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THERMAL AND STRUCTURAL HISTORY OF PALEOZOIC AND PROTEROZOIC ROCKS IN THE VICINITY OF MOLAS PASS, NORTHERN NEEDLE MOUNTAINS, SOUTHWESTERN COLORADO

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Abstract—Apatite fission-track (AFT) data collected along an elevation traverse at Molas Pass in the Needle Mountains of southwestern Colorado record Early to Middle Miocene cooling of this region. A younger thermal pulse that is likely related to Late Miocene magmatism in this region is superposed on the simple cooling trend. High elevation samples from Pennsylvanian to Permian sedimentary rocks, west of Molas Lake, have AFT ages that range from 19.3±3.6 Ma to 13.6±2.8 Ma; the ages decrease systematically with decreasing elevation. In contrast, AFT ages from Proterozoic rocks at lower elevation to the east of Molas Pass do not correlate with elevation and appear to have been affected by a localized, fault-related Late Miocene hydrothermal event. Thermal history modeling of the age and track-length data reveals that the fission-track system in all samples was totally reset prior to 20 Ma as a result of heating during stock emplacement at 26.6 Ma along the southern margin of the Silverton caldera located just a few kilometers to the north. Burial of the area by volcanic and volcaniclastic rocks during formation of the San Juan volcanic field also contributed to thermal resetting. The lag in time between caldera formation at 26.6 Ma and cooling of the higher elevation samples at 19 to 14 Ma and the track length distributions (mean lengths of 13.1±2.8 to 13.9±2.3 µm) suggest that the section was cooling as a result of exhumation as opposed to relaxation of isotherms following volcanism.

INTRODUCTION

Rocks exposed in the vicinity of Molas Pass, which is located in the northern part of the Proterozoic-cored Needle Mountains of southwestern Colorado, preserve a rich history of Proterozoic, Ancestral Rocky Mountain, and Laramide deformation. Volcaniclastic deposits associated with Early Oligocene eruptions in the southwestern San Juan volcanic field are preserved on ridges to the west of the pass (Luedke and Burbank, 2000). The pass lies about 3 to 4 km south of the 26.60±0.04 Ma Sultan stock that was emplaced along the southern margin of the Oligocene Silverton caldera (Luedke and Burbank, 2000; Bove et al., 2001; Gonzales, 2015). Although magmatism generally waned in this part of the San Juan volcanic field after 23 Ma, several small magma bodies were intruded in this area between 23 and 4 Ma, causing localized hydrothermal alteration (Lipman et al., 1976; Bove et al., 2001; Gonzales, 2015). The most notable intrusions are the ca. 9 Ma Chicago Basin rhyolite located 16 km southeast of Molas Pass, sills emplaced at ~17-14 Ma, including the 15.6±1.4 Ma Lime Creek intrusion about 4 km to the southwest (Lipman et al., 1976; Gonzales, 2015), and 7 to 4 Ma stocks that extend from Rico to Placerville located about 20 km to the west (Gonzales, this volume).

Little is known about the post-Oligocene deformation or exhumation history of this thermally-complicated region. High geothermal gradients associated with the voluminous caldera eruptions in the San Juan Mountains likely reset low temperature thermochronometers to depths of several kilometers. Miocene rhyolitic sills emplaced at various depths below what was once a much more extensive volcaniclastic cover (Lipman et al., 1976; Lipman and McIntosh, 2008; Gonzales, 2015) add to the complexity. The interpretation of low-temperature cooling histories in such a thermally complex setting is challenging. The relative importance of simple cooling (due to erosion of overlying rock) versus more complicated cooling histories (involving reheating or reburial histories) can only be constrained with careful analysis of independent geologic data. The preservation of nearby Oligocene volcaniclastic deposits above an unconformity developed on Permian sedimentary rocks provides a key geologic constraint and recent U-Pb dating studies (Gonzales, 2015) have refined our understanding of the timing of emplacement of intrusions. For these reasons, we collected seven samples for apatite fission-track analysis to evaluate the low-temperature Neogene cooling history of this area.

