

The Thermal History of Mount Lamborn in Colorado's West Elk Mountains
using Apatite (U-Th)/He Thermochronology

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Abstract

Mount Lamborn, a granodiorite laccolith in the West Elk Mountains, provides a useful constraint on the extent of the unique exhumation that occurred in the West Elk and Elk Mountain ranges. The concentrated area of exhumation is regarded as a “bullseye” that is surrounded by younger basalt flows (10 Ma) and other igneous plutons that were not buried at depth. The laccoliths in the West Elks have the same age and rock chemistry as the adjacent San Juan Mountain plutons to the south, but the regions have distinctly different topography. The West Elk Mountains show large scale exhumation down to intrusive laccoliths directly related to the bullseye, but the San Juan Mountain plutons are still buried by volcanics. In order to understand when, and ultimately why, exhumation is focused in the West Elks, low temperature apatite (U-Th)/He thermochronology coupled with forward modelling was performed to understand the thermal history of Mt. Lamborn. Six samples were collected along a vertical transect of 1100 meters to capture the change in rock age with depth. Four of the six samples yield ages between 28-40 Ma, and two have younger dates of 22 and 11 Ma, showing no vertical progression as anticipated. From these varying ages, the data tells two stories regarding its thermal history. First, Mt. Lamborn was emplaced at very shallow depths, likely with 500 m but no more than 1000 m of sediment overlying the summit after emplacement. Second, there was an episode of local specific reheating that caused the younger age samples. This reheating episode may be closely linked to basalt dikes that fed Grand Mesa and surrounding structures ca. 10 Ma. Mt. Lamborn therefore helps define the edge of the exhumation bullseye and explains its 3-D shape as dome-like, diminishing in strength toward the edges. The geometry of the bullseye points away from ideas of regional mantle mechanisms or selective river incision but supports small scale perturbations and Rayleigh-Taylor instability.

1. Introduction

1.1 The Problem in the Rockies

Understanding the formation of the Colorado Rocky Mountains has been a cyclic puzzle that geologists have solving for many decades. Some researchers have tried to conclude the timing of the Rockies formation via the mechanism of formation while others have tried to deduce the mechanism from the timing. Countless effort has gone into studying the region, but no consensus has been reached on either the timing or the mechanisms that formed the bewildering peaks. In most orogenic events one tectonic plate collides with another, thickening the crust and producing stark topography. Nearly a thousand miles from any convergent plate boundary, there is no clear evidence of classic accretional tectonics in Colorado. Instead, the Rocky Mountains are the result of a myriad of tectonic events and magmatism across tens of millions of years, all attributing to the topography visible today. Some regions have been studied much more extensively than others, but not all pieces of the puzzle are together. This study is focused on understanding the exhumation rate and timing of Mt. Lamborn in the West Elk Mountains, ultimately trying to understand the mechanism that are responsible for the uplift and local topography.

1.2 Possible Mechanisms

Surface uplift of 2-3 kilometers has occurred across the southern Rocky Mountains and Colorado Plateau over the past 80 million years (Karlstrom et al., 2012). Surface uplift describes the mean change in elevation in a region with respect to the geoid. It is equal to rock uplift minus exhumation, where rock uplift is the displacement of rock to the geoid and exhumation is the displacement of rocks with respect to the surface. The rate of exhumation is equal to the rate

of erosion by tectonic or surficial processes. Simply put, surface uplift is equal to rock uplift minus erosion rate (England and Molnar, 1990). In the Colorado Rocky Mountains, no apparent mechanism can fully support the visible surface uplift, but by understanding the exhumation history of Mt. Lamborn and other laccoliths, one can gain a better grip on the issue at hand.

Several different hypotheses attempt to explain the mechanism responsible for surface uplift. Laramide age (70-40 Ma) surface uplift points toward flat slab subduction and hydration of the continental lithosphere. When Laramide age deformation and isostatic responses to extension and Cenozoic erosion are factored out, there is still 1.6 km of residual rock uplift that is left to be explained in the region (Roy et al., 2009). Removal and sinking of the Farallon slab circa 35-25 Ma assisted in uplift by unloading mass as well as forcing hydration-induced lithospheric melting and subsequent magmatism (Humphreys et al., 2003). Other scholars have suggested a completely different mechanism such as changing climate to be responsible for surface lowering, but rock uplift (Molnar and England, 1990). A leading hypothesis in literature currently surrounds the idea of mantle-driven dynamic topography. It suggests that more recent convection in the mantle pushed up the base of the lithosphere in part with mantle buoyancy increasing (Karlstrom et al., 2012). Important to recognize is the definition of dynamic topography, which is commonly misconstrued. It is described as the change in Earth's surface as the result of mantle convection. This includes the viscous traction applied to the base of the lithosphere by underlying mantle, and in some cases also includes the density and subsequent buoyancy variations within the lithosphere as well (Molnar et al., 2015). This slight difference in understanding allows for estimates ranging from hundreds to over 2000 meters of dynamic topography. Following Laramide age tectonism, the combination of thermal perturbations that create mineralogical changes and dynamic topography are great enough in magnitude to account

for the rock uplift in western Colorado and the Colorado Plateau (Roy et al., 2009). Overall, the broad range of ideas surrounding the region only highlight the uncertainty around it and push for more research.

1.3 Confusion in the West Elks

The West Elk Mountains are made up of Oligocene and Miocene plutons that intrude into older sedimentary layers (Obradovich et al., 1969). These plutons were emplaced at depth and exhumed to the surface, producing the mountains we see today. The troubling parts about this mountain range are both the striking similarities to the San Juan Mountains and the stark differences. Both the San Juans and West Elks consist mainly of intermediate igneous rocks that intruded around 34-29 Ma. The regions share synchronous periods of igneous activity on multiple occasions, such as the West Elk Breccia coinciding with lavas and breccias in the San Juans (Lipman et al., 1969). In the present day, most of the West Elk Mountains consist of exposed igneous plutons that have been fully exhumed to the surface. Conversely, the San Juans consist of plutons buried under volcanics as well as thick layers of the overlying sedimentary sequence. They are located just south of the West Elks and are lithologically identical, so why are the exhumation histories of these two mountain ranges so different from each other?

Most hypotheses blanket exhumation across the Rocky Mountains as a uniform response to their specific proposed mechanism. Other thermochronology data suggests otherwise and favors regionalized exhumation (Abbott et al., 2018). Seismic data from the Colorado Rocky Mountain Experiment and Seismic Transects (CREST), shown in Figure 1, confirm the lack of isostatic root below the Rocky Mountains first mapped by Sheehan (1995) using receiver functions and tomography. Slower seismic waves (negative anomalies) that are recorded under the Rocky Mountains appear from upwelling asthenosphere (Lee and Grand, 1996). The research

suggests a that both de-densified crust and warm advecting mantle are responsible for supporting the topography visible today (Hansen et al., 2013). While these may be responsible for large scale uplift, it is difficult to constrain mantle forces to the scale of the West Elk Mountains, except for the idea of mantle drips and a Rayleigh-Taylor instability. Differential uplift may have been caused by selective river incision during the onset of mantle-driven dynamic topography, but remains to be extrapolated further into the past (Karlstrom et al., 2012). Mt. Lamborn is just one peak in the West Elks, but it will help constrain the western edge of a newly hypothesized “bullseye” of exhumation in the region. The goal of this project is to understand the timing of uplift/exhumation for the granitic plutons in the Elk/West Elk bullseye. Looking at the big picture, this work will help contribute to a larger project trying to understand the uplift timing of the Rocky Mountains and the mechanism that caused the surface uplift.

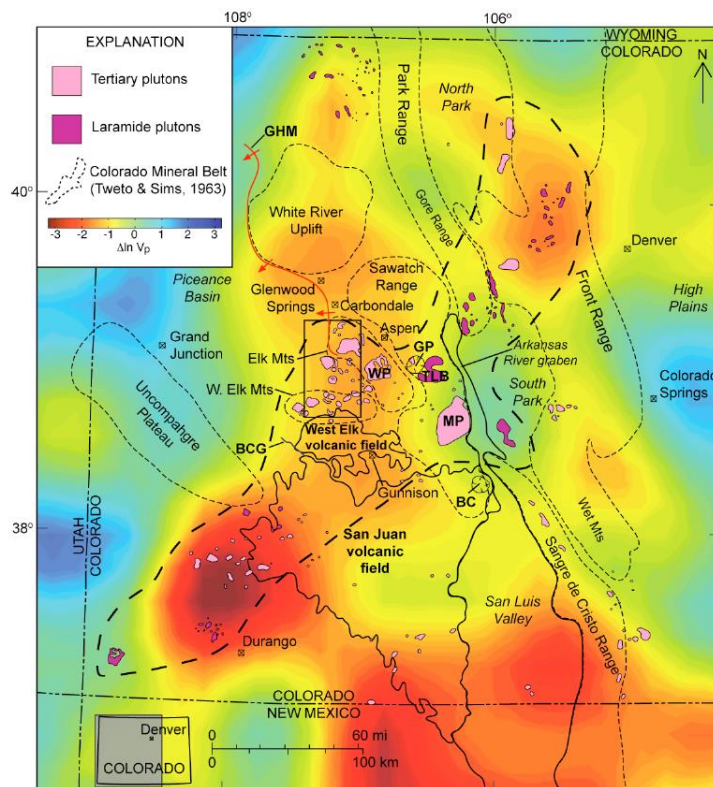


Figure 1. Map of western Colorado marking significant mountain ranges and structural features overlain on seismic tomography data, showing large negative anomalies below West Elk Mountains and San Juan Mountains. Figure from and adapted by Garcia 2011.

