Low-temperature thermal history and landscape development of the eastern Adirondack Mountains, New York: Constraints from apatite fission-track thermochronology and apatite (U-Th)/He dating

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ABSTRACT

The Adirondack Mountains in northern New York State form an elongate, domal exposure of mainly high-grade metamorphic tectonites in a mountainous setting with topographic relief of ~1 km. The origin of the Adirondack Mountains and this relief has long been enigmatic, since the Adirondacks presently lie within an intracratonic setting, inboard of the North American passive margin and far from any active plate boundaries. Through the application of apatite fission-track (AFT) thermochronology and apatite (U-Th)/He (AHe) dating within the eastern Adirondack Mountains, this study provides constraints on both the thermal and erosional effects of Mesozoic passage near a hotspot and the timing of relief development.

AFT thermochronology and AHe dating record relatively stable thermal conditions within the eastern Adirondacks from the Middle Jurassic into the Early Cretaceous. During the Early Cretaceous (ca. 130–120 Ma), the region underwent heating associated with progressive movement near the Great Meteor hotspot, resulting in the temporary establishment of an elevated geothermal gradient. Following regional heating, cooling rates increased considerably (ca. 105–95 Ma), likely due to both thermal doming, producing an increase in erosion rate, and the relaxation of isotherms after passage near the hotspot.

The regional distribution of AFT ages across the eastern Adirondacks reveals no systematic age gradient from core to periphery, which would be expected under conditions of persistent high relief during the decay of a crustal root over many tens to hundreds of millions of years. Instead, thermochronological data suggest that the present relief developed during the Late Cretaceous–Cenozoic through plateau dissection during periodic base-level changes.

INTRODUCTION

The Adirondack Mountains of New York State constitute a region of moderate relief along the tectonically stable eastern margin of North America. The timing and mechanism(s) behind the formation of these mountains remain enigmatic, as indeed does the development of mountainous topography inland of many passive margins (e.g., Gilchrist and Summerfield, 1990). The Adirondack Mountains also represent one of a few regions in the United States, another being the Ozarks of Arkansas-Missouri (Brown and Marshak, 2004; Marshak et al., 2005), where intraplate mountains expose crystalline Precambrian metamorphic terrains. The purpose of our work is to further constrain the Mesozoic to Holocene history of the Adirondacks. Our results, combined with previous work, indicate that the low-temperature thermal history of the eastern Adirondacks coincides with passage near a hotspot during the Cretaceous. Moreover, the regional distribution of apatite fission-track (AFT) ages across the range sheds insight on the age of relief. Though our results have direct implications on the thermal history and landscape development of northern New York, they also outline the particular usefulness of low-temperature thermochronology in recording the thermal and topographic effects of passage near a hotspot (e.g., Crough, 1981; Eby, 1984; Cobbold et al., 2001; Roden-Tice and Tice, 2005; Pik et al., 2008; Roden-Tice et al., 2009) and may contribute to the greater understanding of the formation and/or preservation of relief inland of tectonically stable passive margins (e.g., Braun and van der Beek, 2004; Spotila et al., 2004; Persano et al., 2005).

The Adirondack Mountains of northern New York State form an oval outlier of late Precambrian age rocks connected to the greater Grenville Province of the Canadian Shield through the Frontenac Arch. Mountainous terrain (~1 km of relief) characterizes the eastern Adirondack Mountains, where it exposes mainly orthogneisses and granulite-grade metamorphic rocks.

In this paper, we present results of AFT thermochronology and apatite (U-Th)/He (AHe) dating from a number of key localities to constrain the post-Triassic low-temperature thermal history and the timing of relief development in the eastern Adirondack Mountains (Fig. 1). In particular, we explore the effects of passage over the Great Meteor hotspot ca. 130–95 Ma, the resultant cooling/erosional history, and subsequent relief development. While our study builds on earlier, more regional low-temperature thermochronology studies by Roden-Tice et al. (2000) and Roden-Tice and Tice (2005), our more focused sampling strategy permits significant advances in the understanding of the thermal and tectonic evolution of the Adirondacks.

GEOLOGIC BACKGROUND

The Adirondack Mountains record a protracted geologic history that spans Grenvillian orogenesis to Pleistocene glaciation. The high-grade mineral assemblages and deformation fabrics of the majority of rocks found within the eastern Adirondacks formed during the Grenville orogenic cycle (ca. 1350–1020 Ma; e.g., McLelland et al., 1996; Wasteneys et al., 1999; Heumann et al., 2006). By the Late Proterozoic–Early Cambrian, regional exhumation exposed this Grenville basement at the surface, where it was covered by the Potsdam Sandstone and younger stratigraphic units during rifting and formation of a passive margin along the Iapetus Ocean (e.g., Bird and Dewey, 1970; Cawood et al., 2001). Many of the NE-striking faults now

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found throughout New York State may have originated as normal faults during this Late Proterozoic extension (e.g., Jacobi, 2002).

During the Middle Ordovician, both loading and subsidence, due to overthrusting of Laurentia by the Taconic allochthon, resulted in the creation and/or reactivation of normal faults and burial of much of the eastern Adirondacks and the Mohawk Valley of New York (Bradley and Kidd, 1991). The Devonian to Permian tectonic history of the Adirondack region is not as well constrained. On the basis of temperature-time (*T-t*) histories produced by $^{40}Ar/^{39}Ar$ multidiffusion domain (MDD) K-feldspar models of samples from the Adirondacks (Heizler and Harrison, 1998), and constraints from isopach maps of Middle and Late Devonian strata to the south of the Adirondacks (Faill, 1985), the main effects of the Acadian orogeny on the eastern portion of the Adirondack region were subsidence and burial. K-feldspar thermal models (Heizler and Harrison, 1998) and analysis of fluid inclusions and clay digenesis in sedimentary rocks that flank the Adirondack Mountains (Sarwar and Friedman, 1994) also suggest that sedimentation continued throughout the Mississippian and Pennsylvanian. The late Pennsylvanian to Permian Alleghanian orogeny marks the final event in the Appalachian orogenic cycle and was the last collisional orogeny to affect the Adirondack region (e.g., Hatcher, 2002). K-feldspar thermal modeling suggests that the Alleghanian orogeny produced slow uplift and exhumation in the eastern Adirondacks (Heizler and Harrison, 1998). The effect of Mesozoic continental rifting on the Adirondack region is not well constrained, but it likely resulted in prolonged regional exhumation (Heizler and Harrison, 1998).

Northern New York and New England passed over the Great Meteor hotspot in the Cretaceous, resulting in regional magmatism and landscape modification (Fig. 2; e.g., Crough, 1981). The Great Meteor hotspot is named for the Great Meteor Seamount now located off the west coast of Africa. Through a number of seamounts, including the Corner, Nashville, Gosnold, and Bear, its hotspot track can be traced to offshore Massachusetts (Duncan, 1984; Sleep 1990). The hotspot track is mainly traced through the North American continent via the age progression of kimberlite dikes in Canada (Heaman and Kjarsgaard, 2000) and intrusions in Montréal and New England (Foland and Faul, 1977; McHone and Butler, 1984; Foland et al., 1986). On the basis of $^{40}Ar/^{39}Ar$ ages for plutonic rocks collected from the Monteregian Hills magmatic complex in Quebec (ca. 125 Ma; Foland et al., 1986) and for volcanic rocks collected from New England Seamounts (<100 Ma; Duncan, 1984), the Adirondack and New England regions passed over the hotspot between ca. 125 and 100 Ma (Fig. 2).

During the Cenozoic, the Adirondacks underwent Pleistocene glaciation followed by possible recent surface uplift. Isachsen and colleagues (Isachsen, 1975, 1981; Isachsen and Kelly, 1992) proposed that the Adirondack Mountains are currently experiencing surface uplift at a rate of ~1 mm/yr from the center outward due to thermal doming caused by a Cenozoic hotspot. However, this hypothesis remains controversial.

The MDD feldspar thermal models of Heizler and Harrison (1998) suggest that the rocks now exposed at the surface within the eastern Adirondacks were at a temperature of ~200–150 °C in the Early Jurassic, just above the temperature sensitivity range of the AFT system (~110–60 °C). Previous AFT thermochronology and AHe dating (Miller and Lakatos, 1983; Roden-Tice et al., 2000; Roden-Tice and Tice, 2005) have revealed important general cooling trends and exhumation patterns in the Adirondacks. We build upon this work using a different sampling strategy that focused on the collection of two vertical profiles in two key regions, the southeastern and central-eastern Adirondacks (Fig. 1).

METHODS

Sampling Strategy

AFT thermochronology is a well-established technique for determining thermal/exhumation histories of orogens and for constraining their tectonic development (e.g., Wagner and Reimer, 1972; Gleadow and Fitzgerald, 1987; Hurford, 1991; Gallagher et al., 1998). Combined with the lower-temperature method, AHe dating (e.g., Zeitler et al., 1987; Stockli et al., 2000; Ehlers and Farley, 2003; Reiners et al., 2003; Fitzgerald et al., 2006), these techniques are sensitive