Fission-track thermochronology is a powerful tool for tracking the timing and rate of rock cooling in the temperature range between 120° and 60°C. Confined track-length distributions are especially useful for qualitatively evaluating simple versus complex cooling histories and estimating cooling rate within this important temperature interval. For example, a rock with a simple cooling history on its path from 120°C (ca. 3-4 km depths) to the surface will have a unimodal track length distribution. If the cooling rate is slow (1-5°C/Ma), mean track lengths are typically in the 12 to 13.5 µm range, whereas if the cooling rate is higher (5-10°C/Ma) mean lengths are longer (13.5 to 15 µm) and the distributions are shifted toward longer tracks. In contrast, a rock that has been reheated to temperatures of 60-120°C by younger magmatism and/or hydrothermal alteration on its path to the surface will have a multi-modal track length distribution.

METHODS

Rugged topography offers the opportunity to investigate the depth variability of cooling histories in the crust. Samples were collected along an elevation traverse near Molas Lake between the Animas River to the east at elevation 2725 m (8,938 ft.) and a ridge south of Grand Turk to the west at 3300 m elevation (10,824 ft; Fig. 1). Samples to the east of Molas Lake are from Proterozoic rocks exposed along a trail that parallels the Molas Creek fault zone. This fault was most likely active during Ancestral Rocky Mountain deformation (Thomas, 2007). Samples to the west of Molas Lake are from Pennsylvanian to Permian sandstones; the highest elevation sample is Permian Cutler Formation sandstone collected just below the Oligocene (Donahue, 2016) Telluride Conglomerate. Apatite was concentrated from the samples using standard mineral separation techniques. Fission-track ages were determined using the external detector method, and details about calibration are documented in Table 1. Confined track lengths and the angle of each confined track relative to the c-axis of each apatite crystal were measured using a camera and an image analysis program that has a length measurement accuracy of ±0.2 µm. Note that the full track-length information is provided in the Supplementary Data (*http://nmgs.nmt.edu/repository/index.cfml?rid=201700X3*).

We investigated the thermal history of Molas Pass preserved in the AFT age and track length data with the modeling program HeFTy (version 1.8.3; Ketcham, 2005; Ketcham et al., 2007), incorporating known geologic constraints. We modeled samples with more than 30 confined track-length measurements and with ages passing the χ^2test (Table 1), which is indicative of a single age population.

The most powerful model constraint is the presence of the unconformity that developed on the Permian Cutler Formation prior to the deposition of the Telluride Conglomerate on the west side of the pass. Detrital zircon dates from Donahue (2016) provide a maximum depositional age of ~31 Ma for the Telluride Conglomerate in this particular area. Elsewhere in the San Juan Mountains, lavas and volcaniclastic sedimentary rocks of the 36–38 Ma Conejos Formation rests on this unconformity (Colucci et al., 1991). Thus, we imposed a constraint that the rocks had to be near the surface between 30–38 Ma at temperatures ranging from 15–45°C. Surface temperatures during Eocene time were warm (14.3–18.2°C; Zoborac-Reed and Leopold, 2016). Starting temperatures of lower elevation samples were adjusted to reflect their relative position below the unconformity. For modeling efficiency, we also imposed a very broad constraint that the rocks were at temperatures ranging from 30–200°C between 34 Ma and 1 Ma reflecting the geologic observation that the region was buried to unknown depth beneath Cenozoic volcaniclastic rocks during this time interval and the section may have been locally heated by 14-17 Ma sills. The maximum modeled temperature of 200°C is well above the annealing temperature for fission tracks on geologic time scales (Ketcham et al., 2007). Modern surface temperature was set at 10±5°C. NOAA data for average air temperature (https://www.ncdc.noaa.gov/cdo-web/) derived from nearby Salter, CO is 6°C and ground temperature is usually 3°C warmer (Morgan, 2009).

