Evidence for Differential Unroofing in the Adirondack Mountains, New York State, Determined by Apatite Fission-Track Thermochronology

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ABSTRACT

Apatite fission-track ages of 168–83 Ma for 39 samples of Proterozoic crystalline rocks, three samples of Cambrian Potsdam sandstone, and one Cretaceous lamprophyre dike from the Adirondack Mountains in New York State indicate that unroofing in this region occurred from Late Jurassic through Early Cretaceous. Samples from the High Peaks section of the Adirondack massif yielded the oldest apatite fission-track ages (168–135 Ma), indicating that it was exhumed first. Unroofing along the northern, northwestern, and southwestern margins of the Adirondacks began slightly later, as shown by younger apatite fission-track ages (146–114 Ma) determined for these rocks. This delay in exhumation may have resulted from burial of the peripheral regions by sediment shed from the High Peaks. Apatite fission-track ages for samples from the southeastern Adirondacks are distinctly younger (112–83 Ma) than those determined for the rest of the Adirondack region. These younger apatite fission-track ages are from a section of the Adirondacks dissected by shear zones and post-Ordovician north-northeast-trending normal faults. Differential unroofing may have been accommodated by reactivation of the faults in a reverse sense of motion with maximum compressive stress, σ_1, oriented west-northwest. A change in the orientation of the post–Early Cretaceous paleostress field is supported by a change in the trend of Cretaceous lamprophyre dikes from east-west to west-northwest.

Introduction

The Adirondack Mountains are an elongate domelike exposure of Grenville (ca. 1.0–1.35 Ga; McLelland et al. 1988; McLelland and Chiarenzelli 1990; Mezger et al. 1991; McLelland et al. 1996) high-grade metamorphic rocks in northern New York State (fig. 1; Isachsen and Fisher 1970; McLelland and Isachsen 1986). On the basis of structure and physiography, the Adirondack Mountains can be divided into two regions: (1) the northwest Lowlands, which are composed mainly of metasedimentary rocks and are continuous with the larger area of Grenville-age rocks across the Frontenac Arch in southern Ontario (McLelland and Isachsen 1986; Mezger et al. 1991), and (2) the Adirondack Highlands, which consist of granulite-facies metaplutonic rocks and metasediments (McLelland and Isachsen 1986).

Isachsen (1975) considered the Adirondack Mountains to be an anomalous feature on the eastern North American craton because of their comparatively large areal extent (~27,000 km^2) and present high elevation (up to 1600 m) compared with other uplifted areas on the craton. The Paleozoic unroofing history of the Adirondack region has been studied through subsurface mapping based on drill core data (Rickard 1969, 1973). Isopach maps for Cambrian through Early Ordovician strata (Rickard 1973) and the presence of Paleozoic inliers near Piseco Lake and the Sacandaga River (Fisher et al. 1970) indicate sedimentation in the Adirondack region during this time. A period of brief uplift in the Early Ordovician was followed by burial during the Middle Ordovician (Rickard 1973). Isopachs for Silurian and Devonian strata (Rickard 1969, 1973) showed north-northeasterly trends abruptly terminated at the southern border of the Adirondack massif, suggesting that the isopachs originally crossed the Adirondacks during these times. This evidence and the occurrence of several down-

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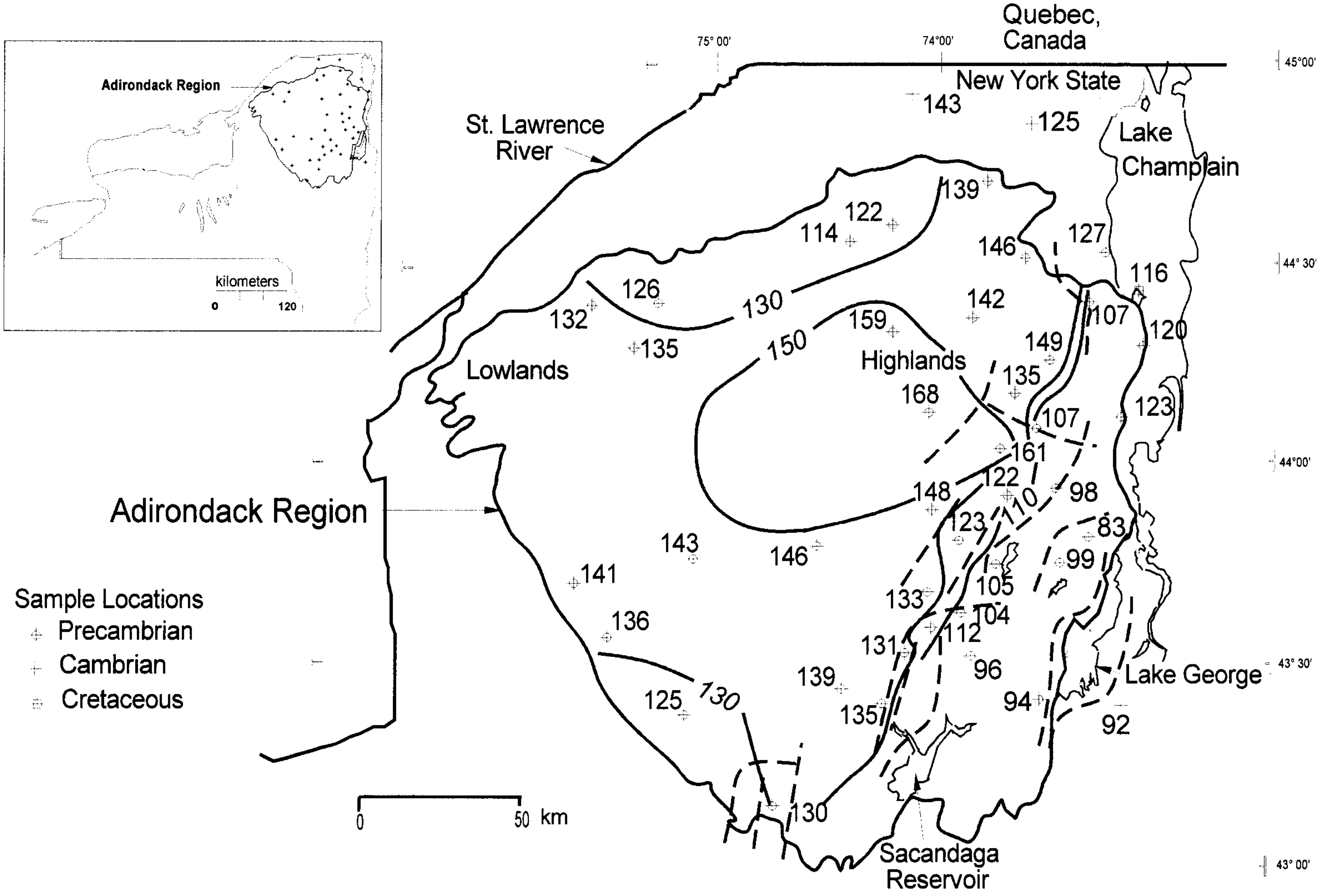

Figure 1. Apatite fission-track ages in Ma for samples from the Adirondack region contoured to highlight fission-track age trends. Standard error is ±10% of fission-track age. Mapped normal faults, shear zones, and lineaments are indicated by dashed lines. Key for symbols for Precambrian, Cambrian, and Cretaceous samples is given on the map. The inset shows a location map for the Adirondack region and fission-track samples in New York State.

dropped Paleozoic fault blocks within the south central Adirondacks indicates a post-Devonian uplift for the Adirondack Mountains.

Heitzler and Harrison (1998) presented $^{40}Ar/^{39}Ar$ K-feldspar ages for the Adirondack region that suggest localized reheating in the eastern Adirondacks during the Ordovician. Their data indicate that this reheating may result from the combined effects of burial and hot fluid migration along normal faults in the eastern Adirondacks during the Taconic orogeny. In addition, $^{40}Ar/^{39}Ar$ K-feldspar ages from the crystalline basement in eastern Adirondacks (Heitzler and Harrison 1998) are consistent with studies that suggest Carboniferous burial in eastern New York (Harris et al. 1978; Friedman and Sanders 1982; Johnsson 1986; Miller and Duddy 1989).