1.4 Thermochronology Method for Understanding Exhumation

Apatite Uranium-Thorium/Helium thermochronology can be an accurate and useful tool for understanding the cooling histories of rocks from erosion and constrains the uplift history of a region to a certain time (Stockli et al., 2000). Thermochronometers use radiometric dating of specific minerals to determine the time at which the mineral began retaining its daughter product. With the intrusion of laccoliths such as Mt. Lamborn in the West Elks, thermochronology gives the time when buried rock passes through an isotherm that allows retention of daughter atoms from their radioactive parents. In the case of (U-Th)/He thermochronology, a closure temperature of $\sim 70^\circ\text{C}$ is necessary for the retention of Helium, and the rocks are found at depths of 1.5-2 kilometers, assuming a geothermal gradient of 40°C/km . Samples of these rocks from Mt. Lamborn were collected along a vertical transect of over 1 km with the purpose of understanding trends in vertical rates of exhumation as well as comparing their overall age to other “bullseye” locations, which range from showing emplacement to reheating ages anywhere between 35-5 Ma. The data acquired from the apatite samples provide a low temperature thermal history of Mt. Lamborn and will aid in explaining the erosion history from the Miocene to present.

2. West Elk Mountains: Setting and History

2.1 Colorado Rocky Mountains

The wide range of topography, deposits, and geologic features in the Colorado Rocky Mountains stem from a varied geologic history. A Precambrian basement was uplifted during the formation of the Ancestral Rocky Mountains roughly 300 Ma. This mountain range disappeared

over time with erosion and was eventually submerged by the Western Interior Seaway, dumping thousands of meters of sediment. The Piceance basin is one depositional region and the location of the West Elks, which intrude into the sedimentary sequence. This feature distinguishes the West Elks from being a part of the Laramide Rocky Mountains. It was not until the late Cretaceous that the sedimentary formations became land, which coincided with the onset of Laramide orogeny.

Since the late Cretaceous, the Laramide orogeny, the Ignimbrite flare-up, and the Rio Grande Rift have all had profound effects on the Rocky Mountain region. Widely believed as the result of the Farallon's subduction under the North American Plate, Laramide orogeny tectonism began during the middle Campanian, about 75 Ma (Tweto, 1975). This continued into the Eocene and is responsible for the northeast trending Colorado Mineral Belt that cuts across the geologic lineaments of Colorado (Chapin, 2012). As Laramide tectonism waned, the middle Tertiary Ignimbrite flare up began. Intermediate composition lavas and breccias were erupted from volcanoes that were scattered around the southern Rocky Mountains from 38 Ma to 26 Ma. This volcanism followed a southward progression of eruption, requiring some form of large-scale tectonic command (Lipman and McIntosh, 2008).

Following this period of magmatism was subsequent rifting, beginning ca. 28 Ma. After first rifting in segments, the Rio Grande Rift fully integrated sometime between 10-5 Ma (Abbey and Niemi, 2018). Significant erosion and relief within the rift developed, and competing theories argue between propagation of the rift northward versus consistent rifting throughout the formation period (Landman and Flowers, 2013). Regardless of direction, this rifting marks the most recent large-scale tectonic activity in the Colorado Rocky Mountains. The region of interest

in this study is well west of the main rift, but other extensional basins and normal faulting are found in the area.

2.2 West Elk Formation

Having occurred prior to Laramide uplift, the Western Interior Seaway is responsible for major sedimentary sequences across Colorado. The West Elk Mountains are in the Piceance Basin which holds over 2 km of deposited sedimentary rock. Its major sedimentary unit is the Mancos shale, about 1300 m thick, reminiscent of the offshore environment during the late Cretaceous. Overlying this shale, regression is indicated by the 700 meters thick Mesaverde formation transitioning from shales to sandstones upward. Caused by Laramide uplift, this marks the change from aquatic to terrestrial environment in the region. Other formations also mark the Laramide, but this largely shows the slow transition to a regressive sequence of the Seaway from uplift. Further up the sequence is the Eocene age Wasatch Formation, nearly 400 meters thick, which was deposited by river deltas carrying sediments eroded from the newly uplifted Rocky Mountains (Heller et al., 2013). This formation marks some of youngest sediment intruded, suggesting plutons were buried by the even younger Green River and Uinta Formations.

Magmatism accompanied the Laramide orogeny, producing a suite of intrusive igneous plutons across the western slope of Colorado. Field and petrographic data from the region divide the plutons into four categories. The first group is the felsic porphyries of the Aspen mining district. These only occur within the Sawatch Range since they formed during the high-angle faulting in the region during the onset of the Laramide. Second, granodiorite porphyry plutons intrude rocks in the sedimentary sequence as young as the Wasatch formation and low-angle thrusts in the Elk Mountains. Third, minor gabbro porphyry and lamprophyre dikes and sills cut into Group 2 plutons in the Elk Mountains and Ruby Range, aligning in age (Miocene-Pliocene)

with other basalt lava flows in the surrounding region. The fourth group is a soda granite exposed at the center of the Treasure Mountain dome in Marble, Colorado, and rhyolite porphyry that occurs around the late Miocene (Obradovich et al., 1969). It is hypothesized that the bimodal suite of basaltic and rhyolitic magmatism during the Miocene is the result of extensional tectonics and partial melting of the lithospheric mantle and lower crust, respectively (Mutschler et al., 1981).

The West Elk Mountains consist of Group 2 plutons. Looking in more depth, these plutons can be further divided into 4 stages of Oligocene igneous activity (Mutschler et al., 1981). Stage A plutons are the significantly larger granodiorites that mark the onset of magmatism in the Oligocene. These include the Sopris, Snowmass, and Whiterock plutons. Once larger plutons crystallized, granodiorite porphyry dikes, sills, and laccoliths were emplaced across the Elk Mountains, Ruby Range, and West Elk Mountains. Granodiorite porphyry can be seen cutting the Stage A plutons, and similar sills, laccoliths, and dikes are in the Elk Mountains, Ruby Range, and West Elk Mountains. These Stage B plutons are more silicic, with between 64 to 68 % silica, but contain mafic xenoliths from Stage A plutons. Following these Stage B plutons, andesitic stratovolcanoes developed in the West Elk Mountains. These produced the West Elk Breccia, similar in composition to the lavas and breccias in the San Juan volcanic field. This marks Stage C igneous activity and was soon cut by a northeast trending zone of small stocks and dike swarms extending from the West Elk Mountains to the Elk Mountains. These stocks and dikes are mafic andesites, with 58 to 62 % silica, and represent the final stage of igneous activity for the Group 2 plutons.

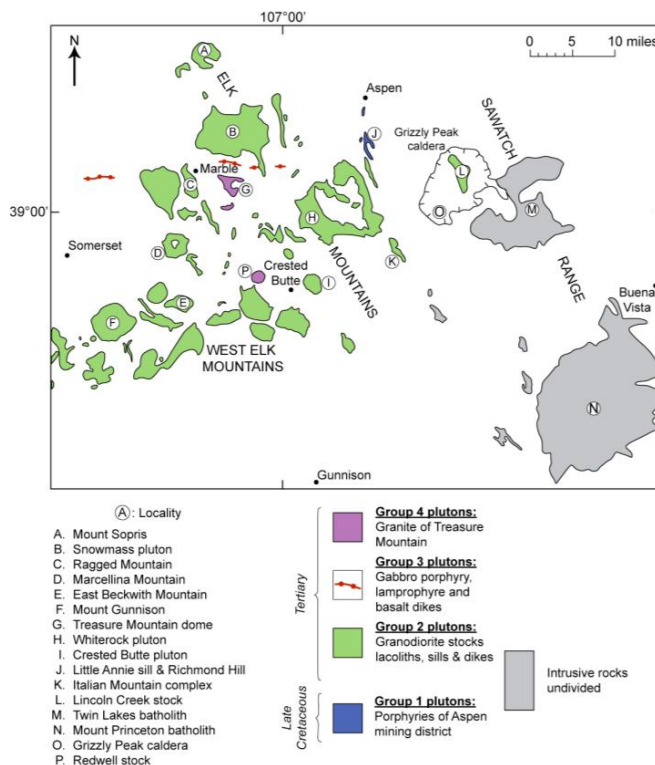


Figure 2. Stages of igneous activity across the Elk and West Elk Mountains. Map originally from Obradovich et al., 1969, and adapted by Garcia 2011.

Prior to any radiometric dating, the Piceance Basin sedimentary deposits provided a relative age for the West Elks Mountains due to superposition and cross cutting relationships. Some of the Group 2 plutons visibly intrude hundreds of meters into the Wasatch Formation, pressing up into the strata and forming dome structures. Others are emplaced more deeply, only into the Mancos. The intrusion into Wasatch sediment implies that the plutons formed during the late Eocene and into the Oligocene, sometime after the Wasatch deposition (Godwin and Gaskill, 1964). The intrusions forced contact metamorphism, resulting in hornfels and quartzite along contacts. During the similar time, volcanism in the region produced extrusives such as the West Elk Breccia. Interbedded tuffs and gravels in the region indicate episodic volcanism over several million years (Gaskill et al., 1981). Magmatism continued variably over time, ultimately subsiding during the Miocene. While other laccolithic mountains are present in the Colorado

Plateau, the West Elk cluster of laccoliths cover a much larger area, have larger individual laccoliths, and are arranged around a central fracture zone. These contrasting characteristics reflect the possibility of different intrusion processes or amount of erosion for West Elk laccoliths relative to other intrusive bodies in the region (Godwin and Gaskill, 1964).

