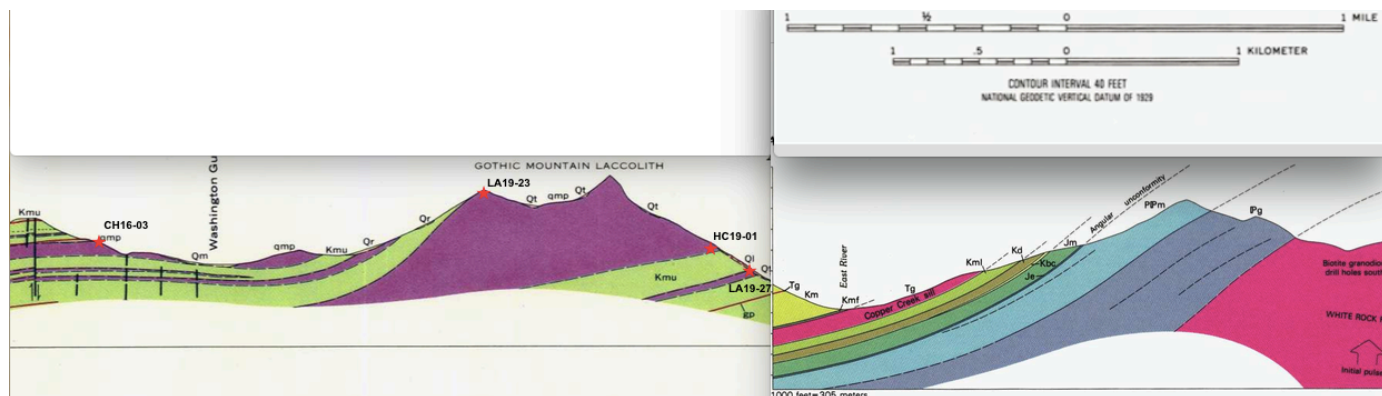


Figure 6. Geologic cross-section of Gothic Mountain showing the western tilt. Sample stratigraphical locations are shown. Modified from Gaskill et al., 1967 and Gaskill et al., 1991.

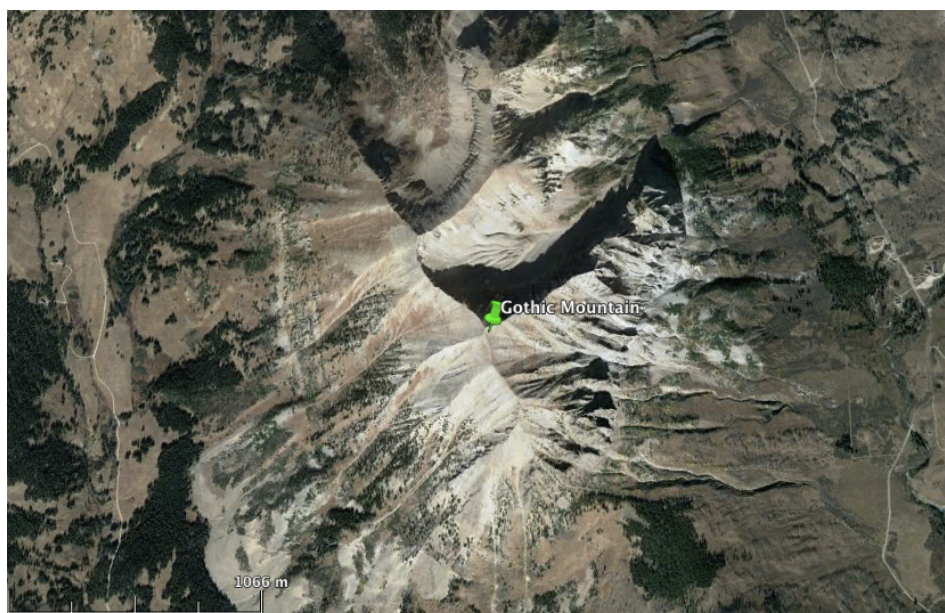


Figure 7. Image showing north eastern glacial cut-away, Google pro 2020.

3. METHODS

3.1 Thermochronology

Determining the cooling history of a rock can be done by using apatite (U-Th)/He thermochronology. If the geothermal gradient is known, as it is for Gothic Mountain (Table 1), the extent of exhumation can also be determined. Radiometric dating of apatite examines, through alpha decay, the ratio of the parent atoms, U, Pb and Sm to He daughter atoms. Alpha decay is where a He atom with two protons and two neutrons is ejected from a radioactive particle. When the radioactive decay takes place the daughter He atom is launched through built up kinetic energy about 20 μm in a random direction through the apatite crystal. when alpha decay happens within apatite crystals, if the crystal has a temperature $> \sim 70^\circ\text{C}$, the He atom will diffuse out and be lost. If the crystal is at temperature $< \sim 70^\circ\text{C}$ the He daughter atom will not escape the apatite crystal; $\sim 70^\circ\text{C}$ is apatite's closing or blocking temperature, and the He atom will remain within the crystal lattice. One can compare the blocked and retained He atoms to the initial parent atoms to determine the time in which the mineral crossed below the closure temperature. This is possible as after the mineral crosses below the closure temperature the ratio of He daughter atoms to the radioactive parent atoms increases. The ratio is proportional to the age. AHe dates can be calculated using the methods described in Ketcham and Hanna (2011). Given the geothermal gradient, and this parent to daughter ratio, one can determine what depth the mineral was when it passed through the closing temperature.