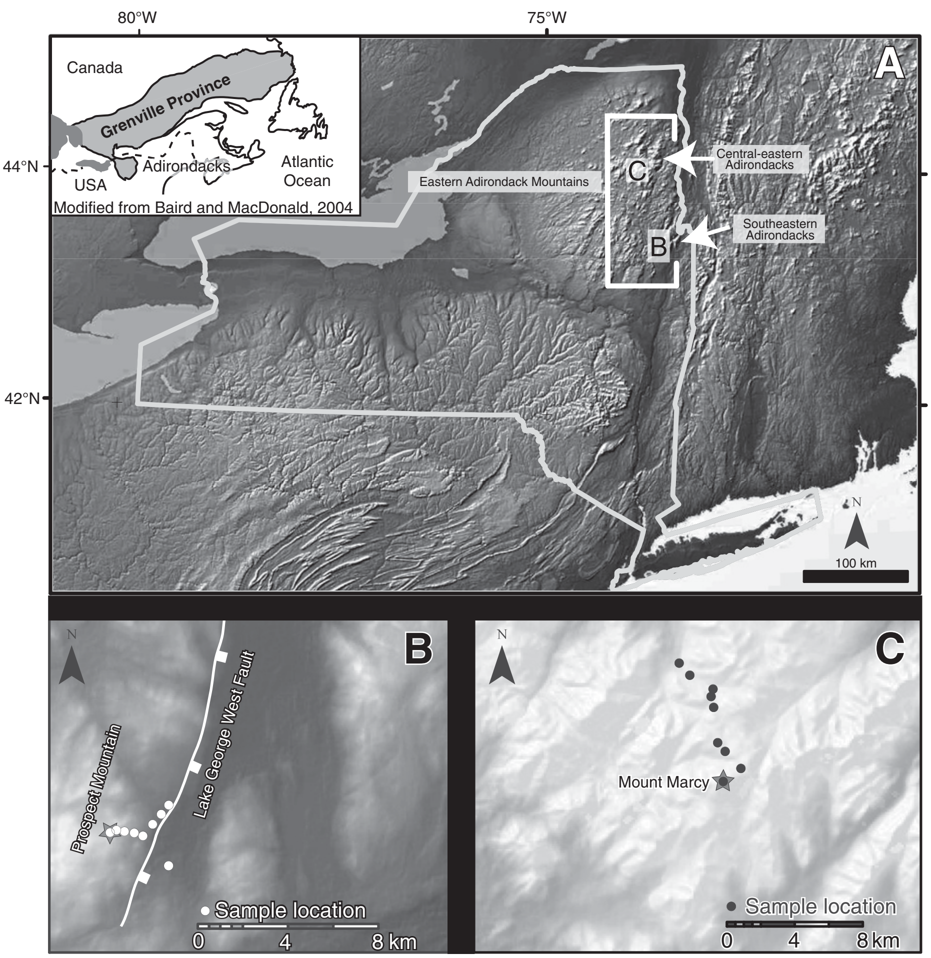

Figure 1. (A) Shaded relief map of New York State. Image was derived from GeoMapApp (http://www.geomapapp.org). The inset shows the location of the Adirondacks within the Grenville Province. The eastern Adirondack Mountains and the subregions of interest are outlined. (B) Sampling profile along Prospect Mountain. The location of the Lake George West fault is from Fisher (1984). (C) Sampling profile along Mount Marcy.

over a temperature range of ~110–40 °C, and generally constrain the exhumation of rocks through the upper 5 km of the crust.

As mentioned already, our study builds on the earlier, more regional studies by Roden-Tice et al. (2000) and Roden-Tice and Tice (2005). Their approach entailed constraining the regional thermal/exhumation history using a broad sampling strategy over a large region, followed by modeling of single samples. The strategy we employ uses focused vertical sampling profiles in select locations, also with modeling of each sample. The regional approach, as compared to the vertical profile approach, does in some cases produce different interpretations. The contrasting interpretations reflect the type of information obtainable and relative precision in determining the thermal/exhumation history using these different strategies. The vertical profile (age-elevation) strategy has the potential to provide less ambiguous information related to the thermal history and exhumation through time, but it can be limited in its geographical coverage as more samples are required. The regional approach allows determination of generalized thermal histories over a larger region, but it lacks precision in the derivation of thermal and exhumation histories through time. Ideally, the combination of both strategies provides more precision with greater regional coverage.

The vertical profile approach allows interpretation of data using the exhumed apatite partial annealing zone (PAZ) or partial retention zone (PRZ) concept (e.g., Fitzgerald and Gleadow, 1990; Wolf et al., 1998; Stockli et al., 2000). The shape and apparent slope of the AFT age-elevation profile and the variation between confined track length distributions (CTLD), combined with the shape and apparent slope of the AHe age-elevation profile and the offset of the two data sets, integrated with modeling, provide an important basis for interpretation.

For AFT data characterized by poor counting statistics, fewer tracks in the CTLD, or AHe ages that display the characteristic of single-grain age variation (e.g., Fitzgerald et al., 2006), a better assessment of data reliability is possible when samples are collected in close proximity in a vertical profile. Likewise, variation of data from within vertical profiles can be better evaluated for its significance because the geographic proximity of data points allows subtle patterns to be recognized. This later point is important because the cooling events we recognize are relatively subtle, and occurred in the Late Jurassic and Early Cretaceous, i.e., significantly long ago that the cooling signal from that time is now a much lower percentage of the total overall signal as tracks have continued to be produced up to recent times. Thus, the use of the vertical profile sampling strategy, multiple thermochronometers, and thermal modeling of samples in close proximity to one another to constrain cooling envelopes allows a better evaluation of viable alternatives, and hence more reliable constraints on the thermal, exhumation, and tectonic histories of a mountain belt.

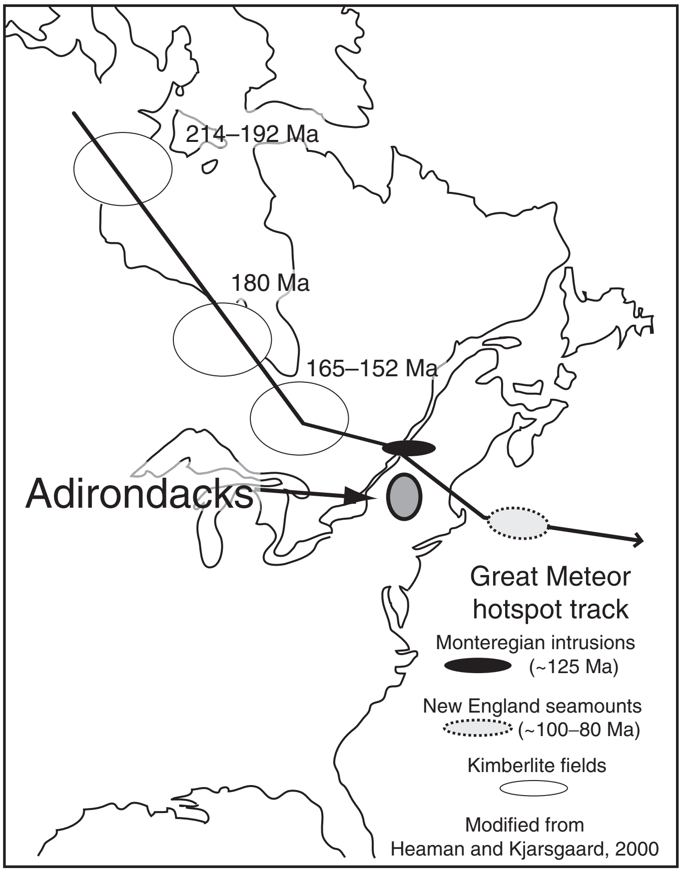

Figure 2. Generalized map of the Great Meteor hotspot track. Depicted are the U-Pb perovskite ages for kimberlite fields in eastern North America (Heaman and Kjarsgaard, 2000) and $^{40}Ar/^{39}Ar$ ages for the Monteregian Hills (Foland et al., 1986) and New England Seamounts (Duncan, 1984).

Two regions were selected for the collection of vertical profiles: the southeastern and central-eastern Adirondacks. The southeastern Adirondacks yield the youngest previously published AFT ages, while the central-eastern Adirondacks contain the greatest relief and the oldest previously published AFT ages within the eastern Adirondacks (Roden-Tice et al., 2000; Roden-Tice and Tice, 2005).

Samples for low-temperature thermochronology were collected in vertical profiles at vertical intervals of ~100 m. On Mount Marcy in the central-eastern Adirondacks, samples were collected from 1620 m to 740 m (~900 m of relief; Fig. 1C), and on Prospect Mountain in the southeastern Adirondacks, samples were collected from 619 m to 119 m (~500 m of relief; Fig. 1B). In the southeastern Adirondacks, sampling was also extended across the Lake George West fault, a normal fault located along the eastern edge of the Adirondacks that was active during the Ordovician, but possibly originated during the late Precambrian (e.g., Fisher, 1984). The sampling strategy was designed to better constrain whether this fault was reactivated during the Mesozoic–Cenozoic. Eight of the nine samples within the Mount Marcy profile were collected from bedrock exposures of anorthosite; one sample (ADK04–19) was collected from a skarn deposit adjacent to a diabase (Table 1). Most samples within the Prospect Mountain profile were collected from bedrock exposures of granitic gneiss with slightly varying compositions; one sample (ADK04–10) was collected from an outcrop of gabbroic gneiss.

Apatite Fission-Track Thermochronology

Rock samples from the Mount Marcy and Prospect Mountain profiles were crushed and

TABLE 1. APATITE FISSION-TRACK DATA

		Elevation (m)	No. of grains	Age (Ma)	2σ error	χ^2 value	Age dispersion	U (ppm)	Dpar (µm)	MTL (µm)	St. dev (µm)	No. of lengths
Mount Marcy	ADK04-12	1620	25	160	13.0	75.12	0.00	16.9	2.90	12.8	1.9	96
	ADK04-14	1410	25	155	14.0	87.13	0.00	12.3	2.98	12.9	1.5	103
	ADK04-15	1320	25	142	13.0	58.44	0.00	17.9	2.88	13.2	1.7	92
	ADK04-16	1270	25	143	19.8	88.03	0.00	11.7	2.49	12.7	1.7	64
	ADK04-18	1100	25	140	11.6	58.06	0.03	25.8	2.54	12.5	1.8	101
	ADK04-19	1035	26	137	19.4	66.82	0.00	6.4	2.40	12.9	2.0	90
	ADK04-20	960	25	138	11.4	85.23	0.00	15.8	3.01	12.8	2.0	67
	ADK04-21	817	25	135	11.2	9.78	9.80	26.3	2.72	12.9	1.8	100
	ADK04-22	740	26	116	12.6	87.97	0.00	12.1	2.33	12.4	2.2	40
Prospect Mountain	ADK03-10	619	25	96	7.2	5.72	9.68	50.7	2.36	13.3	1.2	102
	ADK04-8	543	25	93	6.6	66.98	0.01	49.2	2.30	13.6	1.3	92
	ADK04-9	434	24	100	7.4	9.88	8.58	61.4	2.60	13.2	1.4	85
	ADK03-17	314	25	101	7.2	18.92	6.98	64.1	2.45	12.8	1.4	102
	ADK04-10	229	25	101	7.8	29.76	6.62	99.1	2.56	12.9	1.3	101
	ADK04-17	168	25	99	8.4	0.46	12.92	82.1	2.38	13.1	1.4	103
	ADK03-19	137	26	94	6.4	20.70	6.11	75.6	2.53	13.6	1.3	102
	ADK03-11	128	25	98	6.8	38.98	0.20	44.3	2.17	12.9	1.3	104
	ADK04-6	119	25	99	8.8	0.04	14.90	66.2	2.70	13.8	1.3	104

Note: For all samples, the outer ~3 cm were removed to eliminate any grains that may have been reset by forest fires (Mitchell and Reiners, 2003). All ages are presented as central ages (Galbraith and Laslett, 1993). The χ^2 and age dispersion values are presented as a measurement of single-grain age variation within each sample (e.g., Galbraith and Laslett, 1993). Dpar—mean etch pit diameter parallel to the *c*-axis; MTL—mean track length.

processed for heavy minerals using standard organic heavy liquid and magnetic separating techniques. AFT ages were determined using the external detector method (Gleadow, 1981) and the zeta approach (Fleischer et al., 1975; Hurford and Green, 1983). For each sample, horizontal confined fission-track lengths and their angle to the *c*-axis were measured, as was Dpar (mean etch pit diameter parallel to the *c*-axis; e.g., Burtner et al., 1994).