2.3 Regional Setting and Area of Interest

The West Elk Mountains are in west central Colorado; Carbondale is to the North and Gunnison is to the South. The mountains are comprised of the West Elk laccolith intrusive region in the northern part of the range and the West Elk volcanic field in the southern end. These regions cover a combined area of 2900 sq. km (1300 sq. km in the laccolith region and 1600 sq. km in the volcanic field (Godwin and Gaskill, 1964); (Gaskill et al., 1981). The laccoliths are clustered around a dike swarm and range anywhere from 20-100 square kilometers in area and rise anywhere from 0.5-2km in height above the surrounding area. Geologic features surrounding the West Elks include the Elk Mountains and Sawatch Range to the East, White River Uplift to the North, Piceance Basin and Uncompahgre Uplift to the West, and San Juan Volcanic Field to the South.

The igneous “bullseye” of uplift in the region has some other parameters. It is centered around the Elk Mountains and laccolith cluster of the West Elk Mountains. This removes the West Elk volcanic field from the area of study and constrains the region of interest between areas of basalt magmatism around 10 Ma. This constrained region also isolates all the epizonal granodiorite plutons intruded during the Oligocene and Miocene.

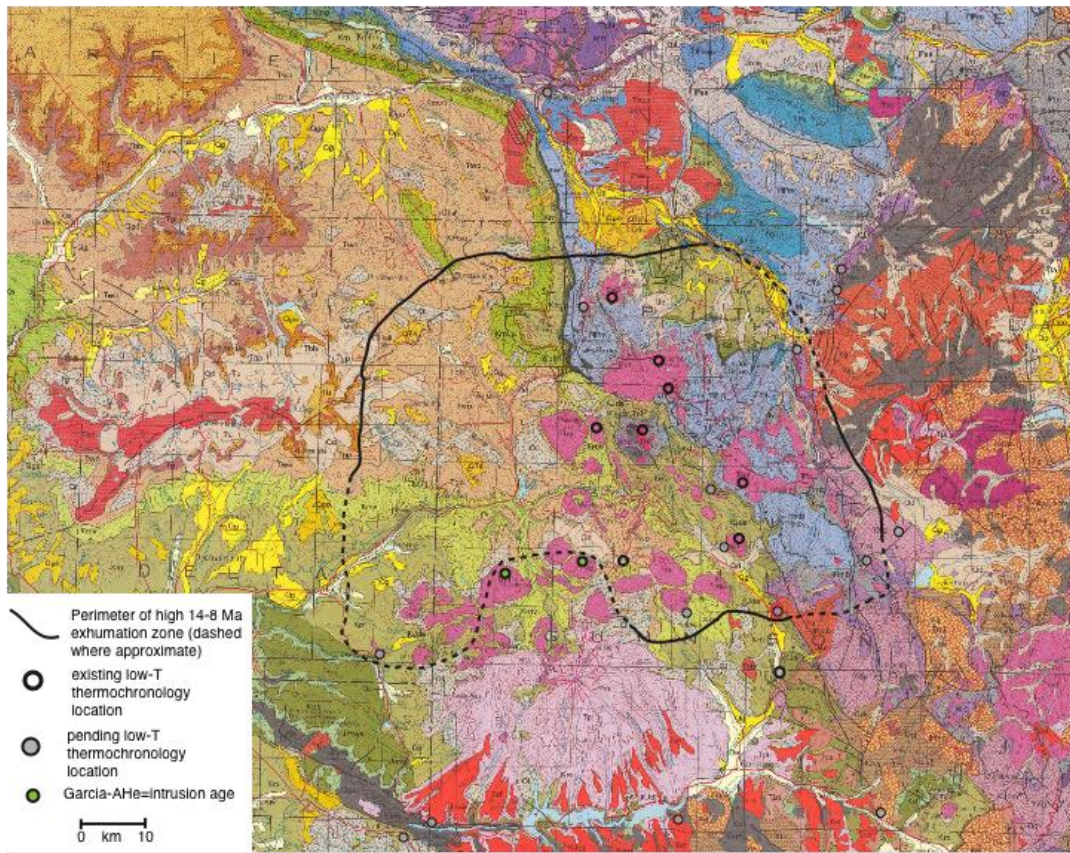


Figure 3. Map of west central Colorado, from Tweto 1979 and adapted by Abbot 2018. “Bullseye” perimeter of exhumation shown by line, with dotted sections working toward true constraint.

2.4 Mount Lamborn

Mount Lamborn is located on the westernmost edge of the bullseye of exhumation, right next to the town of Paonia, on the border between Delta and Gunnison counties, and marks the highest point in Delta County. It is in Gunnison National Forest and its peak has an elevation of 11,402 feet (3,475 meters). It is a laccolith of granodiorite porphyry with phenocrysts of plagioclase, biotite, and hornblende (Gaskill et al., 1981). No samples have previously been collected from this peak for thermochronology purposes; its location as well as over 1 km relief make it an ideal candidate to add to the ongoing project by Lon Abbott and others at the

University of Colorado Boulder surrounding the region. Found on the western boundary of the suggested bullseye, Mt. Lamborn can be used to constrain the exhumation boundary in the west.



Figure 4. Peak of Mt. Lamborn from site of sample MR19-01 looking North. Photo taken by Mitchell Ramba

2.5 Previous Geochronology

The first attempts to accurately date the igneous plutons in the Elk and West Elk Mountains came from Obradovich et al. in 1969. Using the potassium argon (K-Ar) method of radiometric dating on biotite separate, Obradovich matched dates to the 4 groups of igneous activity in the region, for example, 70 Ma ages for the Aspen mining group plutons. Most of the Elk Mountain region provided biotite separates yielding ages from 34-29 Ma. A closure temperature for the biotite crystals of roughly 280 °C is recorded with the method, correlating to emplacement age for the plutons. This assumes the plutons were emplaced shallower than about

7 km, which is very likely, but not impossible. These dates align well with peak volcanism in the San Juan Volcanic Field which was determined to be 35-26 Ma (Lipman and McIntosh, 2008). The igneous rocks associated with the emplacement are intermediate in composition and move toward bimodal activity after initial intrusive events. Data from the West Elk Breccia constrain a minimum age of about 27 Ma in a welded tuff overlying breccia. The Crystal pluton in the center of the bullseye provided much younger dates of about 12.5 Ma, matching the felsic Group 4 plutons (12-18 Ma), and possibly reheated some of the surrounding region (Obradovich et al., 1969).

Recent study of the region by Garcia (2011) recreated the work done by Obradovich with further K-Ar dating along with Zircon U/Pb data. The ages Garcia recorded agree with the initial work done in the region. Data was also collected using Apatite fission track and Apatite Helium (AHe) methods to understand the cooling histories of the Elk and West Elk plutons through the 110 °C and 70 °C isotherms, respectively. Data from these methods suggest two periods of cooling in the region: first and most predominantly from 25-15 Ma, and second from 12-5 Ma in a few select plutons. In most scenarios, there is rapid cooling associated with the plutons soon after emplacement. Outside of the bullseye, basalt capped mesas are dated at 11 Ma, suggesting minimal exhumation outside of the bullseye after that time (Abbott et al., 2018). Precambrian granite just outside the region was sampled and data show it passing through the AHe closure temperature around 61 Ma, emphasizing the large difference in exhumation in and out of the bullseye.

3. Methods and Samples

3.1 AHe Thermochronology

Thermochronology, a subset of radiometric dating, utilizes the decay of radioactive isotopes such as uranium-238 to record the thermal histories of rocks. Apatite (U-Th)/He dating, also called apatite helium (AHe) dating, works by measuring the ratio of daughter (He) to parent (U-Th) atoms present in apatite crystals. Simply put, the more daughter that's been produced, the longer the rock has been above a closure temperature. In this method, U and Th decay to lead (Pb), ejecting alpha, or He, particles. For the West Elk laccoliths such as Mount Lamborn, because cooling allows for retention of helium, apatites can be separated from bulk rock and the ratio of daughter to parent can be measured, ultimately used for calculating the cooling history. Prior to cooling, the plutons were buried by enough sediment that the isotherm was above the closure temperature, which prevented apatite crystals from retaining any daughter helium atoms. Apatite crystals have a partial retention zone of helium between 40 and 80 °C, and fully retain helium when temperatures are below 40 °C (Stockli et al., 2000). Typically, the ages calculated from the AHe method provide the time that each sample passed through the 60-70 °C isotherm. This exact isotherm is variable for multiple reasons. First, it is affected by the grain size of the apatite, so much that smaller grains (50-150 μm average) tend to align with a higher closure temperature, about 70°C (Ehlers and Farley, 2003). Another factor is the effective uranium (eU) of the apatite, which depends on the concentration of the parents, and therefore dependent on grain geometry and size. Grains with lower eU are less affected by radiation damage and tend to have lower closure temperatures.

An important distinction should be made surrounding what the AHe data is providing scientists. A thermochronometer gives the cooling history of a sample rock, but this cooling may be the result of different processes. The most common mechanism for cooling is exhumation. While exhumation could occur during uplift, it may have occurred much earlier, to the degree

that a region was uplifted but the plutons were still buried by a sedimentary stack. Other information must be gathered to understand the full history of the crystal, its parent rock, and the formation region. Some other source of data anomalies may be reheating events that allowed for release of daughter helium, producing a younger age. Other climatic factors may also impact that data produced. As a result, using a thermochronometer to record thermal histories is a process that requires careful interpretation because of discrepancies in apatite crystal sizes, surface areas, and helium retention, but can be useful if a suite of samples is collected or the data are compared with other regional studies.