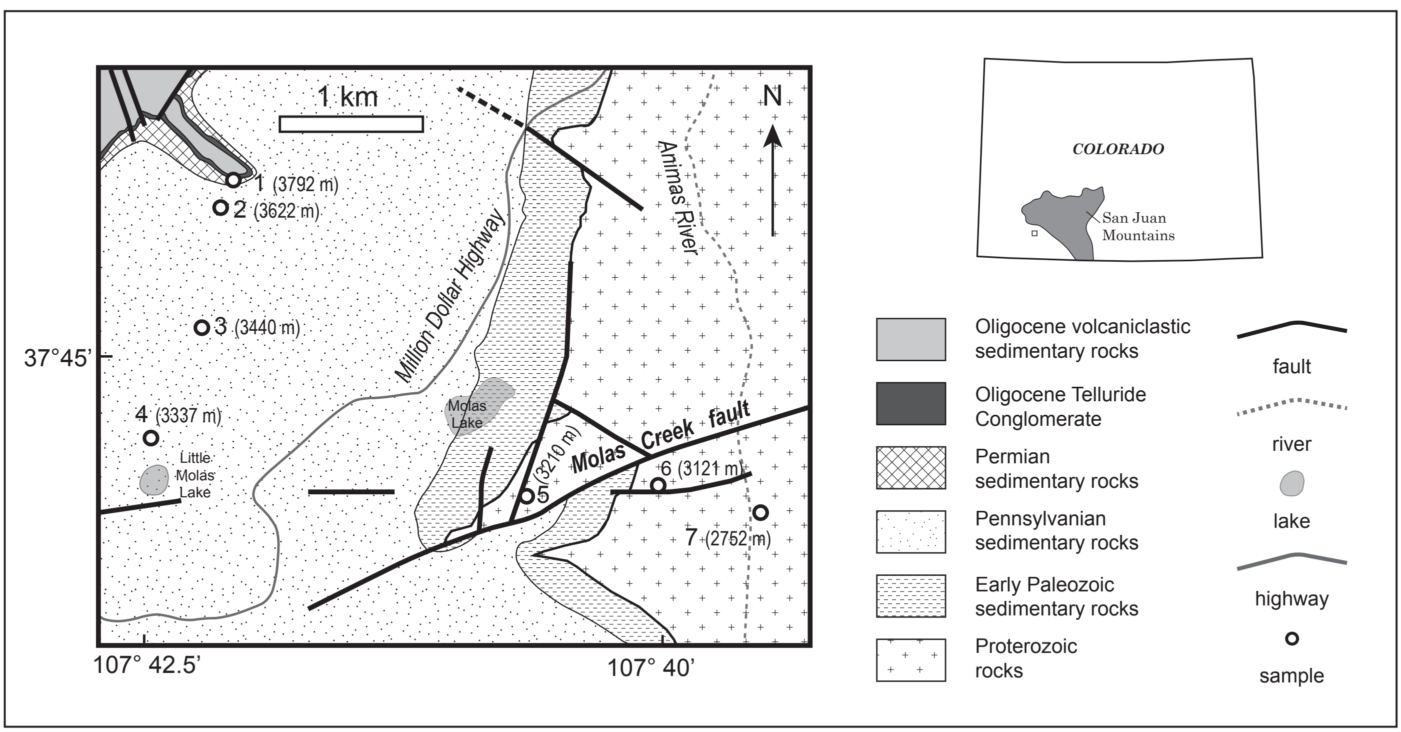

FIGURE 1. Simplified geologic map of Molas Pass modified from Luedke and Burbank (2000) and Thomas (2007) showing the location of the fission-track samples. The numbers in parentheses denote the elevation of each sample.

TABLE 1. Apatite Fission-Track Data for Molas Pass, Southwestern Colorado.