AFT data, including ages, CTLDs, and Dpar values, were used to produce individual thermal models for each sample using the HeFTy thermal modeling program (Ketcham, 2005). This program converges on a best-fit *T-t* history for each sample by generating synthetic *T-t* histories and their resultant AFT age and track length data, which are then statistically compared to the measured data.

(U-Th)/He Dating

We undertook AHe dating on apatite separates from the Mount Marcy profile, but not the Prospect Mountain profile. AFT mounts from Prospect Mountain revealed pronounced core and rim zoning of U, making these apatites unsuitable for AHe dating. Apatite grains were selected for AHe dating under a stereographic microscope at magnifications from 20× to 188×. Grain quality, including the presence of inclusions, was assessed under transmitted light (plane-polarized and cross-polarized) and reflected light while grains were submerged in ethyl alcohol. Optically inclusion-free grains were selected and dated using standard techniques (e.g., Farley, 2002; Ehlers and Farley, 2003).

Radiogenic ^{4}He was measured at the SUNGIRL facility at Syracuse University. Known volumes of highly pure standard ^{4}He and ^{3}He were analyzed to calibrate the mass spectrometer, followed by cold line blank runs to establish background values. Packed in Pt tubules, single grains of apatite were out-gassed using a Synrad Model 48–2 CO_2 laser at 12% output for 3 min and spiked with 5 ncc of highly pure ^{3}He. After getter purification, the He isotopes were measured on a Balzers QMS 200 quadrupole mass spectrometer. Following out-gassing, a re-extract hot blank was performed on the grain under the same conditions as the sample out-gassing, to test for any U- or Th-bearing inclusions. Average cold and hot blank ^{4}He values were 0.001234 ncc over the period during which analyses were completed. Following out-gassing, Pt tubules were sent to the (U-Th)/He Chronometry Laboratory at Yale University (now located at the University of Arizona, Tucson) for the measurement of ^{238}U, ^{232}Th, and ^{147}Sm by isotope dilution on a Finnegan Element 2 inductively coupled plasma–mass spectrometer (ICP-MS). Fragments of Durango fluorapatite standard (Young et al., 1969) were analyzed along with the unknowns, yielding consistent results with an average value of 33.2 ± 0.31 Ma (2σ). When possible, up to five single-grain ages were determined for each sample. Ages were corrected for α-ejection using standard procedures (e.g., Farley et al., 1996).

RESULTS

Southeastern Adirondacks: Prospect Mountain Profile

Apatite Fission-Track Results and Interpretation

AFT ages for samples from the Prospect Mountain profile range from 101 ± 7.8 Ma to 93 ± 6.6 (2σ) Ma (Table 1; Fig. 3). Two samples (ADK04–6 and ADK04–17) fail the χ^2 test and have age dispersion values >10%. The age-elevation trend has a very steep apparent slope. Mean track lengths vary from 13.8 ± 0.26 to 12.8 ± 0.28 µm (2σ) with standard deviations from 1.2 to 1.4 µm. CTLDs show a weak negative skewness. Dpar values range from 2.70 to 2.17 µm, which are considerably higher than measured Dpar values from Durango apatite (2.06 µm), indicating that fission tracks in the Prospect Mountain apatites are more resistant to annealing than in the Durango standard. All AFT ages lie within 2σ error, with a weighted mean of 97.6 ± 2.4 Ma, mean square of weighted deviates [MSWD] = 0.72, leading to the simplest interpretation that this relationship represents rapid cooling at ca. 98 Ma (Fig. 3).

Thermal Modeling and Discussion

Seven of the nine samples from the Prospect Mountain profile were modeled using the HeFTy thermal modeling program (Fig. 4; Ketcham, 2005). All thermal models show a period of rapid cooling between 105 and 95 Ma followed by a decrease in cooling rate near the top of the partial annealing zone (PAZ) (Fig. 4). Some models show a second period of rapid cooling starting in the Miocene. Previously, modeling of AFT data using the Laslett et al. (1987) and Crowley et al. (1991) annealing algorithms produced this type of rapid cooling event at lower temperatures near the end of the model (typically Miocene times), making the interpretation of late-stage cooling in AFT thermal models problematic (Laslett and Galbraith, 1996). To avoid this problem, we used the annealing algorithm presented by Ketcham et al. (1999), which does not produce an unwarranted late-stage cooling event (e.g., Ketcham et al., 2000). Thus, this late-stage (Miocene–Holocene) cooling in our models may be real, although more work is required to constrain its validity. In summary, AFT thermochronology indicates that the southeastern Adirondacks underwent a period of rapid cooling between 105 and 95 Ma.

Central-Eastern Adirondacks: Mount Marcy Profile

Apatite Fission-Track Results

AFT ages for samples from the Mount Marcy profile range from 160 ± 13 Ma to 116 ± 12.6 (2σ) Ma (Table 1; Fig. 5). All samples pass the χ^2 test, and single-grain ages show little age dispersion. Mean track lengths vary from 13.2 ± 0.36 to 12.4 ± 0.70 µm (2σ) with standard deviations ranging from 1.5 to 2.2 µm. All CTLDs exhibit negative skewness, and three samples display weakly bimodal track length distributions (Fig. 5; Table 1). Dpar measurements range from 3.01 to 2.33 µm, and all but four samples have a Dpar > 2.7 µm (Table 1). As with the samples from Prospect Mountain, these values are substantially higher than Dpar measurements made for the Durango standard, indicating that tracks within these apatites are more resistant to annealing.

Apatite Fission-Track Thermochronology Interpretation

AFT ages from the Mount Marcy profile vary systematically with elevation, and the slope of a best-fit regression line to all the data is ~25 ± 5 m/m.y. (1σ; MSWD = 0.84; Fig. 6). The younger age, slightly smaller mean track length, and slightly larger standard deviation (in comparison to the other samples) of the lowermost sample (ADK04–22) indicate a greater degree of annealing. In turn, this suggests a shallowing of the age-elevation curve at the base of the Mount Marcy profile, perhaps due to a decrease in cooling rate or minor regional heating. The age-elevation apparent slope without this lowermost sample is 33 ± 10 m/m.y. (1σ; MSWD = 0.32), which is slightly higher, but within error of, the best-fit slope to all the data.

Due to its very shallow apparent slope, several possible interpretations for the Mount Marcy profile are possible: The average slope may represent slow exhumation with an apparent rate of ~25 m/m.y. from ca. 160 to 115 Ma. Alternatively, the profile may represent an exhumed partial annealing zone, likely with a component of slow cooling. The slope of the partial annealing zone during stable conditions evolves over time and can easily be misinterpreted as

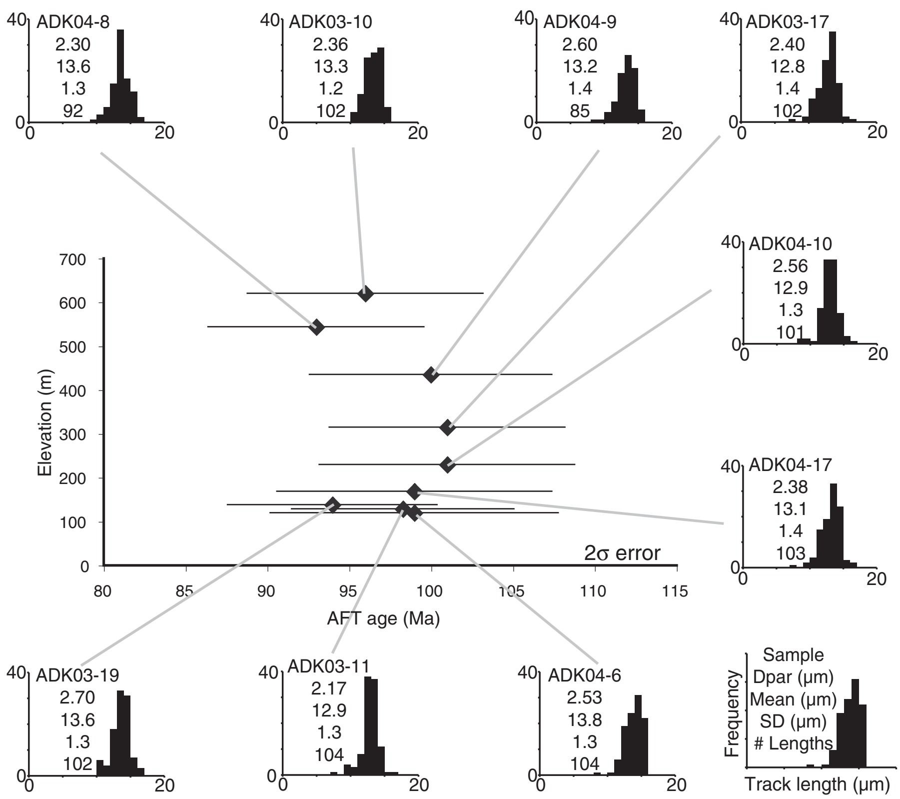

Figure 3. Prospect Mountain apatite fission-track (AFT) age versus elevation plot, including horizontal confined track length distributions (CTLD).

