

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

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Figure 1: Taylor Peak A (4,095m) from the rugged northwest ridge of Star Peak in October 2019.

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Abstract

This research aims to clarify the timing and mechanics behind a sixty kilometer-wide Bull's Eye of exhumation in Colorado's Elk and West Elk mountains that took place about 15-8 million years ago (Ma). To do this, I use the apatite (U-Th)/He low temperature thermochronology (AHe) technique to study the burial history and exhumation rates of granite outcrops that I collected along two vertical transects.

My objective is to constrain the eastern perimeter of the Bull's eye of exhumation and to compare erosion rates from the center towards the edge along a six-kilometer long, 1.2 km high vertical transect that connects from Taylor Peak A's summit at 4,095m (Figure 1) to a site in Castle Creek at 2,891m with already analyzed AHe data.

My data suggest that the eastern edge of the Bull's Eye is a few kilometers east of the summit of Taylor Peak A, near the Grizzly Peak Caldera, and that the White Rock granodiorite at the summit was emplaced at about 500m depth 34 million years ago. AHe dates at four sample sites along an eastern vertical transect agree with White Rock Pluton emplacement age (33.9Ma $\pm$ 1Ma Obradovich, 1969), implying shallow burial (1.5km or less) of the entire eastern side of Taylor Peak A at that time.

Furthermore, comparison to data collected 12km west of my site atop White Rock Mountain suggests that the White Rock Pluton was emplaced along a gradient that rose at least a kilometer from there to the summit of Taylor Peak A.

1. Introduction

My field research site on Taylor Peak A (three mountains in Colorado are named 'Taylor') and Star Peak is located about 23 kilometers south of Aspen, Colorado at the eastern edge of the Elk range, a few kilometers west of the Sawatch range (figure 2). Star Peak is flanked by steep, crumbling White Rock granodiorite ridges. The northwest side and summit of Taylor Peak A are steep, fractured White Rock granodiorite slopes but its eastern side is gentler and dotted with the Precambrian Henry Mountain Granite outcrops formed about 1.7 billion years ago (Ga) (Obradovich, 1969).

Figure 2 below gives a regional picture of Cenozoic volcanism and pluton emplacement in Colorado and shows the location of Taylor Peak A at the tip of the blue arrow. WP is the White Rock Pluton and GP is the Grizzly Peak Caldera, a volcanic eruption and subsequent crater that formed about the same time as the White Rock Pluton 34 million years ago. The Grizzly Peak Caldera (orange dashed line in figure 3) is visible today as an arc of volcanic tuff that makes up the extreme western edge of the Sawatch range (figure 3).

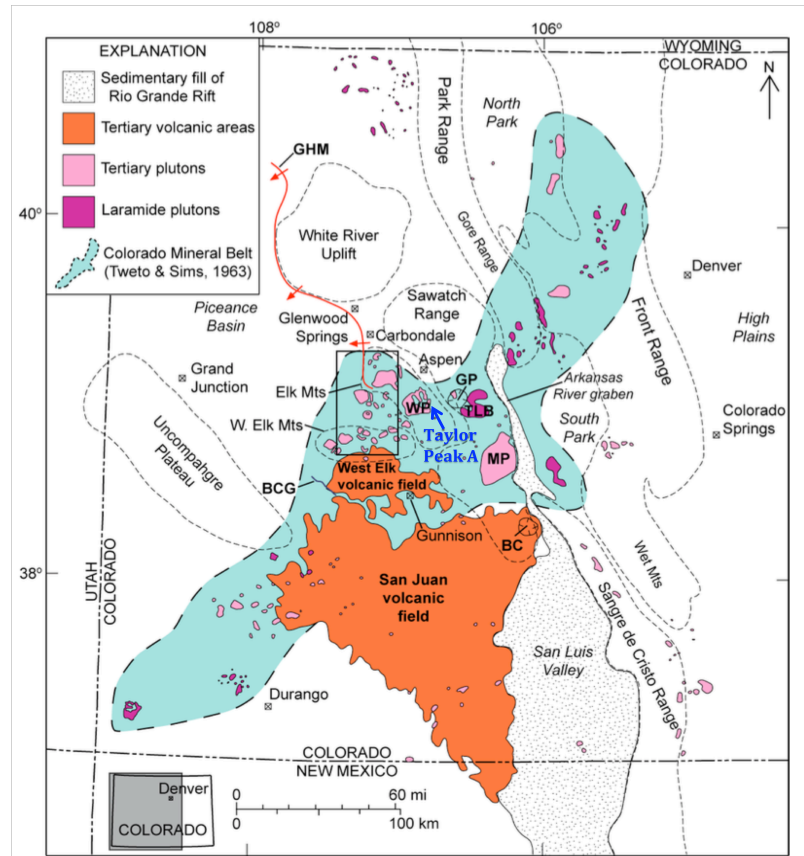


Figure 2: Modified from Garcia, 2012. Study area at tip of blue arrow. WP is White Rock Pluton, GP is Grizzly Peak Caldera. Pink show other granitic plutons emplaced at roughly the same time period.

This study site was chosen because previous thermochronology work in the area implies that it is near the edge of our Bull's Eye of exhumation (conversations with Abbott, 2019). The White Rock Pluton is about 34 million years old and the Henry Mountain Granite is ~1.7 billion years old, some of the oldest rock in Colorado that originated as a crystalline basement layer of the Sawatch range to the east. Because the Bull's Eye perimeter was not well constrained here, I chose to collect two vertical transects that meet at the summit of Taylor Peak A to both look for its edge and to study how erosion rates change from northwest to east across the study area. Figure 3 below shows that the northwest transect goes from that summit to Castle Creek (sample LA19-7) laterally six kilometers and vertically 1200 meters down and that the eastern transect goes from sample 19-RVK-1 at the summit laterally about six kilometers and vertically 972 meters down. The orange dashed line on figure 3 is the Grizzly Peak Caldera and the extreme western edge of the Sawatch range.

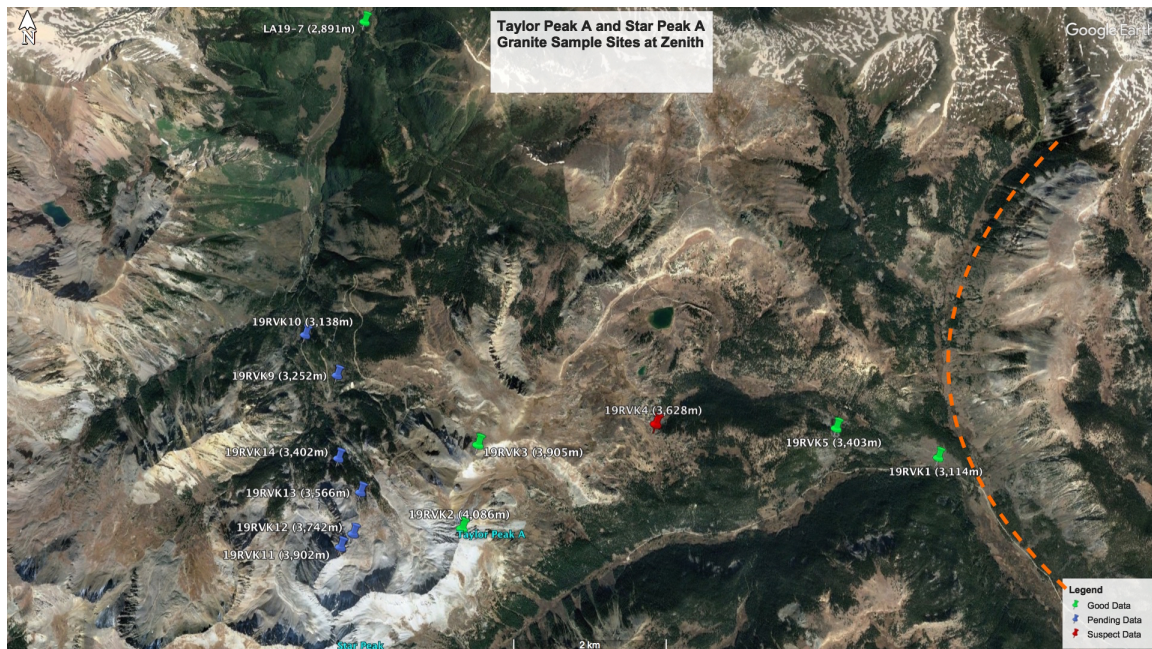


Figure 3: Google Earth Pro, 2020 image of 11 sample sites from zenith. Green pushpins show reliable AHe data collected, red pushpin shows suspect data collected, and blue pushpins are samples collected but not yet processed for AHe data. Orange dashed line is Grizzly Peak Caldera's western front.

My research is a small piece of a larger project led by Dr. Lon Abbott, Dr. Rebecca Flowers, and Dr. James Metcalf through the University of Colorado Boulder's (U-Th)/He thermochronology laboratory (CU TRaIL). Their work builds upon a Master's thesis by (Garcia, 2011) "Cenozoic intrusive and exhumation history of the Elk and West Elk Mountain plutons, southwest Colorado." While Garcia looked at regional-scale uplift histories of six plutons across seven mountains, the ultimate goal of this research is to understand the timing of and geologic processes behind a sixty-kilometer wide focused bull's eye of exhumation in the Elk and West Elk mountain ranges of Colorado that occurred about 15 to 8 million years ago, shown in figure 4. Ages at specific x, y, z coordinates represent when outcrops at that elevation and location were last at AHe closure temperatures or approximately seventy degrees Celsius.

Overall, our larger project traces the timing of cooling for several Oligocene granitic plutons in the Elk and West Elk ranges emplaced during the Ignimbrite Flare-up ~38-24Ma (Lipman, 2007). The team is collecting samples from mountains throughout these two ranges to analyze using a mass spectrometer for uranium, thorium, samarium, and helium content of apatite crystals. These data can be used to estimate when the

sample passed through the $\sim 70^{\circ}\text{C}$ isotherm, which is a technique known as low-temperature (U-Th)/He thermochronology (AHe).

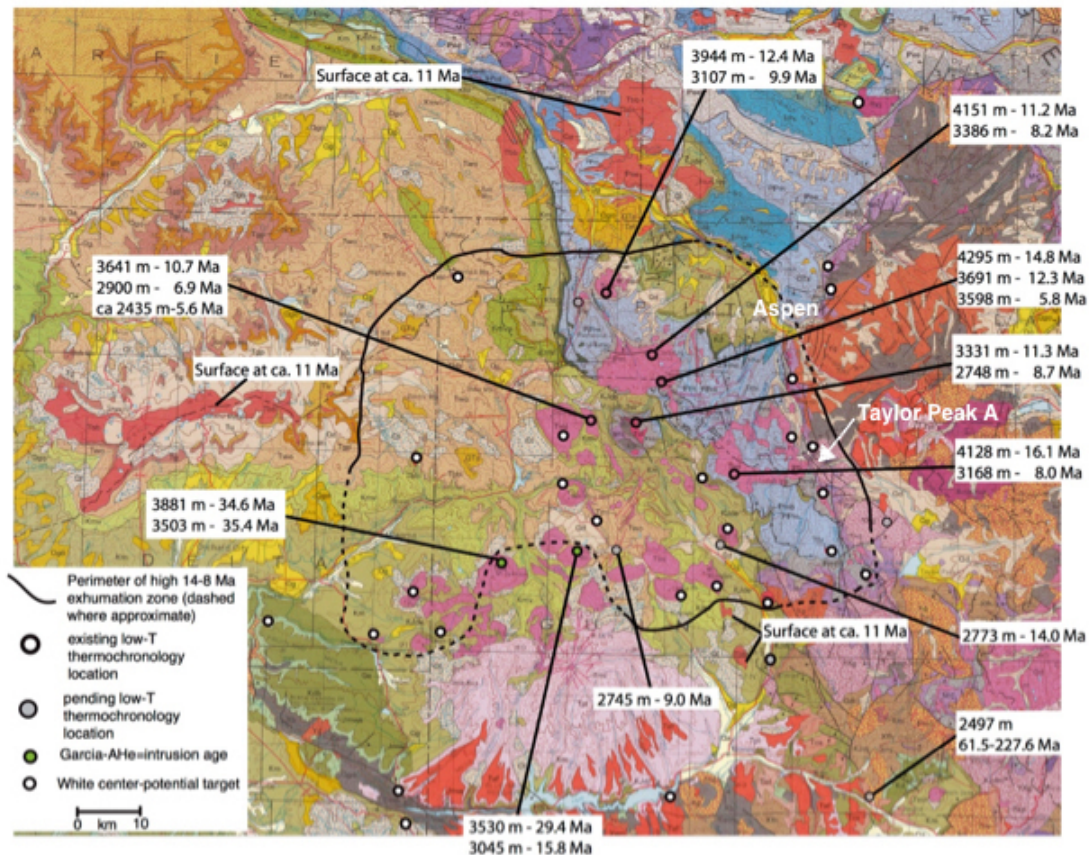


Figure 4: Elk / West Elk Range Bull's Eye of exhumation (Abbott, 2020).

