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Tectono-thermal history of Hartford, Deerfield, Newark and Taylorsville Basins, eastern United States, using fission-track-analysis

by *Mary K. Roden*[1] and *Donald S. Miller*[1]

Abstract

Sixty-four reset apatite fission-track ages (126 ± 9 to 200 ± 17 Ma) and thirteen reset zircon fission-track ages (164 ± 30 to 241 ± 33 Ma) were determined for surface and core hole samples of sedimentary rocks from three widely separated Early Mesozoic basins in the eastern United States: the Hartford-Deerfield Basins in Connecticut and Massachusetts, the Newark Basin in New Jersey, and the Taylorsville Basin in Virginia. These consistently reset fission-track ages suggest a regionally pervasive thermal regime > 200 °C at ~200 Ma, causing the zircon annealing, which then cooled to ~100 °C (apatite fission-track closure temperature) at ~175 Ma and continued cooling to present day temperature. The resetting of the fission-track clocks in the Newark and Hartford-Deerfield Basins was the result of a combination of several thermal perturbations including extensive basalt extrusion and diabase intrusion, hydrothermal fluid circulation, and a higher paleogeothermal gradient as a result of lithospheric extension. The reset apatite and zircon ages from the Taylorsville Basin are the result of cooling subsequent to Alleghanian metamorphism in the eastern Virginia Piedmont.

Keywords: Fission-track data, Mesozoic basins, eastern United States, thermal evolution, lithospheric extension, Alleghanian metamorphism.

Indroduction

The Early Mesozoic basins along the eastern North American continental margin have been investigated using zircon U–Pb age dating (Dunning and Hodych, 1990), $^{40}Ar/^{39}Ar$ analysis (Sutter, 1988) and fission-track thermochronology (Kohn et al., 1988a, 1988b; Roden and Miller, 1989a). In the Newark and Culpepper Basins, Sutter (1988) determined hornblende and biotite $^{40}Ar/^{39}Ar$ plateau ages (crystallization ages) of ~200 Ma for granophyric segregations, basal contact zones, and recrystallized sedimentary xenoliths associated with the basalts and diabase sheets. K-feldspars from the same samples do not yield crystallization ages. Instead, the K-feldspars record a low-temperature thermal event at ~175 Ma which Sutter (1988) suggests to be of hydrothermal origin. Zircons from the Palisades and Gettysburg sills yield U–Pb ages of 201 ± 1 Ma (Dunning and Hodych, 1990) consistent with the $^{40}Ar/^{39}Ar$ crystallization ages of Sutter (1988).

Kohn et al. (1988a, 1988b) have found reset sphene (mean age = 197 Ma), zircon (mean age = 182 Ma), and apatite (mean age = 146 Ma) fission-track apparent ages for samples from the Mesozoic Newark series in southeastern Pennsylvania indicating temperatures > 240 °C (closure temperature for sphene; Harrison et al., 1979; Harrison and McDougall, 1980).

Roden and Miller (1989a) presented preliminary apatite and zircon fission-track ages for three Mesozoic basins: the Taylorsville Basin in Virginia, the Newark Basin in northern New Jersey, and the Hartford Basin in Connecticut (Fig. 1). We found consistently reset apatite and zircon fission-track ages from these three geographically distinct Mesozoic basins. These reset ages suggest a regionally pervasive thermal regime > 175–200 °C existed at ~200 Ma and cooled to apatite fission-track closure temperature (100 °C) at ~175 Ma. This paper will discuss the above data as well as give new results from the Hartford and Deerfield Basins in Massachusetts.

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Geologic background

The Taylorsville Basin in east-central Virginia is a north-northeast trending half graben bounded on the west by the Hylas mylonite zone containing regionally northwest-dipping Upper Triassic sedimentary rocks of the Newark Supergroup (Fig. 1; GOODWIN et al., 1985). Narrow tholeiitic diabase dikes cut the strata locally and are believed to be Early Jurassic in age. Only ~30 km² of the basin is exposed. The remainder is overlapped by Cretaceous sediments of the Atlantic Coastal Plain.

Adjacent to the Taylorsville Basin on the west is the Grenville-age Goochland terrane of the eastern Virginia Piedmont (GATES and GLOVER, 1989). The Goochland terrane is composed of the State Farm Gneiss, which has been dated at 1031 ± 94 Ma by Rb–Sr whole rock techniques (GLOVER et al., 1978, 1982), and the Maidens Gneiss, which overlies the State Farm Gneiss in gradational to sharp contact (GATES and GLOVER, 1989). To the south of the Taylorsville Basin, the Petersburg Granite intruded the Goochland terrane at 330 ± 8 Ma as dated by U–Pb zircon determinations (WRIGHT et al., 1975).