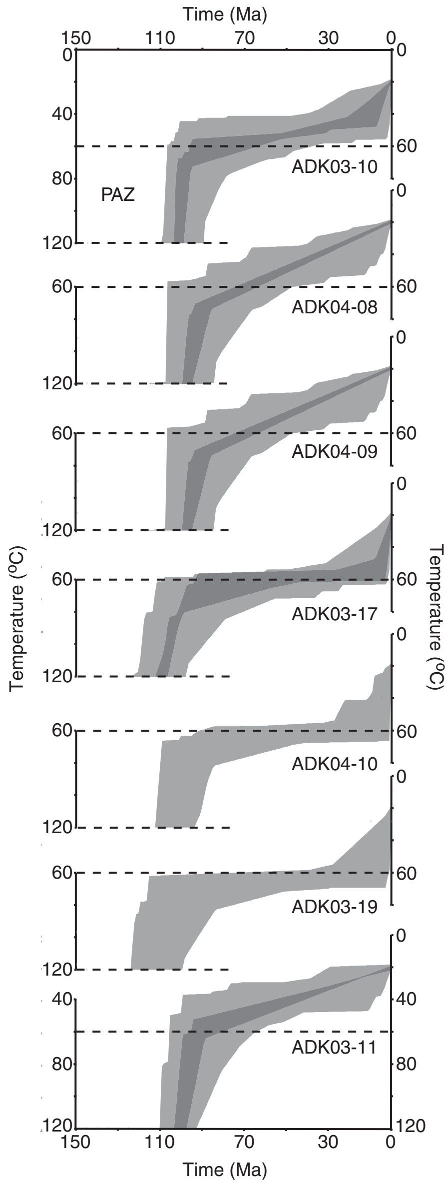

Figure 4. Thermal models constrained using apatite fission-track (AFT) data from the Prospect Mountain profile. Samples are ordered by decreasing elevation from top to bottom. Models were run using the HeFTy program, Ketcham et al. (1999) annealing algorithm, and *c*-axis projection method of Donelick et al. (1999) for a duration of 10,000 random paths or until five paths with a good fit were produced. Dark gray represents the temperature-time (*T*-*t*) region containing paths with a good fit, and light gray represents the *T*-*t* region containing paths with an acceptable fit.

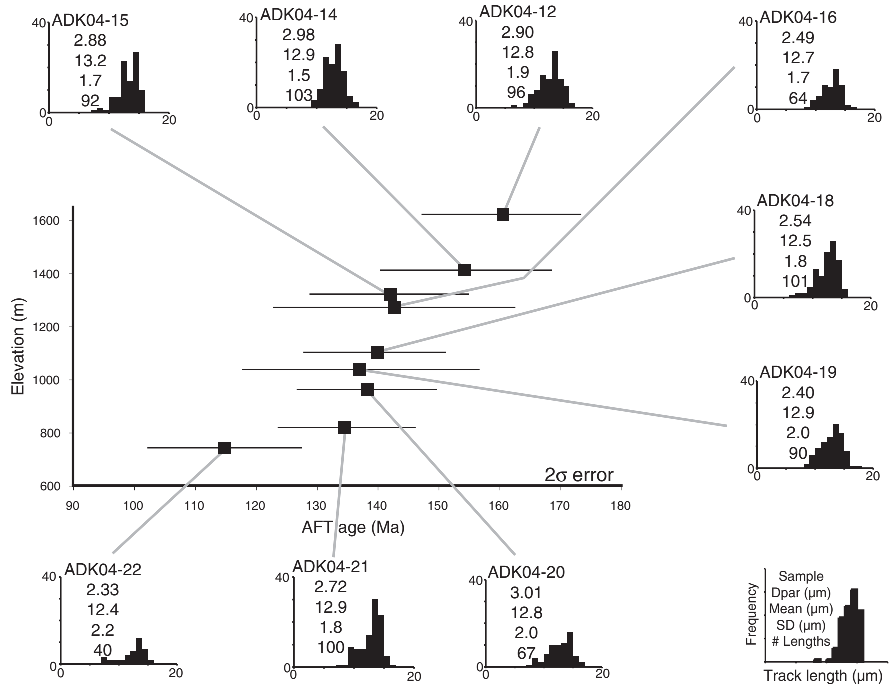

Figure 5. Mount Marcy apatite fission-track (AFT) age versus elevation plot, including horizontal confined track length distributions.

reflecting only exhumation (e.g., Fitzgerald and Stump, 1997). The combination of short mean track lengths (<13 µm), large standard deviations (>1.5), weakly bimodal track length distributions, and a gentle age versus elevation slope is a typical characteristic of an exhumed partial annealing zone (Gleadow and Fitzgerald, 1987).

To evaluate whether this profile represents an exhumed partial annealing zone, the slope of an apatite partial annealing zone was modeled using HeFTy (Ketcham, 2005) under stable thermal conditions over a duration of 50 m.y. and 100 m.y. Models were run assuming an apatite with a Dpar value equal to the Mount Marcy average (2.69 µm). Each models partial annealing zone was produced by first determining the age of apatite samples held at isothermal conditions over 10 °C increments within a temperature range characteristic of the partial annealing zone. These ages were plotted against their isothermal holding temperature to create a *T-t* plot of the partial annealing zone over 50 and 100 m.y. *T-t* plots were converted to age-elevation plots using an estimate for the geothermal gradient, and then they were compared to the slope of the AFT data from the Mount Marcy profile. A geothermal gradient of 20 °C/km was used, which represents an approximation of the present geothermal gradient calculated from heat-flow measurements taken within the anorthosite massif by Birch et al. (1968).

The modeled slope of a stable partial annealing zone formed over 50 m.y. is ~58 m/m.y., decreasing to ~28 m/m.y. over 100 m.y. The Mount Marcy age-elevation slope of ~25 m/m.y. (or 33 m/m.y.) is therefore generally consistent with that of a partial annealing zone that evolved over a time period ≥50 m.y. Because no geologic environment is absolutely stable, the gentle Mount Marcy slope likely represents very slow cooling, in effect combining components of slow cooling and a relict partial annealing zone that evolved over a time period greater than 50 m.y.

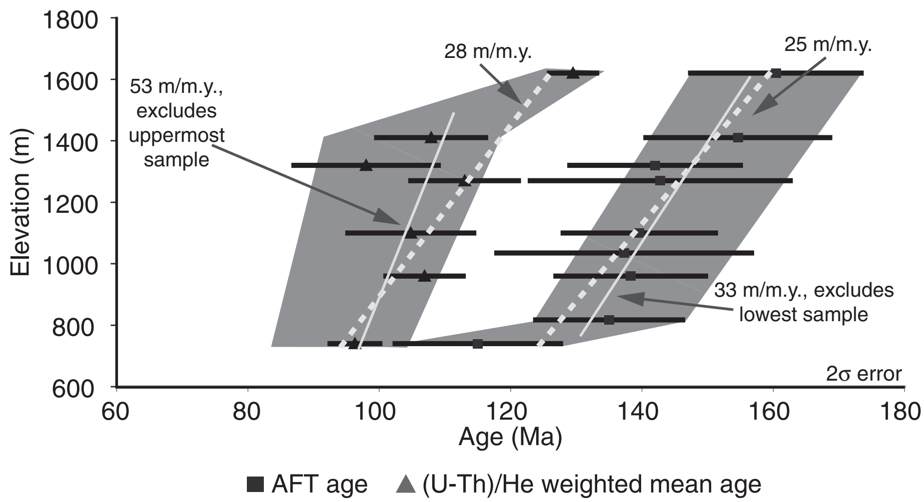

Figure 6. Age versus elevation plot containing both apatite fission-track (AFT) and apatite (U-Th)/He (AHe) ages determined for samples in Mount Marcy profile. The inferred range of possible cooling paths (in gray) and regression lines discussed within the text (solid and dotted lines) are outlined for each data set. Note the apparent overlap of the bottom portion of the AFT profile with the upper portion of the AHe profile, where the region of acceptable cooling paths flattens considerably.

Apatite (U-Th)/He Dating Results

From the Mount Marcy profile, two to five AHe single-grain ages were determined for each sample, with the exception of samples ADK04–19 and ADK04–21 (Table 2). Apatite grains from ADK04–19 contained abundant inclusions, making them unsuitable for AHe dating (e.g., Wolf et al., 1996). All grains selected from ADK04–21 failed the re-extract test, suggesting the presence of U- and Th-bearing inclusions not identified optically.

Single-grain ages vary from 131 ± 12 Ma to 80 ± 12 Ma (2σ), and individual samples show considerable single-grain age variation (Table 2). Because many of the grains analyzed are quite small (60–24 µm radius), they yield large errors associated with the uncertainty in the α-ejection correction (e.g., Farley et al., 1996; Ehlers and Farley, 2003). ADK04–16 and ADK04–22 contained grains that exhibit a very weak correlation between AHe age and radius. However, because no strong correlation exists, weighted mean ages for each sample were calculated by combining single-grain ages (Table 2), and these weighted mean ages correlate systematically with elevation (Fig. 6).

Apatite (U-Th)/He Interpretation

We interpret the Mount Marcy AHe ages as indicative of moderate to rapid cooling through the apatite partial retention zone (PRZ), representing the transition from slow cooling revealed in the Mount Marcy AFT data to the rapid cooling revealed in the Prospect Mountain AFT data. However, a discussion regarding the variation of single-grain AHe ages and other factors is warranted to justify that interpretation.

Intrasample single-grain AHe age variation has many possible causes (e.g., Meesters and Dunai, 2002; Spencer et al., 2004; Fitzgerald et al., 2006; Unruh et al., 2007; Flowers et al., 2009; Spiegel et al., 2009). Fairly straightforward explanations for intrasample age variation include: the presence of inclusions of U-bearing minerals and zoning of parent isotopes (e.g., Farley et al., 1996; Meesters and Dunai, 2002). Inclusions, such as zircon, contribute daughter ^{4}He but are not dissolved during dissolution of apatite grains for ICP-MS measurement of U, Th, and Sm. This results in parentless ^{4}He and an older age. Excluding sample ADK04–21, re-extract tests did not produce any measurable ^{4}He above blank level, as would be expected if inclusions of other U- or Th-bearing minerals were present (e.g., Farley, 2002).

Zoning results in an incorrect α-ejection correction and is enhanced by slow cooling through the partial retention zone (e.g., Meesters and Dunai, 2002). Fission-track mounts show no clear evidence for zoning of U, although we cannot rule out subtle zoning of U or zoning of Th. Element mapping, possibly using an electron microprobe, is one way to further characterize parent isotope zonation, but this is beyond the scope of this study. The "bad neighbor problem" or implantation, where nearby U-bearing minerals implant parentless α-particles into apatite grains, has also been suggested to produce both erroneously old AHe ages and significant single-grain age scatter, specifically in apatite with low (<4 ppm) eU (effective U concentration; U+0.235*Th) concentrations (Spencer et al., 2004; Spiegel et al., 2009). In a sample of volcanic rock with a known simple *T-t* history, Spiegel et al. (2009) identified minerals with U concentrations greater than or equal to concentrations in directly adjacent apatite grains. AHe ages obtained using traditional methods (using an α-ejection correction) were older than the known volcanic age of the sample. However, after physical abrasion and removal of the apatite's outer rim, ages were obtained that overlapped with the volcanic age. Implantation of ^{4}He into the apatite from nearby minerals was proposed in this case to explain the erroneously old ages of unabraded grains.