Preliminary apatite fission-track (AFT) ages ranging from 147 to 86 Ma determined by Miller and Lakatos (1983) indicated an Early Cretaceous unroofing history for the Adirondack region. In addition, Isachsen (1975, 1981) has presented controversial evidence for a recent and ongoing rapid uplift rate of ~2–3 mm/yr in the Adirondacks. This conclusion is based largely on the results of optical resurveys of survey lines across the eastern and central Adirondacks from Saratoga to Rouses Point (1973) and Utica to Fort Covington (1981). Inferred Quaternary neotectonic activity (Isachsen 1975, 1981) is supported by the observation of offset boreholes (Fox et al. 1999) and historical low-magnitude (3.4–5.3) seismicity in the central and northern Adirondack regions (Sbar and Sykes 1973, 1977; Seeber and Armbruster 1989; Revetta et al. 1999).

The potential for active uplift in the Adirondack area prompted a reexamination and expansion of the known Mesozoic unroofing history using AFT ages as a baseline for the ancient uplift. This study presents AFT ages from Proterozoic crystalline rocks, Cambrian Potsdam sandstone, and a Cretaceous lamprophyre dike that suggest differential unroofing occurred in the Adirondack region during the Late Jurassic to Late Cretaceous (fig. 1; table 1).

Methods

Apatite for fission-track analyses was isolated by standard heavy liquid and magnetic separation techniques after disaggregation from 2–3-kg samples. Sample preparation procedures for AFT age and track-length measurements are described by Gleadow (1984). The external detector method was used for AFT age determinations. Small aliquots, 10–20 mg of apatite, were mounted in epoxy on glass slides and polished to expose internal grain surfaces. Spontaneous fission tracks in apatite were revealed by etching for 20 s in 5M HNO_3 at 21°C. The samples were irradiated at the Oregon State University TRIGA reactor, using a nominal flux of 8×10^{15} n/cm^2 for apatite. The neutron flux was monitored by CN1 dosimeter glasses at the top and bottom of the irradiation tube. The Cd ratio (relative to an Au monitor) for this reactor is 14, indicating that the reactor is well thermalized (Green and Hurford 1984).

Fission-track ages were calculated using a weighted mean ζ calibration factor (Hurford and Green 1983) based on Fish Canyon Tuff, Durango, and Mount Dromedary apatite standards (Miller et al. 1985). The following ζ factors were used in the AFT age calculations (names in parentheses are the research assistants responsible for ascertaining the preceding ζ factor): 103.4 ± 2.3 (M. Roden-Tice), 98.3 ± 4.7 (I. Schofield), 88.7 ± 6.5 (R. Sents), 87.1 ± 5.0 (D. Michaud), and 140.7 ± 8.0 (P. Rabideau). The ζ used for each age determination is indicated on table 1. The central age was calculated according to Galbraith and Laslett (1993), using the χ^2 method of Brandon (1992). The AFT age determinations and track-length measurements were made dry on an Olympus BMAX 60 microscope at ×1600. This microscope is equipped with a drawing tube for length measurements, which are digitized on a Cal Comp Model 31120 Drawing Slate that is interfaced with a 386 Zenith PC computer. Table 1 lists the number of track lengths measured in each analysis.

Apatite Fission-Track Results. Apatite fission-track thermochronology has become a standard technique for investigating thermal and burial histories of sedimentary basins (Miller and Duddy 1989; Ravenhurst et al. 1994; Carter et al. 1998) and the unroofing histories of ancient (Crowley 1991; Corrigan et al. 1998) and active orogens (Blythe and Kleinspehn 1998; Brandon et al. 1998). Apatite fission-track analysis includes both the determining of an AFT age and the modeling of time-temperature histories based on the measured fission-track-length distributions. The fission-track technique is based on the formation of damage zones resulting from the spontaneous fission of naturally occurring ^{238}U in U-bearing minerals such as apatite. Fission tracks are retained in apatite below a closure temperature of 100° ± 20°C (Wagner 1968; Naeser and Faul 1969; Naeser 1981). If apatite grains are heated above their closure temperature for times on the order of 1 m.yr., then all existing fission tracks will be annealed, and the fission-track age will be reset. In the case of complete annealing, the AFT age provides a cooling age re-

Table 1. Apatite Fission-Track Data for the Adirondack Region, New York

Locality	AFT age (Ma)	±95% confidence interval	Number of grains	U (ppm)	Mean track length (μm)	Standard deviation (μm)	Number of tracks	Latitude/ longitude	Region
Mount Marcy	168.1	+19.9/−17.8	19	16.3	13.1 ± .2	2.0	70	44.12/73.92	HP
Dix[a]	161.1	+24.2/−21.1	20	18.3	13.7 ± .1	1.1	88	44.08/73.79	HP
Blue Mountain Lake	146.0	+16.3/−14.7	20	48.5	13.0 ± .2	1.5	97	43.87/74.43	HP
Whiteface	141.8	+15.8/−14.2	20	66.6	13.2 ± .1	1.5	102	44.37/73.87	HP
Van der Wacker	148.3	+17.6/−15.7	20	16.0	ND	…	…	43.90/74.09	HP
Hurricane	149.4	+15.9/−14.4	20	58.1	13.5 ± .2	1.6	105	44.24/73.70	HP
Saranac Lake[b]	158.5	+40.1/−32.1	20	10.0	ND	…	…	44.27/74.36	HP
Giant[a]	134.5	+28.7/−23.7	10	15.9	ND	…	…	44.16/73.70	HP
North Fork Boquet[a]	106.8	+17.0/−14.7	10	21.1	13.0 ± .1	1.3	76	44.11/73.69	SE
Lyon Mountain	138.7	+13.5/−12.3	20	76.2	13.2 ± .1	1.1	102	44.71/73.87	N
Terry Mountain	145.6	+13.1/−12.0	20	56.1	ND	…	…	44.57/73.63	N
Vermontville	114.2	+21.7/−18.2	10	31.1	ND	…	…	44.55/74.05	N
Alder Brook	122.2	+11.7/−10.7	20	33.5	ND	…	…	44.45/74.07	N
Altona Flatrock (ss)	124.5	+17.5/−15.4	15	24.1	13.7 ± .2	1.4	61	44.86/73.67	N
Chateguay (ss)	143.2	+21.4/−18.6	20	22.0	ND	…	…	43.93/75.38	N
Kents Corners	131.5	+20.8/−18.0	15	20.1	13.0 ± .2	1.7	102	44.44/75.30	NW
Clifton	126.4	+22.7/−19.3	12	68.2	ND	…	…	44.23/74.78	NW
Fine	135.2	+12.8/−11.7	20	56.3	ND	…	…	44.25/75.14	NW
Port Leyden	135.9	+15.1/−13.6	20	16.4	13.0 ± .2	1.5	94	43.59/75.84	SW
Brantingham Lake	140.7	+17.9/−15.9	12	77.3	ND	…	…	43.69/75.3	SW
Hinckley Reservoir	125.2	+13.2/−11.9	20	43.1	13.6 ± .1	1.0	100	43.36/75.04	SW
Old Forge	143.1	+15.8/−14.3	20	40.2	ND	…	…	43.71/74.97	SW
Little Falls	130.1	+12.9/−11.7	20	50.1	12.5 ± .1	1.5	101	43.04/74.86	SW
Lake Pleasant	138.8	+17.2/−15.3	20	26.1	ND	…	…	43.48/74.4	SW
Gilmantown[a]	135.2	+17.5/−15.5	20	65.8	ND	…	…	43.43/74.31	SW
Moose Mountain	130.8	+14.5/−13.1	20	24.3	ND	…	…	43.50/74.31	SW
North Creek	132.5	+19.2/−16.8	21	36.6	ND	…	…	43.68/73.99	SC
Minerva[a]	122.9	+18.2/−15.9	19	22.8	ND	…	…	43.81/74.01	SC
Baker Brook	112.4	+14.3/−12.7	20	32.6	ND	…	…	43.60/74.06	SE
Johnsburg[c]	104.1	+18.8/−15.9	19	39.3	ND	…	…	43.62/73.96	SE
Pharaoh Mountain[d]	98.5	+14.8/−12.9	20	46.4	ND	…	…	43.82/73.65	SE
Crane Mountain	96.1	+12.5/−11.1	20	40.0	ND	…	…	43.54/73.65	SE
Fort Ann (ss)	91.9	+12.2/−11.2	20	19.5	ND	…	…	43.41/73.52	SE
Lake George	93.9	+9.4/−8.6	20	64.3	13.6 ± .1	1.3	101	43.4/73.71	SE
Ticonderoga	82.7	+12.5/−10.9	15	16.2	13.5 ± .1	.8	62	43.85/73.59	SE
Schroon Lake	104.5	+11.7/−10.5	20	38.0	13.3 ± .1	1.3	80	43.79/73.79	SE
North Hudson	98.1	+11.4/−10.2	20	29.3	ND	…	…	43.95/73.74	SE
Blue Ridge	121.5	+14.3/−12.8	20	16.9	ND	…	…	43.96/73.78	SE
Craig Harbor	123.2	+13.5/−12.2	20	36.2	14.0 ± .1	1.4	99	44.05/73.46	E
Split Rock Point	119.6	+12.8/−11.6	20	71.3	13.7 ± .1	1.4	103	44.27/73.32	E
Willsboro Dike (l)	115.5	+20.7/−17.6	20	11.0	ND	…	…	44.45/73.38	E
Mount Trembleau	127.0	+14.4/−12.9	18	54.7	ND	…	…	44.01/73.40	E
Poke-O-Moonshine	106.7	+12.9/−11.6	17	91.3	13.3 ± .1	.9	40	44.40/73.52	E