In the Taylorsville Basin, the total stratigraphic section, the Doswell Formation, is ~1.4 km thick. It has been subdivided into three members in ascending order: the basal Stagg Creek Member, the Falling Creek Member, and the Newfound Member. One apatite fission-track age was obtained from a sample of Vinita Sandstone from the adjacent Richmond Basin. The Vinita Sandstone is stratigraphically correlative to the Stagg Creek and Falling Creek Members in the Taylorsville Basin based on palynologic and paleontologic evidence CORNETT (1977) and OLSEN (1984).

The Taylorsville Basin is different from the Newark and Hartford-Deerfield Basins because it contains only Middle-Upper Carnian Triassic sediments and lacks extensive early Jurassic tholeiitic basalt flows and diabase sheets (CORNETT, 1977; OLSEN, 1978). It is located further east on the Alleghenian Orogen compared to the Newark and Hartford-Deerfield Basins.

The southern Newark Basin (Fig. 1) and surrounding Precambrian and Paleozoic basement rocks have been studied using fission-track analysis by KOHN et al. (1988a, 1988b). Our samples are from the northern Newark Basin. Maximum stratigraphic thickness in the basin is 6–8 km (SCHLISCHE and OLSEN, 1990).

Two distinct intervals comprise the stratigraphic section. The lower, mainly Upper Triassic, interval contains in upward succession, the Stockton Formation, Lockatong Formation, and Passaic Formation. The upper interval includes three volcanic series: the Orange Mountain, Preakness and Hook Mountain Basalts. Interbedded with the basalts are three sedimentary units: the Feltville Formation (basal), Towaco Formation (middle) and the Boonton Formation (youngest; 198–204 Ma; CORNETT, 1977). Along the basin's eastern edge, Cretaceous and younger coastal plain sediments have unconformably overlapped the Early Jurassic sediments.

The Hartford and Deerfield Basins (Fig. 1) contain stratigraphically equivalent sedimentary sequences. In the Hartford Basin, which extends from southern Connecticut to central Massachusetts, the stratigraphic section is Upper Triassic to Early Jurassic in age and ~3900 m in thickness, including 225 m of tholeiitic lava flows, dikes and sills. The basal unit is the New Haven Formation (Upper Triassic) overlain by the Talcott Flow, which yields a K–Ar date of 187 ± 3 Ma (SEIDEMANN, 1988). In stratigraphic succession upward, the remaining units are the Shuttle Meadow Formation, the Holyoke Flow, the East Berlin Formation (together with the Talcott Flow, these

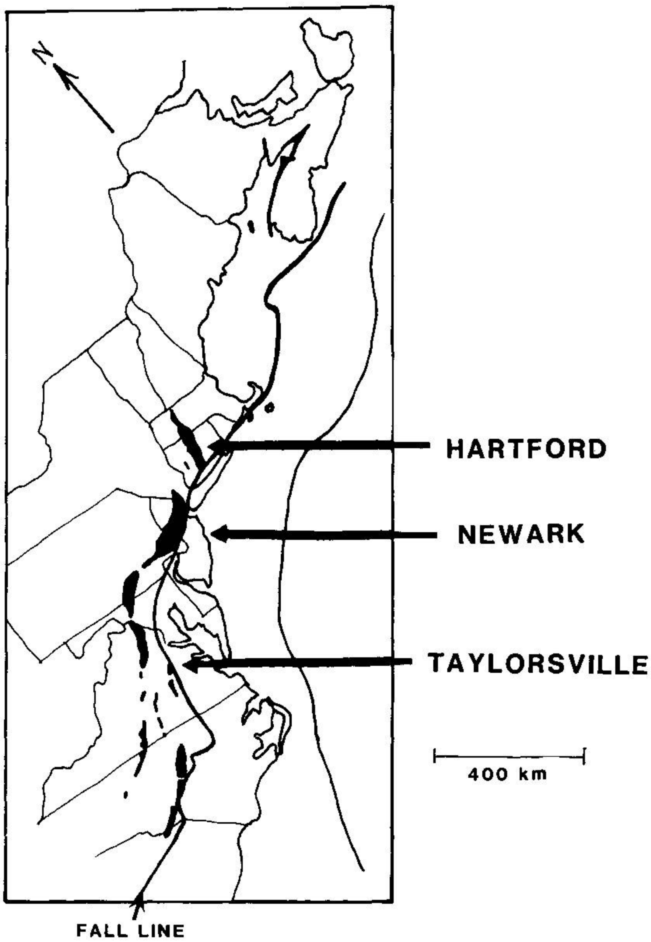

Fig. 1 Northeastern United States with Mesozoic Basins identified.

comprise the Meriden Formation) and the Portland Formation (SEIDEMANN, 1988).