Shuster et al. (2006) demonstrated that the accumulation of radiation damage can modify the closure temperature of the AHe system from the traditionally accepted values, where an increase in radiation damage results in a systematic increase in closure temperature. Flowers et al. (2009) proposed a radiation damage accumulation and annealing model (RDAAM) that uses spontaneous fission-track density as a proxy for radiation damage accumulation over time and its effect on the closure temperature of the AHe system. It has the advantage of predicting the total amount of damage because the AFT partial annealing zone is thought to overlap with the zone of annealing of α damage. In the RDAAM model, Flowers et al. (2009) demonstrated that radiation damage accumulated during slow cooling or reheating after long residence at near-surface temperatures increases the closure temperature of the AHe system. In apatites with high eU, this can result in AHe ages older than AFT ages for a given sample. This work also demonstrated that large variations in intrasample single-grain ages can be explained by radiation damage in a population

TABLE 2. (U-Th)/He ANALYTICAL DATA

	Elevation (m)	U (ppm)	Th (ppm)	Sm (ppm)	He (mmol/g)	Radius (µm)	F_T	Uncorrected He age (Ma)	Corrected He age (Ma)	Error (2σ)	MSWD
ADK04-12a	1620	11.2	45.2	234.2	11.3	44.4	0.718	94.0	130.9	9.4	
ADK04-12b		19.3	34.1	255.5	15.2	64.7	0.776	101.2	130.4	5.2	
ADK04-12c		14.3	24.1	286.8	10.3	51.2	0.738	93.3	126.4	7.1	
ADK04-12d		19.1	34.1	316.3	10.9	40.4	0.690	90.2	130.7	11.7	
Mean		16.0	34.4	273.2	11.9	50.2	0.731	94.7	129.6		
Wt mean									**129.5**	**3.6**	**0.35**
ADK04-14b	1410	14.4	60.3	168.7	10.7	30.3	0.582	68.8	118.3	19.5	
ADK04-14c		11.2	39.0	154.2	7.5	30.3	0.594	67.0	112.8	18.6	
ADK04-14d		12.1	40.7	212.8	8.0	36.4	0.660	67.0	101.6	11.2	
ADK04-14e		21.5	67.1	176.0	11.6	24.4	0.596	57.2	115.3	30.9	
Mean		14.8	51.8	117.9	9.5	30.3	0.583	65.0	112.0		
Wt mean									**107.9**	**8.3**	**0.97**
ADK04-15a	1320	12.5	43.0	211.1	6.9	32.3	0.591	55.6	94.1	13.5	
ADK04-15b		11.3	19.5	167.6	5.7	28.3	0.605	65.3	108.0	20.8	
ADK04-15c		7.4	17.1	113.6	6.4	44.4	0.710	101.4	142.8	10.4	
Mean		10.4	26.5	164.1	6.3	35.0	0.635	74.1	114.9		
Wt mean									**98.0**	**11**	**1.3**
ADK04-16a	1270	9.0	17.1	159.4	5.7	42.4	0.690	80.0	115.9	9.5	
ADK04-16b		6.9	19.1	204.4	3.7	32.3	0.555	58.0	104.6	16.3	
Mean		8.0	18.1	181.9	4.7	37.4	0.623	69.0	110.2		
Wt mean									**113.0**	**8.2**	**1.4**
ADK04-18a	1100	19.0	43.1	314.4	9.5	24.3	0.517	59.1	114.4	31.4	
ADK04-18b		8.2	12.3	282.1	4.6	28.3	0.578	73.8	127.6	25.1	
ADK04-18c		25.4	32.0	320.8	12.0	26.3	0.546	66.3	121.4	27.7	
ADK04-18d		18.2	13.7	234.7	7.5	30.3	0.590	63.3	107.2	17.8	
ADK04-18e		14.3	64.7	204.9	7.7	28.3	0.564	47.7	84.5	16.4	
Mean		17.0	33.2	271.4	8.3	27.5	0.559	62.0	111.0		
Wt mean									**104.8**	**9.6**	**2.8**
ADK04-20a	960	11.7	38.2	236.7	9.2	48.5	0.755	80.9	107.2	6.7	
ADK04-20b		9.7	24.5	252.1	6.0	30.3	0.613	70.0	114.2	18.9	
ADK04-20c		9.8	33.7	248.2	5.8	30.3	0.594	59.4	99.9	16.6	
Mean		10.4	32.1	245.7	7.0	36.4	0.654	70.1	107.0		
Wt mean									**106.9**	**5.9**	**0.65**
ADK04-22a	740	6.2	14.9	75.0	4.4	54.5	0.752	83.2	110.6	6.0	
ADK04-22b		7.7	13.7	110.0	3.8	40.4	0.688	62.5	90.8	8.7	
ADK04-22c		10.1	21.0	123.7	4.2	28.3	0.575	51.3	89.2	17.4	
ADK04-22d		11.1	24.6	106.3	4.5	32.3	0.619	49.8	80.4	11.6	
ADK04-22e		4.2	7.5	95.4	1.9	48.5	0.675	57.5	85.2	7.9	
Mean		7.9	16.3	102.1	3.8	40.8	0.662	60.9	86.4		
									96.3	**3.8**	**10.1**

Note: AHe results are for samples from the Mount Marcy profile. MSWD—mean square of weighted deviates. Mean values for each sample are in bold.

of grains with diverse eU concentrations. In this scenario, older ages are expected for apatites with high eU concentrations, and, correspondingly, younger ages are expected for apatites with lower eU concentrations.

The eU concentration of the Mount Marcy apatites ranges from 37 to 5 ppm, with an average eU of 19.6 ppm. These values are high enough to elevate the closure temperature above traditional values obtained assuming diffusion parameters from studies of Durango apatite (e.g., Farley, 2000) during slow cooling. However, there is no systematic relationship between eU and AHe age, suggesting that radiation damage does not play a role in the single-grain age scatter observed in our data set (e.g., Shuster et al., 2006; Shuster and Farley, 2009). Though some apatites in our study have low eU concentrations, approaching 5 ppm, we do not suspect that α implantation plays a significant role in the intrasample age variation found in the Mount Marcy data set. The anorthosite from which the apatite was separated is mainly composed of plagioclase feldspar. The main U-bearing mineral present is apatite, monazite is not observed, and zircon is found in very small quantities. Moreover, Birch et al. (1968) measured low radiogenic heat production values within the anorthosite massifs of the eastern Adirondacks, indicating very low overall concentrations of radioactive material. Though thin sections were not examined, the lack of other U-bearing minerals in significant quantities makes α implantation from nearby minerals unlikely.

The Mount Marcy AHe data are actually relatively well behaved when compared with many other data sets, notably those characterized by Mesozoic or older ages from stable cratonic regions (e.g., Spotila et al., 2004; Hendriks and Redfield, 2005; Flowers et al., 2009). For example, AHe ages from the Canadian Shield have intrasample single-grain age scatter as large as 600 m.y., and ages commonly older than the AFT age (Flowers et al., 2009).

Other data sets exhibit a more moderate intrasample age variation that is similar to that observed in our AHe data. In the Transantarctic Mountains, Fitzgerald et al. (2006) documented a correlation between cooling rate and AHe single-grain age variation where samples that cooled at rates <4 °C/m.y. had greater AHe age variation than more rapidly cooled samples. They attributed some of this age scatter to the interplay between diffusion and minor variations in parent isotope zonation. Unruh et al. (2007) documented a similar AHe single-grain age scatter in partially reheated samples from Mount Diablo, California, which they attributed to compositionally derived variations in the activation energy of diffusion.

Following the reasoning and discussion of AHe single-grain age variation in Fitzgerald et al. (2006), and incorporating new developments such as the potential significance of radiation damage (e.g., Flowers et al., 2009), the "true" AHe age for each sample is likely to lie between the weighted mean age and the youngest single-grain AHe age. This is because there are so many more external variables that result in an "older than expected" AHe age.

A best-fit regression of all the Mount Marcy AHe weighted mean ages yields a slope of 28 ± 6.5 m/m.y. (1σ) from ca. 130 Ma to 95 Ma (Fig. 6). If these data indeed define a linear age-elevation relationship, the low value of such a slope could represent, as with the AFT data, slow exhumation and/or long residence in the AHe partial retention zone. However, a linear regression through all the data is a poor fit (MSWD = 4.6). Excluding the uppermost AHe weighted mean age, which is significantly older (>120 Ma), a best-fit regression of the remaining lower Mount Marcy AHe mean ages from ca. 108 to 95 Ma yields an age-elevation slope of ~53 ± 14.5 m/m.y. (1σ; MSWD = 2.3). This change in slope at ca. 108 Ma suggests that the rate of cooling increased at that time. This interpretation ties in well with AFT data from Mount Marcy and Prospect Mountain. In effect, the Mount Marcy AHe age-elevation profile represents a composite *T-t* path recording the change from the slow cooling revealed in the Mount Marcy AFT data to the more rapid cooling (ca. 105–95 Ma) revealed in the Prospect Mountain AFT data, as is fully discussed later herein.

Thermal Modeling

HeFTy thermal models, including AHe constraints (Ketcham, 2005), were produced for all nine samples from the Mount Marcy profile (Fig. 7). In general, all models support an interpretation of slow sustained cooling through the apatite partial annealing zone (<1 °C/m.y.) from ca. 160 to 120 Ma. Models for samples ADK04–14, –15, and –18 suggest a slight decrease in cooling rate ca. 140–120 Ma at temperatures characteristic of the upper partial annealing zone. Some thermal models (e.g., ADK04–18 and ADK04–21) suggest Cenozoic cooling similar to that seen in the HeFTy models of the Prospect Mountain AFT data.