3.2 Samples

Six samples were collected on June 8th, 2019 along a vertical transect of Mount Lamborn. Geographic information for each sample can be found in Table 1. Initial confusion led the expedition astray for a couple miles until eventually Lamborn Trail # 894 was found. The trail is managed by the US Forest Service but was poorly marked and covered by lots of fallen trees/debris, and commonly washed out from runoff. The samples collected originated from exposed outcrop at the sample locations, with the primary goal to sample every 200 meters. The trail's difficulty as well as lots of structure and fluvial valleys prevented easy access to outcrops at the desired sampling distances, but six well defined outcrops allowed for a range of samples across more than 1100 m of vertical distribution. Ideally, fresh outcrop is preferred over weathered rock, but in some cases, phenocrysts were visibly altered or weathered away, or the rock matrix has an orange hue from iron oxidizing.

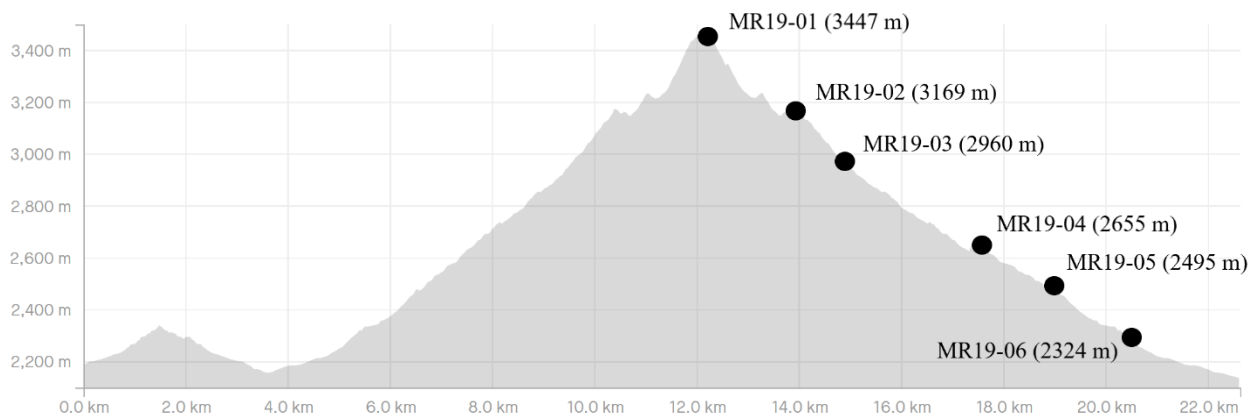


Figure 5. Elevation profile of Mt. Lamborn showing locations for sample collection.

3.3 Mineral Separation

In order to successfully separate apatite grains from the granodiorite porphyry collected, the rock must undergo several stages of mineral separation. The process begins by crushing and pulverizing the material using a Bico Incorporated WD Chipmunk crusher along with a UA pulverizer. These machines reduce the size of the material from initial blocks to grains around 500 micrometers in any dimension. The grains are sieved through a 500 μm mesh screen to prevent larger pieces of the initial material to get through. A hand sample of the bulk rock from each data point is kept for reference if needed.

Specific gravity, or relative density, is the ratio of the density of a substance to the density of a reference material. In most cases, the reference sample is water with a density of 1000 kg/m^3 . Apatite has a specific gravity of 3.2; it is significantly denser than most of the other minerals in granodiorite. The most effective method of mineral separation for apatites utilizes this density contrast. Following pulverization, a Wilfley shaker table is used to remove the large, less dense grains from the mineral separate. This divides the separate into four containers, W1-4. All four parts of the separate are placed into a drying oven set at 60°C to remove water.

Separates were not heated for more than one day in order to prevent any alteration to the Helium concentration in the grains.

Once dry, separates from W1, comprised of the densest grains, undergo further separation techniques. Separates from W2, W3, and W4 are bagged and stored. Next, grains with magnetic properties are removed from the separate. Apatite has no magnetic properties, so it is not removed. Minerals bearing iron, nickel, or other magnetic elements, however, are easily removed through magnetic separation. The first step uses a hand magnet to remove the largest, most magnetic ferrous grains from the separate. Next, an S.G. Frantz laboratory separator containing an electromagnet is used to exploit the paramagnetic (weak attraction) and diamagnetic (weak repulsion) of individual grains that are flowing down a chute through the induced field. The separate is run through the separator twice, first with the current at 0.35 Amperes and next at 0.60 A. For both runs, the chute is angled at 20° to allow for the most effective separation. The remaining non-magnetic separates were bagged for the next step, and magnetic ones are stored in bags based on magnet strength.

The final step of mineral separation utilizes a high density solution: lithium metatungstate (LMT). It has a specific gravity of 2.95 from the production facility, and reclaimed LMT was used with a specific gravity of at least 2.85. Any grains of apatite will sink in the solution while those of quartz and feldspar float. The non-magnetic W1 separate is divided into 50 mL Falcon polypropylene centrifuge tubes. Each tube is filled up to 7.5 mL with grains, and LMT is filled up to the 45 mL mark. Next, the tubes are capped and placed in a centrifuge that cycles at 2000 rpm for 2 minutes. Based on the quantity of separate available at this stage for each sample, either 4 or 8 tubes are filled in order to balance the centrifuge. This creates a layer of LMT “light” grains at the top of the tube and small pile of final separates at the base. Tubes are held at

the 15 mL mark in liquid nitrogen to freeze the base and allow for removal of light material. All LMT is rinsed with DI water from grains and eventually reclaimed. The final product is called the LMT “heavy” separate.

3.4 Picking Apatite Grains

Using a Leica M165 stereo microscope, individual apatite grains were picked from the final separates for each sample. While hundreds of grains were present, only select ones possessed the qualities necessary to provide accurate data. Adequate grains have an average size of at least 60 μm on any axis, as a smaller grain has more Helium loss when particles are ejected (Ehlers and Farley, 2003). Next, the grain must not possess inclusions. These are crystals of other minerals that can be seen inside or included in the apatite. It is difficult to determine the inclusion mineral and whether it contains helium producing radioactive elements that would skew data, thus apatites with inclusions are inappropriate for analysis. Ideally, apatites should be euhedral in shape, and clear/gem-like in appearance. While some samples have high concentration of apatite, others did not. This resulted in running some grains that were not optimal, but produced AHe ages consistent with those obtained from other grains in the sample. For example, MR19-03 yielded a low number of apatites while MR19-05 yielded a high concentration of them. In sample MR19-04, grains had some scuffs and did not exhibit a perfect euhedral shape.

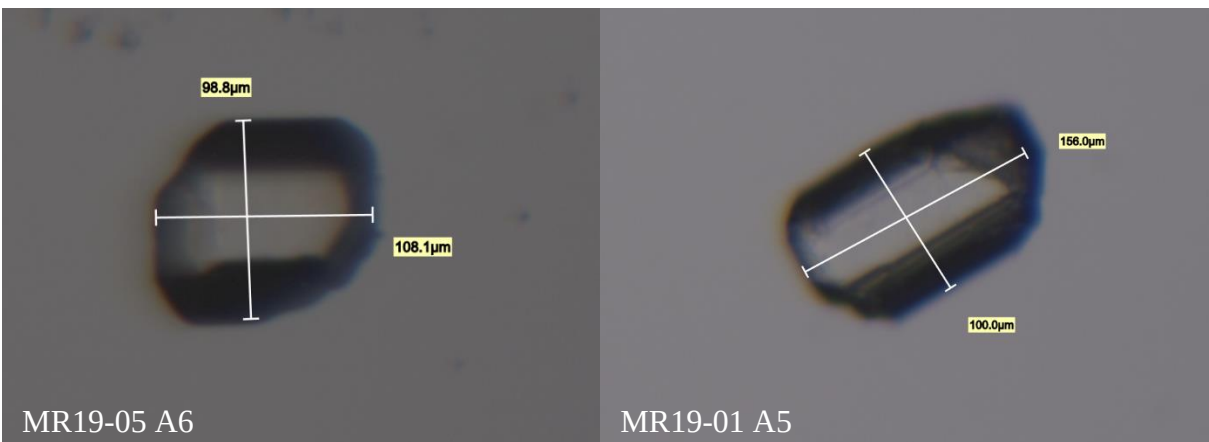


Figure 6. Apatite grains exhibiting size, shape, and inclusion free requirements.

3.5 (U-Th)/He Dating

(U-Th)/He dates were recorded for 5 apatite grains at each of the 6 sample locations, resulting in 30 data points. Once grains met the basic requirements to be analyzed, they were packed individually into Niobium tubes. Radiogenic ^4He was then measured using an ASI Alphachron He extraction and measurement line at the University of Colorado Boulder Thermochronology Research and Instrumentation Lab (CU TRaIL). Each sample underwent stepwise degassing, cycling through prograde, retrograde, and final prograde heating steps to remove all ^4He from the grain. Gas was then spiked with ^3He , purified using SAES getters methods, and measured on a Balzers PrismaPlus QMG 220 quadrupole mass spectrometer. The process was repeated at least once more to ensure all gas from the crystal was released and measured. Following this, concentrations of uranium, thorium, and samarium were determined in the degassed apatite grains. Each grain was spiked with ^{235}U and ^{230}Th tracer and dissolved. The dissolved fluid was then run through a Thermo Element 2 magnetic sector ICP-MS and analyzed for U, Th and Sm concentrations. One Durango apatite was run for calibration, producing reasonable data ($28 \text{ Ma} \pm 1.6 \text{ 2s}$). Raw dates calculated from concentrations of U, Th, and Sm are corrected for alpha ejection, which is based on the size and geometry of the apatite grain.