Note. Apatite FT ages given as central ages (Galbraith and Laslett 1993). $\zeta = 103.4 \pm 2.3$ for CN1 glass (MR-T) except for samples with footnotes a, b, c, and d. ND = not determined. Lamprophyre and sandstone are designated by (l) and (ss), respectively. Adirondack regions are indicated by HP (High Peaks), SE (southeast), N (north), NW (northwest), SW (southwest), SC (south central), and E (east).

[a] $\zeta = 98.3 \pm 4.7$; I. Schofield, undergraduate assistant.

[b] $\zeta = 140.8 \pm 8.0$; P. Rabideau, undergraduate assistant.

[c] $\zeta = 88.7 \pm 6.5$; R. Sents, undergraduate assistant.

[d] $\zeta = 87.1 \pm 5.0$; D. Michaud, undergraduate assistant.

cording the time the rock containing the apatite passed through its closure temperature. For the most common type of apatite, F-rich apatite, the temperature range of ~60°–100°C is referred to as the partial annealing zone, or PAZ. By assuming a geothermal gradient and a surface temperature, the apatite PAZ can be used to infer burial depth and the magnitude of denudation (Brown 1991; Brandon et al. 1998).

Confined track-length measurements in apatite, combined with the AFT age, help constrain the cooling history of a rock below 100°C. Track-length distributions for apatite from rapidly cooled rocks, such as volcanics, yield characteristic long mean track lengths and small standard deviations ranging from 14 to 15 (±0.8–1.3) μm (Gleadow et al. 1986). In contrast, apatite from rocks that have cooled slowly through the apatite PAZ will yield shorter mean track lengths and larger standard deviations in the range of 12–14 (±1–2) μm (Gleadow et al. 1986). Experimental annealing studies of fission tracks in apatite (Laslett et al. 1987; Carlson 1990; Crowley et al. 1991) have yielded the basis for algorithms used to calculate model thermal histories for samples within the apatite PAZ (Green et al. 1989; Crowley 1993; Issler 1996). An AFT age and track-length distribution can be used to constrain the low-temperature portion of the rock's thermal history by calculating model time-temperature paths from the rock's cooling age to the present.

Miller and Lakatos (1983) determined AFT ages ranging between 147 and 86 Ma for five anorthosite samples from the Adirondacks, three from the High Peaks region, and two (one surface and one drill core) from Wadhams in the Lake Champlain lowlands. This study determined AFT ages for 39 samples of Proterozoic gneisses, anorthosites, and metasediments; three samples of Cambrian Potsdam sandstone; and one sample of an Early Cretaceous lamprophyre dike from throughout the Adirondack region (fig. 1; table 1). This geographically widespread survey was done to expose any areas of differential uplift/unroofing within the Adirondacks.

The AFT ages determined in this study range from 168 to 83 Ma, with a standard error of ~±10% of the FT age (fig. 1; table 1). The High Peaks and central portion of the Adirondack Mountains yielded the oldest AFT ages, 168–135 Ma, suggesting that this region was unroofed earliest, beginning in the Middle Jurassic and extending into the Early Cretaceous (fig. 1; table 1). Confined track-length measurements for five samples from the central High Peaks region yielded mean track lengths ranging from 13.0 to 13.7 μm and standard deviations of 1.1–2.0 μm (table 1). Mount Marcy, the highest peak, with an elevation of 1710 m, gave the oldest AFT age of 168 Ma (fig. 1; table 1) and a negatively skewed track-length distribution with a distinct tail of short tracks (i.e., <10 μm; fig. 2*a*), indicating slow cooling through the apatite PAZ. Whiteface (1460 m) and Dix Mountains (1457 m), the fifth and sixth highest summits in the Adirondack anorthosite massif, also yielded Middle to Late Jurassic cooling ages, 142 and 161 Ma, respectively (fig. 1; table 1). The track-length distribution for Whiteface Mountain yielded a similar mean track length and standard deviation to that for Mount Marcy (13.1 ± 2.0 and ±1.5 μm, respectively; fig. 2*b*; table 1). Dix Mountain gave a longer mean track length (13.7 μm) and smaller standard deviation (1.1 μm) than the other High Peak samples (table 1). These data suggest that Dix Mountain spent a shorter residence time in the apatite PAZ compared with the other High Peak samples.

In the northwest Adirondack lowlands, three samples of Proterozoic gneiss yielded slightly younger AFT ages, 126–135 Ma, than those from the central High Peaks region (fig. 1; table 1). Apatite yields from the west-central Adirondacks were poor, and no AFT ages could be determined for samples from this area. Samples from along the southwestern margin of the Adirondack massif gave a range in AFT ages from 125 Ma for a metasedimentary sample at Hinckley Reservoir to 141 Ma for a nelsonite at Port Leyden (fig. 1; table 1). North of the High Peaks region, the AFT ages decrease slightly, ranging from 114 Ma near Vermontville to 146 Ma at Terry Mountain (fig. 1; table 1). Two samples of Cambrian Potsdam sandstone from north of the Adirondack area yielded comparable AFT ages to those determined for the crystalline rocks, 125 and 143 Ma (fig. 1; table 1). All of the AFT ages determined for samples from areas north, northwest, and southwest surrounding the central High Peaks are consistent with unroofing during the Early Cretaceous (fig. 1; table 1).

Track-length distributions for samples from the peripheral regions of the Adirondacks, Kents Corners, Hinckley Reservoir, Little Falls, and Lyon Mountain yielded mean track lengths of 12.5–13.6 μm and standard deviations of 1.1–1.7 μm (fig. 3*a*, 3*b*; fig. 4*a*, 4*b*; table 1). Most of these track-length distributions (e.g., Little Falls: fig. 4*a*; table 1), suggest slow cooling and prolonged residence in the apatite PAZ. The sample from Hinckley Reservoir, which is located along the southwestern border of the Adirondack crystalline terrane, yielded a longer mean track length of 13.6 μm and a smaller standard deviation of 1.0 μm than the other samples (fig. 3*b*; table 1). These results suggest that the Hinckley Reservoir sample experienced a slightly different cooling history from the others, including less time spent in the apatite PAZ.