My sample sites were chosen by overlaying a geologic map onto a topographic map. Surface granite outcrops were selected at $\sim 200\text{m}$ vertical intervals. Granite outcrops are at fixed elevation on a mountain slope whereas talus could have originated from anywhere higher. Two hundred vertical meters is a good distance to compare AHe data between rocks that have undergone uplift because it is close enough to allow for multiple sites up a mountain to be measured and far enough apart that it fits with the AHe technique's resolution uncertainty of approximately 15% (or a few million years).

The AHe technique allows us to estimate when a granite sample was last at $\sim 70^{\circ}\text{C}$ or about 1.5 km depth, depending on geothermal gradient. (A geothermal gradient of $40^{\circ}\text{C}/\text{km} * 1.5\text{km} + 10^{\circ}\text{C}$ average air temperature = 70°C). Data that show different ages at different elevations in close proximity can imply rates of uplift, if interpreted

cautiously. It is important to also consider local heating events like dike intrusions (AHe date reset), climate change-driven erosion, and isostatic rebound from denudation of overlying rock (Molnar and England, 1990).

Uranium, thorium, and samarium within apatite crystals undergo spontaneous alpha decay, which releases ^4He . This ‘alpha ejection’ launches helium atoms $\sim 20\ \mu\text{m}$ in any random direction. Above $\sim 70^\circ\text{C}$, decay produces ^4He that all diffuses out of the crystal. 40°C to 70°C is the partial retention zone (PRZ) where some helium is retained within the crystal. Below 40°C , no Helium diffuses out of the crystal (Farley, 2002). The temperature at which Helium begins to be trapped within the crystal is called the closure temperature. 70°C is a good approximation and is used in this project for consistency.

AHe dates can also represent heating pulses such as the White Rock Pluton emplacement or Grizzly Peak Caldera formation that occurred about thirty-four million years ago. Results from complementary Elk Range projects (Garcia, 2011; Hielt, 2016; McCorkel, 2017) that collected AHe data from granite outcrops closer to the center of the Bulls-Eye’s express patterns of deep burial and fast exhumation of up to 3.5 kilometers (conversations with Abbott, 2020) during the middle Miocene epoch.

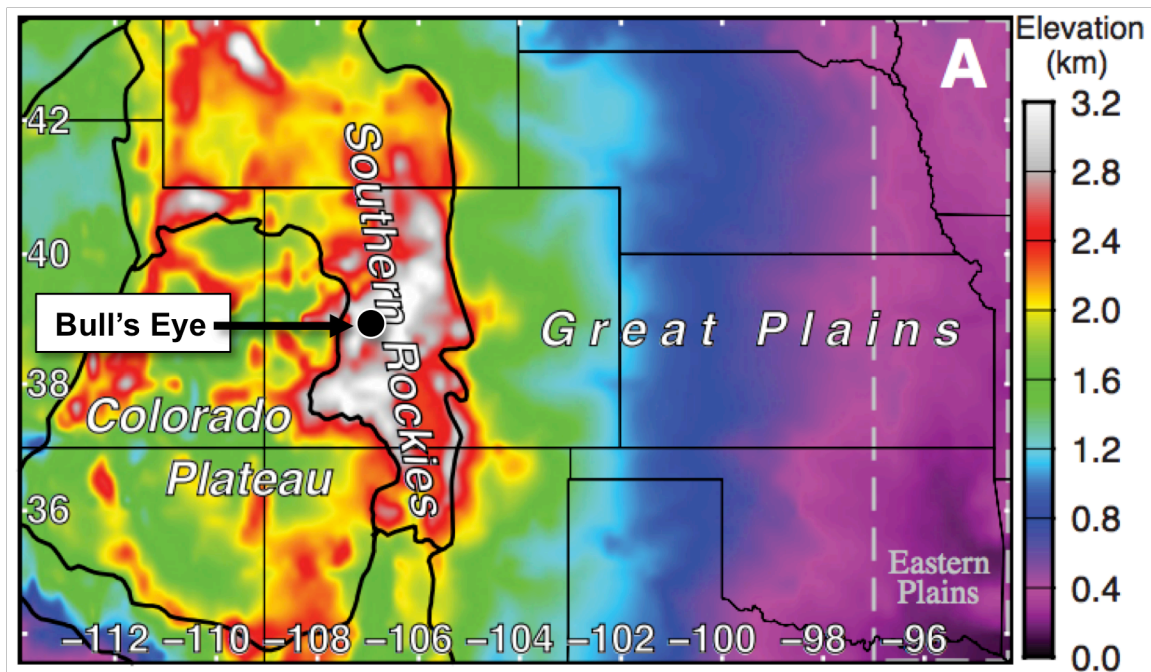


Figure 5: Modified from Levandowski, 2018. Bull's eye approximate location and Colorado's mid-plate high elevation.

Modern-day Colorado's average elevation is ~ 1.9 kilometers above mean sea level (figure 5), the highest of any state in the United States, despite its position at the

interior of the North American plate. Unlike many relatively cool cratons at plate interiors, the Elk Mountains sit above an unexpectedly warm geothermal gradient possibly due to a thin crust ($< 45\text{km}$), and a thin lithosphere that implies there is no Airy crustal root beneath Colorado, despite high topography (Karlstrom, 2012). What geologic processes could have created this Bull's Eye of exhumation that exists in the Elk and West Elk mountains of Colorado and how does it change spatially and temporally as one travels from the center towards the perimeter?

At the outset of this project, I set out to test two hypotheses. 1: *The eastern edge of the Elk / West Elk bulls eye o-f exhumation is atop or a few kilometers east of the summit of Taylor Peak A (4,095m) and AHe closure dates will lessen in age as elevation decreases until an inflection point after which they will grow in age as they approach the Grizzly Peak Caldera.* 2: *Erosion rate(s) along a northwest vertical transect (trending towards the Bull's eye center) can be estimated with elevations and AHe dates from multiple sample sites.*

2. Regional Geologic History

The Elk and West Elk mountains are a southeast to northwest trending range of peaks that reach over 4,200 meters. The Elks are home to towering granite and sedimentary peaks, U-shaped glacial valleys, and complex faults and folds. The town of Aspen is rich in mining history and is surrounded by up to nineteen-hundred meters of topographical relief.

A series of island arc-continental collisions about 1,700 million years ago caused the Yavapai Orogeny and formed crystalline intrusive igneous rocks that make up a basement layer of the Colorado Rockies today (Abbott & Cook, 2012). Henry Mountain granite, which forms the gentle eastern transect of Taylor Peak A at about 3,900m and lower, is a Precambrian basement layer of the Sawatch Range and this rock unit was later displaced up and west over Elk range sedimentary layers during the Laramide Orogeny. The Elk range is unique in Colorado because its Precambrian igneous basement layer is not exposed at the surface (Bryant, 1979). For the next billion years or so, many rock formations in the Elks and across Colorado were created and erased by mass erosion events but have left scarce evidence.

Starting about five hundred and thirty million years ago, the area around Aspen was covered by a shallow, warm inland sea. This continental sea advanced and retreated numerous times over the next few hundred million years and deposited rock layers like the Leadville Limestone, the Belden Formation and the Gothic Formation (Bryant, 1988).

The Belden conglomerate is a mixture of sandstone, limestone, dolomite, and shale that was deposited in the nearby Eagle basin during this time. This lithologic unit contains brachiopod and ancient plant fossils. It is between 150 and 450m thick (Bryant, 1979). The Belden has been metamorphosed on Taylor Peak A into marble and this shallow marine formation is the stratigraphic level at which the White Rock pluton intruded on Taylor Peak A ~ 34 million years ago (figure 6).

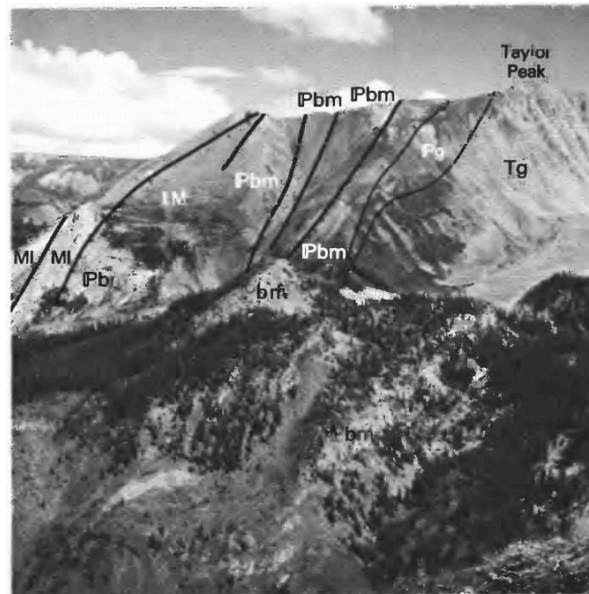


FIGURE 66.—Setting of Pitkin Iron Corp. mine, Hayden Peak quadrangle, viewed east from 3,666-m knob on ridge south of Castle Creek. Photograph taken in 1964 before much mining took place. Tg, granodiorite; Pg, Gothic Formation hornfels; IPbm, Belden Formation marble; ML, Leadville Limestone. Heavy lines, faults; light lines, contacts. IM, iron mine.

Figure 6: Bryant, 1979.

By the end of the early Cretaceous period (around 100Ma), the region was covered by the Western Interior Seaway and fine mud and clays settled in a mile-thick layer called the Mancos Shale. Radiometric dating of ash layers within this rock unit from volcanoes hundreds of miles away suggests that the Aspen area was covered by the sea until ~ 71.5Ma (Bryant, 1988).

Between seventy-three and forty-three million years ago, the Fallaron plate shallowly subducted under the North American Plate and thrust up the overlying crust into mountains in an event known as the Laramide Orogeny (Abbot & Cook, 2012). This collision uplifted regions all across Colorado, farther north into Wyoming, and farther south into New Mexico. Unlike other mountain ranges such as the Himalayas, that are built upon a thick crustal foundation, the Colorado Rockies have anomalously thin crust beneath high topography, hence why they are called ‘rootless’ (Hansen, 2013). A different mechanism than thick underlying crust must support Colorado’s high topography. During the Laramide Orogeny, the Henry Mountain granite, among others, was uplifted and thrown west a few kilometers over top of Elk Range sedimentary layers.

Following the Laramide mountain building event, removal of the Fallaron plate may have caused the now hydrated and chilled overlying North American plate to contact the hot asthenosphere beneath (Humphreys et Al, 2007) and set off one of the most dramatic periods of magmatism in Earth history: the Ignimbrite Flare-up. Between 36 and 23 million years ago (Lipman, 2007), the flare-up caused the mantle to lose density and widespread Oligocene intrusions along fault weaknesses such as the Castle Creek fault zone and the Elk Range thrust system (Tully, 2009) into the Elks, West Elks, and San Juan Mountains, creating uplift and regional subsurface heating (Garcia, 2011).

Figure 7 below illustrates some volcanism caused by the flare-up and estimates the extent of volcanic rocks created in this event before erosion. Our project focuses on plutons and associated heating events that occurred during the Ignimbrite Flare-up that largely eroded in the Elks / West Elks but remain on the surface today in the San Juan Mountains as an extensive layer of high-elevation volcanic tuff. The intrusions of these plutons 30-34Ma likely caused uplift, however, our Bull’s Eye of exhumation happened in a focused sixty-kilometer wide circle between 15-8Ma- much more recently than emplacement.

In the Elk and West Elk Mountains, the White Rock granodiorite pluton (33.9Ma +/- 1Ma) was emplaced (Figure 7); to the northeast, the Grizzly Peak Caldera formed at 33.9Ma +/- 1.1Ma. (Obradovich, 1969.) The White Rock pluton is one of many large magmatic emplacements in the region thought to have caused considerable uplift of overlying rock layers. The sources of magma may have been from both lithospheric and

asthenospheric mantle (Farmer, 2008). The protracted Ignimbrite Flare-up could have elevated geothermal gradients for millions of years locally and regionally.

About twenty-nine million years ago, after the removal of the Fallarón plate, the Rio Grande Rift (RGR) began. The RGR is an extensional, protracted geologic event that still occurs today. Extensional basins from Colorado to Mexico exist in a South to North trend. Rifts are associated with low gravity anomalies, thin crust, high subsurface heat, and basaltic dikes (Keller, 1999).