4. Results

4.1 AHe Ages

Table 2 contains the data for each individual apatite. Values in bold indicate grains that were not included in the data analysis and were disregarded. Out of 33 grains, 6 were removed from further analysis. Most recognizably, MR19-01 A4 had exponentially exaggerated date values, most likely from of an inclusion. It is possible the inclusion contained large amounts of helium and disrupted the measurement. MR19-05 A3 was dismissed for showing an unusually high ratio of thorium to helium. MR19-05 A1, while still yielding a date within reason, was disregarded because of its extremely high analytical uncertainty due to very low helium and eU concentrations. Following this, a minimum eU of 3 was required for use of data in order to remove any other possible sources of error from low uranium content.

The raw dates measured underwent alpha ejection correction, which is represented by the term F_t . F_t quantifies the amount of helium produced during decay that is still retained. The corrected date is therefore nearly equal to the raw date divided by the alpha ejection correction value, always producing an older date. Figure 7 shows the correlation between age and elevation across the six sample locations. Ages were averaged between all accepted grains in each location. To account for general uncertainty in age data and low eU values of the apatites, 15% error bars are incorporated for each data point. Samples MR19-01, MR19-02, MR19-04, and MR19-06 all yield older ages, sometime between 28-40 Ma. Falling out of this pattern are samples MR19-03 and MR19-05. MR19-03 data give an average age of 22 Ma and MR19-05 data result in an average age of 11 Ma.

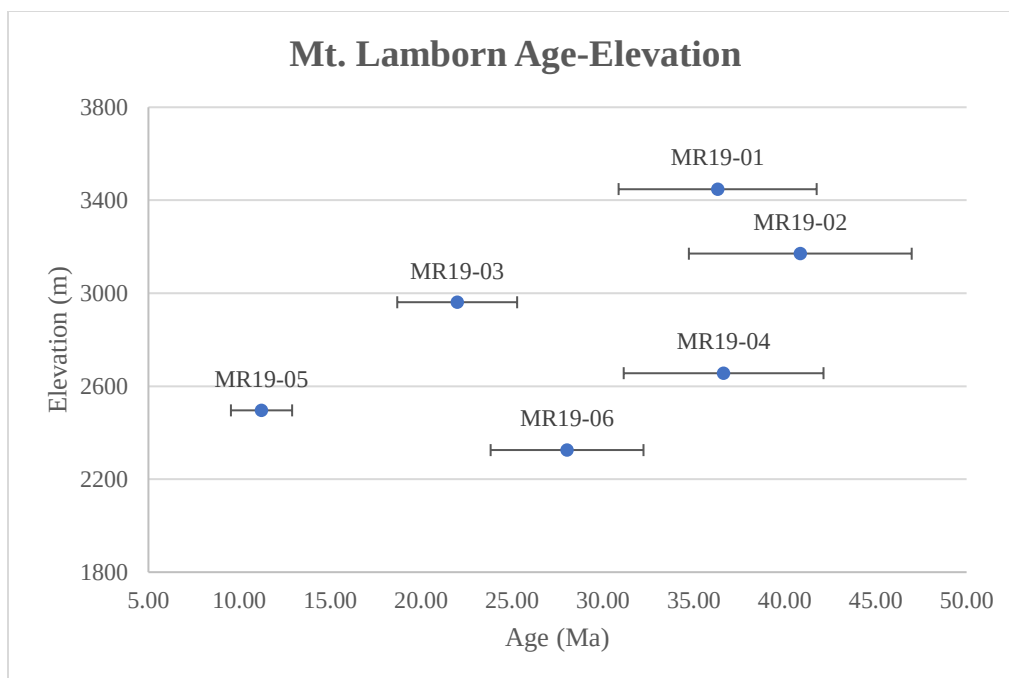


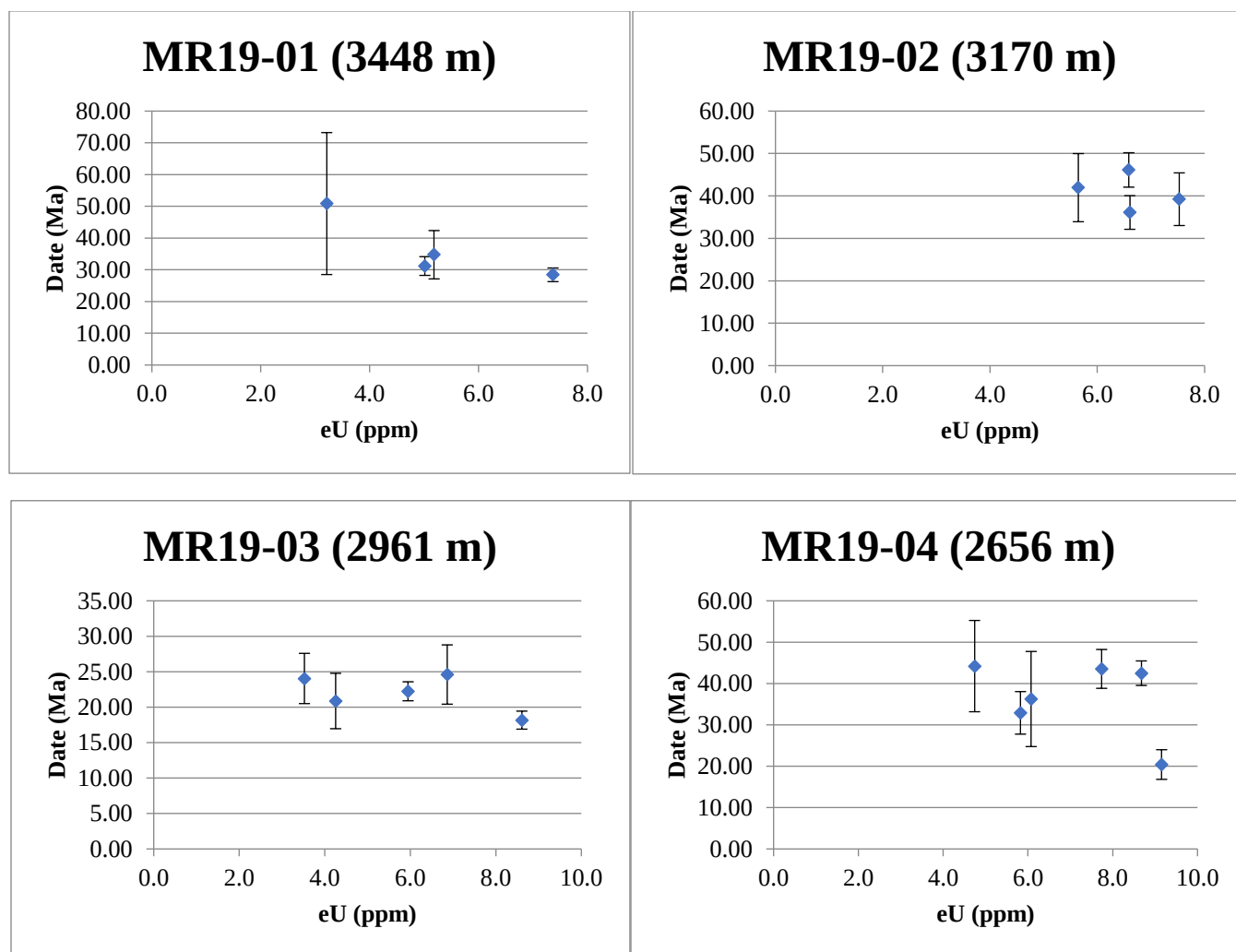
Figure 7. Age-elevation plot of Mt. Lamborn sample location data.

4.2 Effective Uranium Relationship

The effective uranium concentration is a parameter that adds the decay of the U and Th parents based on their strength of alpha productivity, written as $[U] + 0.235[Th]$. The ideal method for measuring radiation damage is Raman spectroscopy, but in most cases that is not available, so date-eU correlations are used to understand radiation's effect on helium diffusivity (Guenther et al., 2013). Comparing all grains within a sample, the date-eU correlations also provide useful information on the cooling history of the sample. For example, a positive correlation between date and eU suggests slow cooling because apatites with higher eU accumulate more radiation damage and develop a higher closure temperature, resulting in older dates. Alternatively, fast cooling rates produce uniform dates with no eU correlation because there is insufficient time for helium diffusivities to change during cooling (Flowers et al., 2009).

The data in this study, shown below in Figure 8, exhibit no clear eU-date correlations, and almost every grain yielded an eU lower than 10 ppm. While this is enough to calculate age

from, it is far too low for radiation damage to alter the closure temperature between. The plots show the analytical uncertainty in age measurement, which has an upper and lower bound of 2σ . Overall, the data provide consistent ages, with most grains falling within the uncertainty of each other. As mentioned above, all grains with an eU below 3 were disregarded due to the excess amount of data points available for each sample. Each of the low eU grains are therefore omitted from the age-elevation average values as well as the date-eU plots below.