Sample Number	Field ID	Rock Type	Latitude	Longitude	Elevation (m)	Number of Grains Analyzed	ρs x 10^5 t/cm²	ρi x 10^6 t/cm²	ρd x 10^5 t/cm²	Central Age (Ma) (±1 S.E.)	$P(\chi)^2$ (%)	Mean Track Length (µm) (± 1 S.D.)
1	07NM05	Permian Cutler Formation	37.76142	-107.7021	3792	20	1.21 (143)	4.86 (2878)	1.63039 (5200)	19.3 (1.8)	99	13.3±2.3 (33)
2	07NM06	Penn Hermosa Formation Ss.	37.75892	-107.7033	3622	20	0.79 (94)	4.22 (2498)	1.61678 (5200)	14.5 (1.6)	99	14.1±1.1 (11)
3	07NM07	Penn Hermosa Formation Ss.	37.75178	-107.7045	3440	20	0.79 .(101)	4.21 (2694)	1.60038 (5200)	14.3 (1.6)	99	13.1±2.8 (35)
4	07NM08	Penn Hermosa Formation Ss.	37.74512	-107.7083	3337	20	0.84 (108)	4.71 (3016)	1.59343 (5200)	13.6 (1.4)	99	13.7±1.7 (36)
5	07NM02	Proterozoic Twighlight Gneiss	37.74225	-107.6783	3210	20	1 (125)	4.67 (2916)	1.66429 (5200)	17 (1.7)	94	13.9±2.3 (32)
6	07NM04 (altered)	Proterozoic Twighlight Gneiss	37.74273	-107.66825	3121	20	0.39 (20)	3.44 (886)	1.63498 (5200)	8.8 (2.0)	99	n.d.
7	07NM03	Proterozoic Whitehead Granite	37.74120	-107.6600	2752	18	0.3 (20)	1.59 (534)	1.64685 (5200)	14.7 (3.4)	99	n.d.

ρs - spontaneous track density
ρi - induced track density (reported induced track density is twice the measured density)
Number in parenthesis is the number of tracks counted for ages and fluence calibration or the number of tracks measured for lengths.
ρd - track density in muscovite detector covering CN-6 (1.05 ppm); Reported value determined from interpolation of values for detectors covering standards at the top and bottom of the reactor packages (fluence gradient correction)
S.E. = standard error
$P(\chi)^2$ = Chi-squared probability
n.d. = no data
$\lambda f = 1.551 \times 10^{-10} yr^{-1}$, g=0.5
zeta = 4772 ± 340 for apatite
Mean track lengths not corrected for length bias (Laslett et al., 1982)
Etch time 20 seconds, 5M nitric acid

We also explored a second scenario involving late Miocene intrusive activity mildly reheating the area, causing short tracks. In this case, the Molas Pass area was near the surface during the Late Eocene to early Oligocene, and then was strongly heated by the formation of the Silverton caldera. Cooling followed caldera formation. The area was locally heated by alteration associated with buried late Miocene intrusions that caused pyrite alteration observed in sample 6.

RESULTS

The higher elevation samples within the Pennsylvanian to Permian sedimentary section west of Molas Lake (samples 1 through 4 on Fig. 1) have AFT ages that range from 19.3±3.6 Ma (sample 1) to 13.6±2.8 Ma (sample 4; 2 sigma error). The ages follow the expected trend of decreasing age from higher elevation to lower elevation (Fig. 2). The mean track lengths of samples containing more than 30 measured confined tracks are 13.1±1.7 to 13.7±2.8 µm, indicative of moderate post-19 Ma cooling rates. In contrast, the AFT data from the Proterozoic rocks at lower elevation to the east of Molas Pass (samples 5-7 on Fig. 1) are generally of low quality and the ages do not correlate with elevation. The lowest elevation sample collected near the Animas River (sample 7) has little apatite (<20 grains) and the uranium concentration is low. As a consequence, the error in the age is large and no confined tracks were observed. Apatite from sample 6 similarly has a low uranium concentration and no confined track lengths were found. In addition, this sample, which lies near a strand of the Molas Creek fault zone, is mineralized with pyrite; the AFT age seems anomalously low (8.8±4.0 Ma) and may have been affected by post-late Miocene (10 to 8 Ma) hydrothermal alteration. The only Proterozoic sample with apatite containing a moderate amount of uranium that allowed measurement of confined track lengths is located ca. 30 m below the Great Unconformity between the Proterozoic and early Paleozoic rocks (sample 5 on Figure 1). The AFT age of 17.0±3.4 Ma for this sample is older than many of the AFT ages in the Pennsylvanian sedimentary rocks west of Molas Lake, but the ages statistically overlap. The mean track length is 13.9±2.3 µm, also within error of the Pennsylvanian samples.