Table 1. Geothermal gradient at Gothic (Decker et al., 1988)

Locality	Map code	North Latitude (DD)	West Longitude (DD)	Elevation (m)	Depth Range (m)	Thermal Conductivity (W/mK)	Geothermal Gradient (°C/km)	Heat Flow (mW/m ²)
Gothic	GOT1	38.988	106.945	3250	220 - 860	3.29	39.2	112
	GOT2	38.988	106.945	3232	300 - 380	3.59	36.5	108
	GOT3	38.988	106.945	3262	160 - 680	3.41	39.0	105
							Mean values:	108

3.2 Samples

Gothic Mountain is located in the Gunnison national forest 1.5 km southwest of the town of Gothic. Gothic mountain's 12,631 ft peak is a popular hiking destination, which made the hiking route north of the peak an ideal place to collect a vertical transect. Sample locations can be seen on Figure 8.

Lon Abbott collected a sample from the summit of Gothic Mountain in 2019 (LA19-23). Summit samples are very important as they tend to provide the oldest AHe date, or the bottom boundary, to be compared with lower, normally more recently exhumed, samples to calculate the exhumation rate.

One sample was collected from the Elkton Sill by Coleman Hiett in 2016 (CH16-03), the highest stratigraphically but not topographically. This is the most western sample and its topographical and stratigraphical relationship with LA19-23 will provide excellent information as to whether or not tilting occurred before or after exhumation. If tilting happened before exhumation then the stratigraphically highest but lower sample in topographic comparison (CH16-3) would be older than the stratigraphically lower but topographically highest sample (LA19-23).

One sample was collected by Lon Abbott in the sill stratigraphically below the Gothic

Mountain laccolith about 2.8 km north of Gothic Mountain's peak (LA19-27). This sample would be helpful in determining the tilt exhumation timings and is the lowest stratigraphically and vertically which is useful for calculating exhumation rates.

The last sample was collected by Hector Camm in 2019 at the eastern base of the laccolith that is exposed due to glaciation (HC19-01). This sample was collected to see if lateral erosion produced by the lateral retreat of a glacial cirque headwall had a greater effect on the exhumation ages than standard vertical erosion. The samples was taken from the base of a glacial cutaway so if the exhumation ages were older than expected (close to LA19-23's ages), this could suggest that the lateral retreat's influence on exhumation ages should be considered more seriously.

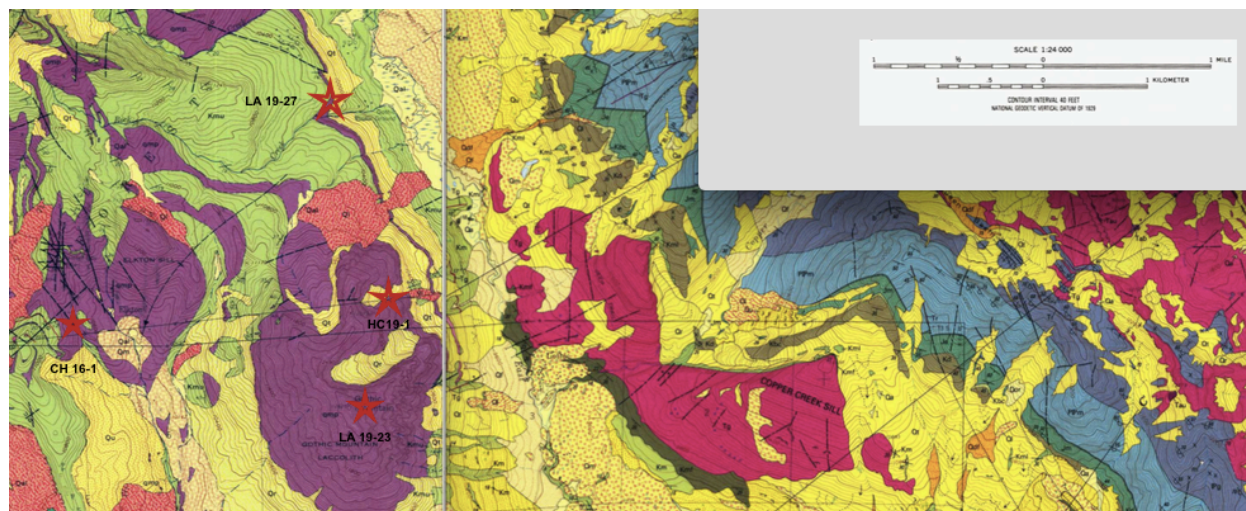


Figure 8. Geologic map of the Gothic Mountain. Sample sites are labeled. Modified from Gaskill et al., 1967 and Gaskill et al., 1991.

3.3 Mineral Separation

Apatite grains were analyzed at the University of Colorado Thermochronology Research and Instrumentation Laboratory (TRaIL). Samples were broken up in the field for transport purposes and also to be an adequate size to fit in the Braun Chipmunk VD67 jaw crusher. After the jaw crusher further broke down the samples, a Bico pulverisor was used to grind the samples down to be sieved through a USA Standard Testing Sieve No. 35 of $<500\text{ }\mu\text{m}$. Next the samples were passed over a Humpherys Wilfely Table and dried in a Quincy Lab oven at 65°C to undergo initial density separation. After the samples were dry, they were first passed over by a hand magnet to remove highly magnetic material, then fed through a magnetic Barrier Laboratory Separator two times, at $0.35\text{A}/20^{\circ}$ and $0.60\text{A}/20^{\circ}$. This final magnetic separation isolated the least magnetic material, including apatite, zircon, feldspar, and quartz. To remove the feldspar and quartz heavy liquid Lithium Metatungstate (LMT) density separation was used, this concentrated the apatite grains enough to be hand picked through a Leica M165 binocular microscope using a calibrated digital camera to capture images and record the lengths/widths of the apatite grains. Grains had to be larger than $70\text{ }\mu\text{m}$ in any given length and width; the apatite grains needed to be void of inclusions, and euhedral.