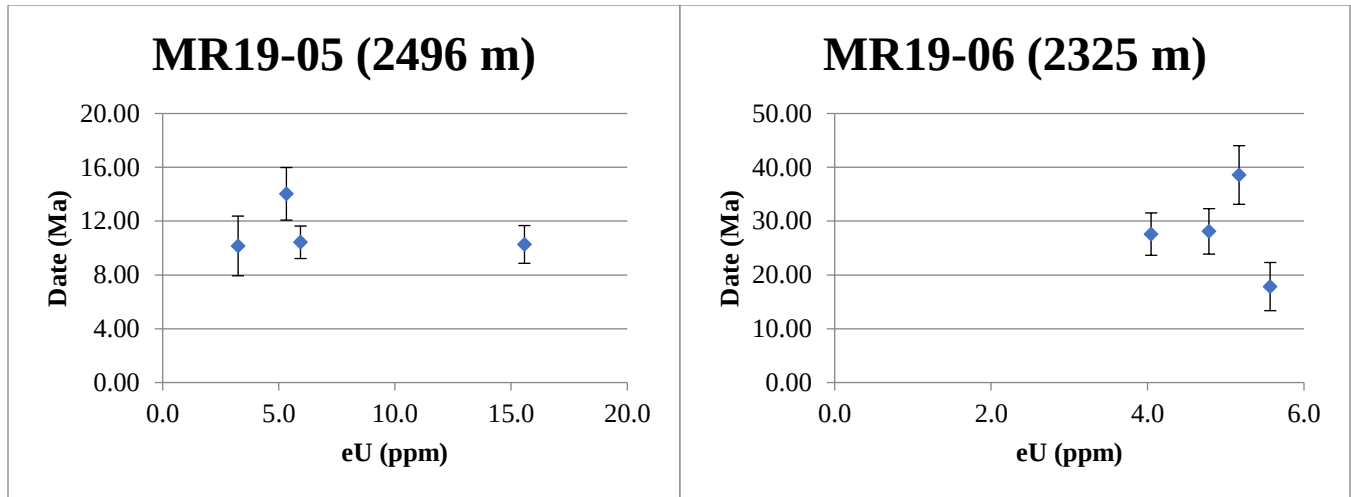


Figure 8. Date-eU plots for all 6 sample locations along Mt. Lamborn vertical transect.

4.3 HeFTy Modelling

Data provided from the AHe method can undergo several different time-dependent, temperature-sensitive thermal histories and still provide the same age. By understanding the behavior of the system on a geologic timescale, one can use a forward model to simulate time-temperature conditions and map out the thermal history of a sample. Ketchum (2005) provides this ability with the program HeFTy (helium and fission track). HeFTy utilizes both forward and inverse models, but because of the relative simplicity in the Mt. Lamborn data, only forward models are used in order to explore more quantitative estimates of thermal histories.

Version 1.9.3 of the HeFTy software was used for forward modelling. In order to provide accurate results, the grain geometries and thermal parameters were input first. Sample by sample, the concentrations of U, Th, and Sm are input along with average grain radius, mean eU, mean raw date, and standard deviation of the raw date. Following this, the temperature parameters were created. The upper limit is 200 °C to simulate the emplacement temperature that K-Ar dating marks, and the lower limit final temperature was set to 10 °C to mimic surface temperature conditions. The system was calibrated to follow the RDAAM (radiation damage

and annealing model) developed by Flowers (2009). This allows for accurate measurement of closure temperature using sample input data. The model is then ready to operate, and time-temperature data are plotted using geologic intuition, resulting in ages that an apatite would yield under those conditions.

The results for samples MR19-01, 03, 05, and 06 are shown below. After several attempts to recreate the ages measured with the thermochronology, the plots below show the best fit thermal histories for each sample. Samples MR19-01 and MR19-06, from the highest and lowest elevations of the transect, have identical plots that show rapid cooling from high to low temperature. MR19-03 and MR19-05 have younger ages, but because they lie in the middle of the transect, they must have followed the initial rapid cooling. Therefore, a younger reheating event must have occurred in order to bring the sample temperatures above the closure temperature. By passing the closure temperature, all helium would be lost, and the age reset. These reheating events are most likely brief and abrupt on a geologic timescale, such as shallow magmatic events. In order to accommodate, the forward models for MR19-03 and MR19-05 show short periods of reheating and the temperatures necessary to match the recorded ages.

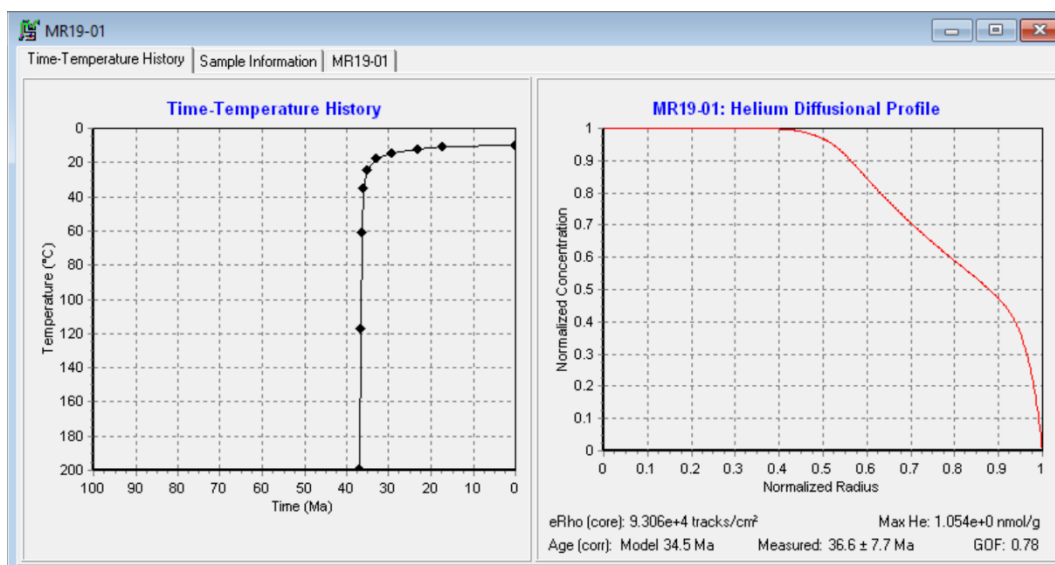


Figure 9.1. MR19-01 HeFTy model. Displays rapid cooling from emplacement time to achieve measured age.

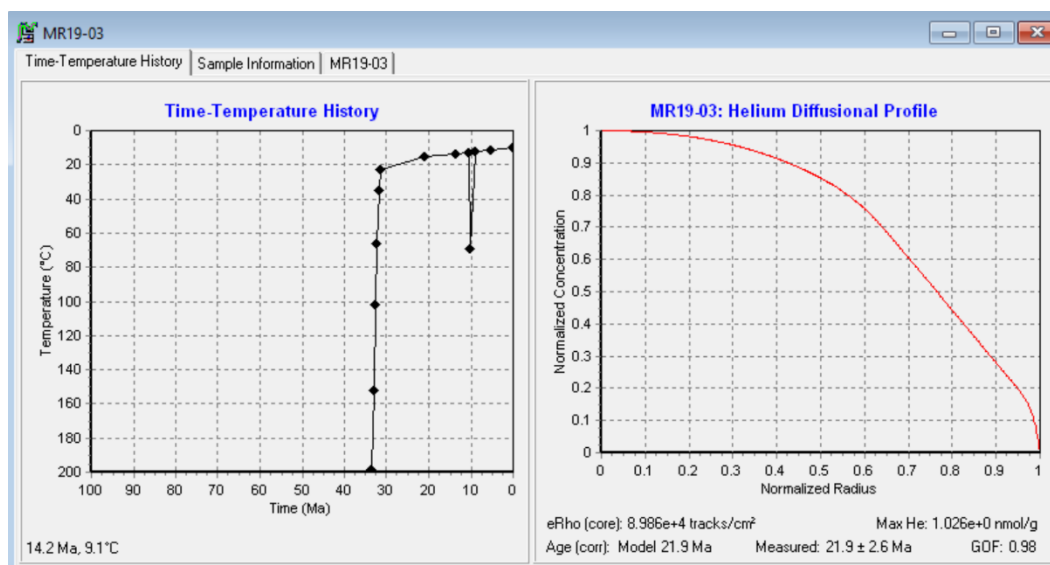


Figure 9.2 MR19-03 HeFTy model. Same initial thermal history, but reheating necessary to reach a 22 Ma date.

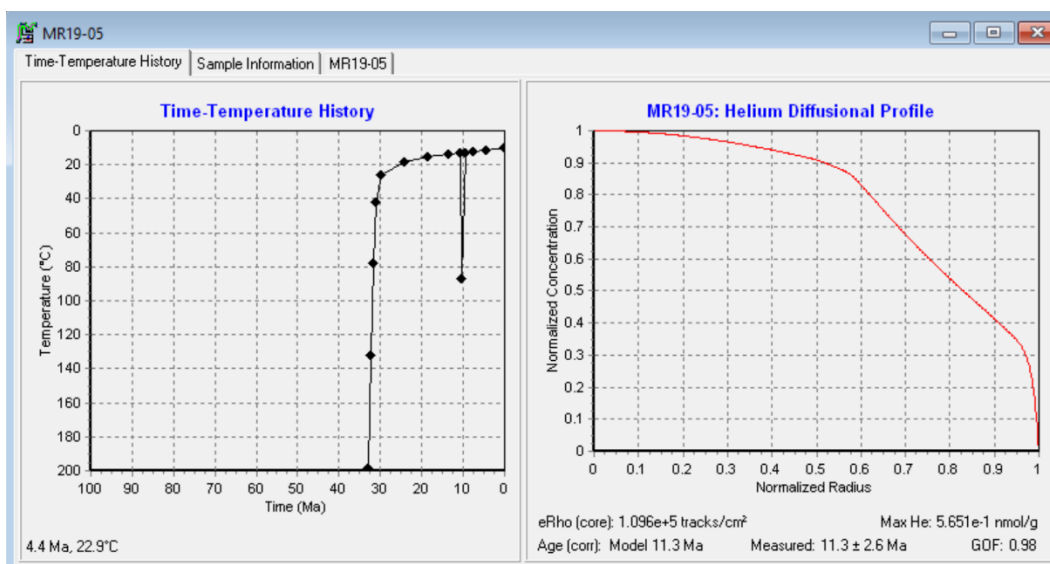


Figure 9.3 MR19-05 HeFTy model. Reheating past the closure temperature necessary to release all retained helium and reset the age of the apatite.