Distinctly younger AFT ages, 112–83 Ma, were determined for samples from the southeastern Adirondacks, including the summits of Pharaoh Mountain (767 m, 99 Ma) and Crane Mountain (966 m, 96 Ma) and samples from lower elevations as far east as Fort Ann (92 Ma; fig. 1; table 1). This part of the Adirondack massif is cut by numerous north-northeast-trending high-angle normal faults, shear zones, and lineaments (Isachsen and Fisher 1970), including the graben containing Lake George

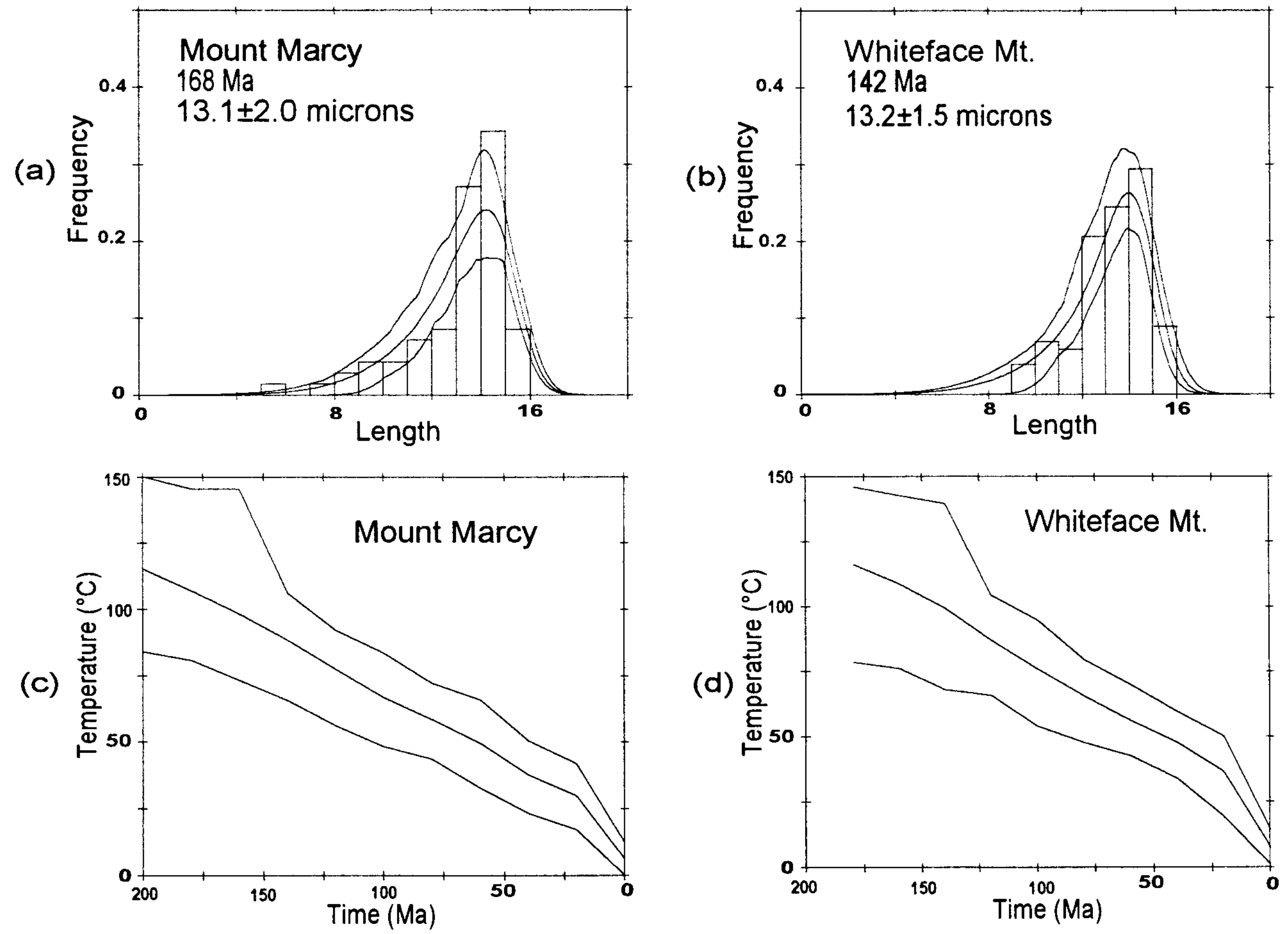

Figure 2. Measured (histogram) and calculated (curve) apatite fission-track-length distributions at the 0.05 level, using AFTINV32 (Issler 1996) for samples from the Adirondack High Peaks region: *a*, Mount Marcy; *b*, Whiteface Mountain. Model thermal history at 0.05 level using Crowley et al. (1991) annealing model and AFTINV32 (Issler 1996) for samples from the Adirondack High Peaks region: *c*, Mount Marcy; *d*, Whiteface Mountain.

and Schroon Lake (fig. 1). Samples, from opposite sides of mapped faults or shear zones that yielded offset AFT ages, include Baker Brook (112 Ma)/Moose Mountain (131 Ma) and North Hudson (98 Ma)/Blue Ridge (122 Ma; fig. 1; table 1), with the younger age occurring on the eastern side of the faults. Although these AFT ages overlap within 1σ error, all of the AFT ages in the southeastern Adirondacks are ≤112 Ma, indicating a regional trend of young AFT ages (fig. 1; table 1).

Samples from the southeastern section of the Adirondacks (e.g., Lake George and Schroon Lake) that yielded the youngest AFT ages gave short mean track lengths, 13.3–13.6 μm, and small standard deviations, 0.8–1.3 μm (fig. 5*a*, 5*b*; table 1). These track-length distributions suggest a relatively short time spent in the apatite PAZ (~60°–100°C).

Thermal History Models. Model time-temperature histories were calculated for eight Adirondack samples, using measured track-length data, the Crowley et al. (1991) six-parameter annealing equation for Durango apatite, and the inverse model of Issler (1996). The inverse model, AFTINV32, generates a set of random forward-model thermal solutions that are used to calculate apatite fission-track age and length parameters to compare with the measured data (Issler 1996). Observed track-length distributions are compared with the predicted cumulative track-length distributions by using the Kolomogorov-Smirnov statistic at the 0.05 significance level. The predicted fission-track ages are required to be within two standard deviations of the measured age.

In this study, we chose to use coefficients for Durango apatite (Crowley et al. 1991) to solve the