3.4 Alphacron He Extraction

Five grains from each sample were selected for AHe analysis; they were large enough in size, mostly euhedral and inclusion free. The grains were separately packed into Nb tubes, $\sim 5\text{mm}$, and loaded into an ASI Alphachron He extraction and measurement line to measure radiogenic ^4He . To do this, the Nb loaded with apatites were placed in a UHV extraction line ($\sim 3 \times 10^{-8}$ torr) and heated with a 50W, 6A diode laser to $\sim 800 - 1100^{\circ}\text{C}$ for 5 to 10 minutes. In order to degas the apatite grains, they are spiked with ^3He and analyzed on a Balzers PrismaPlus

QME 220 quadrupole mass spectrometer. Using a $^{235}\text{U} - ^{230}\text{Th} - ^{145}\text{Nd}$ tracer in HNO_3 , the degassed apatite grains were dissolved and baked at 80°C for 2 hours. To determine the concentrations of U, Th and, Sm, the apatite grains were spiked with ^{235}U , ^{230}Th and ^{145}Nd tracer, dissolved in HNO_3 and heated to 80°C for 2 hours. The concentrations were then measured using a Thermo Element 2 magnetic sector ICP-MS.

4. RESULTS

All grains that underwent AHe dating provided reliable results. The Re values and Effective Uranium concentrations (eU) are important aspects of the data and were examined to ensure these results were clean and reliable (Table 2).

Re values were high enough for every grain. If the grains did not degas all the ^4He in the first laser extraction, Re values would be too low. All the grains had Re values $>99.0\%$, which is acceptable.

Effective Uranium concentrations (eU) is the measurement of the amount of U and Th in the sample, with the Th concentration normalized to U in a way that accounts for the number of alpha decays produced by each one (as the Th produces fewer alpha particles than U does). The more alpha particles produced, the higher the extent of the radiation damage to the crystal. An eU value $>2\text{ppm}$ is desirable and all the grains from each sample were $>22.5\text{ ppm}$ which is excellent as the higher the eU value, the more He atoms have been created and the easier they are to detect.

Taking this all into account, the last time when each grain crossed the 70°C can be calculated. The five grains taken from the peak of Gothic Mountain (3851 m) had an average age

of 10.29 Ma (Figure 9). The five grains taken from the sill stratigraphically below Gothic Mountain had an average age of 12.16 Ma (Figure 10). The five grains taken from the base of the Gothic Mountain Laccolith (3323 m) on the eastern side had an average age of 18.72 Ma (Figure 11). The five grains taken from the Elkton Sill (3432 m), stratigraphically above Gothic Mountain, had an average age of 10.34 Ma (Figure 12).

LA19-23 (3851 m)

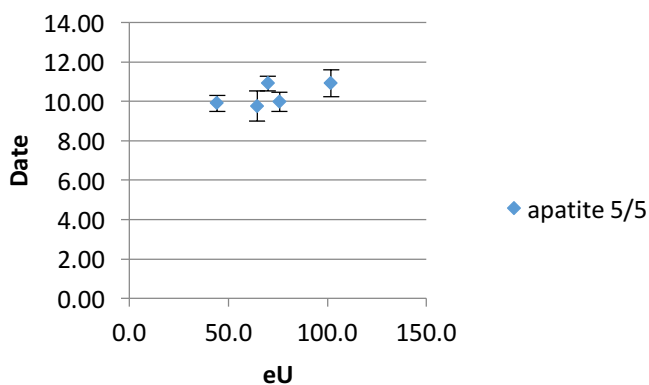


Figure 9. Age distribution of apatite grains from LA19-23 (top of laccolith).

LA19-27 (3122 m)

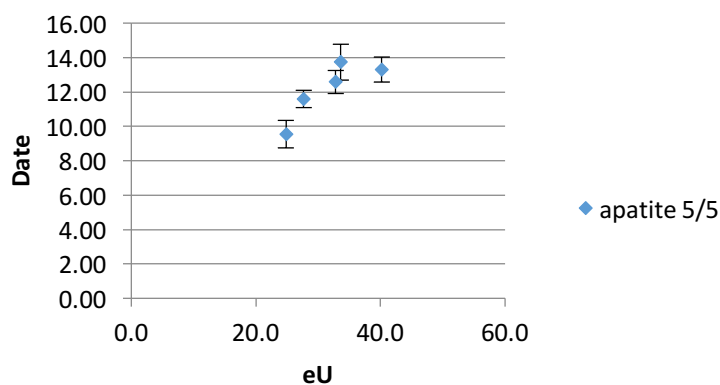


Figure 10. Age distribution of apatite grains from LA19-27 (sill below laccolith).