Beginning about fifteen million years ago, rapid exhumation within our Bull's Eye occurred, uplifting the Elk and West Elk Ranges. The mysterious mechanics behind this exhumation is the ultimate target of our research, but the time span of this exhumation seems to have occurred between ~15Ma and 8Ma (conversations with Abbott, 2020) based on previous thermochronology work in the region.

Another important consideration is the complex effect of Rio Grande Rift development over the past thirty million years that has thinned regional crust and uplifted the land surface on its periphery. During the Pleistocene or past 2.3 million years, glacial and interglacial cycles have occurred in Colorado, shaping cirques and U-shaped valleys and leaving tongue-shaped rock glaciers in the alpine today. Rock glaciers are considered “rock conveyor belts” (Anderson, 2011) on mountains. Several of these rock glaciers flank Star Peak and Taylor Peak A in 2020 (figure 1).

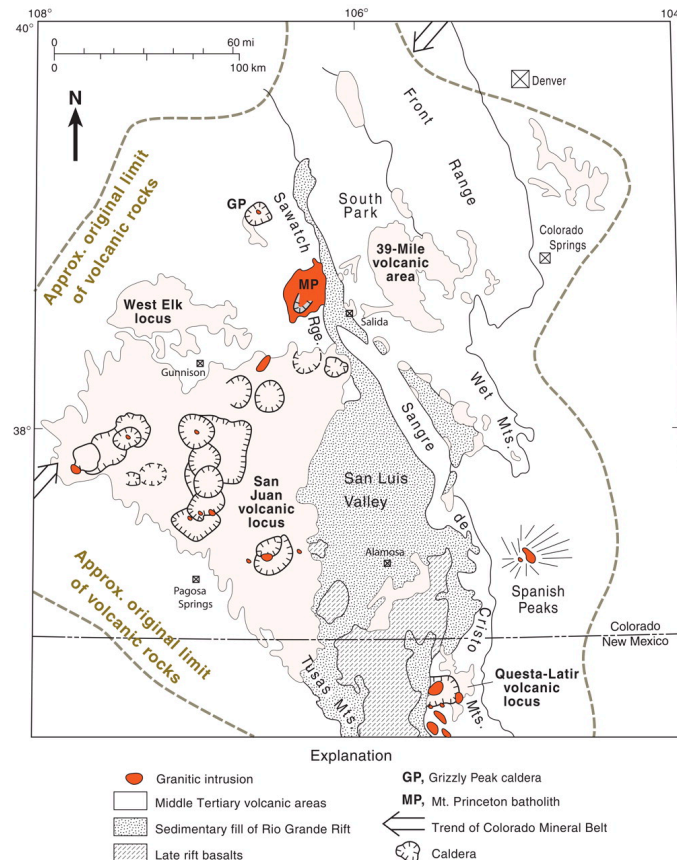


Figure 7: Lipman, 2007 Study area at 'GP'. Dashed line is estimated extent of volcanic rocks before erosion, perhaps linking San Juan volcanism to the timing of Elk / West Elk pluton emplacements.

3. Previous Elk / West Elk Thermochronology Research

Our Bull's Eye exhumation project builds upon a Master's thesis by Garcia, 2011. That work focused on seven vertical transects across multiple plutons in the Elk / West Elk Range (figure 8). Garcia used thermochronometry (multiple thermochronology methods used together that give different dates of closure temperatures, such as Apatite Fission Track and $^{40}\text{Ar}/^{39}\text{Ar}$ dating). Garcia identified two pronounced periods of exhumation and cooling in the Cenozoic: a slow rate between 25 and 15 million years ago and much faster rate between 12 and 5 million years ago. Garcia's data also suggest that northern Elk / West Elk plutons were emplaced at greater depth and cooled more slowly than southern plutons. That research considers the hot, low velocity mantle flow and thin crust beneath to be a possible cause of Elk / West Elk range Miocene exhumation (Garcia, 2011).

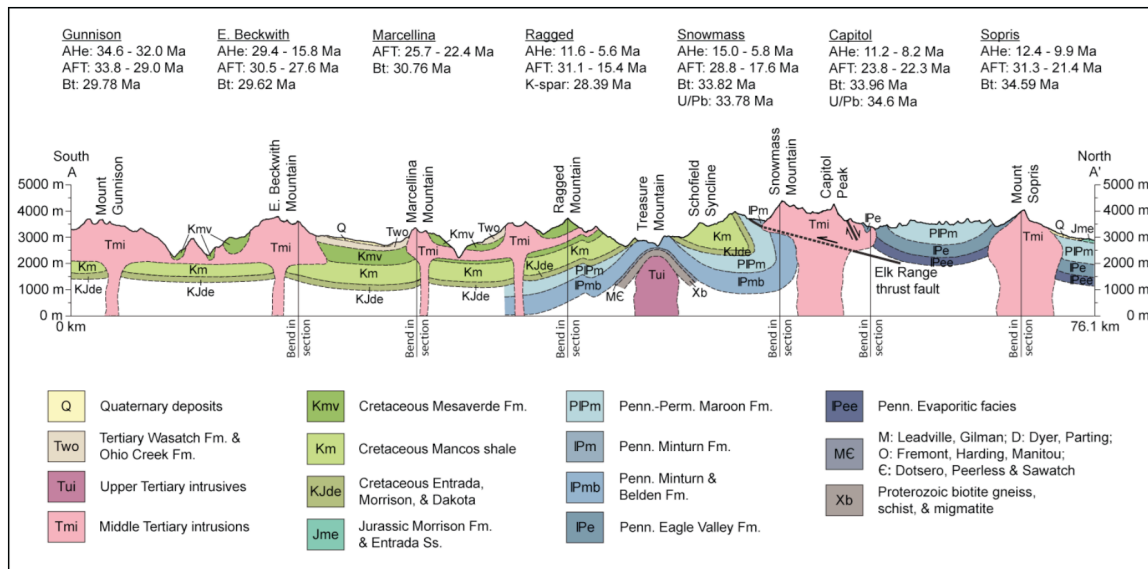


Figure 8: Garcia, 2011 Cross section of area where seven transects were taken and measured with various Thermochronology techniques, including AHe.

Garcia's work is built upon by the results from the CREST project (Karlstrom et al, 2012), which used thermochronology of vertical transects to decipher river incision rates (approximately 150-800m per million years). Different incision rates were compared to regional seismic data. Further research used tomography to image the crust beneath the Colorado plateau, and recorded an anomaly of low p-wave velocity, thin crust, and low Bouguer gravity beneath the Bull's Eye (figures 7 & 8). Karlstrom et al, (2012) contend that regional exhumation rates accelerated about ten million years ago, spatially coinciding with low-seismic-velocity crust and mantle (figure 9) of the Aspen Anomaly, which implies a warm mantle flow beneath the Colorado Rockies- possible supporting evidence for a geothermal gradient of $\sim 38^{\circ}\text{C}/\text{km}$ that we see today.

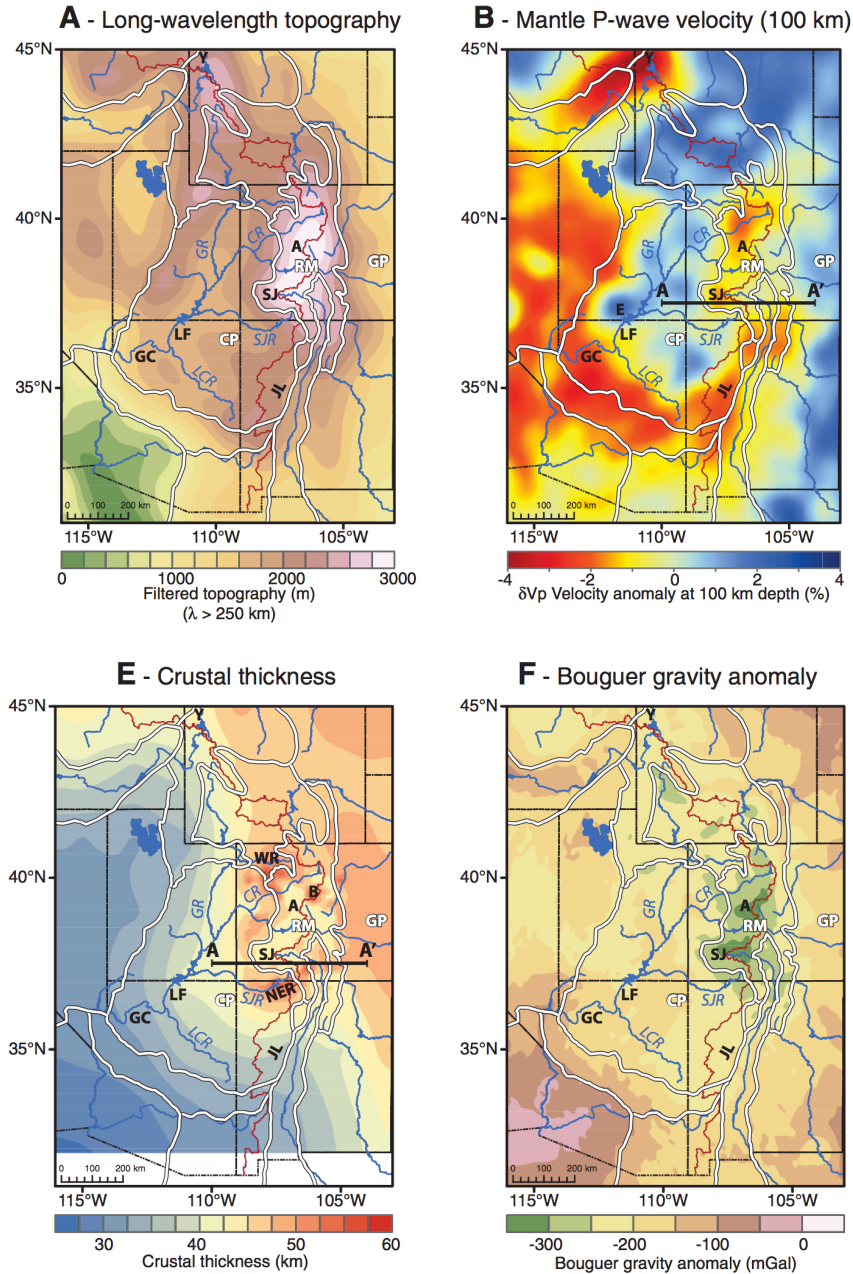


Figure 9: Karlstrom, 2012. Standalone 'A' represents Aspen Anomaly.

Two honor's theses at CU Boulder, in collaboration with my advisor Lon Abbott, collected AHe thermochronology data in our Bull's Eye of exhumation. Hielt (2017) focused on incision rates of the Crystal River and estimated that 600m of exhumation occurred near the Treasure mountain dome between 11.3Ma and 8.7Ma at a rate of ~218m/Ma.

McCorkel (2017) collected AHe data from White Rock Mountain, approximately 12.7 km west of my study site (figure 25). Results from that project suggest that that summit was at 1.5km depth about 13 million years ago and that 1km of rock on White Rock Mountain cooled from 13-8Ma with an erosion rate of $\sim 181\text{m/Ma}$ (McCorkel, 2017).

Lon Abbott (CU Boulder) has also collected numerous AHe thermochronology data from mountains within and outside the Bull's Eye of exhumation (figure 4). This regional geologic map, adapted from Tweto (1979) is overlain by those AHe ages at varying elevations from different mountains. The Bull's Eye AHe ages represent data collected through both our multi-year project and by Garcia in 2011 (white boxes in figure 4). My project looks to add to this Bull's Eye of data near its eastern edge.

4. Methods

4a. In the Field



Figure 10: Field Sampling essentials. A compass, 1M HCL (acid) bottle, and geologic map were also used.

Field sampling took place over three days in October 2019. My advisor Lon Abbot and I removed material from two different vertical transects that connect at the

summit of Taylor Peak A. Eleven samples (~50kg total) were collected from Taylor Peak A (4,095m) and Star Peak A (4,121m) in the Elk Range (figure 3).

We used a 4 Lb sledge hammer and a rock chisel to dislodge granites from outcrops and break them open to collect fresh internal pieces (less exposed to surface weathering). Granites were broken into fist-sized fragments to fit in the laboratory rock crusher and about 2/3 of a gallon-sized Ziploc bag per site was bagged. Field notes, outcrop photos, and GPS coordinates with calibrated elevation were taken (figure 10).



Figure 11: Taylor Peak A (4,095m) from its gentle northeast shoulder.