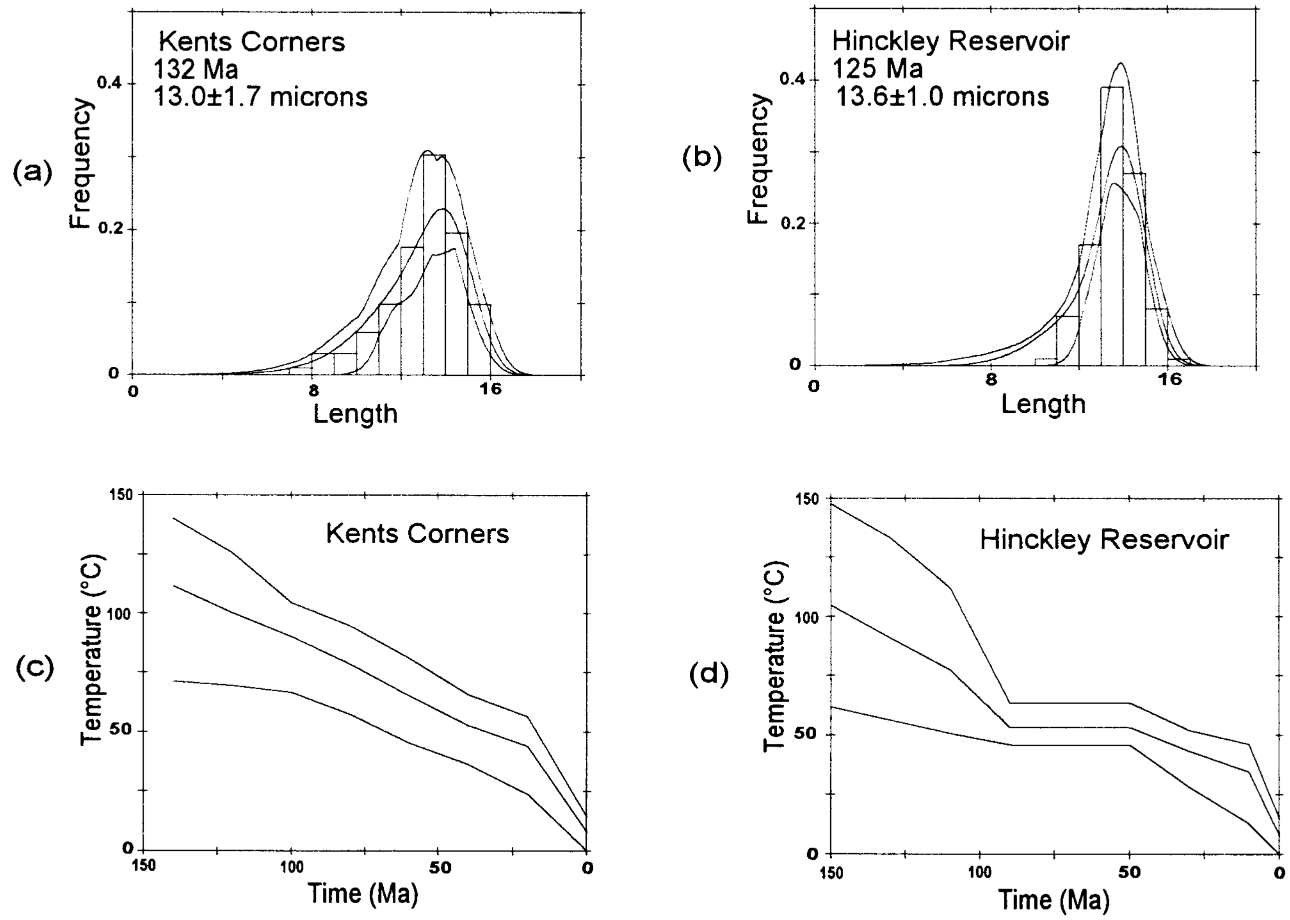

Figure 3. Measured (histogram) and calculated (curve) apatite fission-track-length distributions at the 0.05 level using AFTINV32 (Issler 1996) for samples from the northwestern and southwestern Adirondack regions: *a*, Kents Corners; *b*, Hinckley Reservoir. Model thermal history at 0.05 level using Crowley et al. (1991) annealing model and AFTINV32 (Issler 1996) for samples from the northwestern and southwestern Adirondack regions: *c*, Kents Corners; *d*, Hinckley Reservoir.

empirical apatite fission-track-annealing equation of Crowley et al. (1991) in the AFTINV32 model. Funding was not available for compositional analysis of the Adirondack apatites by electron microprobe. On the basis of etch pit size and appearance, it was qualitatively assumed that the apatites in our samples were F rich and similar to Durango in composition (Crowley et al. 1991). In the southeastern Adirondacks, where the youngest AFT ages are found, we sampled a variety of rock types including anorthosite, metasedimentary rocks, charnockitic and granitic gneisses, and amphibolites. Because the AFT ages from all these different rock types are within the 112–83 Ma age range, we suggest that compositional variation of the apatites is not a cause of AFT age variation in the Adirondacks. Further evidence against compositional variation being a factor in Adirondack AFT age differences is shown in the comparison of the AFT ages for Mount Marcy (168 Ma) and North Hudson (98 Ma; fig. 1; table 1), both of which are from anorthosite samples.

Figures 2–5 show comparisons of the fit of the measured track-length histograms and calculated track-length distributions (probability density functions) for the preferred thermal history calculated by the model. Each figure also gives a plot of the exponential mean (preferred) thermal solution plus the bounding temperature envelopes containing all statistically acceptable solutions. The preferred thermal solution is the middle line on the time-temperature plot, and the top and bottom lines represent the limits of acceptable solutions (fig. 2*c*, 2*d*; fig. 3*c*, 3*d*; fig. 4*c*, 4*d*; fig. 5*c*, 5*d*). The

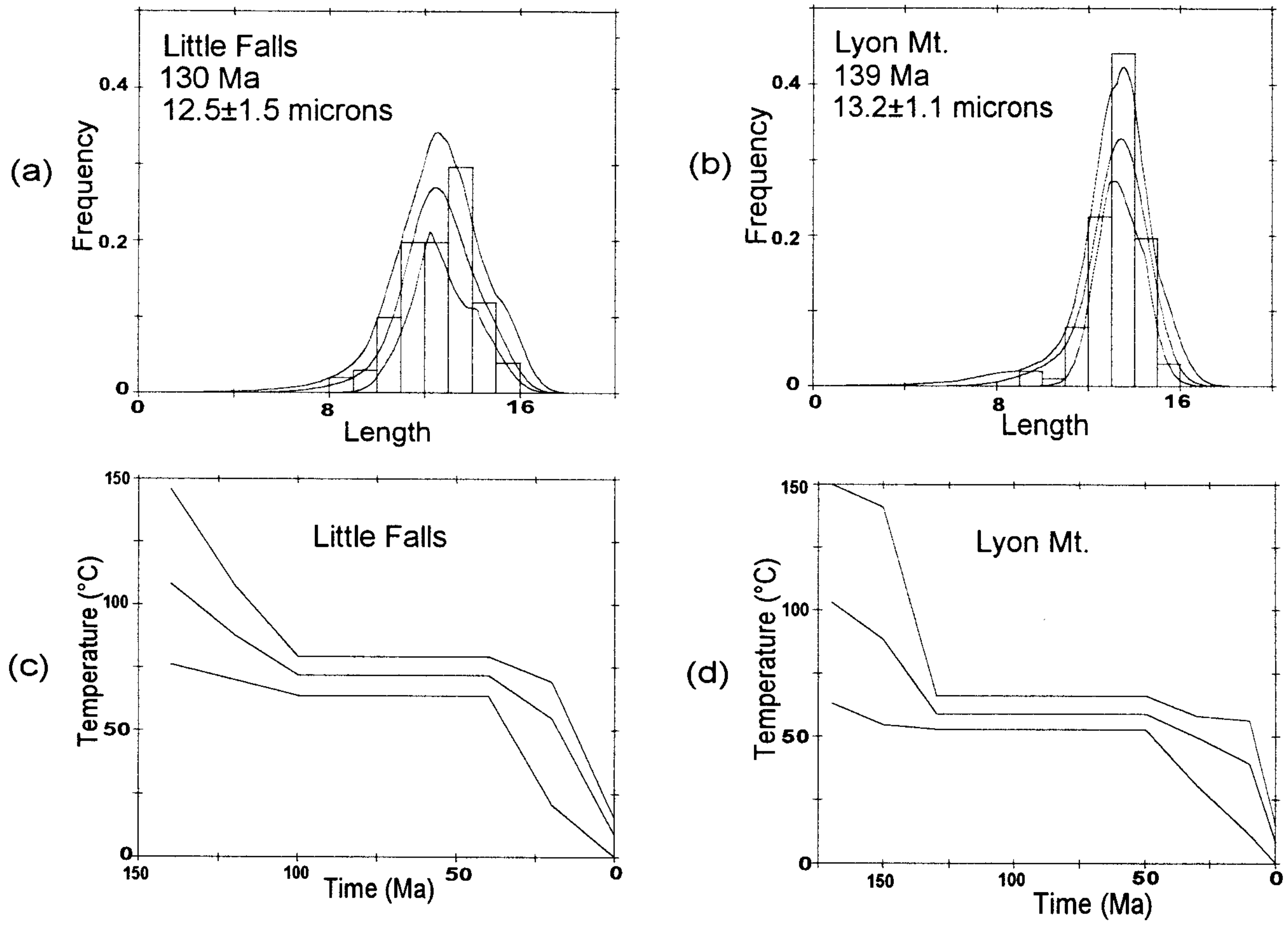

Figure 4. Measured (histogram) and calculated (curve) apatite fission-track-length distributions at the 0.05 level using AFTINV32 (Issler 1996) for samples from the southern and northern Adirondack regions: *a*, Little Falls; *b*, Lyon Mountain. Model thermal history at 0.05 level using Crowley et al. (1991) annealing model and AFTINV32 (Issler 1996) for samples from southern and northern Adirondack regions: *c*, Little Falls; *d*, Lyon Mountain.

corresponding calculated track-length distribution for the mean temperature solution is the middle curve on the calculated track-length plot, and the top and bottom curves indicate the range of acceptable track-length distributions (fig. 2*a*, 2*b*; fig. 3*a*, 3*b*; fig. 4*a*, 4*b*; fig. 5*a*, 5*b*).