HC19-1 (3323 m)

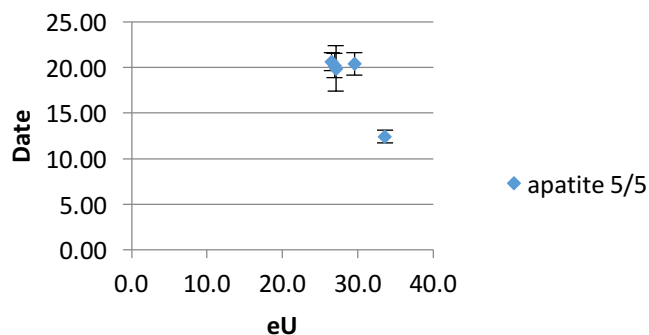


Figure 11. Age distribution of apatite grains from HC 19-1(base of laccolith).

CH16-3 (Elkton Sill by Gothic Peak)

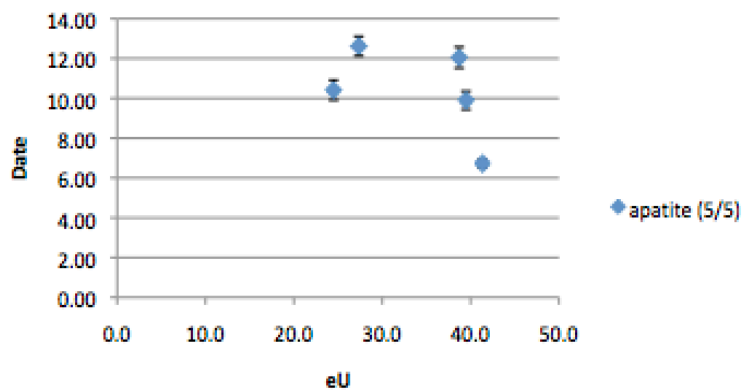


Figure 12. Age distribution from apatite grains in Elkton Sill (above laccolith).

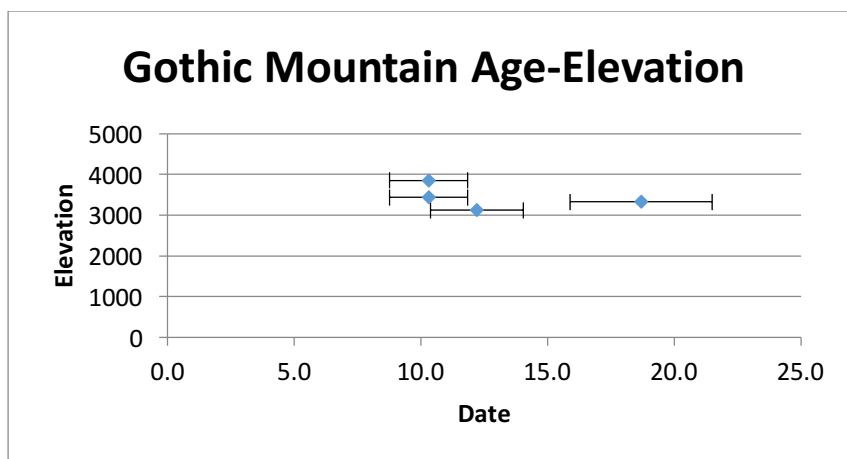


Figure 13. Age elevation plot of Gothic Mountain apatite, 15% error bars were added to encapsulate known and unknown factors. 15% is standard.

Table 2. Selected results from Gothic Mountain apatites, 2020

Full Sample Name	4He (nmol/g)	eU	4He (ncc)	Re (%)	Raw Date It (Ma)	Ft	Corrected Date (It) (Ma)	Analytic Unc. (Ma)2σ	Elevation (m)
LA19-23_a01	4.472	101.9	0.365	100.0	8.06	0.737	10.92	0.67	3851
LA19-23_a02	2.414	64.5	0.125	99.9	6.85	0.699	9.76	0.76	3851
LA19-23_a03	3.050	70.0	0.195	100.0	7.98	0.729	10.91	0.36	3851
LA19-23_a04	1.729	44.3	0.103	100.0	7.14	0.718	9.90	0.41	3851
LA19-23_a05	3.093	75.8	0.373	99.0	7.51	0.751	9.98	0.48	3851
Average Date:							10.29		
HC19-1_a01	1.922	26.9	0.058	99.7	13.08	0.643	20.25	1.34	3323
HC19-1_a02	1.975	27.1	0.078	99.8	13.37	0.670	19.90	2.50	3323
HC19-1_a03	2.156	29.6	0.064	99.8	13.36	0.652	20.41	1.24	3323
HC19-1_a04	1.556	33.6	0.059	99.7	8.49	0.680	12.44	0.68	3323
HC19-1_a05	1.972	26.5	0.065	99.6	13.63	0.658	20.63	1.00	3323
Average Date:							18.72		
LA19-27_a01	1.576	32.8	0.098	100.0	8.83	0.699	12.59	0.67	3122
LA19-27_a02	1.696	33.6	0.060	100.0	9.24	0.670	13.74	1.04	3122
LA19-27_a03	0.889	24.8	0.042	100.0	6.57	0.686	9.55	0.80	3122
LA19-27_a04	1.952	40.2	0.067	100.0	8.89	0.666	13.31	0.74	3122
LA19-27_a05	1.310	27.7	0.131	100.0	8.70	0.749	11.59	0.50	3122
Average Date:							12.16		
CH16-3_a01	1.108	24.5	0.151	99.9	8.29	0.794	10.41	0.5	3432
CH16-3_a02	1.682	39.5	0.211	100	7.82	0.789	9.9	0.46	3432
CH16-3_a03	1.891	38.7	0.124	100	8.93	0.739	12.05	0.53	3432
CH16-3_a04	1.401	27.3	0.094	100	9.38	0.741	12.62	0.49	3432
CH16-3_a05	1.237	41.4	0.243	99.7	5.51	0.819	6.73	0.21	3432
Average Date:							10.34		