In the Deerfield Basin, the redbed sequence from oldest (Upper Triassic) to youngest (Early Jurassic) includes the Sugarloaf Arkose (2000 m thick), the Deerfield Basalt (120 m thick) and the Turners Falls Sandstone (600 m thick) which grades eastward into the Mount Toby Conglomerate (alluvial fan facies; STEVENS and HUBERT, 1980). The total stratigraphic section is ~2600 m thick.

Apatite and zircon fission-track ages and track length measurements

TECHNIQUE

The fission-track method is based on the formation of damage zones resulting from the spontaneous fission of ^{238}U atoms in apatite and zircon crystals. Fission-tracks are retained in these minerals below a closure temperature estimated to be 100 ± 20 °C for apatite (WAGNER, 1968; NAESER and FAUL, 1969; GLEADOW and DUDDY, 1981; NAESER, 1981) and 175–200 °C for zircon (HARRISON et al., 1979; HARRISON and McDOUGALL, 1980). If the apatite and zircon grains are subjected to temperatures greater than their respective closure temperatures for times on the order of 10^6 years, then all existing fission-tracks will be annealed and the fission-track age will be reset. In the case of complete annealing, the apatite and zircon fission-track ages provide cooling ages recording the time these minerals passed through their respective closure temperatures.

Confined horizontal track length measurements, along with the fission-track ages, are an integral part of the thermal history interpretation of a rock sequence. Mean confined track length measurements between 14 and 15 μm and standard deviations of the track length distributions ranging from 0.8–1.3 μm are characteristic of slightly annealed spontaneous track length distributions which form in rapidly cooled volcanic apatites that have not been exposed to temperatures > 50 °C subsequent to initial cooling (GLEADOW et al., 1983, 1986). For apatites subjected to slow cooling (plutonic conditions), in the temperature range of 70–125 °C, the confined track length distributions have mean track lengths in the 12–14 μm range and standard deviations of the track length distributions between 1.0 and 2.0 μm (GLEADOW et al., 1986).

The analytical techniques used to determine the apatite fission-track ages and confined track length distributions are described in RODEN and MILLER (1989b). The zircon fission-track ages were determined by external detector method also. Aliquots of 10–20 mg of zircon were mounted in teflon and polished to expose an internal grain surface. Tracks in zircon are etched for 4–30 hours in a KOH–NaOH eutectic melt at 225 °C. Samples were irradiated with thermal neutrons to induce fissioning of the ^{235}U in the zircon at the Oregon State University TRIGA reactor in Corvallis with a fluence of 2×10^{15} neutrons/cm^2.

RESULTS

Taylorsville Basin. – Surface Samples. Two surface samples of Precambrian metamorphic rocks, Maidens Gneiss (T1) and State Farm Gneiss (T2) gave apatite fission-track ages of 172 ± 9 Ma and 174 ± 10 Ma, respectively (Tab. 1; Fig. 2). A sample of Petersburg Granite (T4) yielded an apatite fission-track age of 180 ± 10 Ma. A surface sample of Vinita Sandstone (T3) from the Richmond Basin yielded apatite and zircon fission-track ages of 167 ± 18 Ma and 217 ± 23 Ma, respectively.

Core-Hole Samples. – A total of 33 samples from six drill cores, located in the northeastern unexposed part of the Taylorsville Basin (courtesy of Texaco), yielded apatite fission-track ages from 135 ± 7 Ma, T8 (bottom-hole), to 200 ± 17 Ma, T5 (top-hole; Tab. 1) throughout the depth interval sampled (153 m to 1683 m). Table 1 lists representative top-hole and bottom-hole samples from each drill core from the Taylorsville Basin. Zircon fission-track ages from five bottom-hole samples range in age from 186 ± 25 Ma (T12) to 241 ± 33 Ma (T10; Tab. 2).