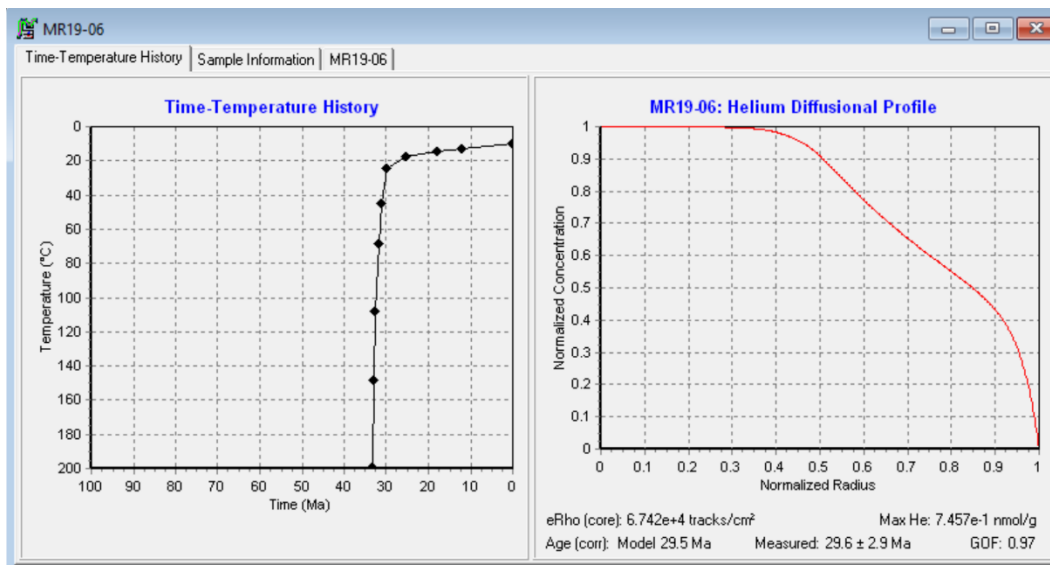


Figure 9.4. MR19-06 HeFTy model. Lowermost sample exhibiting same cooling history as MR19-01.

5. Discussion

5.1 Mount Lamborn Thermal History

While no high temperature thermochronology has been performed on Mt. Lamborn, its proximity and identical lithology to surrounding intermediate peaks in the region suggest it was emplaced from 29-34 Ma along with the other laccoliths. Samples MR19-01, 02, 04, and 06 provide dates that are between 28-40 Ma, which is interpreted as the same as their emplacement age. It was first hypothesized that the samples would provide younger ages and possible erosion rates, but the idea that they align with emplacement age provides an important look into the southwest region of the West Elk laccolith field.

Since all of the samples across the full vertical transect surround the 30 Ma emplacement age range, the entire laccolith could not be emplaced anywhere but very close to the surface. If a geothermal gradient of about 40 °C/km is considered from other work in the region, and the surface temperature is 10 °C, the closure temperature for helium retention in apatite is around 1.5 km. Since the sample collected at the lowest elevation, MR19-06, lines up with emplacement

age and is roughly 1 kilometer below the top sample, the summit of the laccolith must have been emplaced no deeper than about 500 meters for all samples to provide emplacement age. This implies that at the time of intrusion there was at most 500 meters of sediment above the laccolith. Mt. Lamborn intrudes into the Mancos shale, which supported initial theories of deeper burial. The idea that there was not much sediment (< 500 m) at the time of emplacement suggests there might have been notable erosion of the overlying sedimentary formations prior to Oligocene magmatism after the Laramide.

HeFTy models support the idea of rapid cooling and shallow emplacement. In both the top and bottom samples of the vertical transect, it was necessary to cool to near surface temperatures in order to retain enough helium to match AHe dates. Since we have both a top and on bottom sample with the same thermal history, the samples in between must also have at least the same initial cooling and shallow emplacement associated with it. However, samples MR19-03 and MR19-05 both have younger ages, 22 and 11 Ma, respectively. In order to produce data with younger ages, helium must be lost from apatite crystals. The easiest way to do this is by reheating the grains, allowing helium to diffuse out. It is not uncommon for there to be secondary intrusion of magma in the region, leading to younger dates for other peaks such as Crystal Pluton (Garcia, 2011). In the Mt. Lamborn corner of the West Elk Mountains, however, there are not many large scale magma reheating events. Although, Grand Mesa is nearby and located only 40-50 km to the northwest. This basalt capped mesa yields K-Ar ages of roughly 10 Ma (Marvin et al. 1966). The region of basalt extrusion was most likely near the eastern edge of Grand Mesa and was fed by a series of dikes and plugs (Cole and Sexton, 1981).

Theoretically, basalt pipes that fed the Grand Mesa basalt flows could have migrated upwards through the region of Mt. Lamborn. Each sample along the transect is separated by at

least a kilometer horizontally and 200 meters vertically, so basalt dikes could have passed near one sample location without reheating another. In the case of MR19-05, a reheating would have completely reset the helium age of the grains. HeFTy forward models suggest that temperatures over 70 °C are necessary to completely reset age if only a brief episode of warming is provided by a dike. For MR19-03, an age of 22 Ma suggests partial loss of helium, and if brief reheating from basaltic magma occurred, a temperature around 40-50 °C is necessary. Temperatures may have been lower if the reheating event lasted longer, but in the case of grand mesa, the basalt venting did not last an extensive amount of time.

It is worth noting how significant samples MR19-04 and MR19-06 are when understanding Mt. Lamborn. If neither of these samples were collected and a full transect was not completed, then the data would appear as if MR19-03 and MR19-05 were cooled due to later exhumation related to burial in the bullseye. In fact, the samples were cooled after reheating events. The vertical transect constrains all samples to a rapid initial cooling, and therefore allows us to search for reheating events that would lower any ages in the sample data.

5.2 West Elk Range Comparison

Major laccoliths such as Snowmass Mountains and Mount Sopris in the West Elk and Elk Mountain regions were not exhumed until about 11 and 13 Ma, respectively (Garcia, 2011). These plutons were intruded at depth at the same time as Mt. Lamborn but are found near the center of the exhumation bullseye. When looking at the whole region, the uplift and exhumation that is present weakens in magnitude toward the edges, including many of the southern West Elk laccoliths to a lesser degree. Mount Lamborn is included in this trend since it did not undergo exhumation to the same magnitude as the more central plutons. Other work currently being done on the eastern and southern edges of the bullseye also shows less exhumation. On the southwest

and southeast edges of the bullseye region are Young's Peak and Carbon Mountain, respectively. Both peaks show ages of emplacement from data collected by Abbott as ongoing research.

This project grows our understanding of the bullseye region and how it might have formed. Figure 10 shows an adaptation of the bullseye where the new constraint should be drawn. Mt. Lamborn confirms shallow emplacement and low magnitude exhumation on the edges of the bullseye. It also explains the emplacement ages recorded by Garcia for the south central East Beckwith and Gunnison plutons. The “outer rim” of minor exhumation should be included in the bullseye but needs to be recognized as weaker in magnitude. While this is just an estimate, further work needs to be performed around the edges to continue constraining the region, possibly rounding it out even more.

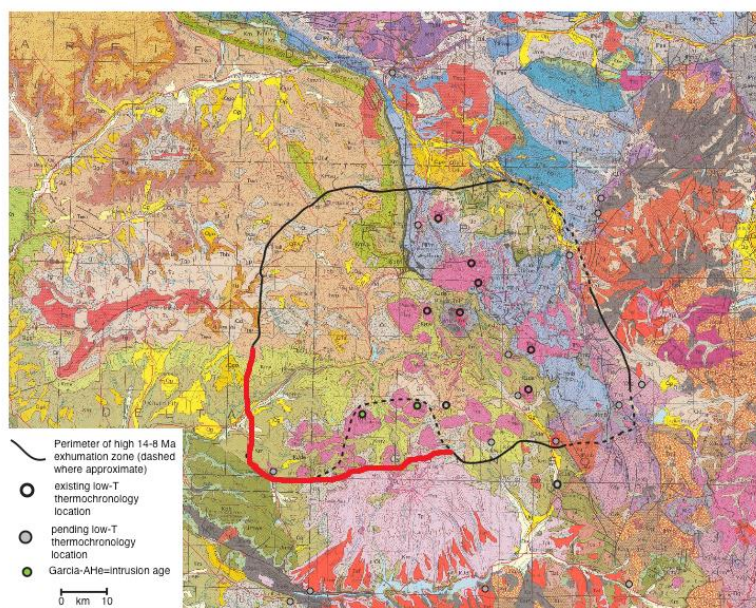


Figure 10. Map of proposed bullseye exhibiting new boundary marked in red

5.3 Implications for Mechanism

With the bullseye region smaller than originally proposed, the mechanism responsible for exhumation should be considered in a different lens. Ideas such as mantle-driven topography and climate change proposed as mechanisms for exhumation of the Rocky Mountains have played their role, but don't seem feasible to explain such a small, pinpoint region in west central Colorado. The idea that this bullseye is smaller than first thought only strengthens the argument against these methods. Alternatively, it is interesting to think that laccoliths in the West Elks were shallowly placed around the edges of the bullseye and placed at depth near the center. Understanding why this pattern exists in the first place should be the focus of additional study and relating it to exhumation timing may show a better connection to mechanisms. The mantle and climate forces may be responsible after all for this exhumation, and the real reason why we only see exhumation in the central bullseye is because more sediment was overlying the emplaced laccoliths. Once erosion reached the shallowly emplaced plutons, it would act much slower than on sedimentary deposits.