The thermal history models for all of the Adirondack samples show a period of relatively rapid unroofing, 0.8°C/m.yr., from ~20–25 Ma to the present (figs. 2, 3, 4, 5). This period of rapid Miocene and younger cooling has been interpreted to be the result of the extrapolation of short-time-duration (<1 yr) laboratory annealing experiments, on which the equations are based, to geologic time scales. Some authors, including Blackmer et al. (1994) and Boettcher and Milliken (1994), have suggested that this period of possible Miocene exhumation may be evidence for a major unroofing event in the Tertiary. These hypotheses are beyond the scope of our present investigation and will not be discussed in this article.

Best-fit preferred thermal model solutions were determined for High Peaks region samples from Mount Marcy, 168 Ma, and Whiteface Mountain, 142 Ma, (fig. 1) by using a cooling-only thermal history (fig. 2*a*–2*d*). The model yielded an average cooling rate of ~0.6°C/m.yr. from 200–180 Ma to the present. The mean thermal history solution suggests continuous slow unroofing for the central High Peaks region of the Adirondack massif since Late Jurassic time.

The sample from Kents Corners, 132 Ma, in the northwestern Adirondack Lowlands (fig. 1) was used to model the time-temperature history for that region. As for the High Peaks samples, a cooling-only thermal history is the preferred model for the

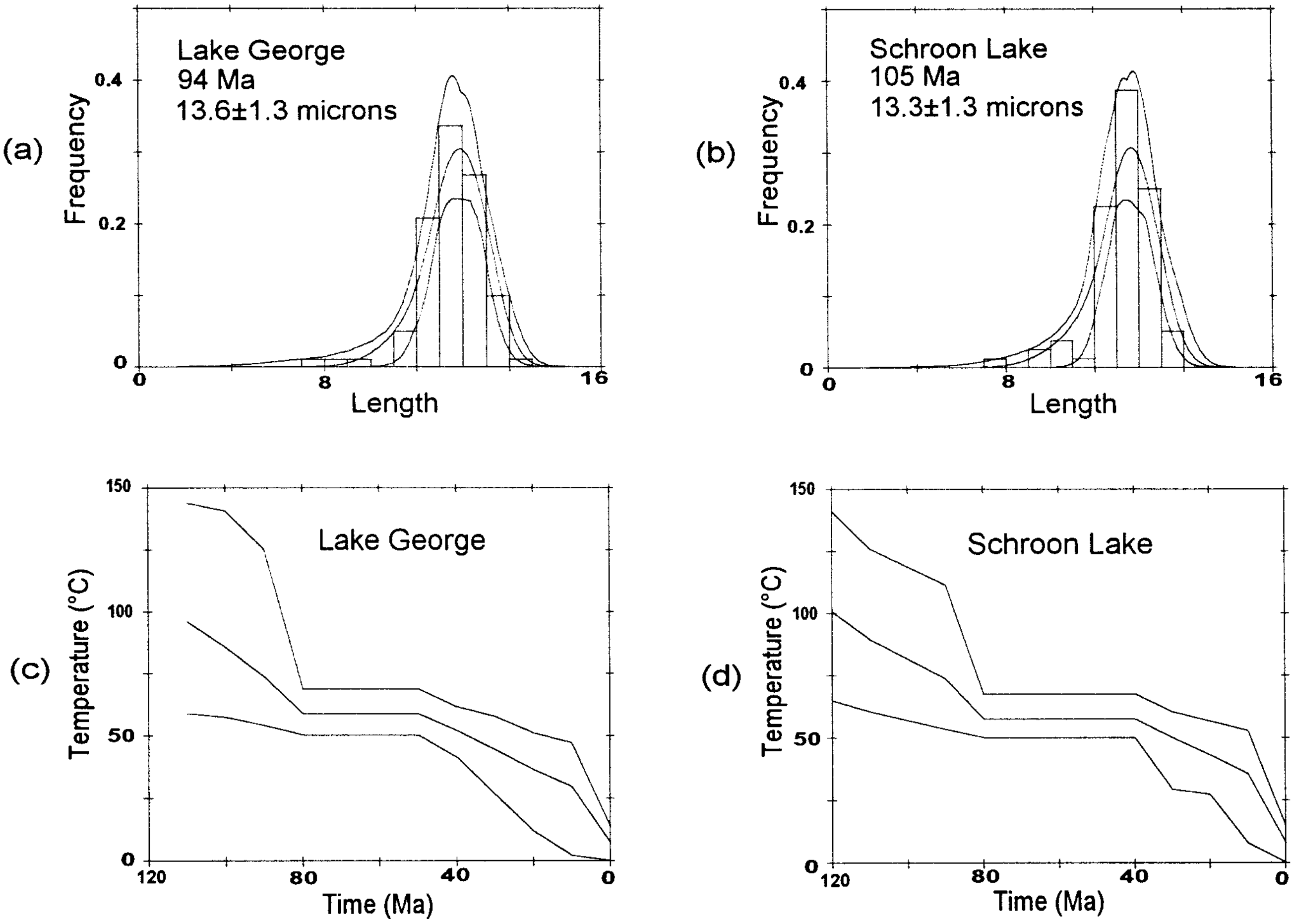

Figure 5. Measured (histogram) and calculated (curve) apatite fission-track-length distributions at the 0.05 level using AFTINV32 (Issler 1996) for samples from the southeastern Adirondack region: *a*, Lake George; *b*, Schroon Lake. Model thermal history at 0.05 level using Crowley et al. (1991) annealing model and AFTINV32 (Issler 1996) for samples from the southeastern Adirondack region: *c*, Lake George; *d*, Schroon Lake.

northwestern Adirondack Lowlands (fig. 3*a*, 3*c*). The best fit thermal solution yields an average cooling rate of 0.5°C/m.yr. from 140 Ma to the present. The model results suggest that the northwestern Lowlands have experienced continuous, slow unroofing beginning in the Late Jurassic to Early Cretaceous.

Samples from Hinckley Reservoir, 125 Ma; Little Falls, 130 Ma; and Lyon Mountain, 139 Ma, along the southern and northern margins of the Adirondack region (fig. 1) yielded very different model time-temperature histories from those of the High Peaks and northwestern Lowlands. All of the preferred thermal models for these samples required three-stage cooling histories, with the middle stage being a period of long-term residence in the apatite PAZ (fig. 3*b*, 3*d*; fig. 4*a*–4*d*). An initial moderately rapid cooling of 0.9°C/m.yr. (Hinckley Reservoir and Little Falls) to 1.3°C/m.yr. (Lyon Mountain) started earliest along the northern border at Lyon Mountain at ~170 Ma and later from 140–150 Ma in the south at Little Falls and Hinckley Reservoir (fig. 3*b*, 3*d*; fig. 4*a*–4*d*). This is followed by varying times spent in the apatite PAZ with little temperature change, 40 (Hinckley Reservoir) to 80 Ma (Lyon Mountain). From 40–50 Ma to the present, the model thermal histories suggest cooling rates of 0.4°C/m.yr. and 1°C/m.yr. (fig. 3*b*, 3*d*; fig. 4*a*–4*d*).