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

Ft alpha ejection correction

5. DISCUSSION

Looking at AHe results for LA19-23, LA19-27 and CH16-03, it shows that the Gothic Laccolith crossed the closure temperature (70°C) between 10-12 Ma. Each sample had an average closing age close to 11 ± 2 Ma. These samples cover the stratigraphic span of the data set and all sit at varying elevations and at the same time have similar closing times. This means that the Gothic Laccolith underwent rapid exhumation around 11 Ma and that >1.5km of erosion has taken place since 11 Ma.

The erosion rate can be calculated from the slope of the line on an age-elevation plot (Figure 13). This image shows that the slope of that line is infinite. That means that 700 m of exhumation (the height difference from top sample to the bottom one) occurred in a time interval smaller than the uncertainties in the dates. Given that those age uncertainties are about ± 15 there is an age uncertainty of about 8.5-11.5 Ma, or about 3 m.y. By taking 700m/3m.y the minimum exhumation rate at Gothic seems to be about 233 m/m.y., which is among the fastest rates documented in the bull's-eye.

The erosion rates at Gothic were too quick to infer if stratigraphic location or elevation had a greater effect on exhumation ages. The speed of exhumation meant that the ages at CH16-03, the stratigraphically highest, and LA19-23, the topographically highest, were not different enough to deduce if tilting happened before or after exhumation.

The final hypothesis of glacial cutaways effect on exhumation ages could not be proven. This is also due to extremely high exhumation rates at Gothic Mountain. The most obvious reason is that HC19-01 was way older than the samples above and below it. Given that HC19-01 sits stratigraphically and vertically lower than the summit sample, LA19-23, HC19-01 should have a younger exhumation age than LA19-23 if vertical erosion was the sole influence on the

exhumation age. If glaciation affected the exhumation age HC19-01's age would be closer to the age found at the summit; it was in fact far older than LA19-23 too old to have been influenced by the glacier.

HC19-01 passed through its closure temperature much earlier than the other samples, around 18 ± 3 Ma. This was unusual as HC19-01 is not the highest topographically or stratigraphically, but given the spatial distances between each sample it can be explained. My original idea was that due to the Rio Grande rifting, faulting may have caused cooler surface water to infiltrate to the base of the laccolith above the Mancos shale and run underneath the laccolith along the western tilt to where HC19-01 is. Abbey (2018) argues that hydrothermal movements can affect exhumation ages but in this case it seems unlikely as the flow rate would be just too low to influence the temperatures at the base of the laccolith. Ground water in fractured beds moves faster than most other aquifer materials. In fractured igneous rocks hydraulic conductivity at its most is around 1m/day (Heath, 1983). It is not hard to believe that ground water could percolate down to the depths of HC19-01 but as ground water temperatures mimic that of the geothermal gradient, no matter how fast it is flowing, the geothermal temperatures are always replenished from below. Furthermore, the fractured rock will eventually feed a confined aquifer which will likely have a hydraulic conductivity of around 10^{-6} m/day. When the confined aquifer is fully saturated, the hydraulic conductivity of the ground water in the fractured rock feeding the aquifer will be reduced to 10^{-6} m/day. This hydraulic conductivity is too small to allow for surface water to cool the base of the laccolith. This means that this hypothesis can be ruled out.

The most likely cause the early closing date of HC19-01 samples is due to variance in surface topography. Given HC19-01 is the eastern most sample, a valley may have existed east

of the Gothic peak and above HC19-01 which would have made HC19-01 shallower. Being shallower it would also be cooler due to the geothermal gradient making its exhumation age older. This valley could have existed and not influenced the closing time of any of the other samples as shown by Figure 14. Further analysis of samples east of Gothic Mountain would be needed to provide more evidence. It would be interesting to test the extent of this early Miocene valley. White Rock Pluton sits on the other side of the East River and a sample NM17-07, that is 4.7 km east of HC19-01 at an elevation of 3168 m, has not been influenced by this Miocene incision (McCorkel, 2017). Sample CH16-1 as shown in Figure 13 has been collected but not analyzed and could provide vital evidence to the existence and size of this valley and if it is similar to the "Proto-Grand Canyon" which existed <23 Ma (Flowers et al., 2008). This incision discovered by Flowers and her team was providing evidence that a kilometer scale valley could have existed and locally influenced exhumation ages. Evidence of the presence of the paleo valley at CH6-01 and other sites to constrain the valley's boundaries would be indicated by old exhumation ages like HC19-01 (~20Ma). More research needs to be done on this to constrain this valley. NM17-08, a sample analyzed near Crested Butte Mountain (Figure 14), south of Gothic mountain, was found to have an age of 14 Ma which is older than expected. This suggests that the paleo channel over HC19-01 may have also influenced NM17-08 and that the paleo river channel would have been flowing from north to south.