East transect (4,086m to 3,114m, away from center of Bull's eye, towards Grizzly Peak Caldera): on the gentle east by northeast shoulder of Taylor Peak A (figures 3 & 11, we sampled a vertical transect from the summit to ~500m west of the Grizzly Peak Caldera's western edge. All samples taken along this transect, aside from the White Rock summit sample, were from stratigraphic unit **Xh** (early Proterozoic Henry Mountain granite, approximately 1.7GA (Tweto, 1979). Henry Mountain granites had large phenocrysts (up to 1cm in diameter) and ranged from pink to gray in color.

Northwest transect (4,086m to 2,891m towards center of Bulls eye): on the steep northwest flanks of Taylor Peak A (figures 1 & 3) and Star Peak, samples were collected from the Taylor Peak A summit (figure 12) down to Castle Creek road near Ashcroft town site at approximately 200 meter vertical intervals within stratigraphic unit **Tw** (Intrusive Granodiorite of the White Rock Pluton, age $\sim 33.9\text{Ma} \pm 1\text{Ma}$). Samples were also collected from the rugged northwest ridge of Star Peak at similar elevation intervals. White Rock granodiorites were fine to very fine grained and ranged from gray to white. Lon Abbott previously collected and processed a White Rock pluton sample from 2,891m along Castle Creek road, six kilometers due north of Taylor Peak A's summit (figure 3).

Equipment (mostly in figure 10): Garmin GPS 64ST, DeWalt 4 Lb sledgehammer, Stanley Fatmax rock chisel, Suunto basic compass, USGS Collegiate Wilderness Geologic Map, USFS topographical map, gallon-sized Zip-lock sample bags (~ 16), Rite in the Rain field notebook, pencils, a dropper bottle of diluted HCL acid, and iPhone 6s.



Figure 12: Taylor Peak A summit site 19-RVK-2 at 4,086m that connects both vertical transects.

4b. In the Rock Lab

Samples were fed into a Braun CHIPMUNK VD67 rock crusher, an attached BICO Pulverizer, and then sieved through a Fisher Standard USA No.35 500 micrometer mesh. Once 80-90% of total sample volume was finer than this diameter, larger grains were bagged and stored away.

Grains finer than 500 μ m were poured over a Humphrey's Wilfley table, a shaking water stream system that separates heavy and light grains by flowing water along a series of longitudinal bars. Buckets that collected the heaviest W1 grains to the lightest W4 grains of wet material were dried in a Quincy Lab Inc. model 40GC oven for 24-36 hours at 65°C. The heaviest material (Zircon and Apatite-rich) was isolated for further separation and the rest was labeled and stored away.

Once dried, the W1 (heavy) sample portion was spread thin onto butcher paper and a plunger-style hand magnet was used to separate out highly magnetic material. Next, a Frantz LB-1 electromagnetic barrier separator was used at 20° angle at a voltage of .35A then .60A to draw out progressively less magnetic grains. Magnetic grains were bagged and labeled and stored away at each step. The non-magnetic portion was bagged and tagged as *Ready for LMT*.

Eight disposable centrifuge tubes were each filled with ~7.5ml of sample (60mg total) then topped off to 45ml of Lithium Meta Tungstate (2.85-2.90g/cm³). Samples were placed in a Fisher Scientific Marathon 3200 centrifuge (4 or 8 to maintain balance within the precisely balanced centrifuge calibration) and spun at 2000RPM for two minutes. Next, tubes were submerged in liquid nitrogen to the ~15ml line for three minutes and left in a tray for another five minutes to form an ice plug, which isolated the denser (and hopefully apatite-rich) portion at the bottom of the tubes from the less dense material like quartz and feldspars near the top.

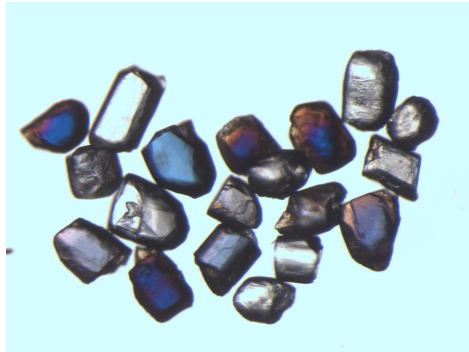
Lithium Meta Tungstate is water soluble and costly (~\$1,000 per liter) so it was reclaimed by rinsing grains repeatedly with de-ionized water then filtering the liquid. Direct LMT is poured through a coffee filter then a Q2 filter and bottled after density is measured with a hydrometer. LMT + DI water is poured through successive #5 and #2 filters, then evaporated over a hot plate under a fume hood until hydrometer-measured density is ~ 2.85-2.90g/cm³. Reclaimed, filtered LMT poured into a bottle for reuse.

LMT heavy and LMT light grain portions were dried (for an hour) in the laboratory oven at 65°C and heavy density grains were poured into a glass PYREX sample dish that was filled 2/3 full with filtered ethanol.

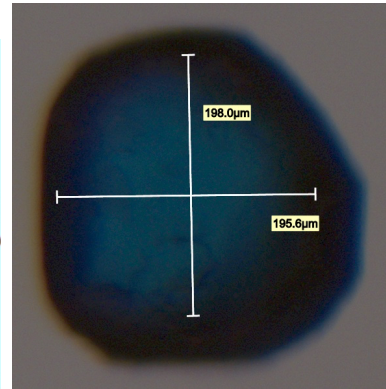
4c: In the CU TRaIL Microscope Laboratory



*LEICA M165C Scope
Figure 13*



*19-RVK-1 Apatite candidates (5 packed)
Figure 14*



*19-RVK-5_a3_LW1 at 388x zoom
Figure 15*

In the CU microscope laboratory, a LEICA M165C binocular microscope (figure 13) attached to a LEICA DMC5400 digital camera with the LEICA Application Suite X software was used to select apatite grains for size, euhedral shape, and to be free from inclusions and surface weathering (figures 14 & 15). Both inclusions and weathering (oxidation) may contain uranium, which could introduce error into sensitive (U/Th)-He measurements and give erroneously old closure temperature dates (Farley, 2002).

Apatite crystals were chosen with lengths and widths larger than 80 microns on both major crystal faces (figure 15). Also, grains were chosen preferentially for ‘Gemmy’ appearance, transparency, and few fractures. Fractures can be internal crystal pathways that facilitate helium diffusion, making dates appear younger than they really are (Fitzgerald, 2006). Once five apatite grains were chosen, they were measured for length and width on both of their two major faces and crystal characteristics were described. For more details about how apatite crystal characteristics can lead to (U/Th)-He errors, see the appendix section on AHe uncertainties.

Grains were packed in niobium tubes that were pinched on top and bottom with tweezers into a “ravioli” to contain the grain, loaded into plastic tubes, and given to the

CU TRaIL lab manager for mass spectrometer analysis (figure 16), along with an excel file detailing crystal dimensions and observations.

4d. In the Thermochronometry and Instrumentation Lab (CU TRaIL)



Figure 16 : ASI Alphachron He extractor

As described by (Hiett, 2017), Niobium “packets” containing apatite crystals were placed in an ASI Alphachron He extractor and measurement line (figure 16) at the Thermochronology Lab (CU TraIL). To enable ^4He extraction, apatite crystals were heated with a 25W diode laser (UHV conditions) to between 800 and 1100°C for about ten minutes. Purified ^3He was then added to make and measured on a mass spectrometer (Balzers PrismaPlus QME 220 quadrupole) to make sure that apatite were completely degassed. Next, apatite crystals were dissolved and prepared for uranium, thorium, and samarium analysis. ^{255}U , ^{230}Th , and ^{145}Nd were used to spike apatite crystals still in niobium tubes, placed into nitric acid (HNO_3), and heated to 80°C for 120 minutes. Samples, now dissolved, were analyzed for amounts of uranium, thorium, and samarium with an ICP-MS. Following methods standardized by (Ketchum, 2011), AHe corrected closure dates were calculated with grain dimensions, concentrations of ^4He , and parts per million concentrations of U, Th, and Sm (table 1).

5. Results

AHe data was collected from apatite crystals in granites at five sample sites along the 972 meter vertical eastern transect from the summit of Taylor Peak A to about 500 horizontal meters short of the Grizzly Peak Caldera’s western edge (figure 3). Twenty-six

inclusion-free apatite grains were analyzed for (U/Th)-He data then an Ft correction was applied to Raw Dates. Ft is the fraction of helium produced that is kept within the crystal. The Ft correction approximately divides raw dates by the Ft fraction to get corrected dates, according to conversations with Metcalf, 2020.

Uranium, thorium, and samarium measurement uncertainties were also calculated and labeled as analytical uncertainty. Samarium is included because it decays to neodymium and its alpha ejection can account for 1-10% ^4He in a crystal (Belton et Al, 2004). Effective uranium (eU) = $[\text{U}] + .235[\text{Th}]$ and it is proportional to apatite closure temperature. In other words, the more internal crystal damage that an apatite crystal sustains through alpha decay over time, the higher its ^4He closure temperature will be (Flowers, 2009). See the appendix section on uncertainties for more about factors that limit the resolution of the AHe technique.

The summit sample also connects in a 6km long, 1.2km high northwest transect to Lon Abbott's LA19-7 Castle Creek sample at 2,891m (figure 3). Table 1 selects results for sample name and apatite grain number, effective Uranium (eU), Ft-correction, Corrected Date (AHe closure date), analytical uncertainty, and sample site elevation.

Full Sample Name	eU	Ft	Corrected Date (It) (Ma)	Analytic Unc. (Ma) 2 σ	Elevation (m)
19RVK-2_a01	67.9	0.683	28.89	1.62	4086
19RVK-2_a02	49.7	0.615	31.29	1.99	4086
19RVK-2_a03	23.3	0.675	23.60	1.26	4086
19RVK-2_a04	71.6	0.688	32.83	1.52	4086
19RVK-2_a05	67.6	0.685	30.57	1.30	4086
		Average Date:	29.44	<i>White Rock Pl.</i>	<i>Granodiorite</i>
19RVK-3_a01	68.8	0.806	33.41	1.36	3905
19RVK-3_a02	45.3	0.687	33.06	1.49	3905
19RVK-3_a03	48.6	0.714	34.75	2.04	3905
19RVK-3_a04	13.7	0.662	29.90	4.20	3905
19RVK-3_a05	43.7	0.700	34.24	1.33	3905
19RVK-3_a06	16.0	0.797	27.89	1.06	3905
		Average Date:	32.21	<i>Henry Mtn.</i>	<i>Granite</i>
19RVK-4_a01	26.4	0.613	130.84	10.36	3628
19RVK-4_a02	41.2	0.633	75.20	7.94	3628
19RVK-4_a03	15.8	0.770	142.88	7.72	3628
19RVK-4_a04	26.0	0.794	43.61	3.42	3628
19RVK-4_a05	15.7	0.734	62.08	6.66	3628
<i>Suspect Data</i>		Average Date:	90.92	<i>Henry Mtn.</i>	<i>Granite</i>

19RVK-5_a01	19.4	0.791	33.53	1.23	3403
19RVK-5_a02	31.2	0.794	33.74	1.40	3403
19RVK-5_a03	29.3	0.812	34.74	1.51	3403
19RVK-5_a04	27.9	0.810	33.21	1.15	3403
19RVK-5_a05	23.0	0.872	29.84	2.99	3403

Average Date: **33.01** Henry Mtn. Granite

19RVK-1_a01	26.0	0.878	29.72	1.28	3114
19RVK-1_a02	12.6	0.841	26.34	1.93	3114
19RVK-1_a03	5.9	0.872	28.31	1.59	3114
19RVK-1_a04	11.8	0.813	30.76	1.58	3114
19RVK-1_a05	10.6	0.860	26.70	1.08	3114

Average Date: **28.37** Henry Mtn. Granite

LA19-7_a01	7.8	0.689	11.16	0.94	2891
LA19-7_a02	10.8	0.693	11.04	0.72	2891
LA19-7_a03	12.3	0.679	19.21	0.93	2891
LA19-7_a04	8.1	0.676	11.05	0.80	2891
LA19-7_a05	9.4	0.664	17.46	1.35	2891

Lon Abbott's Data **Average Date:** **13.98** White Rock Pl. Granodiorite

Table 1: Selected Data. eU (effective Uranium) = $[U] + .235[Th]$ is a proxy for internal crystal damage. Greater eU is proportional to higher crystal closure temperature. Corrected dates are approximately the Raw Date (not listed) divided by the f_t correction (a function of a crystal volume's relation to random-direction $20\mu m$ alpha decay stoppage distance that estimates helium percentage lost from the crystal over time).