Confined horizontal track lengths were measured for both surface and core apatite samples. The mean track length for the surface samples ranges from 11.9 ± 1.5 μm for the State Farm Gneiss (T2) to 12.7 ± 1.3 μm for the Petersburg Granite (T4). For the drill core samples, the mean track length for the top-hole samples is 12.5 ± 1.6 μm. This mean track length shows a general decrease down hole to a mean track length of 11.6 ± 1.7 μm for the bottom-hole samples (Tab. 1).

Newark Basin. – Sample locations for the Newark Basin are shown in Fig. 3. The sedimentary formations sampled were the Passaic Formation, the Feltville Formation, and the Boonton Formation with a total of five samples. Two samples of the Palisades Diabase were analyzed also.

Apatite fission-track ages for the sedimentary samples range from 126 ± 9 Ma (N2) to 196 ± 23 Ma (N6; Tab. 1; Fig. 3). The Palisades Diabase

Tab. 1 Apatite fission-track results for four Mesozoic basins: Deerfield, Hartford, Newark and Taylorsville, eastern U.S.

Sample Number	Formation	Fission-track Age [Ma] (No. of grains)	X^2 [%]	Uranium [ppm]	Track Length (No of tracks) (μm)	Standard Deviation (μm)
DEERFIELD BASIN, MASSACHUSETTS						
D1	Sugar Loaf Arkose	128± 7* (21)	29	32	13.0 ± 0.16* (103)	1.64*
D2	Mount Toby Congl.	130± 21 (4)	60	13	13.3 ± 0.33 (30)	1.78
D3	Turner Falls	118± 9 (20)	43	14	13.6 ± 0.16 (89)	1.47
HARTFORD BASIN, MASSACHUSETTS-CONNECTICUT						
H1	New Haven	138 ± 9 (18)	15	18	13.81 ± 0.19 (18)	0.76
H2	East Berlin	147 ± 10 (8)	92	31	13.66 ± 0.13 (92)	1.12
H3	Portland	174 ± 11 (19)	90	17	13.81 ± 0.17 (63)	1.31
H4	Portland	179 ± 20 (12)	44	21	13.35 ± 0.17 (89)	1.63
H5	East Berlin	155 ± 11 (20)	28	17	13.53 ± 0.12 (102)	1.27
H6	East Berlin	180 ± 12 (14)	<1	23	12.93 ± 0.13 (101)	1.26
H7	Portland	153 ± 12 (10)	59	23	13.53 ± 0.13 (100)	1.27
H8	Portland	135 ± 9 (18)	22	23	13.64 ± 0.13 (100)	1.09
H9	New Haven	143 ± 8 (20)	61	24	13.64 ± 0.11 (102)	1.39
H10	New Haven	156 ± 10 (20)	89	19	13.86 ± 0.21 (34)	1.23
H11	New Haven	166 ± 16 (20)	1	20	13.41 ± 0.13 (102)	1.33
H12	Portland	154 ± 11 (22)	58	15	13.99 ± 0.14 (101)	1.41
H13	East Berlin	177 ± 10 (20)	1	23	13.80 ± 0.12 (111)	1.22
H14	New Haven	160 ± 9.2 (20)	81	22	13.72 ± 0.13 (100)	1.27
H15	New Haven	140 ± 8 (22)	77	23	13.11 ± 0.16 (100)	1.59
H16	Portland	107 ± 8 (11)	48	29	13.39 ± 0.16 (83)	1.46
H17	New Haven	118 ± 9 (15)	65	22	13.61 ± 0.34 (22)	1.54
NEWARK BASIN, NEW JERSEY						
N1	Passaic	137 ± 8 (20)	9	29	13.10± 0.16 (51)	1.16
N2	Passaic	126 ± 9 (19)	70	24	13.83± 0.15 (85)	1.33
N3	Palisades Diabase	153 ± 17	79	10	13.76 ± 0.13	0.94