It is possible that more regionalized surface processes were at work to provide such isolated exhumation. Surficial events may also be the reason why not all laccoliths in the West Elks are affected equally. Selective river incision is possible and may have worked in conjunction with mantle processes (Karlstrom et al., 2012). A bullseye shape of exhumation is not typical for river incision mechanisms, however. Further constraint on the shape and distribution of exhumation may help solve the mechanism question and a larger dataset overall needs to be compiled. Regardless, the region has been subject to several episodes of magmatism since the emplacement of the West Elk laccoliths, so there is still a chance that dynamic processes are happening underneath the surface.

Similar to dynamic topography but on a much smaller scale is the promising idea of a mantle drip and Rayleigh-Taylor instability. Imagining the layers of Earth during West Elk formation, there is warm hot mantle asthenosphere with a cooler Farallon plate overlying it, creating a density inversion. While the interface is stable for a short period, any small perturbation causes instability. This instability grows into a mantle drip, with cool material sinking into the warm asthenosphere, allowing for warm material to flow upward. This model of a flowing earth is feasible on geologic timescales. The shape of a drip also supports the shape of the bullseye and why there is more exhumation in the center than the edges. While an exciting idea to consider, more work needs to be done to understand the thermal history of the region and isostatic capabilities an instability may have.

6. Conclusion

Apatite (U-Th)/He data collected along a vertical transect combined with forward thermal models indicate shallow, rapid emplacement of the Mt. Lamborn laccolith. With emplacement ages around 30-34 Ma throughout the 1100 meter transect, we can assume that no more than 500 m of sediment was on top of the pluton during emplacement. The age of 30-34 Ma aligns with other emplacement ages of laccoliths throughout the West Elks and major magmatic periods the San Juans experienced. There are several other comparable features between the West Elk and San Juan plutons, but the laccoliths of the West Elks have been exhumed through overlying volcanics and sediments, exposing them on the surface. The bullseye of regional exhumation is inherently unique to the area, indicating some mechanism is responsible for its presence.

Mantle processes are a possible cause, and the reheating of samples MR19-03 and MR19-05 support the theory of episodic magmatism and mantle forces acting below the region. The data gathered in this study mainly show emplacement and clarify the exhumation bullseye,

showing decreasing exhumation outward. It ultimately extends the bullseye radially outward from previously proposed versions by Abbott and others at the University of Colorado. Surface processes and paleo topography are likely to have affected the region and are very scalable, but align with no prior evidence in the region or the geometry of the bullseye. A mantle drip may explain why there is more exhumation near the center but is hard to pin down in the confusing and magmatic Rocky Mountain region. Overall, there is still ambiguity regarding the cause of exhumation, but more research that aims to constrain the size of the region, as well as the timing of events that occurred within it, will aid in determining a more definite answer.

Appendix

Table 1

Sample Information

Sample	Lithology	Latitude (DMS)	Longitude (DMS)	Elevation (m)
MR19-01	Granodiorite	N 38° 48' 8.30"	W 107° 31' 21.94"	3448
MR19-02	Granodiorite	N 38° 48' 25.50"	W 107° 31' 20.83"	3170
MR19-03	Granodiorite	N 38° 47' 14.37"	W 107° 31' 35.05"	2961
MR19-04	Granodiorite	N 38° 47' 17.21"	W 107° 32' 41.59"	2656
MR19-05	Granodiorite	N 38° 47' 16.41"	W 107° 33' 10.06"	2496
MR19-06	Granodiorite	N 38° 47' 38.22"	W 107° 33' 37.51"	2325

Table 2

Apatite (U-Th)/He data from Mt. Lamborn vertical transect

Sample ^a	Mass (mg)	rs (mm) ^b	4He (nmol/g)	U (ppm)	Th (ppm)	Sm (ppm)	eU (ppm) ^c	Th/U	Raw Date (Ma)	F _t ^d	Corrected Date (Ma)	Analytic Unc. (Ma) 2s
MR19-01_a01	1.56	41.36	0.588	3.96	4.47	22.49	5.0	1.1	20.92	0.662	31.19	2.95
MR19-01_a02	1.50	40.60	0.075	1.66	1.07	7.19	1.9	0.6	7.07	0.661	10.58	3.68
MR19-01_a03	0.93	35.80	0.581	2.91	1.30	14.62	3.2	0.4	32.25	0.623	50.87	22.36
MR19-01_a04	0.86	34.44	400.337	4.04	8.80	0.33	6.1	1.0	5313.91	0.593	6224.57	1626.60
MR19-01_a05	1.73	45.59	0.810	5.40	8.37	27.21	7.4	1.6	19.72	0.686	28.43	2.15
MR19-01_a06	1.02	37.02	0.646	4.22	4.08	23.03	5.2	2.2	22.23	0.630	34.74	7.61
MR19-02_a01	2.00	46.52	1.195	4.44	9.15	26.55	6.6	2.1	32.43	0.695	46.13	4.06
MR19-02_a02	1.92	45.80	1.162	5.42	8.95	32.83	7.5	1.7	27.54	0.694	39.23	6.21
MR19-02_a03	1.51	41.47	0.897	4.60	8.55	30.04	6.6	1.9	24.17	0.660	36.10	3.96
MR19-02_a04	0.85	34.67	0.828	4.24	5.99	34.05	5.6	1.4	25.82	0.601	41.95	8.03
MR19-02_a05	3.38	55.61	0.306	1.83	2.17	10.51	2.3	1.2	23.33	0.782	29.60	2.83
MR19-03_a01	1.82	47.80	0.616	5.89	11.59	31.29	8.6	2.0	12.84	0.700	18.17	1.27
MR19-03_a02	1.09	37.37	0.598	4.91	8.31	27.01	6.9	1.7	15.59	0.625	24.60	4.18
MR19-03_a03	3.68	60.28	0.567	4.54	5.97	23.38	5.9	1.3	17.09	0.763	22.24	1.34
MR19-03_a04	2.80	50.77	0.347	2.71	3.47	16.41	3.5	1.3	17.53	0.721	24.04	3.54
MR19-03_a05	1.67	42.62	0.337	2.92	5.66	18.27	4.3	1.9	14.12	0.669	20.86	3.91

MR19-04_a01	0.73	35.29	0.646	7.03	9.04	41.14	9.2	1.3	12.60	0.607	20.41	3.58
MR19-04_a02	1.14	41.14	1.377	6.09	11.02	39.89	8.7	1.8	28.26	0.655	42.50	2.96
MR19-04_a03	1.37	40.27	0.716	4.52	5.53	24.45	5.8	1.2	21.97	0.659	32.90	5.14
MR19-04_a04	1.96	46.16	1.323	5.37	10.08	31.58	7.7	1.9	30.56	0.694	43.54	4.70
MR19-04_a05	0.85	34.84	0.764	4.78	5.50	27.60	6.1	1.1	22.41	0.607	36.25	11.50
MR19-04_a06	1.04	42.17	0.784	3.81	3.97	21.16	4.7	1.0	29.50	0.658	44.21	11.04
MR19-05_a01	1.65	43.57	0.005	0.09	0.00	0.01	0.1	0.0	10.13	0.684	14.60	58.36
MR19-05_a02	1.83	43.47	0.284	3.82	6.39	21.05	5.3	1.7	9.56	0.673	14.03	1.95
MR19-05_a03	1.82	45.01	0.861	5.08	15.33	21.73	8.7	3.0	17.94	0.682	26.12	1.78
MR19-05_a04	1.72	44.96	0.629	14.78	3.33	76.96	15.6	0.2	7.20	0.693	10.27	1.40
MR19-05_a05	2.47	49.36	0.248	4.44	6.37	21.02	5.9	1.4	7.50	0.713	10.43	1.21
MR19-05_a06	1.87	42.73	0.128	2.73	2.16	17.16	3.2	0.8	6.99	0.679	10.16	2.22
MR19-06_a01	1.12	36.30	0.475	3.75	4.40	23.22	4.8	1.2	17.64	0.617	28.10	4.22
MR19-06_a02	0.80	32.90	0.162	1.48	0.00	2.53	1.5	0.0	19.96	0.582	33.30	14.55
MR19-06_a03	0.80	34.14	0.698	4.44	3.10	30.00	5.2	0.7	23.85	0.605	38.58	5.45
MR19-06_a04	0.87	33.63	0.336	4.18	5.90	30.27	5.6	1.4	10.70	0.587	17.84	4.48
MR19-06_a05	1.83	43.71	0.438	3.33	3.06	24.48	4.0	0.9	19.10	0.681	27.59	3.93

^a all grains are apatites, as noted by the “a” in the grain number

^b equivalent spherical radius

^c effective uranium concentration

^d alpha ejection correction

*MR19-01_a04 removed from dataset for extreme helium content and uncertainty

*MR19-01_a02, MR19-02_a05, MR19-05_a01, MR19-06_a02 removed for having an eU < 3 ppm

*MR19-03 removed from dataset for high Th/U ratio

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