Model time-temperature histories for samples from Lake George, 94 Ma, and Schroon Lake, 105 Ma, in the southeastern Adirondacks (fig. 1) also yield three-stage thermal solutions (fig. 5*c*, 5*d*). Both samples show an initial rapid cooling rate, ~1.0°C/m.yr., from 110–120 Ma to 90 Ma (fig. 5*c*, 5*d*). At 90 Ma, there is an increase in the slope of the cooling curve to ~1.2°C/m.yr. This slight steepening of the time-temperature path may indicate a reactivation of uplift coincident with the time of changing compressive stress directions from east-west to northwest-southeast in the southeastern Adirondacks, as suggested by McHone (1978). At 80 Ma, both samples remain at ~60°C in the apatite PAZ for 30–40 m.yr. (fig. 5*c*, 5*d*), and at 40–50 Ma, the preferred thermal solutions for both samples indicate renewed unroofing at a rate of ~0.8°C/m.yr.

Initial unroofing along the northern and southern Adirondack margins began ~20–30 m.yr. later than it did in central High Peaks region, based on the AFT ages and preferred thermal model results. This suggests that the High Peaks area was at a higher initial elevation than the peripheral regions. If the topography of the Adirondack Mountains in the Late Jurassic to Early Cretaceous was similar to the present topography, then the highest elevations would have been in the High Peaks and south-central regions. The 40–80 Ma residence times in the apatite PAZ suggested by calculated thermal models for the peripheral Adirondack samples could indicate burial by sediments being eroded from the central and southern Adirondack massif. Deposition began earliest at ~130 Ma in the most proximal location to the north of the High Peaks at Lyon Mountain and slightly later at ~90–100 Ma along the more distant southern margin at Little Falls and Hinckley Reservoir (fig. 1). Model time-temperature histories for the northwestern Lowlands sample from Kents Corners do not show any evidence of a long-term residence in the apatite PAZ (fig. 3*c*). This sample was located too far (~120 km) from the areas of highest elevation to be buried significantly by the eroded sediment. In support of this inference, the preferred thermal model for this sample shows only cooling. Preferred thermal models for samples from Schroon Lake and Lake George suggest that the southeastern Adirondacks were unroofing at a cooling rate of ~1°C/m.yr. from ~120 to 80 Ma. During most of this time, time-temperature histories calculated for samples from the northern, northwestern, and southwestern margins of the Adirondacks indicate that these areas were already buried by sediment shed from the central massif to temperatures of ~60°C in the apatite PAZ. Sediment shed from the southeastern Adirondacks would have been deposited to the east in Vermont or further south in New York State. At ~80 Ma, active unroofing in the southeastern Adirondacks ceased for a significant period of time, ~40 Ma (fig. 5*c*, 5*d*).

The model time-temperature paths for all the peripheral Adirondack samples (fig. 3*c*, 3*d*; fig. 4*c*, 4*d*) suggest renewed unroofing at ~40–50 Ma, during the Eocene, which is not a period of active tectonism along the Atlantic continental margin. This possible pulse of unroofing that began during the Eocene may be still active at present and may support evidence for ongoing uplift in the Adirondacks (Isachsen 1975, 1981).

Mechanisms for Differential Unroofing in the Adirondack Mountains. Significantly younger AFT ages from the Proterozoic metamorphic rocks and Cambrian Potsdam sandstone in the southeastern Adirondacks suggest that differential unroofing occurred in this part of the massif in post–Early Cretaceous time. The AFT age data from the New York Appalachian basin (Miller and Duddy 1989) help define the post-Ordovician thermal history of the Adirondack region. Miller and Duddy (1989) presented AFT age results that indicated that the Devonian clastic sedimentary wedge in the Catskill region was cooled rapidly during the Early Cretaceous (120–140 Ma) as a result of the removal of 3–4 km of sediment at this time. The Mesozoic unroofing history of eastern North America has been further constrained by AFT analyses. Roden and Miller (1989) presented AFT age results suggesting that 3.4 km of sediment was removed from northeastern Pennsylvania during the Early Jurassic. Roden (1991) determined AFT ages for Devonian sedimentary rocks and bentonites that indicated unroofing was regionally contemporaneous along the strike of the southern Appalachian basin with Triassic-Jurassic extensional opening of the Atlantic. On the basis of these AFT data, eastern North America appears to have undergone widespread unroofing during the Mesozoic, and southern New York State underwent the same during the Early Cretaceous.

In their thermal history study of the Adirondack Mountains, Heizler and Harrison (1998) found that the ^{40}Ar/^{39}Ar K-feldspar analyses from the eastern Adirondacks indicated a thermal pulse of ~300–350°C during the Ordovician (~450 Ma). Their data indicated the Ordovician thermal event may be a combination of Taconic thrust sheet burial and hot fluid migration focused along the network of north-northeast-trending normal faults in the eastern Adirondacks. On the basis of their data and the AFT ages presented in this article, it is reasonable to suggest that the southeastern Adirondack region has been periodically active both tectonically and thermally from the Ordovician through the Late Cretaceous.

Our AFT age data for the Adirondack region are in agreement with the idea that Late Triassic through Early Cretaceous was a time of extensive unroofing and erosion along the eastern coast of North America. The Adirondack area appears to have seen two periods of unroofing, one in the Late Jurassic to Early Cretaceous (~160–120 Ma) throughout most of the region, and a second in the Early to Late Cretaceous (~110–80 Ma) in the southeast.

The mapped division between AFT ages of the High Peaks (~170 Ma) and the southeastern Adirondacks (~100 Ma) is sharply defined along a north-northeast-trending lineament/fault system from Baker Brook in the southwest to Poke-O-Moonshine in the northeast. Most of the faults/lineaments along the southeastern and southern margin of the Adirondacks strike north-northeast. These faults are inferred to have originated as normal faults that initially accommodated the thermal subsidence of a passive margin after Late Proterozoic rifting (Zen 1967; Bird and Dewey 1970). Many of these linear features were active steep, eastward-dipping normal faults in Ordovician time (Fisher 1980; Cisne et al. 1982). The Lake George and Schroon Lake graben contain downfaulted Ordovician limestones as evidence of an extensional stress field. At present, the higher topography remains on the western side of these faults, stepping down toward the east to the Champlain and Hudson River lowlands.

Early to Late Cretaceous uplift in the southeastern Adirondacks is contemporaneous with the intrusion of the Monteregian Hills plutons in southern Quebec and associated dikes in Quebec, Vermont, and the Champlain Valley of New York between 140 and 118 Ma (Eby 1984*a*, 1987; McHone 1984; Foland et al. 1986). Emplacement of the Monteregian plutons and dikes has been explained by the following mechanisms: (1) it is the result of a hotspot track that formed the Monteregian Hills, the younger White Mountains, and the New England Seamounts during the Mesozoic (Crough 1981; Morgan 1983; Duncan 1984; Sleep 1990) or (2) it is the product of deep-seated alkali basalt magmas intruded along tectonically active "weak zones" or deep fractures in the lithosphere (McHone 1981; McHone and Butler 1984; McHone et al. 1987).

McHone (1978) relates a change in the trend of Early Cretaceous lamprophyre dikes in the Champlain and Monteregian areas (from east-west to northwest) to a clockwise rotation of the extension directions from north-south between ~136 and 125 Ma to north-northeast/south-southwest between 124 and 96 Ma. During the Early Cretaceous in the Champlain Valley and southeastern Adirondacks, the maximum compressive stress, σ_1, rotated from east-west to northwest-southeast. The change in the stress field may have been in response to plate motions associated with the final opening of the North Atlantic.

Differential unroofing in the southeastern Adirondacks, as indicated by our AFT data, could have resulted from one of the following mechanisms: (1) increased heat flow or hydrothermal fluid circulation associated with intrusion of the Monteregian magmas during the Cretaceous; (2) differential Mesozoic sedimentation in the Adirondack region, with the central High Peaks region being less buried than the southeastern margin; and (3) reactivation of east-dipping normal faults and shear zones to a reverse sense of motion during the Late Cretaceous.