IMPLICATIONS AND INTEGRATION OF THE THERMOCHRONOLOGY DATA

Integration of the Apatite Fission-Track and (U-Th)/He Constraints

As indicated by the shape of the AFT and AHe age-elevation trends (Figs. 6 and 8), our

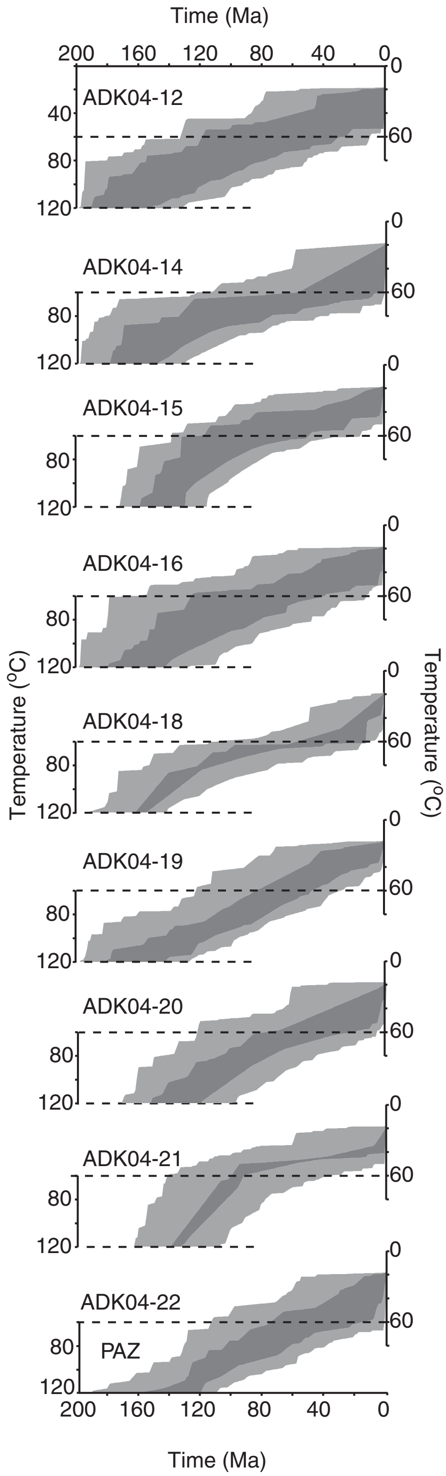

Figure 7. Thermal models constrained using apatite fission-track (AFT) data from the Mount Marcy profile. Samples are presented in the same manner and were modeled using the same parameters as described for Figure 4. Dark gray represents the temperature-time (*T-t*) region containing paths with a good fit, and light gray represents the *T-t* region containing paths with an acceptable fit.

interpretation of data from the eastern Adirondacks is that it records relatively slowly cooling through the partial annealing zone (and partial retention zone) during the Middle–Late Jurassic. During the Early Cretaceous, a period of more rapid cooling took place ca. 105–95 Ma, recorded by the Prospect Mountain AFT and Mount Marcy AHe data, although cooling appears to have been more rapid in the Prospect Mountain profile.

That rapid cooling ca. 105–95 Ma is not more pronounced in the Mount Marcy AFT thermal models is purely understandable given the long time period over which fission tracks have been accumulating and the relatively subtle nature of the cooling event. It is likely that the position of these samples in the upper partial annealing zone (higher structural level) just prior to the onset of rapid cooling, combined with the short duration of this event, did not produce a large enough signal in the CTLD to be well resolved by thermal modeling. The relatively low U concentration in the Mount Marcy apatites (~12 ppm), resulting in the low number of fission tracks in the sample, as well as horizontal confined track lengths, also makes resolution of this cooling even more difficult. Previous studies have encountered this situation; for example, deBruijne (2001), in a thermochronology study of central Spain, pointed out that low concentrations of U will limit the sensitivity of models to rapid cooling events, especially those of a relatively short duration and low magnitude.

For the Mount Marcy region, the overlap of the 130 Ma AHe age (Fig. 6) with the AFT data suggests an apparent congruence between the two data sets. This overlap can be used to both estimate the geothermal gradient at the time of overlap (ca. 130–120 Ma) as well as fit the relative position of the AHe age-elevation profile with the AFT profile (Fig. 8).

The paleogeothermal gradient at the time of overlap (ca. 130–120 Ma) is estimated using the closure temperature for the AFT and AHe systems and the elevation difference between the overlapping ages. Using a cooling rate of ~0.5 °C/km, as suggested by the gentle slope of the age versus elevation plot and the HeFTy modeling results, the closure temperature for the AFT system is estimated at ~96 °C (e.g., Brandon et al., 1998). Determining the closure temperature for the AHe system is slightly more problematic. Studies typically cite the closure temperature of the AHe system at 50–115 °C, depending on the cooling rate, grain size, and degree of radiation damage (e.g., Farley, 2000; Shuster et al., 2006; Shuster and Farley, 2009). We estimated the closure temperature for the AHe system using a number of methods to bracket the range of realistic values. First, we calculated the mean grain radius (50 µm) for sample ADK04–12, which has a weighted mean age that overlaps with the AFT age profile. We used a cooling rate of ~0.5 °C/m.y. (although changing the cooling rate by 1 °C matters little), an infinite cylinder geometry, the activation energy and frequency factor from Farley (2002), and the closure temperature equation of Dodson (1973). As suggested by Farley (2000), we added two degrees Celsius to the closure temperature to account for the effect of α-ejection on the He gradient during diffusion. Following this method, the estimated AHe closure temperature for ADK04–12 is 45 °C. However, because this sample cooled very slowly, the accumulation of radiation damage may have been significant enough to modify the AHe closure temperature (Shuster et al., 2006; Shuster and Farley, 2009). Taking radiation damage into account, we also estimated the closure temperature in two additional ways. First, using Figure 5 in Shuster et al. (2006), based on their trapping diffusion model that uses total ^4He concentration as a proxy for radiation damage, the closure temperature of sample ADK04–12 is estimated at ~50 °C. Second, using the RDAAM approach of Flowers et al. (2009), the closure temperature is estimated at 64 °C, which is much higher than that predicted using the traditional closure temperature method of Dodson (1973) or the model of Shuster et al. (2006). As previously mentioned, the RDAAM approach differs from that of Shuster et al. (2006) in that it predicts a large increase in closure temperature at moderate to high eU concentrations and very slow cooling rates.

The difference between the AFT and AHe closure temperatures (64–32 °C) divided by the difference in the elevation between the two samples (~850 m) yields a geothermal gradient between ~60 and 38 °C/km at ca. 130–120 Ma. This estimate is much higher than present conditions (~20 °C/km), but it may be reasonable given the proximity of the Adirondacks to the Great Meteor hotspot during the Cretaceous. For example, at similar distances away from the active Yellowstone hotspot, heat flow values can reach 100–80 mW/m^2 (e.g., Smith and Braile, 1994; Smith et al., 2009). If the Great Meteor hotspot had similar thermal properties, these values correspond to a geothermal gradient as high as 65–55 °C/km using the thermal conductivity of anorthosite, the rock type sampled along the Mount Marcy profile. This indicates that, although the geothermal gradient calculated from the low-temperature thermochronology data is high for a stable craton, it is reasonable given the regions proximity to the Great Meteor hotspot ca. 130–120 Ma.

Based on the foregoing discussion, our interpretation of the combined AFT and AHe data sets is that they record slow cooling reflecting stable tectonic and thermal conditions in the Middle Jurassic followed by a period of regional heating and the establishment of an elevated geothermal gradient ca. 130–120 Ma. Regional heating was followed by rapid cooling ca. 105–95 Ma.

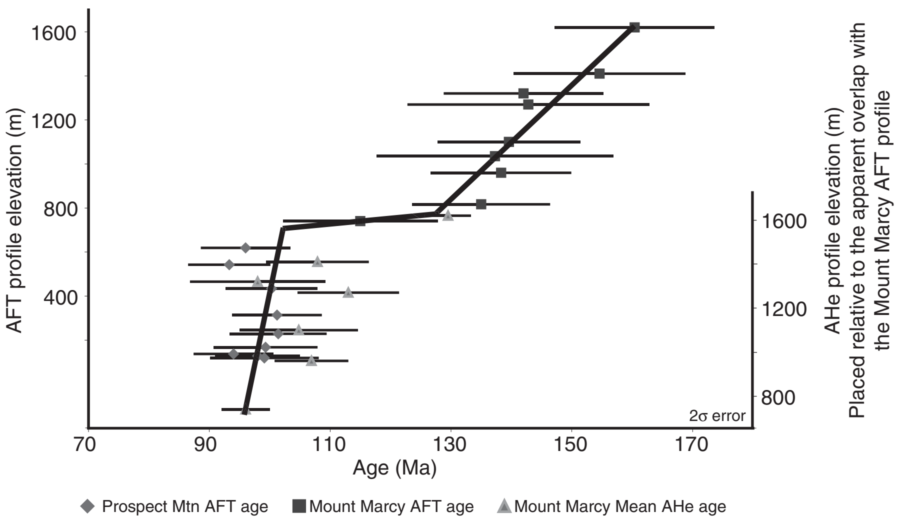

Figure 8. Apatite fission-track (AFT) data (Mount Marcy and Prospect Mountain) plotted against elevation, along with the adjusted position of the Mount Marcy apatite (U-Th)/He (AHe) data using the apparent overlap between the Mount Marcy AFT and AHe ages to constrain the relative position of the AHe profile. The black line depicts a three-stage cooling history.

Tectonic Interpretation: Movement over a Hotspot

The *T-t* history as documented by the AFT and AHe results, and interpretation herein, was penecontemporaneous with movement of the eastern Adirondacks and New England over the Great Meteor hotspot during the Early Cretaceous (e.g., Crough, 1981). On the basis of the age progression of igneous bodies, the hotspot track can be traced across New England from the Monteregian Hills of Quebec (ca. 125 Ma; Foland et al., 1986) to seamounts off the coast of Massachusetts (Fig. 2; ca. 100 Ma; Duncan, 1984). Within the easternmost edge of Adirondacks and western Vermont, the intrusion of hypabyssal mafic dikes roughly overlaps with the timing of passage over the hotspot (K-Ar ages of 136 ± 7 and 105 ± 4 Ma; McHone, 1978). Seismic-reflection and seismic-refraction studies have identified a zone of layered reflectors in the middle crust under the eastern Adirondacks that could represent a mafic intrusion of the same age (e.g., Brown et al., 1983; Klemperer et al., 1985), although this is unconfirmed.

A low-velocity zone under the eastern Adirondacks and adjacent New England is interpreted as a residual effect of the Great Meteor hotspot (Li et al., 2003). A similar low-velocity zone described over a broad region located near the Yellowstone hotspot (e.g., Foster, 2008; Smith et al., 2008) supports the interpretation of Li et al. (2003). The Yellowstone low-velocity zone has been interpreted to result from ongoing delamination of a portion of the lithosphere of the Wyoming craton in response to the approaching Yellowstone hotspot (Foster, 2008). Before interpreting our data in the context of passage near a hotspot during the Early Cretaceous, we examine the possible thermal effects of a hotspot on the lithosphere.

Thermal Effects of a Hotspot on the Lithosphere and Interpretation

Hotspot-induced regional heating will increase the geothermal gradient, resulting in partial or complete annealing of fission tracks within samples residing in, or just above (at higher crustal levels), the partial annealing zone prior to heating. Delamination of the mantle lithosphere under a hotspot, as discussed previously with respect to the Yellowstone hotspot, is expected to produce dynamic uplift over a broad region as asthenophere replaces the mantle lithosphere. Also, any hotspot-induced magmatism that results in pooling at the base or injection into the crust would increase crustal thickness and possibly result in an isostatic response (e.g., McKenzie, 1984).