Thermal history models are illustrated in Figure 3; these apply the constraint that the area was near the surface during the late Eocene to Oligocene. The gray envelope encompasses thermal histories that are good fits to the fission-track age and length data, and the hatched pattern encompasses acceptable fits. "Good" paths have a goodness-of-fit (GOF) between model and data of p=0.5 or greater, and "acceptable" paths have a GOF of 0.05<p<0.5, where p is the probability of failing the null hypothesis that the model and data are different (Ketcham et al., 2007). Note that the models calculated a wide range of "good" thermal histories (a wide gray envelope) before the middle Miocene and a narrow range of histories (thinner gray envelope) after middle Miocene. This is because the

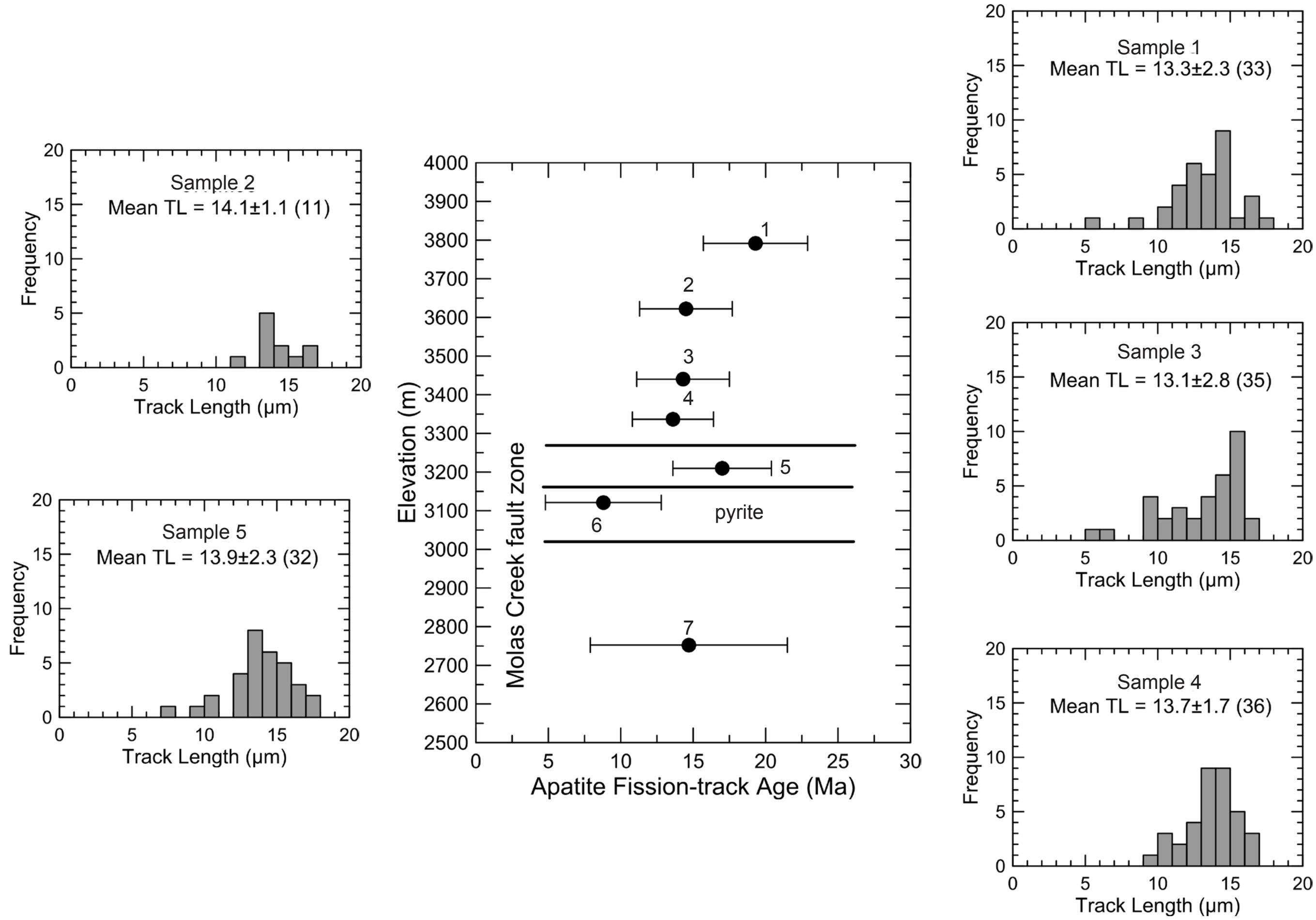

FIGURE 2. Age-elevation plots and track-length distributions for AFT samples from Molas Pass. The numbers in parentheses are the total number of track-length measurements.