The Monteregian Hills intrusives are located ~180 km north of the southeastern Adirondacks, and although the Champlain Valley contains a number of Cretaceous lamprophyre dikes, no Cretaceous dikes outcrop in the vicinity of our samples that yielded young AFT ages (Isachsen and Fisher 1970). Eby (1984*a*) determined that the Monteregian Hills are very shallow level intrusives (~3–4-km depth) because their AFT ages are comparable to their Rb-Sr crystallization ages (~120 Ma). Personal field observation of the contact relationships between Mount Royal and Mount Johnson, Quebec, and the Ordovician sedimentary country rocks suggest that these magma bodies were relatively dry and cool on intrusion. The contact metamorphic aureoles of Mount Royal and Mount Johnson (pyroxene and hornblende hornfels facies, respectively; Eby 1984*b*) are relatively small, on the order of ~20–40 m, and contain no evidence of hydrothermal alteration. Cretaceous lamprophyre dikes, which we have observed in the Champlain Valley, are small (~1 m wide) and show no evidence of metamorphism or hydrothermal mineral deposits at their contacts with the country rocks. Our AFT age of 116 Ma (fig. 1; table 1) for a Cretaceous lamprophyre dike on Willsboro Point is probably a good estimate of its crystallization age and also indicates a shallow intrusion depth (3–4 km). All of these observations suggest that our young AFT ages from the southeastern Adirondacks are not the result of increased heat flow or hydrothermal activity concentrated along north-northeast normal faults during the Cretaceous.

Direct evidence of Mesozoic sedimentation in the northeast is only preserved in the Triassic-Jurassic arkosic sandstones of the Newark basin of New York and New Jersey and in the Hartford-Deerfield basins of Connecticut and Massachusetts. There is no record of Mesozoic sedimentation in the Adirondack region, and several AFT studies based throughout the Appalachian orogen (Miller and Duddy 1989; Roden and Miller 1989; Roden 1991) have indicated that during the Jurassic and Cretaceous, widespread unroofing occurred in eastern North America.

The AFT ages determined in this investigation indicate that at ~170 Ma (Middle Jurassic), Mount Marcy was buried to a depth of ~4 km, assuming a geothermal gradient of 25°C/km. Preferred thermal histories based on the measured track-length distribution for Mount Marcy suggest a slow, linear cooling rate of 0.6°C/m.yr. from ~170 Ma to the present. Given these constraints, a denudation rate of ~0.024 km/m.yr. can be calculated. In contrast, the model time-temperature histories for both samples from the southeastern Adirondacks, Schroon Lake and Lake George, yield an initial denudation rate of ~0.040 km/m.yr. assuming a cooling rate of 1°C/m.yr. and a geothermal gradient of 25°C/km. At 90 Ma, the model thermal histories indicate a slight steepening of the cooling curve to 1.2°C/m.yr., which yields a denudation rate of ~0.048 km/m.yr.

The difference in these denudation rates can be demonstrated if we estimate and compare the amount of erosion that occurred in the High Peaks region with that for the southeastern Adirondacks after each area was uplifted through AFT closure temperature of 100°C. A depth of ~4 km is estimated for the 100°C isotherm if a surface temperature of 15°C and a geothermal gradient of 25°C/km are assumed. Thus 1.2 km of erosion would have occurred from Mount Marcy between ~170 and 120 Ma, the time at which the southeastern Adirondacks began to unroof. In the next 30 m.yr., 1.2 km would have been eroded from the southeastern Adirondacks and another 0.48 km in the following 10 m.yr. We suggest that these rapid denudation rates for the southeastern Adirondack region cannot be explained simply by erosional denudation. Tectonic denudation processes are required, and we favor Late Cretaceous reactivation of east-dipping normal faults and shear zones. This is supported by the coincidence of orientation of the trends of faults and shear zones with the trend of the boundary between the "older" and "younger" AFT ages. A compressional stress field with σ_1 trending west-northwest would be most suitable to promote this reactivation in a reverse sense of fault motion. Unfortunately, it is highly improbable that our fission-track method can locate a specific fault along which movement could have occurred. The majority of mapped post-Ordovician faults characteristically occur in wide zones with much talus or other ground cover, and the mapped fault trace is often inferred by constraints of bedrock type and surface topography. Fault plane surfaces are rarely observable in the field, making it impossible to evaluate any kinematic indicators such as slickenlines that might be present and indicate the direction of fault motion. For example, in a detailed field study of the north-northeast-trending McGregor-Saratoga-Ballston Lake fault system, Isachsen et al. (1981) found few kinematic indicators, and of those found, about one-half indicated a normal fault sense of motion, while the rest indicated a reverse sense of motion.

Stanley (1980) described a north-trending fault system in northern Vermont that shows about 800 m of displacement. He has suggested an early Mesozoic age for the faulting because the faults crosscut Paleozoic compressional structures and are crosscut by, in at least one instance, a Cretaceous lamprophyre dike (Zen 1972). The stress field that would be associated with these north-trending Mesozoic faults is considered extensional (Stanley 1980). In contrast, McHone (1978) described a compressional stress field with σ_1 trending east-west initially and rotating west-northwest by 124–96 Ma, based on a pattern of changing trends of lamprophyre dikes in the Champlain Valley. This conflicting evidence suggests a changing orientation of the paleostress field in the Champlain Valley and southeastern Adirondacks post–Early Cretaceous.

Recent evidence for a compressive stress regime in the Adirondack region includes offset blasting boreholes exposed in modern roadcuts (Fox et al. 1999), deep borehole breakouts, and earthquake fault plane solutions (Sbar and Sykes 1977; Seeber and Armbruster 1989). Although these studies conclude that maximum stress, at present, is not west-northwest but approximately east- to east-northeast-trending, this stress orientation remains compressive. The rotation of the paleostress field in the Adirondacks may have occurred during the Eocene (~40 Ma), a period of renewed cooling and unroofing, indicated in the model time-temperature histories of the samples from the southeastern margin of the Adirondack massif.

Conclusions

Apatite fission-track ages of 168–135 Ma for samples from the Adirondack High Peaks indicate that unroofing occurred in this region during the Late Jurassic to Early Cretaceous. Model time-temperature histories based on apatite track-length distributions suggest continuous slow unroofing with an average cooling rate of 0.6°C/km. The northern, northwestern, and southwestern Adirondack perimeter samples yield generally younger AFT ages of 146–114 Ma, indicating unroofing during the Early Cretaceous. Calculated time-temperature paths from track-length measurements suggest three-stage cooling histories, in which the second stage is a significant period of time (40–80 Ma) spent in the apatite PAZ with little temperature change. The younger AFT ages and model time-temperature histories suggest that the delayed exhumation of the peripheral Adirondack areas resulted from burial by detritus shed from the High Peaks.

Samples from the southeastern Adirondacks yield distinctly younger and abruptly discontinuous AFT ages ranging from 112 to 83 Ma, indicating unroofing occurred in the Early to Late Cretaceous. Preferred thermal models for these samples also suggest three-stage cooling histories. There is a slight increase in slope of the model time-temperature paths at ~90 Ma that supports our hypothesis of reactivated uplift along existing faults at this time. The models also suggest that this region experienced a shorter residence time (30–40 Ma) in the apatite PAZ, at temperatures of ~60°C, than the residence times calculated for other peripheral Adirondack samples.

Unroofing in the Adirondacks was initiated in the central High Peaks region during Late Jurassic and Early Cretaceous time and progressed outward to the perimeter of the Adirondack region by the end of the Early Cretaceous. In the southeastern area of the Adirondacks, unroofing was delayed until the Early Cretaceous and continued through the Late Cretaceous. Later, more rapid unroofing in the southeastern Adirondacks may have resulted from a change in the compressive stress field that reactivated east-dipping normal faults to a reverse sense of motion.

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