Sample Number	Formation	Fission-track Age [Ma] (No. of grains)	X^2 [%]	Uranium [ppm]	Track Length (No of tracks) (μm)	Standard Deviation (μm)
		(20)			(55)	
N4	Palisades Diabase	148 ± 16 (20)	85	13	n.d.***	
N5	Boonton	150 ± 9 (18)	51	67	12.69 ± 0.31 (30)	1.09
N6	Feltville	196 ± 23 (6)	98	31	14.76 ± 0.20 (11)	0.98
N7	Passaic	161 ± 12 (17)	85	14	14.11± 0.25 (91)	1.56
TAYLORSVILLE BASIN, VIRGINIA						
T1	Maiden's Gneiss	172 ± 9 (20)	65	76	12.49 ± 0.15 (81)	1.39
T2	State Farm Gneiss	174 ± 10 (18)	30	34	11.91 ± 0.26 (32)	1.46
T3	Vinita Sandstone	167 ± 18 (14)	99	27	n.d.***	
T4	Petersburg Granite	180 ± 10 (20)	30	21	12.72 ± 0.15 (73)	1.29
T5	Doswell (CH1,0.15)**	200 ± 17 (20)	25	25	13.09 ± 0.07 (323)	1.33
T6	Doswell (CH1,1.68)	137 ± 9 (20)	30	39	11.84 ± 0.13 (99)	1.34
T7	Doswell (CH2,0.35)	135 ± 9 (10)	88	26	12.37 ± 0.15 (100)	1.48
T8	Doswell (CH2,1.68)	135 ± 7 (20)	50	40	11.07 ± 0.14 (100)	1.39
T9	Doswell (CH3,0.50)	171 ± 10 (18)	40	31	12.28 ± 0.16 (100)	1.57
T10	Doswell (CH3,1.68)	154 ± 9 (20)	22	32	11.28 ± 0.17 (99)	1.67
T11	Doswell (CH4,0.52)	179 ± 11 (20)	75	26	12.59 ± 0.14 (110)	1.52
T12	Doswell (CH4,1.65)	152 ± 13 (20)	<1	44	11.13 ± 0.23 (104)	2.37
T13	Doswell (CH5,0.61)	171 ± 11 (20)	70	16	n.d.***	
T14	Doswell (CH5,1.68)	153 ± 11 (20)	1	37	11.63 ± 0.17 (77)	1.51
T15	Doswell (CH7,0.67)	185 ± 13 (20)	30	17	n.d.***	
T16	Doswell (CH7,1.04)	175 ± 15 (20)	99	11	12.53 ± 0.21 (74)	1.76

* ± one sigma, one standard error, and one standard deviation, respectively. ** the numbers in parenthesis indicate the core hole and depth (kilo meters) in core from surface, respectively. *** n.d. means not determined. Ages calculated by the zeta (ξ) method using the standard apatites from Fish Canyon Tuff, Durango and Mount Dromedary. A complete age data set is available in Appendix 1.

yields an apatite fission-track age of 153 ± 17 Ma (N3) for the upper part of the sill and 148 ± 16 Ma (N4) for the bottom. A Passaic Formation sample (N2) yields a zircon fission-track age of 252 ± 37 Ma. A sample of the Boonton Formation (N5), the youngest formation in the basin, gives a zircon fission-track age of 338 ± 60 Ma (Tab. 2; Fig. 3).

Track length distributions were measured for six Newark Basin apatite samples. The mean track length ranges from 12.7 ± 1.1 μm for a sam-