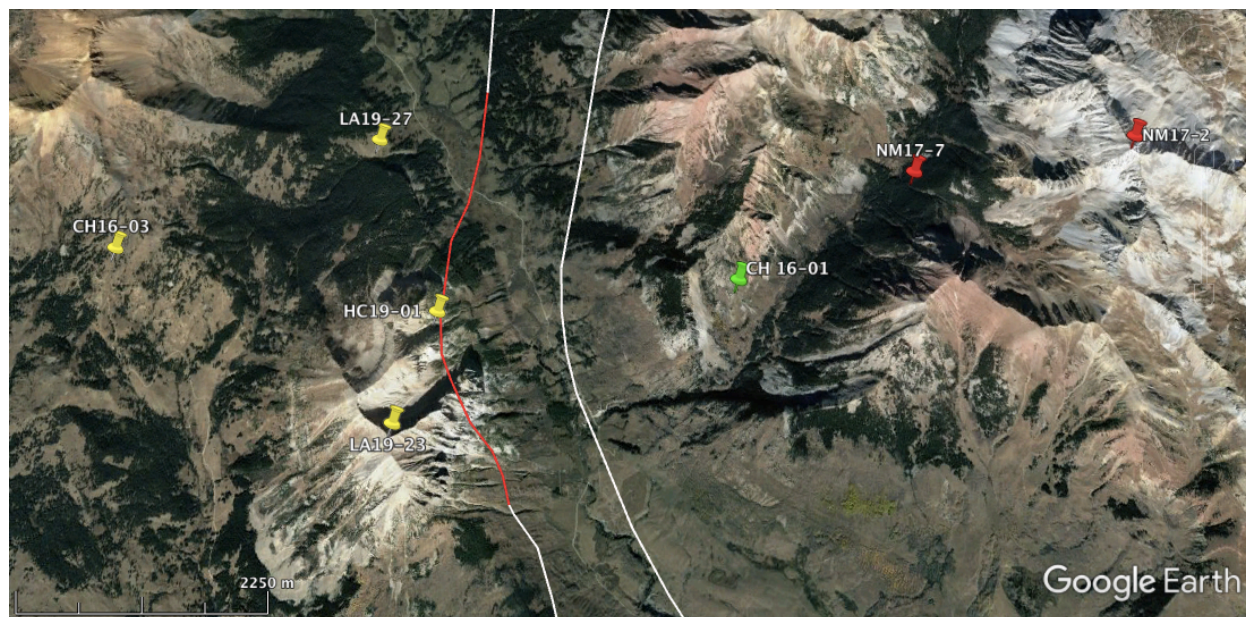


Figure 14. Site of possible Miocene incision between Gothic Mountain and White Rock Pluton. The western edge of the channel shown in red is deduced from HC19-01. The white boundary is estimating the other edges of the channel, more data is required to pinpoint where they really lie. The yellow pins are from this study, red pins are dated samples from McCorkel, 2017, and the green pin has not been dated yet, Google pro 2020.

For future work to analyze this paleo channel, I would first recommend trying to determine the width of the channel by collecting samples east of HC19-01. CH16-01 is a good place to start to see if this has been affected by the incision. Incision width sample (IWS) 1 and 2 would also provide good points to collect and analyze samples (Figure 15). They are positioned within river tributaries which may have cut down to in-situ granite. The locations would also help to constrain the western edge of the paleo channel. IWS 3 could help determine if HC19-01 is further away from the edge as we presume. IWS 4a/b, depending on in situ sample availability, would be excellent to constrain the center of the channel. Comparing HC19-01 with the suggested IWS samples would help determine the width and depth of the channel. It is important to do this first before moving on to predicting the location of the channel north and south of Gothic. Knowing the width of the channel would enable searching for the north and south locations of the channel far easier as we would have an idea of how sparse the samples can be.

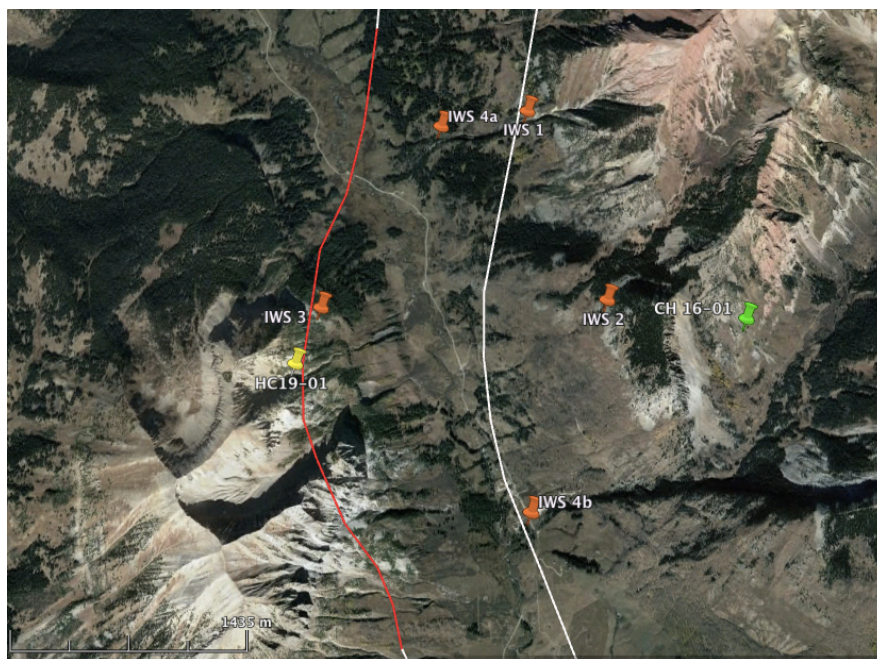


Figure 15. Showing suggested future sample sites (orange pins), Google pro 2020.