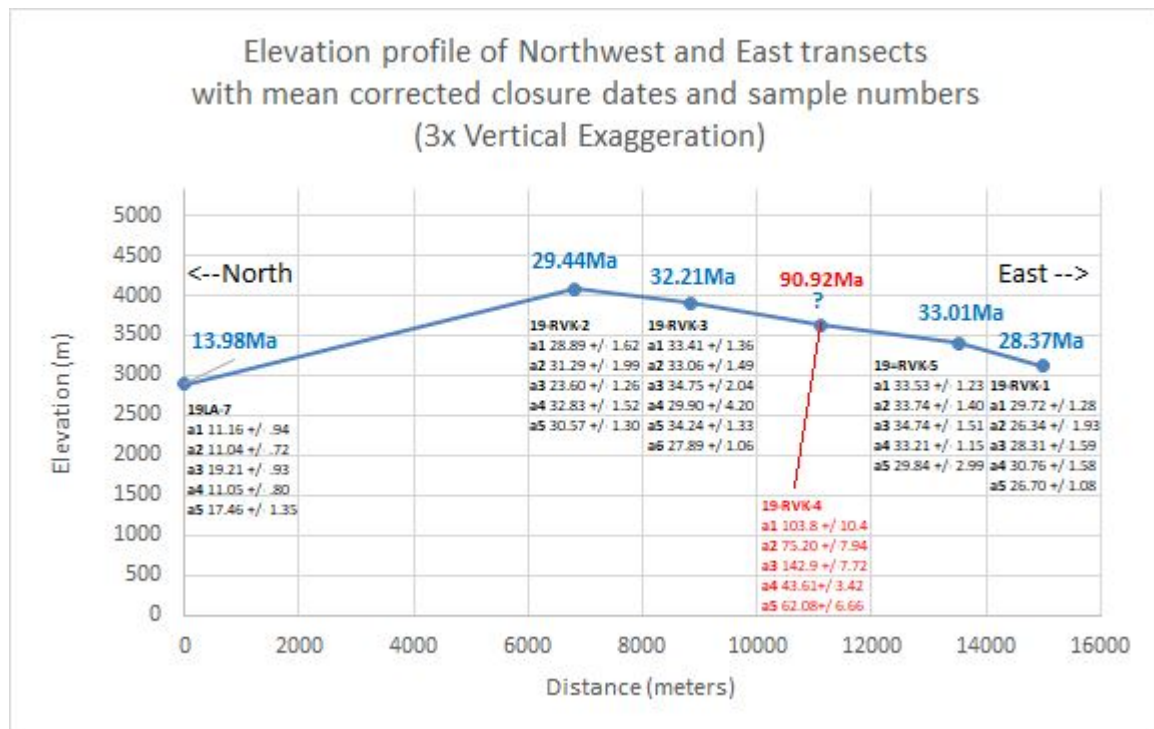


Figure 17: Apatite 4He data from sites along both transects. Does not include standard 15% total uncertainty applied to corrected dates for analysis. Lon Abbot's Castle Creek sample at far left. Sample nearest to Grizzly Peak Caldera at far right. Average ages of grains in each sample suite are in blue. Suspect data is in red. Corrected dates with analytical uncertainty below bold sample numbers.

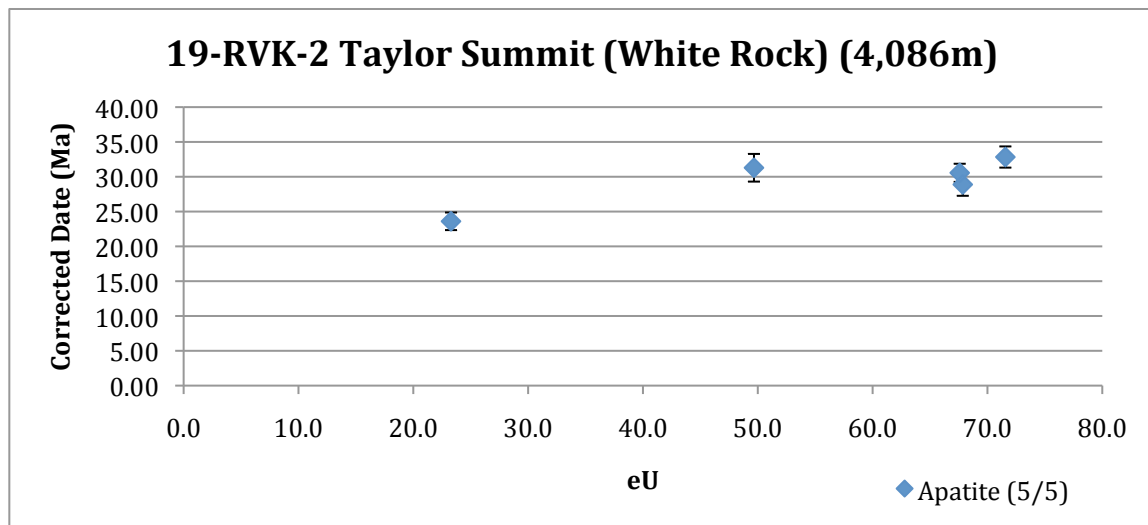


Figure 18: Analytical uncertainty. No well-defined Date-eU correlation (Low age/eU grain may be an outlier) but its 15% uncertainty overlaps that of other grains and there is no good reason to exclude it.

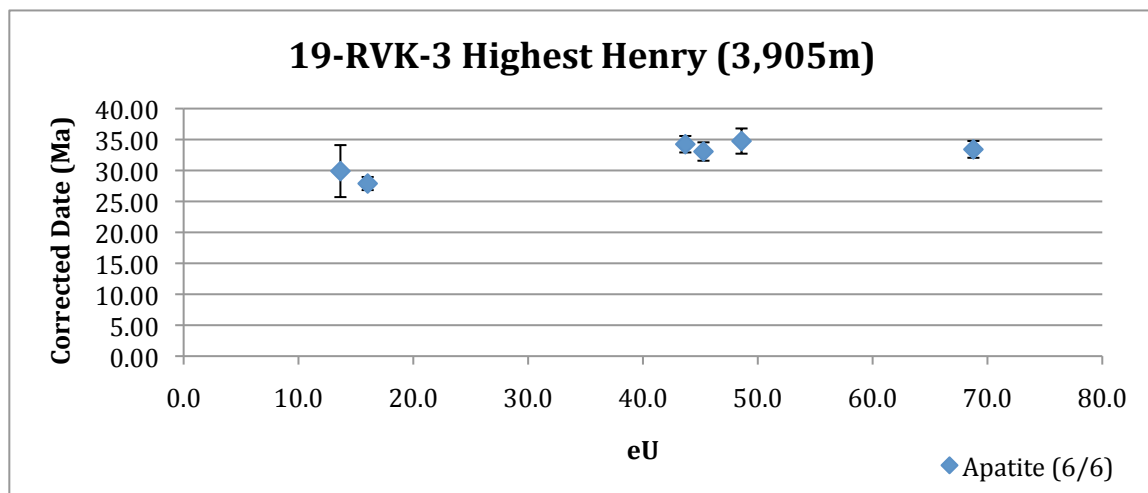


Figure 19: Analytical uncertainty. No Date-eU correlation. Henry Mtn. Granite

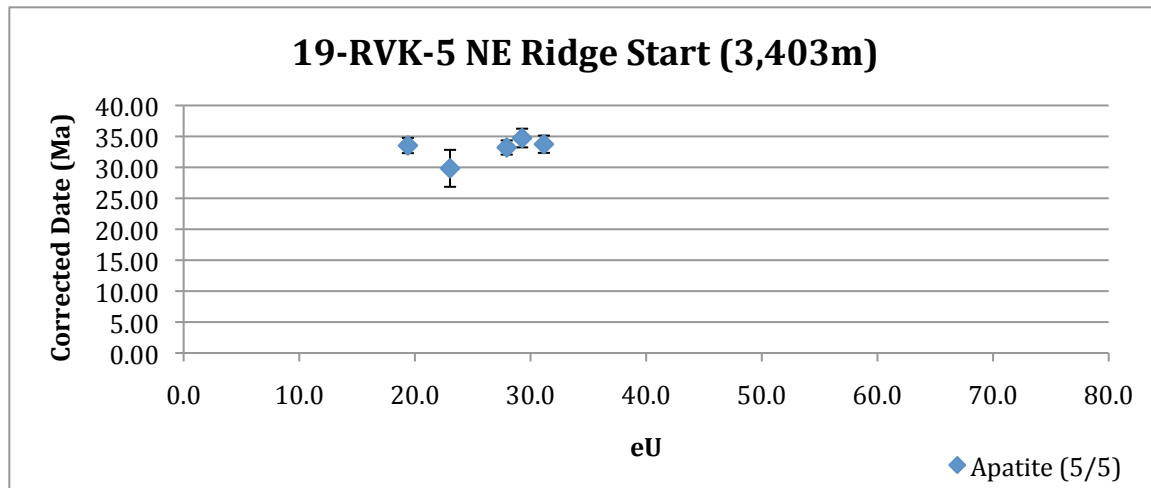


Figure 20: Analytical uncertainty. No Date-eU correlation. Henry Mtn. Granite

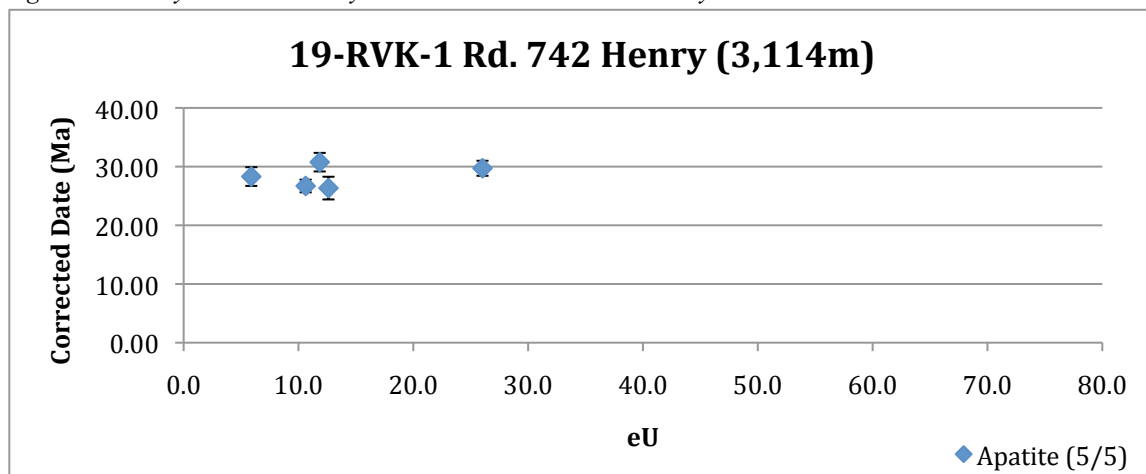


Figure 21: Analytical uncertainty. No Date-eU correlation. Closest to Grizzly Caldera. Henry Mtn. Granite

6. Discussion

Closure temperature (T_c) and effective Uranium (eU) are positively correlated and a graph of eU versus corrected dates for multiple grains can show if that suite of grains was fast cooling (no eU and date trend) or slow cooling (positive eU to date correlation) (Flowers, 2009). My grain suites at each sample site (figures 18-21) show no good correlation between eU and Corrected Date, so it is likely that after White Rock Pluton emplacement or resetting magmatism (for Henry Mountain Granite) that all my samples along the east transect cooled relatively quickly below T_c . Although figures 18 & 19 appear to show weak positive correlations, due to 15% AHe resolution uncertainty, these are considered to not be correlated (conversations with Metcalf, 2020).

Due to my AHe ages overlapping with White Rock pluton emplacement age ($\sim 33.9\text{Ma} \pm 1\text{Ma}$) within uncertainty (figure 23), rocks along the 972m eastern transect likely cooled in concert, soon after the White Rock pluton was emplaced. Although AHe resolution does not allow us to know exact cooling rates, no correlations between eU and dates, despite a wide range of eU values $> 2\text{ppm}$ in each sample, allow us to infer that apatite in the four granitic samples passed through the partial helium retention zone too quickly for internal crystal damage to factor meaningfully into ^4He diffusion. Low eU values lead to helium measurements that are too close to background levels to be reliable (conversations with Abbott, 2020).

Alpha decay is the spontaneous radioactive decay that gives off a helium atom. According to Flowers (2009), when uranium decays to thorium, and releases alpha decay, alpha ejection occurs in any random direction with a stopping distance of ~ 20 micrometers. Therefore, alpha ejection that occurs at 20 microns distance from an apatite crystal surface has a chance of losing ^4He to the environment (Farley, 2000). To minimize uncertainty caused by this lost fraction of helium, crystals with a length and width of greater than 80 microns are selected.