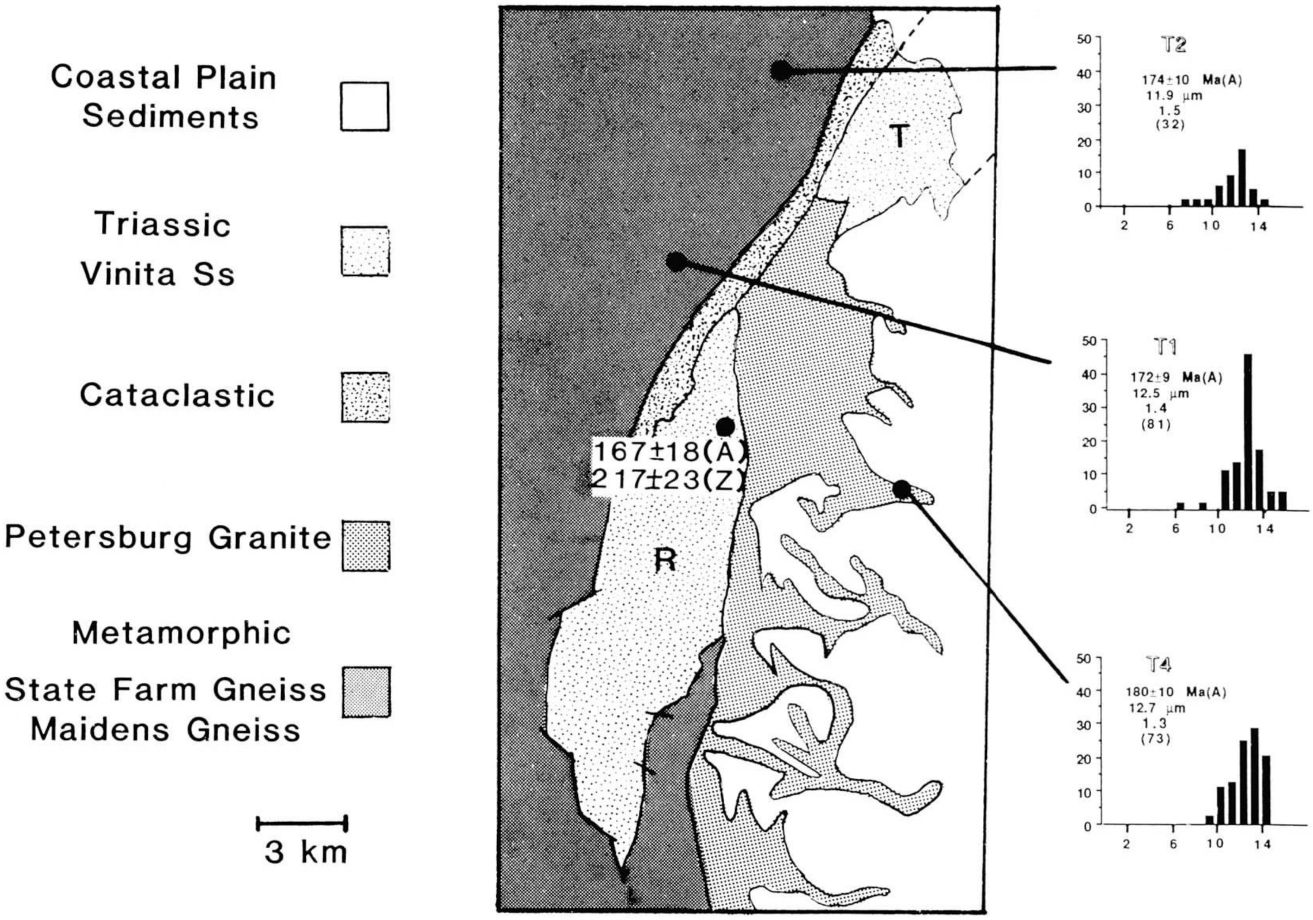

Fig. 2 Taylorsville Basin: Fission-track ages and track length data and distributions. Table 1 gives meaning of various datum. (A) = apatite fission-track age, (Z) = zircon age. T = Taylorsville Basin; R = Richmond Basin.

ple of Boonton Formation to 14.1 ± 1.6 µm for a sample of Passaic Formation (Tab. 1).

Hartford and Deerfield Basins. – In the Hartford Basin, twenty apatite fission-track ages were determined for samples of the New Haven Formation, East Berlin Formation and Portland Formation (Fig. 4). These ages range from 107 ± 8 Ma (H16) to 179 ± 20 Ma (H4; Tab. 1; Fig. 4). Five zircon fission-track ages, ranging from 164 ± 34 Ma (H8) to 238 ± 26 Ma (H3), were measured also (Tab. 2; Fig. 4). Mean confined track lengths for the Hartford Basin apatite samples range from 12.9 ± 1.3 µm for the East Berlin Formation to 14.0 ± 1.4 µm for the Portland Formation.

Three samples representative of the major formations in the Deerfield Basin, the Sugarloaf Arkose, Turners Falls Sandstone, and the Mount Toby Conglomerate, were analyzed. The apatite fission-track ages ranged from 118 ± 9 Ma (D3) to 130 ± 21 Ma (D2; Tab. 1; Fig. 4). Mean confined track lengths for the Deerfield Basin apatite samples range from 13.0 ± 1.6 µm for the Sugarloaf Arkose to 13.6 ± 1.5 µm for the Turners Falls Sandstone (Tab. 1).

Discussion

Hartford and Deerfield Basins – All of the apatite and zircon fission-track ages determined for sedimentary samples from these basins are reset indicating that temperatures exceeded at least 100 °C for all samples and 175–200 °C for those which give reset zircon ages. These reset apatite and zircon fission-track ages are cooling ages of the sedimentary basin. Samples on which zircon fission-track ages were determined are from locations as widely separated as 30–45 km throughout the Hartford Basin in both north-south and east-west directions (Fig. 4; Tab. 2). The reset zircon fission-track ages for these samples (164 ± 34 to 238 ± 26 Ma) suggest a basin wide thermal event > 175–200 °C at ~200 Ma.