As Snodgrass Mountain lies between Crested Butte and Gothic Mountain, and because the sample from Crested Butte (NM17-08) was far older than expected considering its location in the bull's-eye, Snodgrass Mountain would be the next study after determining the paleo-valley width (Figure 16). An eastward vertical transect from the peak of Snodgrass Mountain would provide an excellent idea of where the paleo-channel flowed to from Gothic Mountain. It will also give information on possible meandering of the channel. At Gothic Mountain, the western side of the channel runs clearly from north to south, and if the exhumation ages on the east of Snodgrass Mountain are not ~20 Ma, this would suggest a meandering river as it did not influence Snodgrass's eastern face.



Figure 16. Showing Gothic, Snodgrass and Crested Butte Mountains. The paleo channel seems to have affected exhumation ages at Gothic and Crested Butte. The effect on Snodgrass Mountain would provide valuable information on the nature of the paleo valley, Google pro 2020.

6. CONCLUSIONS

The results found in this thesis support the theory of rapid exhumation within the bull's-eye found in the Elk Mountains. Rapid exhumation in the bull's-eye is consistent in all the studies done thus far, as well as this thesis. Gothic Mountain was also found to have one of the

fastest exhumation rates within the bull's-eye meaning this is the most central part of the bull's-eye with data (Figure 17).

The time of tilting and the glacial effect on exhumation ages could not be tested as the exhumation rates were so high at Gothic and HC19-01 had a very old unexpected age.

The age of HC19-01 has given rise to the idea of a potential paleo valley which exhumed the earth above HC19-01. The future work suggested will provide an excellent opportunity to map this paleo valley which may provide some evidence as to why the centralized rapid exhumation happened in the bull's-eye and why it is spatially limited.

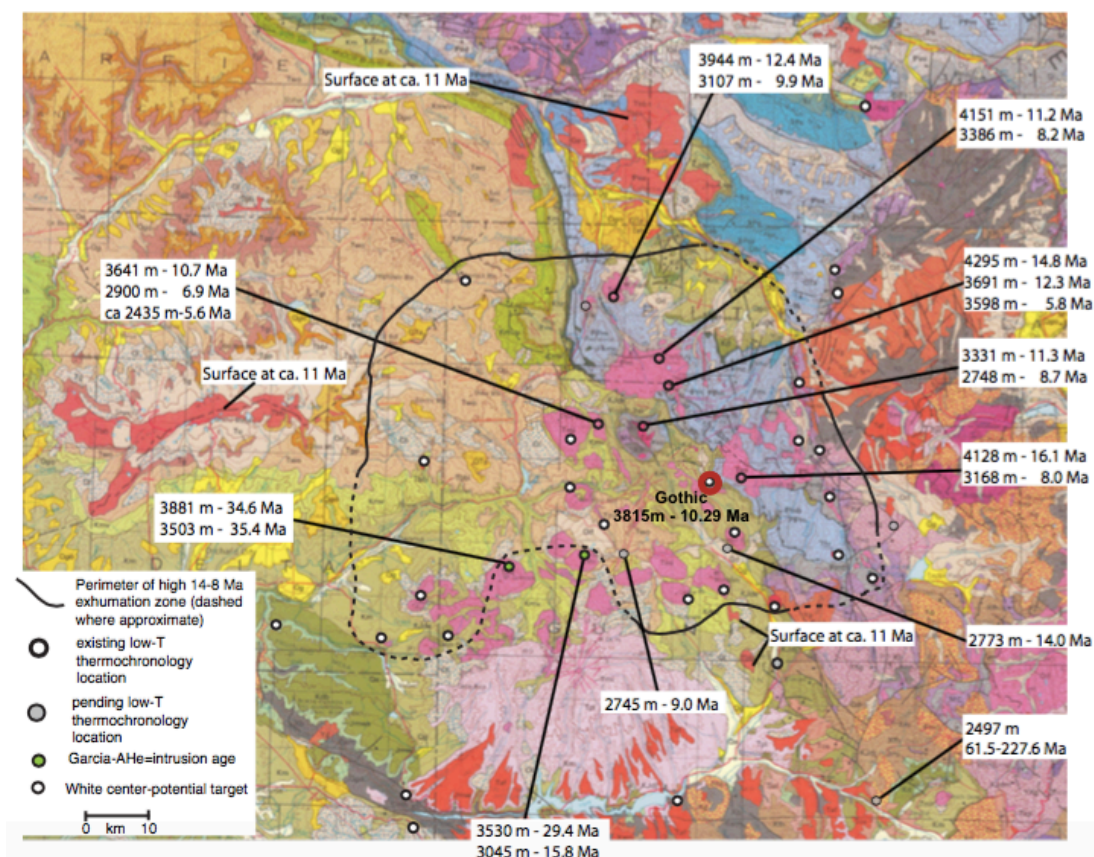


Figure 17. Gothic Mountain age at the center of the bull's-eye (Abbott 2020).

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References

Abbey, A. 2018. *Assessing Rio Grande rift Development and Exhumation in the Southern Rocky Mountains Using Techniques in Low-temperature Thermochronometry*. University of Michigan.