Hotspots commonly produce domal surface uplift of >1 km and exhumation over a broad region with a radius of hundreds to thousands of kilometers as a result of dynamic uplift (e.g., Sengor, 2001). Following dynamic uplift, regional cooling and partial subsidence associated with the relaxation of isotherms occur as the region moves away from the hotspot. Regional cooling is thus influenced by: (1) erosion associated with the increase in elevation and relief during thermal doming and possible injection of magma, and (2) relaxation (lowering) of isotherms as the region moves away from the hotspot.

We suggest that the AFT data and AHe ages record relatively stable thermal and tectonic conditions from the Late Jurassic into the Early Cretaceous (Fig. 9). During the Early Cretaceous (ca. 130–120 Ma), the Adirondack region experienced regional heating associated with the progressive movement toward and over the Great Meteor hotspot. This heating ultimately resulted in the temporary establishment of an elevated geothermal gradient.

Thermal doming, and the formation of relief (due to erosion), is responsible for the initial phase of rapid cooling at ca. 105 Ma. The onset of rapid cooling via exhumation was probably earlier than that recorded by the data, since it most likely began during regional heating. Previously, using landscape evolution models, Pazzaglia and Brandon (1996) proposed a possible episode of dynamic uplift within the Central and Northern Appalachians that roughly overlaps with Cretaceous passage over the hotspot, supporting our interpretation of the thermochronology data. Following passage over the hotspot, rapid cooling continued as the Adirondack region moved away from the hotspot and isotherms relaxed back to their stable cratonic levels. This prolonged the period of elevated cooling rates to ca. 95 Ma, well beyond the timing of hotspot activity in the region. We cannot constrain whether injection of magma into the crust—with a resultant isostatic response and concomitant erosion—also contributed to the cooling history recorded by the low-temperature thermochronology. More geochronology data on dikes is needed to confirm the significance of Mesozoic magmatism in the Adirondacks. If injection of magma in significant amounts occurred, exhumation would be prolonged

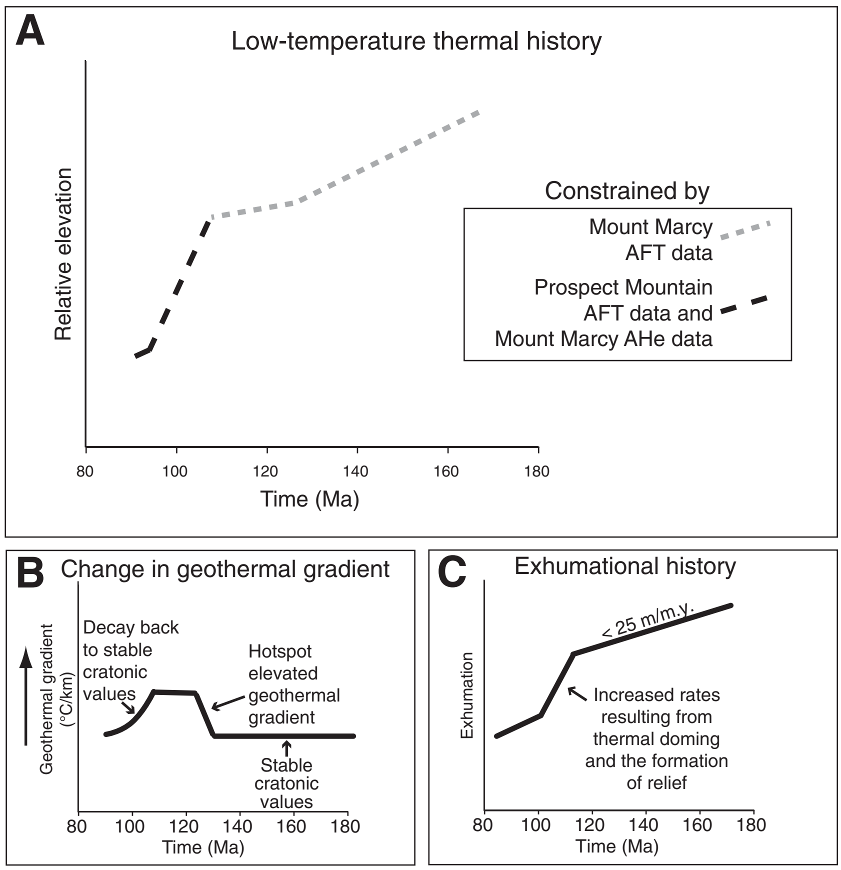

Figure 9. (A) Qualitative temperature-time (*T-t*) history for the eastern Adirondack Mountains depicting the contribution of both the thermal (B) and erosional (C) effects of the Great Meteor hotspot on the *T-t* history.

following passage over the hotspot, driven by an isostatic response to crustal thickening.

Comparisons with Previous Thermochronology Studies

Previous regional-scale thermochronology studies of the Adirondacks and New England have also commented on the effects of the Great Meteor hotspot on the thermal history of these regions. Roden-Tice et al. (2000) interpreted Late Jurassic–Late Cretaceous AFT ages from the Adirondacks as the result of progressive unroofing from the central-eastern region (high peaks) outward. Roden-Tice and Tice (2005) reevaluated that interpretation in the context of a hotspot, suggesting that movement over a hotspot was responsible for elevated cooling rates during the Early–Late Cretaceous in the southeastern Adirondacks but not in the central-eastern Adirondacks (high peaks), which underwent an earlier period of elevated cooling rates in the Late Jurassic, based mainly on thermal models and AFT–AHe age pairs for individual samples. In contrast, our sampling strategy combining the collection of a vertical profile and thermal modeling has produced results that suggest the south-central and southeastern Adirondacks share a similar thermal history and the thermal effects of the hotspot were more regionally extensive in the Adirondacks than previously suspected.

More recently, Roden-Tice et al. (2009) identified a NE-trending corridor of middle–Late Cretaceous cooling ages through New Hampshire and into southern Maine that roughly overlaps with the low-velocity zone in the upper mantle identified by Li et al. (2003). Roden-Tice et al. (2009) proposed that regional extension resulting from passage over the Great Meteor hotspot produced the regional exhumation recorded within this corridor. In southern New England, normal fault reactivation along the eastern border fault of the Hartford Basin (Roden-Tice and Wintsch, 2002) and Ammonoosuc fault in the Connecticut River Valley has also been proposed to result from passage over the Great Meteor hotspot (Roden-Tice and Tice, 2005). Roden-Tice and Tice (2005) called upon regional extension accommodated along NE-striking faults to explain the transition from older ages in the high peak region of the Adirondacks to younger ages in the southeastern Adirondacks.

To further explore the possible reactivation of normal faults in the southeastern Adirondacks during, or following, the middle Cretaceous, AFT ages were compared across the Lake George West fault. Normal faulting will typically disrupt the age versus elevation pattern if it occurs during or subsequent to cooling through the partial annealing zone, displacing older AFT ages on the downthrown hanging-wall block to lower elevations (e.g., Fitzgerald, 1992; Foster and Gleadow, 1996). Such a disruption in the AFT age-elevation pattern is best revealed when there is a significant variation of AFT age with elevation (i.e., where the apparent slope is gentle, such as in an exhumed partial annealing zone). We do not see an AFT age discontinuity across the Lake George West fault. Instead, AFT ages are within error on the footwall and hanging-wall blocks. However, the apparent slope of the Prospect Mountain AFT profile is very steep, so such an age offset would be extremely hard to resolve, regardless of whether a fault was active during, or subsequent to, cooling through the partial annealing zone. So, while we do not refute possible reactivation of faults along the eastern edge of the Adirondacks, our AFT data simply do not constrain the timing of movement on the Lake George West fault.

An examination of the general AFT age-elevation relationship across the entire eastern Adirondacks (Fig. 10) indicates that AFT ages are roughly equal for samples collected at the same elevation throughout the range. This pattern of ages is better explained by dissection of a plateau rather than offset along normal faults (see following for more discussion).

Timing of Relief Formation in the Adirondack Mountains

Spatial trends in AFT ages can provide constraints on the age of the relief in a mountain range. The new AFT data, combined with previous data from Roden-Tice and Tice (2005), and previous geophysical studies can be interpreted to constrain the timing of relief development within the eastern Adirondack Mountains (Fig. 10). For example, in mature mountain ranges, prolonged erosion, associated with the decay of a crustal root, commonly produces an exhumation gradient across the range; greater amounts of erosion occur across the high-relief core of the range, and lesser amounts occur over the lower-relief periphery (e.g., Reiners et al., 2003). Such differential exhumation is commonly expressed as an AFT or AHe age gradient at the surface, with younger ages in the core of the range and progressively older ages toward the periphery (e.g., Reiners et al., 2003). AFT age patterns in the Adirondacks do not show an AFT age gradient, indicating that it is unlikely that the eastern Adirondacks represent a slowly eroding, ancient mountain range associated with the decay of an orogenic crustal root. In addition, seismic-refraction studies (e.g., Taylor and Toksoz, 1979; Li et al., 2003) reveal a crustal thickness of ~35–40 km for the eastern Adirondacks, indicating little or no remnant crustal root.

Instead, the regional AFT age-elevation pattern (Fig. 10) favors progressive dissection and down-wearing of a regional plateau surface. In addition, thermochronology can pose constraints on the timing of dissection. Significant exhumation prior to ca. 130 Ma is not supported by the AFT and AHe data, since the preservation of a fossil AFT partial annealing zone from ca. 160 to 130 Ma indicates that very little erosion took place during this time. Rather, significant relief likely formed during and subsequent to passage of the eastern Adirondacks near the Great Meteor hotspot.