AFT data are insensitive to the thermal history prior to ca. 20 Ma for the highest elevation sample (sample 1) and prior to 14 to 17 Ma for the lower elevation samples.

The multi-constraint models that incorporated a middle Miocene re-heating event did not improve the fit of the models to the data, except in one instance. The additional heat pulse allowed the models to fit the small peak of short tracks observed in sample 3 located northwest of Molas Pass (Fig. 4). This peak might not be real and might disappear if additional track lengths had been available for measurement; we typically analyze 100 confined tracks. Furthermore, no alteration was observed at the sampling site. Thus, the simple erosional cooling model with only one geologic constraint adequately fits all of the data, and the more complex model does not improve the fit except in one case that has a small sample size.

DISCUSSION

The thermal history pattern in Figure 3 indicates that the fission-track system was totally reset prior to 20 Ma, most likely as a result of the heating associated with the development of the 26.6 Ma Silverton caldera system and related hydrothermal alteration located just a few km to the north. Extensive dolomitization and silicification has affected the Pennsylvanian and Mississippian rocks in the area (David Gonzales, personal communication, 2017). Burial of the region by a significant thickness of now-eroded volcanic and volcaniclastic rocks related to the development of the San Juan volcanic field also contributed to heating of the section. Generally magmatic systems cool within 1-2 Ma of emplacement (e.g. Garcia, 2011), especially at the shallow level in the crust indicated by the unconformity. Thus, the lag of about 10 Ma between post-magmatic relaxation of isotherms at ca. 26 Ma and the timing of cooling recorded by the middle Miocene AFT ages at about 19 Ma imply that these data are related to Early to Middle Miocene exhumation that began about 19 Ma. The amount of section removed is difficult to determine because the geothermal gradient at the time is uncertain and could locally be high. The models suggest that the 14-19 Ma ages reflect the time the rocks cooled through 60-100°C. Possible reheating of the section by the nearby 14 to 17 Ma sills is not indicated in the track length distributions. Note that the implied steady cooling shown in the models is not well constrained below about 60°C. The younger age and the pyrite mineralization associated with sample 6 located in the Proterozoic rocks southeast of Molas Lake could be related to localized hydrothermal fluids associated with buried late Mio-