Abbott, L. and Cook, T. 2012. *Geology Underfoot: Along Colorado's Front Range*. Mountain Press Pub. Co.

Abbott L. 2020 Using Apatite (U-Th)/He Thermochronology to Determine Exhumation Rates and the Topographical History of the Elk Mountains In prep.

Bryant, B. and Martin, P.L. 1988. The geologic story of the Aspen region: mines, glaciers, and rocks. *US Geological Survey Bulletin* 1603:53.

Chapin, C.E. and Cather, S.M. 1994. Tectonic setting of the axial basins of the northern and central Rio Grande Rift. *GSA Special Papers* 291:5–25.

Decker, E.R., Heasler, H., Buelow, K., Baker, K. and Hallin, J. 1988. Significance of past and recent heat-flow and radioactivity studies in the Southern Rocky Mountains region. *Geological Society of America Bulletin* 100(12):1851-1885.

England, P., and Molnar P. 1990. Surface Uplift, Uplift of Rocks, and Exhumation of Rocks. *Geology* 18(12):1173. doi:10.1130/0091-7613(1990)018<1173:suuora>2.3.co;2

Farmer, G., Bailey, T. and Elkins-Tanton, L.T. 2008. Mantle source volumes and the origin of the mid-Tertiary ignimbrite flare-up in the southern Rocky Mountains, western U.S. *Lithos* 102(1-2):279-294.

Flowers, R.M., Farley, K.A., Wernicke, B.P. 2008. Unroofing, incision, and uplift history of the

southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry. *GSA Bulletin* 120(5/6):571-587, May/June.

Garcia, R.V. 2011. Cenozoic intrusive and exhumation history of the Elk and West Elk Mountain plutons, southwest Colorado, MSc thesis, New Mexico Institute of Mining and Technology, p. 1-160.

Gaskill, D.L., Mutschler, F.E., Kramer, J.H., Thomas, J.A., Zahony, S.G. 1991. Geologic map,, Gunnison County, Colorado, U.S. Geological Survey, GQ- 511, scale 1:24000.

Gaskill, D.L., Mutschler, F.E., Mutschler, F. 1967. Geologic map of the Oh-Be-Joyful Quadrangle, Gunnison County, Colorado, U.S. Geological Survey, GQ- 578, scale 1:24000

Google Earth Pro, 2020.

Heath, R.C. 1983. Basic ground-water hydrology. U.S. Geological Survey Water-Supply Paper 2220:86.

Hiett, C. 2017. *Constraining the Timing of River Incision in the Upper Colorado Drainage Basin Using Apatite (U-Th)/He Thermochronology in the Elk Mountains, Western Colorado*. University of Colorado.

Humphreys, E., Hessler, E., Dueker, K., Farmer, G., Erslev, E. and Atwater, T. 2003. How Laramide-Age Hydration of North American Lithosphere by the Farallon Slab Controlled Subsequent Activity in the Western United States. *International Geology Review* 45(7):575-595.

Jones, C.H., Farmer, G., Sageman, B. and Zhong, S. 2011. Hydrodynamic mechanism for the Laramide orogeny. *Geosphere* 7(1):183-201.

Karlstrom, K. E., Coblenz, D., Dueker, K., Ouimet, W., Kirby, E., Van Wijk, J., Schmandt, B., Kelley, S., Lazear, G., Crossey, L.J., Crow, R., Aslan, A., Darling, A., Aster, R., MacCarthy, J., Hansen, S.M., Stachnik, J., Stockli, D.F., Garcia, R.V., Hoffman, M., McKeon, R., Feldman, J., Heizler, M., Donahue, M.S., and Grp, C. W. 2012. Mantle-driven dynamic uplift of the Rocky Mountains and Colorado Plateau and its surface response: Toward a unified hypothesis. *Lithosphere* 4:3–22.

Kelleher, R. 2020. *Locating the Eastern Edge of a Sixty Kilometer-Wide Bull's Eye of Miocene-Age Exhumation Near Taylor Peak A in Colorado's Elk Mountains with Apatite (U-Th)/He Thermochronology*, University of Colorado.

Keller, R. (1999). The Rio Grande rift: A geological and geophysical overview. Rocky Mountain. *Geology* 34:121-130. 10.2113/34.1.121.

Ketcham, R. and Hanna, R. 2011. Expert-Guided CT Beam Hardening Correction for Heterogeneous Natural Materials. May. doi:10.5242/iamg.2011.0283

Levandowski, W., Jones, C.H., Butcher, L.A., and Mahan, K.H., 2018. Lithospheric density models reveal evidence for Cenozoic uplift of the Colorado Plateau and Great Plains by lower-

crustal hydration: *Geosphere*, v. 14, no. 3, p. 1150–1164,

McCorkel, N. 2017. *Examining Spatial Patterns of Exhumation in Colorado's Elk Mountains During the Late Miocene Using Apatite (U-Th)/He Thermochronology*. University of Colorado.

Pederson, J., Karlstrom, K., Sharp, W., McIntosh, W. 2002. Differential incision of the Grand Canyon related to Quaternary faulting—Constraints from U-series and Ar/Ar dating. *Geology* ; 30 (8): 739–742.

Pederson, J.L. 2008. The mystery of the pre-Grand Canyon Colorado River—Results from the Muddy Creek Formation. *GSA Today* 18:3. doi: 10.1130/GSAT01803A.1

Tully, J.E. 2009. *Structural interpretation of the Elk Range thrust system*. University of Montana State.