Samples from the northern Hartford and Deerfield Basins yield slightly younger apatite fission-track ages (107 ± 8 Ma to 140 ± 8 Ma; Tab. 1; Fig. 4) and shorter mean track lengths with larger standard deviations of the track length distributions (13.0 ± 1.6 µm to 13.6 ± 1.5 µm) than those samples from the southern Hartford Basin (135 ± 9 Ma to 180 ± 12 Ma; 12.9 ± 1.3 µm to 13.9 ±

Tab. 2 Zircon fission-track results for three Mesozoic basins: Hartford, Newark and Taylorsville, eastern U.S.

Sample Number	Formation	Fission-track Age [Ma] (No. of grains)	X^2 [%]	Uranium [ppm]
HARTFORD BASIN, MASSACHUSETTS-CONNECTICUT				
H1	New Haven	167 ± 30* (10)	<1	149
H3	Portland	238 ± 26 (10)	92	378
H5	East Berlin	178 ± 34 (5)	24	550
H7	Portland	184 ± 24 (7)	10	430
H8	Portland	164 ± 34 (10)	<1	835
NEWARK BASIN, NEW JERSEY				
N2	Passaic	252 ± 37 (10)	99	377
N5	Boonton	338 ± 60 (7)	85	302
TAYLORSVILLE BASIN, VIRGINIA				
T3	Vinita Sandstone	217 ± 27 (12)	73	370
T6	Doswell (CH1,1.68)**	229 ± 38 (7)	9	415
T8	Doswell (CH2,1.68)	188 ± 21 (10)	40	466
T10	Doswell (CH3,1.68)	241 ± 33 (10)	94	285
T12	Doswell (CH4,1.65)	186 ± 25 (10)	<1	467
T14	Doswell (CH5,1.68)	195 ± 26 (12)	68	354

* ± one sigma. ** the numbers in parenthesis indicate the core hole and depth (kilometers) in core from surface, respectively. Ages calculated by the zeta (ξ) method using the standard apatites from Fish Canyon Tuff, Durango and Mount Dromedary. A complete age data set is available in Appendix 2.

1.2 µm; Tab. 1; Fig. 4). Time-temperature (tT) histories for the northern Hartford and Deerfield Basin samples, calculated using the apatite fission-track age and track length distributions and the mathematical expression of LASLETT et al. (1987) based on Durango apatite annealing, yield results which suggest cooling to apatite fission-track closure temperatures occurred in the Middle to Late Jurassic (140–180 Ma; Fig. 5). The model tT paths indicate the rocks spent ~20–40 Ma in the 80–100°C temperature range in order to produce shorter mean track lengths and larger standard deviations of the track length distributions than those determined for samples in the southern part of the Hartford Basin (Fig. 5).

The northern Hartford Basin samples are from locations close to those from which PRATT et al. (1988) obtained temperatures of maximum pyrolitic yield, (T_{MAX}) > 465°C, that are overmature for petroleum generation. PRATT et al. (1988) suggest that the wide range of hydrogen indices and T_{MAX} values they obtained from the East Berlin and Portland Formations in the northern Hartford Basin indicate anomalously high heat flow. The younger apatite fission-track ages and broader track length distributions with shorter mean