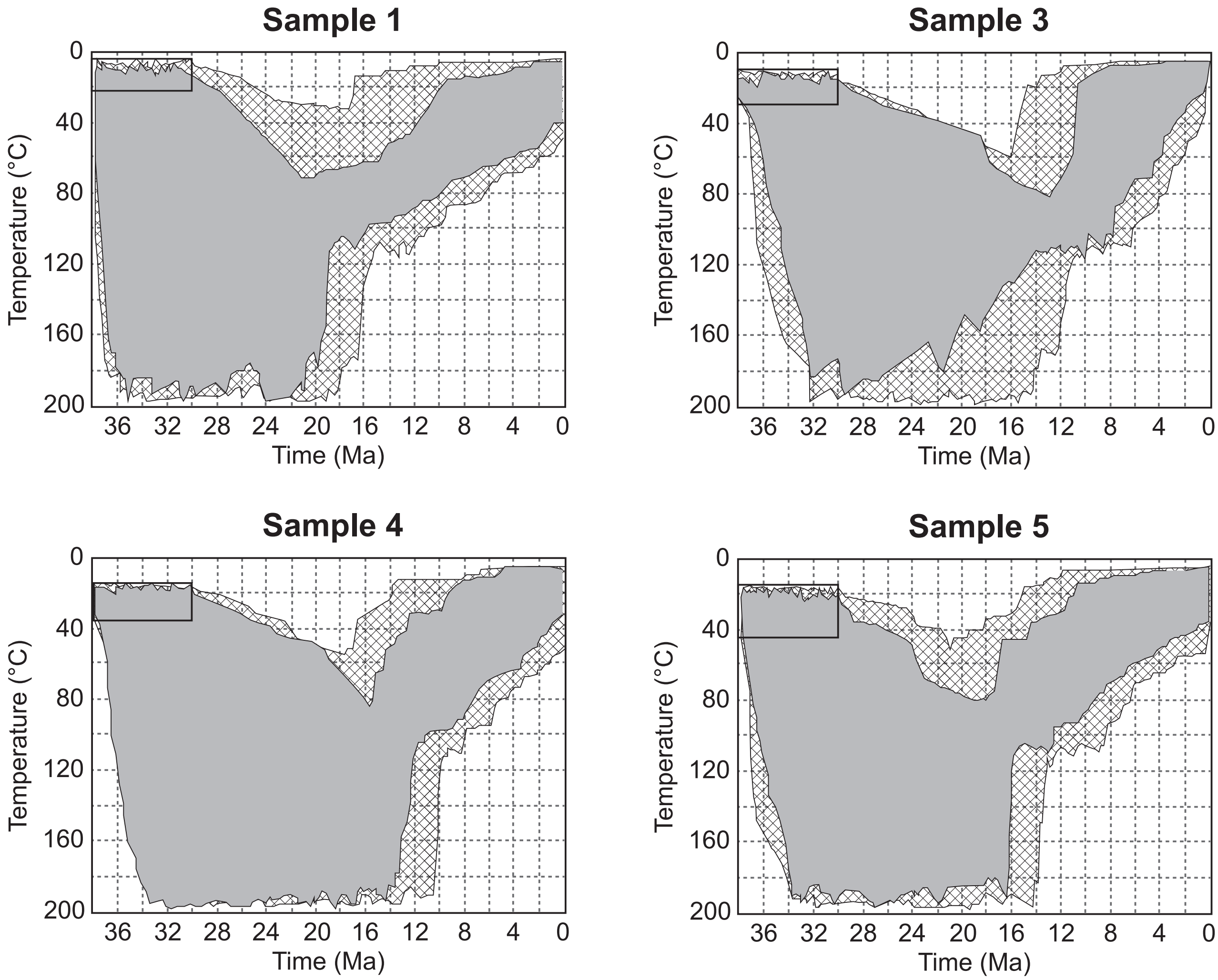

FIGURE 3. Time-temperature histories that fit AFT age and length data from the four samples (1, 3, 4, and 5) with more than 30 confined track length measurements. The gray area outlines "good" fits and the hatched area outlines acceptable fits. The black rectangles show the starting conditions for each model. The histories are poorly constrained between 20 and 38 Ma because the fission-track system was totally reset at 26.6 Ma by the emplacement of the Sultan stock.

cene intrusions similar to the 4-10 Ma intrusions reported both east (Chicago Basin) and west (Rico) of our study area. Sample 3 may have also been affected by the late Miocene localized thermal pulse, although the evidence in this case is not a strong.

The AFT age of the highest elevation Proterozoic rocks (sample no. 4) on the east side of the NNE-striking strand of the Molas Pass fault is slightly older than the lowest elevation samples (sample no. 7) in the Pennsylvanian sedimentary rocks to the west. This relationship could indicate that this strand of the Molas Pass fault has been active since the middle-Miocene and has caused east-side-down offset across the fault; however, the ages statistically overlap and east-down offset is not consistent with mapped relationships across the fault (Thomas, 2007). The only certain indication that the Molas Pass fault was slightly re-activated during the Miocene is the presence of hydrothermal alteration and a youthful, but hard-to-interpret AFT age adjacent to one strand of the fault.

A recent study postulated post-10 Ma denudation and uplift of the Colorado Rockies based in part on thermochronology studies in the southeastern Needle Mountains near Chicago Basin (Karlstrom et al., 2012). In the broader context of uplift of the Rocky Mountain region, our work also supports Miocene, in this case post ~19 Ma, cooling due to uplift and erosion of rocks that once covered the San Juan Mountains.