Alpha ejection in apatite causes damage within the crystal lattice that traps helium, causing crystals that accrue more alpha decay damage over geologic timescales to retain *more* helium. (Flowers, 2009). Resetting events like the emplacement of the White Rock Pluton that dramatically heat up then cool down a crystal (annealing) reverse this damage effect and lower a crystal's closure temperature. (Shuster et al, 2009).

6a. Exclusion of 19-RVK-4 data from analysis

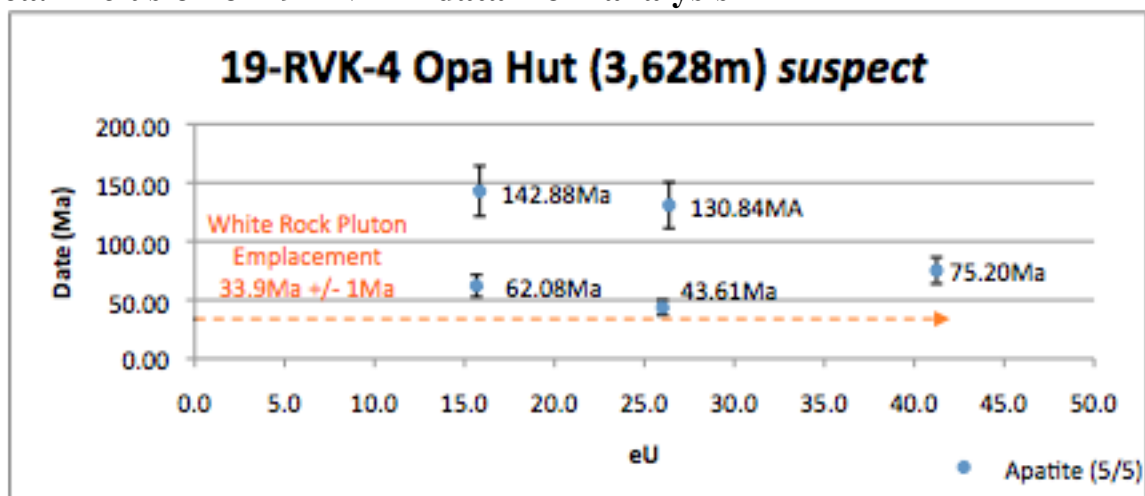


Figure 22: large data scatter, possibly due to U-bearing inclusions; all dates are older than White Rock emplacement age (~33.9Ma), even with standard AHe 15% uncertainty applied.

Full Sample Name	eU	Ft	Corrected Date (lt) (Ma)	Analytic Unc. (Ma) 2 σ	Elevation (m)
19RVK-4_a01	26.4	0.613	130.84	10.36	3628
19RVK-4_a02	41.2	0.633	75.20	7.94	3628
19RVK-4_a03	15.8	0.770	142.88	7.72	3628
19RVK-4_a04	26.0	0.794	43.61	3.42	3628
19RVK-4_a05	15.7	0.734	62.08	6.66	3628
		Avg Date:	90.92		
Suspect Data					

Table 2: Showing corrected dates that imply U-bearing inclusions or surface weathering that contains U, (much older dates than White Rock emplacement age of ~33.9Ma +/- according to Obradovich, 1969).

All five apatite grains from sample 19-RVK-4 reflect corrected closure dates that are older than the ~34Ma geologic age of the White Rock Pluton and the Grizzly Peak Caldera – two concurrent ignimbrite flare-up events that probably reset local (U-Th)/He dates. Because sample #3 (higher elevation) and sample #5 (lower elevation) geographically bookend the Opa's Taylor Hut sample (#4) (figure 3), it is likely that 19-RVK-4 data do not accurately represent the elapsed time since closure temperature because heating events that diffused He out of apatite in the higher and lower outcrops would also have also heated granitic rocks in between.

The sample suite's youngest corrected date is 43.61Ma (figure 22 and table 2) with an analytical uncertainty of +/-3.42Ma (15%). At the minimum range of total uncertainty (37.06Ma), the grain appears to have a closure date that is approximately 3Ma older than the ignimbrite heating events mentioned above, two million years older than the 1.0Ma geologic uncertainty in the White Rock's biotite K-Ar age (Obradovich, 1969). Because of this discrepancy, the large scatter of dates (43.61Ma to 142.88Ma) and that the directly higher and lower elevation Henry Mountain samples have corrected dates that overlap White Rock Pluton emplacement age, sample 19-RVK-4 is excluded from analysis. We suspect that U-bearing inclusions (or uranium-rich surface weathering) are the source of AHe closure ages exceeding White Rock emplacement age of ~33.9Ma.

6b. Revisiting two initial hypotheses

Exploring hypothesis 1. The eastern edge of the Elk / West Elk bulls eye of exhumation is atop or a few kilometers east of the summit of Taylor Peak A (4,095m) and

AHe closure dates will lessen in age as elevation decreases until an inflection point after which they will grow in age as they approach the Grizzly Peak Caldera.

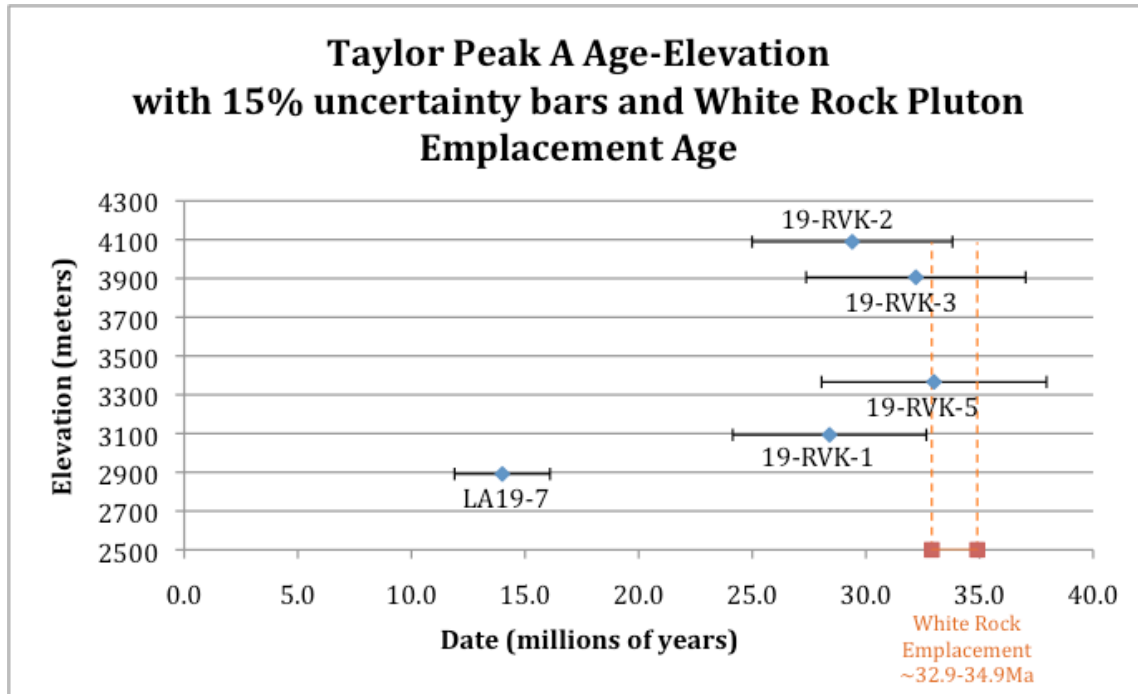


Figure 23: Age-Elevation plot of east transect vs. White Rock geologic age (33.9Ma $\pm$ 1Ma).

Data suggest that the eastern edge of our Bull's Eye of exhumation is within a few hundred lateral meters of the Grizzly Peak Caldera's western front, six kilometers east of the summit of Taylor Peak A (figure 3). This is because the physical structure of the Grizzly Peak Caldera is intact (figure 3), so it is the last known point along my eastern transect's trajectory where minimal erosion has occurred since ~34Ma. Data from four sample sites imply that granite outcrops along my easterly 972-meter vertical transect cooled together rapidly to closure temperatures of about 70°C soon after the emplacement of the White Rock Pluton (33.9Ma $\pm$ 1Ma Obradovich, 1969). Figure 23 shows four sample sites that agree with White Rock Pluton emplacement age within uncertainty. 19-RVK-1 in figure 23 appears to be slightly outside the White Rock Pluton emplacement age, however, 33.9Ma $\pm$ 1Ma is a K-Ar biotite cooling age from (Obradovich, 1969) that may have a larger uncertainty than only 1Ma.

Because corrected dates overlap one another and agree within uncertainty, it is reasonable to infer that sampled surface outcrops along the eastern transect cooled more or less concurrently to below 70°C about 34 million years ago. This implies that the

entire eastern side of Taylor Peak A, including the summit, was near the earth's surface when the White Rock Pluton was emplaced.

If the geothermal gradient 34 million years ago was $\sim 40^{\circ}\text{C}$ per kilometers depth, then it follows that samples along this vertical transect were probably no deeper than 1.5km deep $\sim 34\text{Ma}$ because $(40^{\circ}\text{C}/\text{km} \times 1.5\text{km} + 10^{\circ}\text{C}$ average air temperature $= 70^{\circ}\text{C})$. According to (Decker, 1995), Gothic mountain's modern geothermal gradient is about $38^{\circ}\text{C}/\text{km}$. Considering how widespread both the local and regional volcanism was during the Ignimbrite flare-up, $40^{\circ}\text{C}/\text{km}$ seems to be a good estimate and possibly a conservative one. See the appendix section on geothermal uncertainties for details about why geothermal gradients are complicated to measure accurately.

Fourteen million years ago, the outcrop at sample site 19LA-7 in Castle Creek was about 1.5km below the earth's surface (figure 24). Because the summit of Taylor Peak A is about 1.2 kilometers above 19LA-7, it follows that the summit could have been buried under only ~ 300 meters of material 14 million years ago (dashed brown line on figure 24 below). This assumes overlying flat topography.

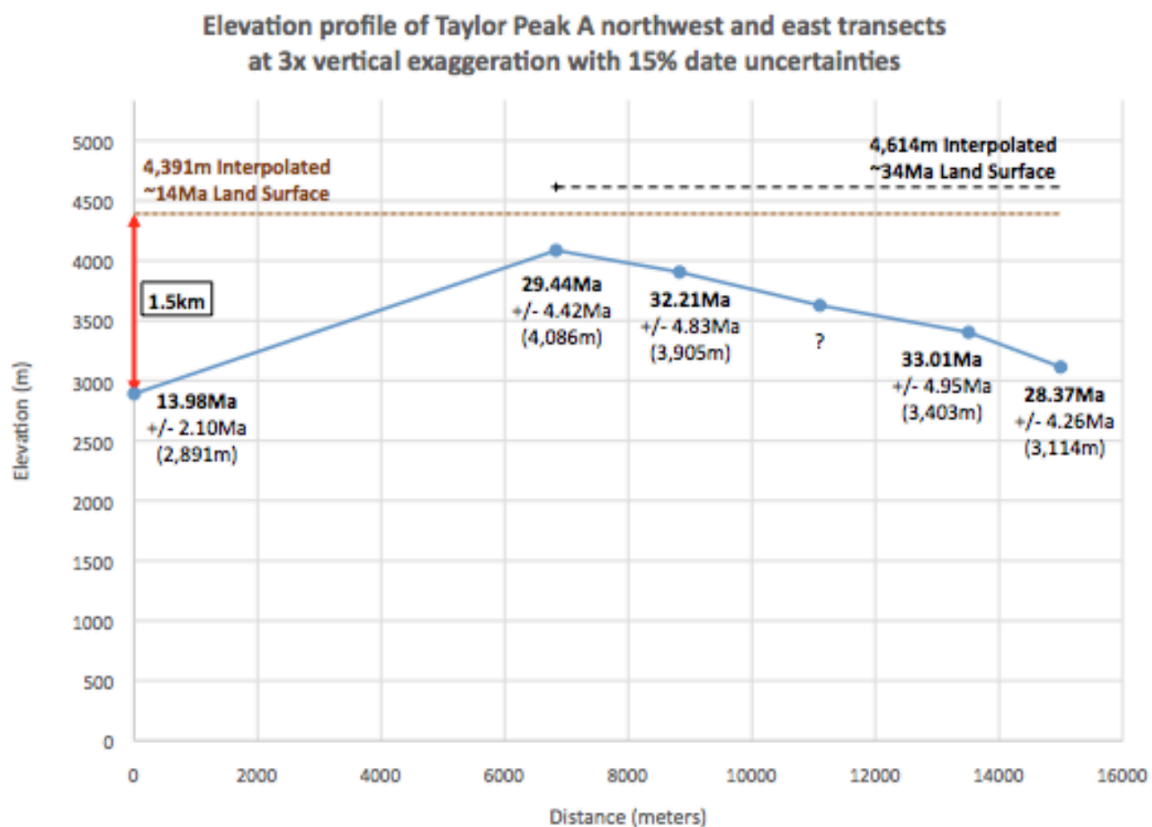


Figure 24: Possible land surface elevations above Taylor Peak A 14 million years ago (dashed brown line) and 34 million years ago (dashed black line). Northwestern transect (left) and eastern transect (right).