The Adirondack Mountains are located near the Appalachians, a mountain range characterized by prolonged slow exhumation over many tens to hundreds of millions of years (e.g., Spotila, 2005). Bounding the eastern edge of the ancient Appalachian orogen in the Central and Southern Appalachians, there is the Blue-Ridge escarpment, which most likely formed during Triassic rifting along eastern North America (e.g., Spotila et al., 2004, and references therein). Rugged topography and highland (or upland) plateau topography of the Appalachians extend northeast and includes the Adirondack Mountains. The evolution of passive margins and rift-margin escarpments, and the application of thermochronology to evaluate competing end-member models such as escarpment retreat or progressive down-wearing, is complex (e.g., Braun and van der Beek, 2004; Persano et al., 2005) and well beyond the scope of this paper. Nevertheless, we note that there are some broad similarities between AFT and AHe data in the Southern and Central Appalachians and the Adirondacks. While in the Southern and Central Appalachians low-temperature thermochronology suggests that the Blue Ridge escarpment (dividing the coastal piedmont from the uplands, or plateau) formed as a rift-flank escarpment and evolved by prolonged erosion without tectonic rejuvenation (e.g., Spotila et al., 2004), the situation may be more complex in the Adirondacks. There, the regional AFT age-elevation pattern suggests dissection of a plateau that was influenced by passage of North America over the Great Meteor hotspot, resulting in an elevated geotherm, thermal doming, and dynamic uplift, erosion, and relaxation of isotherms. Thermal doming may have reactivated N- NNE–striking faults along the Champlain and Lake George Valleys in a normal sense. Although we could not identify middle Cretaceous offset along the Lake George West fault, others have identified the reactivation of faults in a normal sense elsewhere throughout New England (Roden-Tice and Wintsch, 2002; West and Roden-Tice, 2003; Roden-Tice and Tice, 2005; Roden-Tice et al., 2009), which Roden-Tice et

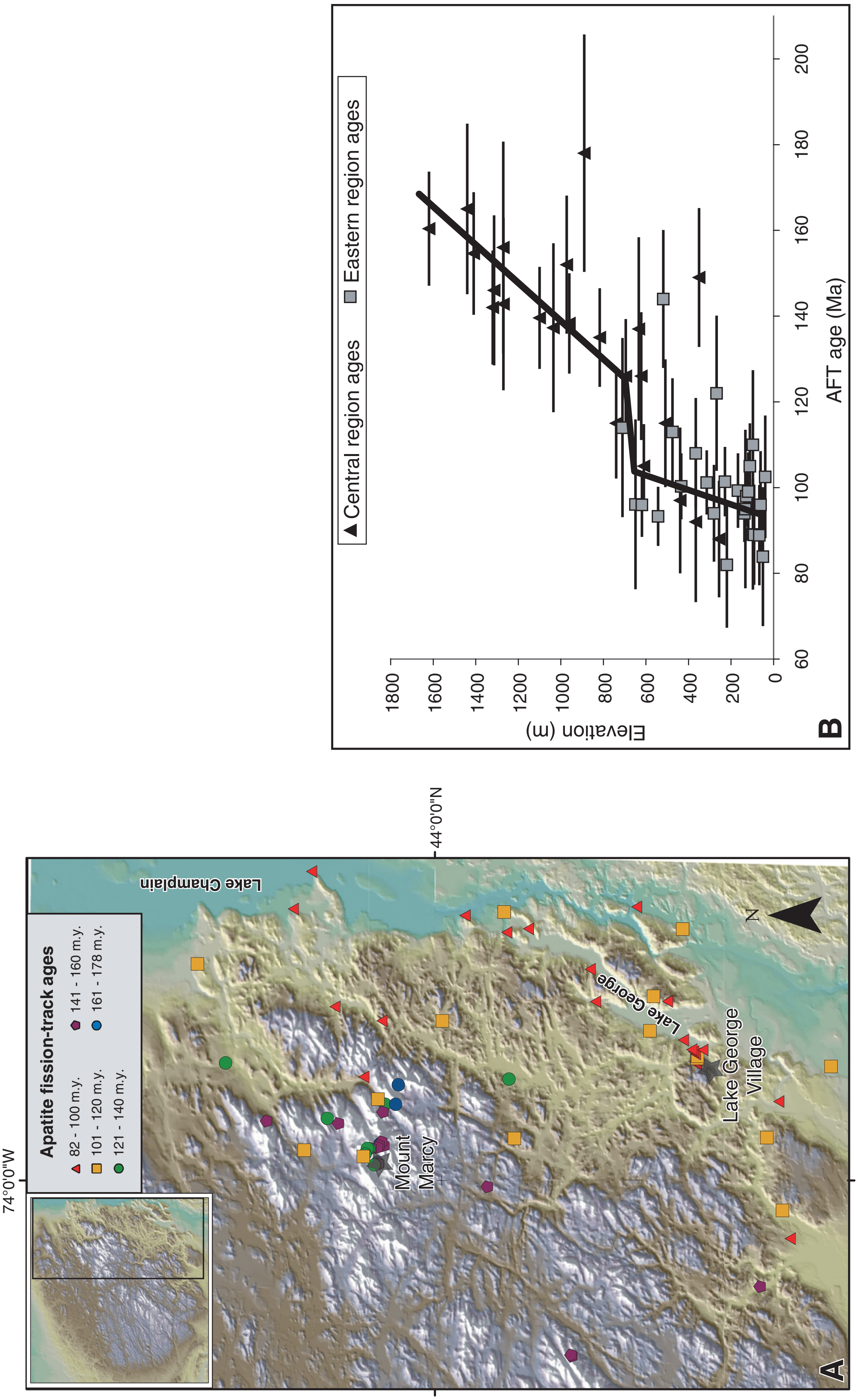

Figure 10. (A) Digital elevation model of the Adirondack Mountains with apatite fission-track (AFT) ages. Ages are from Roden-Tice and Tice (2005) and this study. (B) Regional AFT ages from map A plotted against elevation.

al. (2009) proposed were activated by NW-SE–oriented extension (Faure et al., 1996) driven by a long-lived thermal anomaly produced by passage over the Great Meteor hotspot. Therefore, it is plausible that thermal doming caused N-NNE–striking faults along the Lake George and Champlain Valleys to be reactivated in a normal sense, producing a drop in base level along the eastern edge of the Adirondacks and causing the resultant fault scarp to undergo down-wearing or retreat. The high-grade gneisses and plutonic rocks of the Adirondacks, being more erosion resistant than surrounding rock types, may have remained relatively high because of their lower erodibility. Our data are consistent with slow cooling and prolonged denudation, and the formation of relief following passage near the hotspot, as some thermal models support slow sustained cooling after the Middle Cretaceous, followed by a possible increase in cooling rate during the Miocene. We note that possible late Cenozoic cooling must be interpreted with caution because it is at the limit of the AFT and AHe modeling capabilities. More work is needed to confirm any Cenozoic increase in cooling rate; however, it is reasonable to consider an increase in cooling rate during the Cenozoic (suggesting increased erosion rates associated with the formation of relief) as a strong possibility, as others have suggested a Miocene rejuvenation of relief in the adjacent Central and Northern Appalachians (e.g., Pazzaglia and Brandon, 1996).

Factors that influenced erosion and the development of relief in the Adirondacks subsequent to rifting and passage near the hotspot include: changes in base level due to faulting or changes in global sea level, and glacial erosion. A general global decrease in sea level during the Cenozoic (e.g., Haq et al., 1987; Stanford et al., 2001) may have contributed to a base-level drop of ~150–100 m. Additionally, multiple glaciations during the Quaternary, resulting in glacial scouring (e.g., Denny, 1974), episodes of catastrophic outflow from glacial lakes, and changes in local base level due to variations in lake level during late to postglacial times could all have made minor contributions to renewed relief within the eastern Adirondacks and adjacent Champlain Valley. Dissection during regional surface uplift and thermal doming by a more recent hotspot, as suggested by Isachsen and colleagues (Isachsen, 1975, 1981; Isachsen and Kelly, 1992), would also have contributed to the formation of the present relief. We reiterate that the presence of a Cenozoic hotspot under the Adirondacks is controversial and remains to be substantiated.

The Adirondack Mountains share many characteristics with the Ozark Plateau of Missouri and Arkansas, the commonality of which may place constraints on the formation of each region. The Ozark Plateau presently lies in a tectonically quiescent region and has ~600 m of relief with Precambrian basement juxtaposed against younger sedimentary rocks (Marshak et al., 2005). The present bedrock surface has remained near upper-crustal levels since the Neoproterozoic while the Ozarks experienced periodic episodes of burial and exhumation, underwent late Paleozoic shortening, as well as passed over a hotspot during the Cretaceous, as recorded in the regional low-temperature thermal history (e.g., Corrigan et al., 1998; Brown and Marshak, 2004; Marshak et al., 2005). Analysis of stream incision throughout the Ozark Plateau suggests renewed relief development during the Cenozoic (Marshak et al., 2005).

Marshak et al. (2005) suggested that the Ozark Plateau started to form in the Late Proterozoic to early Paleozoic when the buoyant Precambrian felsic intrusions that comprise the core of the region were brought to upper-crustal levels as a fault-bounded block. Due to its buoyancy, this block remained in the upper crust, with periodic episodes of exhumation and relief formation in response to Cretaceous hotspot–induced doming (forming and reactivating normal faults), as well as loading and unloading along its margins resulting in changes in local base level (Marshak et al., 2005). The hypothesis of Marshak et al. (2005) may be applicable to periodic relief rejuvenation in the Adirondacks. The high-grade core of the Adirondack Mountains is largely composed of meta-plutonic rocks of intermediate to felsic composition, and it was exposed at the surface by the latest Precambrian, subsequent to which it experienced numerous episodes of burial and exhumation throughout the Paleozoic and Mesozoic (e.g., Heizler and Harrison, 1998), with the low-temperature thermochronology data presented in this paper highlighting the Mesozoic–Cenozoic portion.

CONCLUSIONS

Low-temperature thermochronology in the eastern Adirondack Mountains documents relatively stable thermal and tectonic conditions from the Middle–Late Jurassic (ca. 160 Ma) to the Early Cretaceous (ca. 130 Ma), as evidenced by the gentle AFT age versus elevation slope of the Mount Marcy profile in the central-eastern Adirondack Mountains. This time of relative thermal and tectonic stability was interrupted by the passage of this region near the Great Meteor hotspot during the Early Cretaceous. Passage near the hotspot steepened the geotherm, partially resetting fission tracks in the lowermost Mount Marcy samples, and shallowing the lowermost portion of the Mount Marcy age-elevation profile. Using the overlap of the Mount Marcy AFT and AHe profiles, the elevated geothermal gradient in the Early Cretaceous (ca. 130–120 Ma) is estimated at ~60–38 °C/km. Regional heating resulted in thermal doming (possibly due to delamination of a portion of the mantle lithosphere) and surface uplift, with subsequent increased erosion producing a period of elevated cooling rates starting ca. 105 Ma. Elevated cooling rates continued following passage over the hotspot as isotherms relaxed back to their initial state and the region returned back to relatively stable cratonic conditions. AFT ages across the eastern Adirondack Mountains do not show any significant exhumation gradient. Rather, the general AFT age elevation pattern across the eastern Adirondacks suggests that relief formed through the progressive dissection of a plateau during the Cretaceous to Cenozoic.

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