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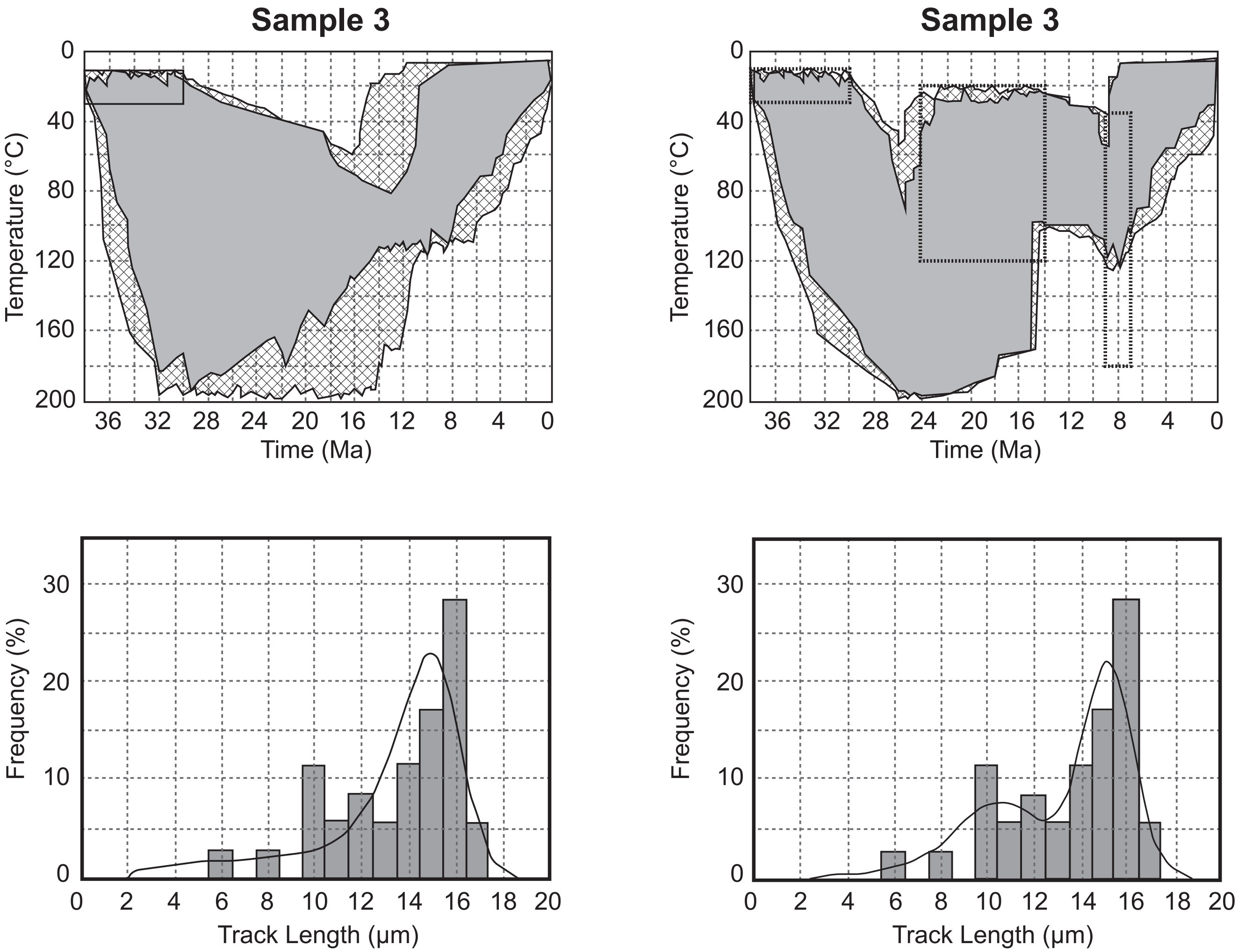

FIGURE 4. Comparison of the results of the simple thermal history with a single starting condition constraint (black rectangle) versus the thermal history with multiple constraints that includes a late Miocene thermal event (dashed rectangles) for sample 3, the only sample that showed an improved fit with the more complex history.

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