If the elevation difference between the top and bottom of my eastern vertical transect did not change from White Rock Pluton emplacement time until now, then the summit of Taylor Peak A, which is 972m higher than the low eastern sample, would have been emplaced 500m or less below the surface (dashed black line on figure 24). Because we do not independently know the paleo-topography, this flat surface model is used.

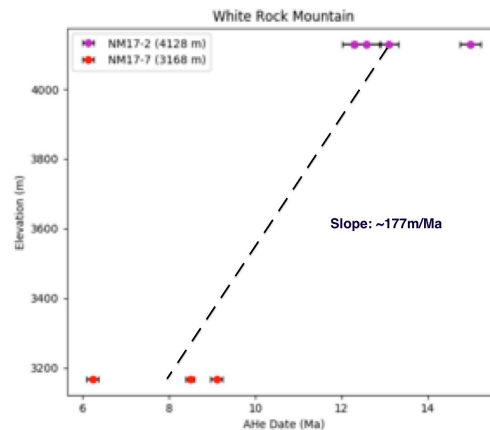


Figure 25: Modified from McCorkel, 2017. 960m vertical transect. $\sim 181\text{m/Ma}$ erosion rate from $\sim 13\text{-}8\text{Ma}$. Slope of dashed line represents approximate erosion rate in meters per million years.

The shallow emplacement of the Taylor Peak A summit White Rock granodiorite contrasts with research by (McCorkel, 2017 in figure 25) on White Rock Mountain, 12.7 km to the west, that places his summit outcrops $\sim 1.5\text{km}$ below Earth's surface about 13 million years ago (figure 25). We anything about uplift or erosion on White Rock Mountain between 34Ma and 14Ma so we can only infer that the summit outcrop was at least 1.5km deep at time of emplacement. Both summits today are at $\sim 4,100\text{m}$ elevation. This difference in depth of burial between White Rock Mountain and Taylor Peak A implies that there was a emplacement gradient from west to east that rose at least 1 km across 12.7 horizontal kilometers of the White Rock Pluton (figure 26).

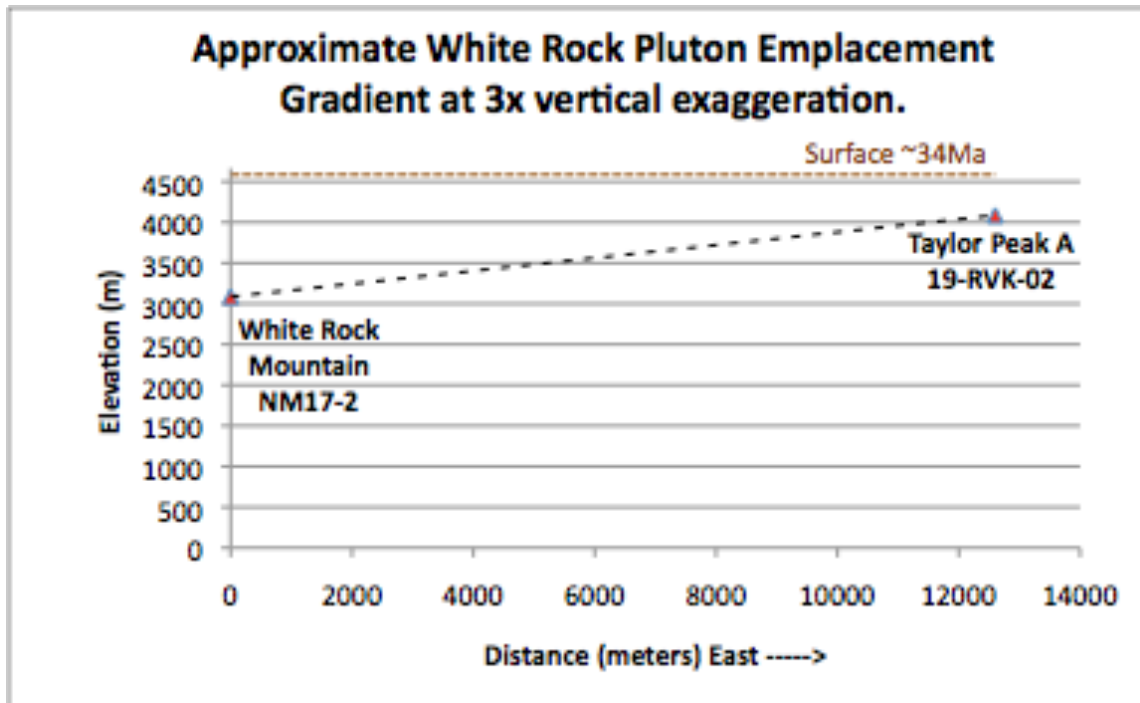


Figure 26: 3x vertical exaggeration of estimated White Rock pluton emplacement gradient slope.

The dashed brown line on figure 26 above is 500 meters above the summit of Taylor Peak A at ~4,600m. The vertical exaggeration is three times. Slope of emplacement at 1:1 scale can be computed by $\Delta y / \Delta x$ or (1,000m elevation / 12,700m distance) or (slope ≈ 0.08). That is approximately the rising gradient of White Rock Pluton emplacement from the summit of White Rock Mountain to the summit of Taylor Peak A 34Ma, if we assume that the outcrop at the summit of White Rock Mountain experienced zero exhumation between ~34Ma and 13Ma.

I hypothesize that this estimated upslope could be the result of weaknesses in the crust, such as faults, that magma followed during White Rock Pluton emplacement. This area has extensive faulting from the Laramide Orogeny (~73-40Ma), including the Elk Range thrust sheet, so it is possible that there was a subsurface fault here that drove magma upwards towards Earth's surface in a west to east trajectory across 12.7 km.

Exploring hypothesis 2. Erosion rate(s) along a northwest vertical transect (trending towards the Bull's eye center) can be estimated with elevations and AHe dates from multiple sample sites.

Erosion rate between the summit and the Castle Creek site can be estimated as an average over the past 14Ma, but it cannot be well constrained to the middle Miocene

epoch to reflect Bull's Eye exhumation-caused erosion with present data. According to (Ehlers, 2005), if we plot cooling ages against elevation, the slope of the line can tell us erosion rate. Figure 24 above shows both sites, so $\Delta\text{elevation}/\Delta\text{age}$ or $(4086\text{m}-2891\text{m})/(29.4\text{Ma}-13.98\text{Ma}) \approx 77$ meters per million years, which is represented by 1/3 the slope of the line that connects the two leftmost points on figure 24. However, with only two data points, and six kilometers of horizontal and 1.2km of vertical distance between them, we can only infer that an average erosion rate of about 77m/Ma occurred between them over the past 34 million years. We need more data in between to constrain the rates to expected Miocene-age uplift, similar to the date interval of (McCorkel, 2017).

It is likely that the erosion rate at Taylor Peak A's summit was significantly less than at the Castle Creek site since 14Ma. Shown on the dashed brown line in figure 24 above, Castle Creek at 2,891m, underwent about 1.5km of erosion since 14ma. Over the course of 14Ma, that point experienced an average of slightly more than 100 meters per million years of erosion. However, with more data points, such as at 19-RVK-10, about 200m higher in the NW transect (figure 3), we may be able to constrain the erosion rate to the middle Miocene. The summit at 4,086m experienced only about 300m of erosion during that time span. This contrasts with erosion rates closer to the Bull's eye center that average about 200m/Ma over ~5 million year time spans in the middle Miocene, shown calculated from age-date comparisons at specific sites in figure 4 and drawn from conversations with Abbott (2020). 300 meters of erosion over 14 million years is a rate of slightly more than 20m/Ma. In other words, on the average over the past 14 million years, the Castle Creek site has experienced five times the erosion of the summit site. However, there is a good chance that water and glaciers (over the Pleistocene especially) caused some of this erosion, so more sites along the northwest transect are key to calculating what the erosion was in the middle Miocene age to separate the Bull's Eye exhumation effect from glacial cycles over the past 2.3 million years.

It is expected that the overlying layers that eroded off the summit were the Pennsylvanian age Belden Marble Formation and the Gothic Formation hornfels that contact the White Rock pluton emplacement terminus on the northwest slopes of Taylor Peak A (figure 6). According to (Bryant, 1979), the Gothic Formation is 300-800m thick and the Belden Formation is 150-450m thick in the region. Surface volcanic rocks from

ignimbrite flare up volcanic eruptions may also have comprised some of the overlying material (figure 7).

6b. Future Work

More AHe data collection from my northwest vertical transect White Rock pluton samples would constrain the timing and erosion rates on Taylor Peak A's and also better constrain the eastern edge of the Bull's Eye of exhumation. Samples 19-RVK-10, 19-RVK-11, 19-RVK-12, and 19-RVK-14 are already collected and ready to be crushed. Sample 19-RVK-13 is at the picking stage, possibly ready to pack in Niobium tubes.

More vertical transects on more mountains within the Bull's Eye will draw us closer to understanding when and why the Colorado Rockies reached their present high elevation. Constraining the Bull's Eye perimeter will allow us to focus on the patterns of exhumation within it.

An animation of the entire bulls eye (with rotatable perspective) could represent the timing and magnitude of exhumation of different mountains that rise against a datum. Timing could be scaled (one second = 100kyr, for example) and perhaps AHe technique-derived patterns of uplift could help reveal patterns of whatever mysterious mechanisms powered this focused Bull's Eye of exhumation during the middle Miocene epoch.

7. Conclusions & New Hypotheses

Apatite (U-Th)/He low temperature thermochronology is a powerful tool for understanding when granites last cooled below $\sim 70^{\circ}\text{C}$. It can be effectively used to approximate the timing of subsurface heat pulses (such as pluton emplacements or volcanism) or as a proxy for uplift and erosion if used at specific locations of igneous rocks on mountain slopes along a vertical transect. This technique has an uncertainty of approximately fifteen percent or a few million years. See the appendix section on uncertainties for hypotheses about how we could reduce uncertainty and refine the technique's resolution.

Through the use of this AHe technique, with knowledge of its limitations, this research project has produced four new hypotheses that are supported in this text.

1. The eastern edge of our Bull's eye of exhumation appears to be a few kilometers east of the summit of Taylor Peak A, near or at the western edge of the Grizzly Peak Caldera. Further AHe analysis of samples already collected from Taylor Peak A

and Star Peak can help constrain the edge of the Bull's eye here. Sample 19-RVK-10 at ~3110m towards Castle Creek is especially interesting, because is at comparable elevation to the low sample on the Eastern transect near the Grizzly Peak Caldera and it could help constrain broad erosion rate calculations on the northwest side of Taylor and Star Peaks.

2. The entire eastern side of Taylor Peak A has probably been buried at less than 1.5km depth since the Oligocene (34Ma) and the summit (White Rock granodiorite) could have been emplaced at a depth of less than or equal to 500m. The northwestern transect, averaged over the last 14 million years, eroded at approximately 77.7 meters per million years, but this conclusion needs more intermediate data points to be separate the timing and magnitude of the Bull's Eye exhumation caused erosion from other events such as Pleistocene glacial erosion and Castle Creek river incision.

3. Castle Creek's summit underwent about 200m of erosion between 34Ma and 14Ma and about 300m of erosion from 14Ma until today. This implies that it is near the edge of the Bull's eye because its erosion is small relative to other mountain summits closer to the center.

4. Taylor Peak A's summit was emplaced at least one kilometer closer to Earth's surface than the White Rock Mountain summit, implying that there was an emplacement gradient that rose from west to east across 12.7 km of the White Rock Pluton at a steepness of approximately 0.08. Today the summits are both at about 4,100m elevation.

8. Thank You

Lon Abbott for being the most helpful and patient thesis advisor. Thank you for teaching me how to map rock units, how to sample, how to process rocks, and how to look at my work and the world with a more scientific eye. Here's to many more mountains, my friend.

Peter Blanken and Bryan Hynek for being on my committee, for giving me time and helpful feedback, and for encouraging me when I was mired in the complexities of the project and the rabbit holes of tangential research!

Becky Flowers for allowing me to use the CU TRaIL Laboratory and for being a wonderful teacher.

Jim Metcalf for being a wizard on the microscope, for answering a million little technical questions, and for hustling to process all of our data before the laboratories were locked down due to the COVID-19 outbreak.

All my friends and family for a lifetime of love and support and for never letting me give up on my dreams.

Appendix A: Uncertainties and Errors

Uncertainty is a range that bookends a value (e.g. age $\pm 1\text{Ma}$) whereas error is the difference between the measured value and the true value.

In this section, I explore some AHe technique uncertainties in an attempt to reduce them and improve the resolution of the technique.

I applied a 15% uncertainty to my data to encapsulate known and unknown factors that affect the accuracy of this apatite Low Temperature (U/Th)-He technique. This matches the HeFTy-modeling standard of uncertainty. The true amount of uncertainty in these measurements is impossible to know with present technology and techniques so 15% is used as a high end member. AHe technique's uncertainty is probably closer to 7-10% (conversations with Metcalf, 2020).

Analytical Uncertainty

Dates are given as a $\pm$ value in millions of years after each Apatite mass spectrometer run. These are simply uranium, thorium, samarium measurement uncertainties, represented as 2σ . As observed by laser ablation ICP-MS, parts per million measurement error is $\sim 5\%$ (Farley, 2011).

Geologic Uncertainty:

K-Ar dating of biotite within the White Rock pluton mplacement and Grizzly Peak Caldera have geologic uncertainty of $\pm 1\text{Ma}$ and 1.1Ma respectively, as defined by (Ordovich, 1969). K-Ar is a cooling age that could have uncertainty greater than 1Ma .

Human Error

Potential sources of contamination exist through out the granite crushing and apatite picking processes. The rock crusher, disc mill, sieves, lab oven, Frantz magnetic separator, rock lab counter tops, microscope lab counter tops were often covered in grains of unknown origin from previous researchers. The probability that contamination reaches mass spectrometer analysis and affects data is low, however, because finding inclusion-free apatite of sufficient size is rare. Error due to poor labeling practice is more likely.

During the separation process, breaking an LMT ice plug will mix up heavy and light density grains, creating a large amount of unwanted material under the microscope. These extraneous layers (quartz and feldspar, for example) multiply the amount of time required to pick a sample and make it harder to see crystal inclusions. It is recommended

to submerge 50ml sample tubes into liquid Nitrogen for 3 minutes to the 15ml line and let them sit for five minutes to form a solid ice plug. Two tubes can be submerged simultaneously.

Hand measuring crystals in Leica Suite X software, connected to the microscope by digital camera, determines the crystal volume that is used in the alpha ejection correction that corrects the raw date measurements. Measurements are only as good as the researcher's accuracy and often a compromise must be reached if an apatite is sheared in half at an oblique angle or has a broken face. Also, it is clearer to observe crystal face edges in the microscope than it is in the shadowy image transmitted to the computer screen, where the line-measuring tool is. Intact apatite crystals would reduce error here.

Machine Error

Apatite crystals have a Hexagonal crystal system, a long c-axis, six fold symmetry, and a Moh's hardness of about 5. Damage to apatite crystals during grain separation, probably caused by the steel crusher and disc mill plates, leads to apatite crystals that are sheared off obliquely to the long C-axis. The damage is likely due crushing because shearing occurs in clean, straight lines. None of the twenty-six crystals that yielded AHe data were doubly terminated, inclusion-free, and more than eighty microns wide. Not only are broken apatite crystals harder to identify, but they also can introduce error because the broken-off fraction (within 20 μ m range) could have alpha ejected into the remaining crystal portion (Abbott, 2020 personal communication) and make the AHe date appear *older* than it really is.

Using ultra sonic vibration crushing methods could minimize this crystal damage- and reduce uncertainty. The sonic vibration works by scaling up frequency of sound waves and it remotely crushes rocks along fracture planes and through the weaker matrix (Zhou, 2019). A research experiment comparing the current crusher and grinder methods with an ultrasonic variable frequency method could clarify if having more well-shaped apatite grains for microscope analysis will justify the potential extra cost.

Zonation

Uranium and Thorium zonation within crystals is not constant and crystals are not sphere shaped- Apatite is hexagonal, more resembling a cylinder. We assume spherical shape of crystals for Ft correction, because the math works out better. The Ft correction

also assumes that Uranium and Thorium are distributed equally through out the apatite crystal (conversations with Metcalf, 2020). In reality, U/Th atoms are randomly distributed through out the crystal, sometimes concentrating in the core, sometimes along the rim, and sometimes rather equally. If an apatite is core-rich, then most ^4He is retained within the crystal during alpha ejections and corrections erroneously add more Helium, resulting in corrected dates that are *older* than true dates (Meesters, A. & Dunai, T., 2002). If an apatite is rim-rich, then more ^4He is lost from the crystal than expected and the Ft correction is an underestimate, resulting in corrected dates that are *younger* than true closure dates. This ft uncertainty due to U/Th zonation is thought to be up to 30% (Hourigan, 2005). Uranium within or on (such as surface weathering) within 20 microns physical distance from a measured apatite crystal, can alpha eject into our crystal, implanting “parentless” ^4He , and making our corrected dates *older* than true dates (Kohn et al, 2008).

Geothermal Gradients

One of the trickiest uncertainties to quantify when connecting cooling rates with depth is measuring the geothermal gradient. The geothermal gradient is not linear with depth, it can change laterally over short distances, and it changes through time. Colorado’s modern high heat flow implies thermal sources in the crust (Decker, 1988).

Accurately measuring a specific location’s geothermal gradient today is an imprecise task. The gradient increases with a thin lithosphere (hotter), more Uranium-rich rocks that decay groundwater traveling through subsurface fractures, rock layers’ thermal conductivities, and mantle temperatures flux from below (reduced flow) (Decker, 1988). It is estimated that the modern Gothic Mountain geothermal gradient (within 5km of the White Rock pluton and within 20km of Taylor Peak A) is approximately $38^\circ\text{C}/\text{km}$ (Decker, 1995). Seismic imaging of the crust beneath the Elk Range shows that present Moho depth is less than forty-five kilometers (Hansen, 2013).

The geothermal gradient is also likely to change over time and to be different laterally, even over short distances. Six kilometers horizontal difference in geothermal gradient (between my summit sample and the Castle Creek sample) cannot be measured exactly in a time and cost effective way in a local area that has faulting pathways (Castle Creek Fault Zone), reduced flow from mantle sources, radiogenic heat (decay) from

Figure 28: Anticipated sample sites on Geologic Map. Modified from Fridrich, 1998. Not exactly where I did sample but a guide I used in the field.

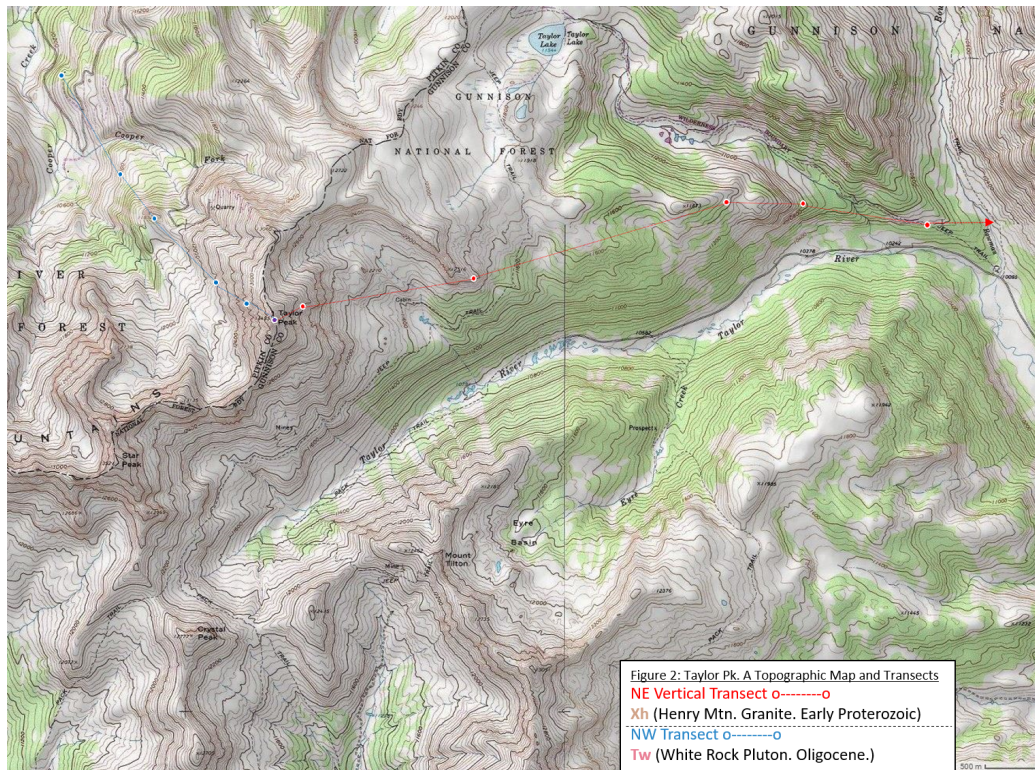


Figure 28: Topographical map used to estimate sample locations. Used in the field to navigate! Modified from USA topo map overlay through Google Maps.

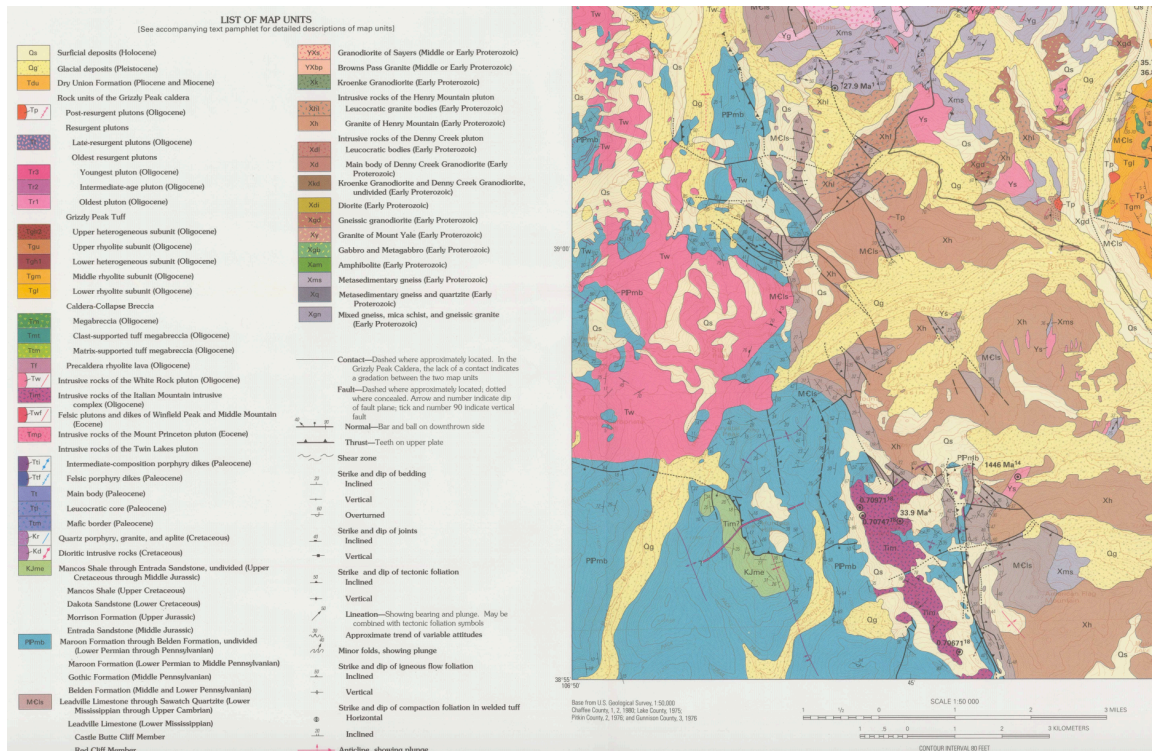


Figure 29: Modified from Fridrich, 1998. Geologic map of Taylor Peak A vicinity with lithology key.



Figure 30: The possibly unclimbed northwest ridge Star Peak A in October 2019.



Figure 31: Google Earth Pro Landsat view of sample area in relation to Aspen, CO. From zenith, to scale.

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