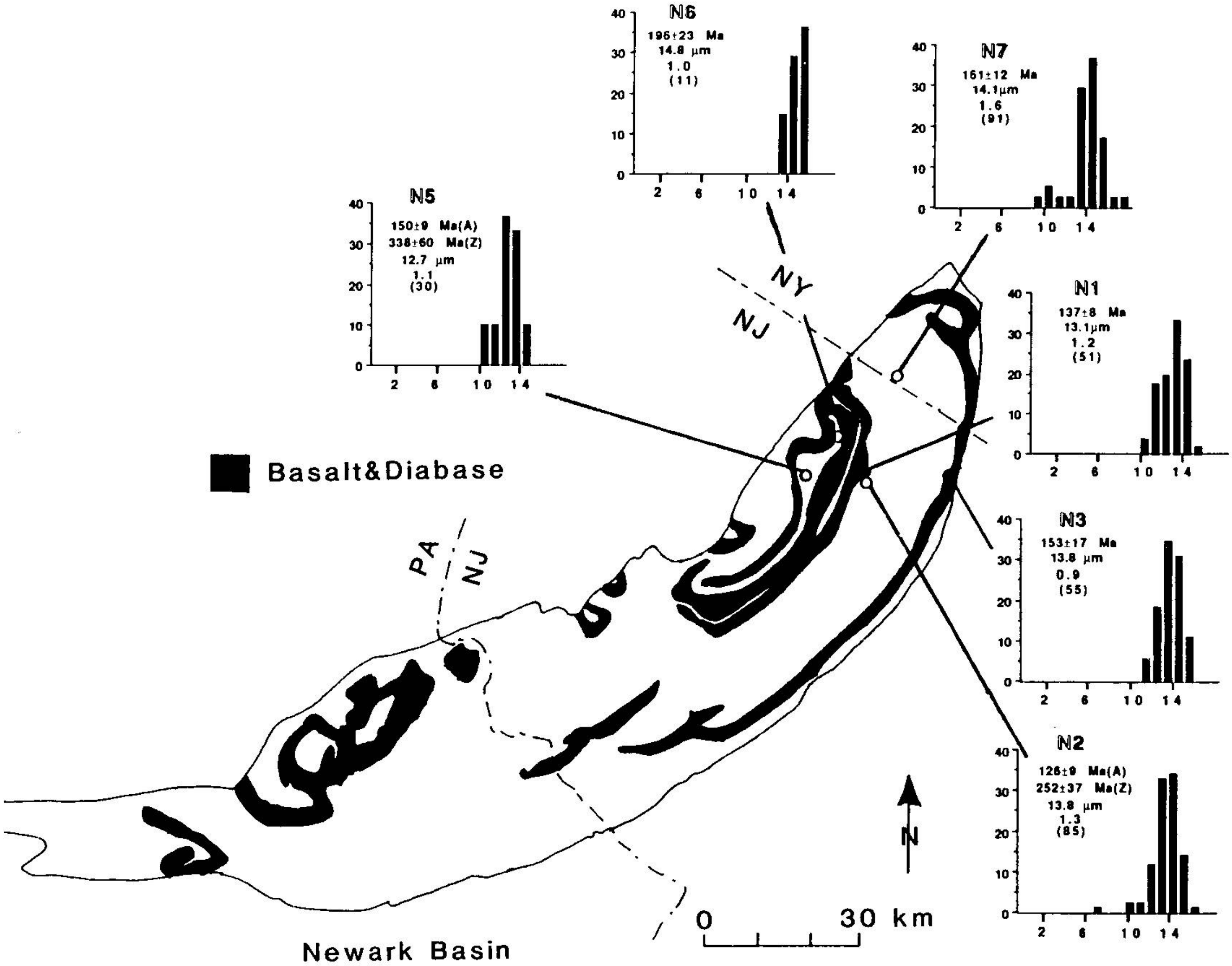

Fig. 3 Newark Basin: Fission-track ages and track length data and distributions. Table 1 gives meaning of various datum.

track lengths measured for this region suggest the high thermal pulse occurred ~10–20 Ma later than in the southern Hartford Basin (Tab. 1; Fig. 5). Because zircon fission-track ages have not been determined for these samples, the maximum temperature attained in the northern Hartford and Deerfield Basins is based on the apatite fission-track closure temperature of 100 ± 20 °C.

Within the southern Hartford Basin, the confined track length distributions yield variable mean track lengths and standard deviations. This complexity is shown by the track length distributions which suggest both fairly rapid cooling (long mean track lengths and small standard deviations; 13.5–13.9 ± 1.1–1.4 μm) and slower cooling (shorter mean track lengths and larger standard deviations; 12.9–13.6 ± 1.3–1.6 μm; Tab. 1).

The samples which yield track length distributions indicative of fairly rapid cooling were taken from the southeastern portion of the basin near the eastern border fault (H3, H7, H12, H13, H14), the central part of the basin which is cut by numerous faults, and basaltic flows or diabase intrusives (H2, H5), and the east-central basin near Manchester, CT (H8). The locations for samples, H2, H5, and H8 correspond roughly with areas identified as having high thermal anomalies based on organic geochemical analyses (Pratt et al., 1988). Pratt and Burrus (1988) and Pratt et al. (1988) have suggested that these localized areas of higher heat flow are the result of hydrothermal circulation based on field and fluid inclusion studies indicating that petroleum and aqueous fluids migrated repeatedly through fracture networks during basin deformation. It is possible that the track length distributions from the southern Hartford samples which record rapid cooling may show the effects of the same hydrothermal pulse as recorded by the organic geochemical indicators.

The samples from the southern Hartford Basin, which yield shorter mean track lengths and

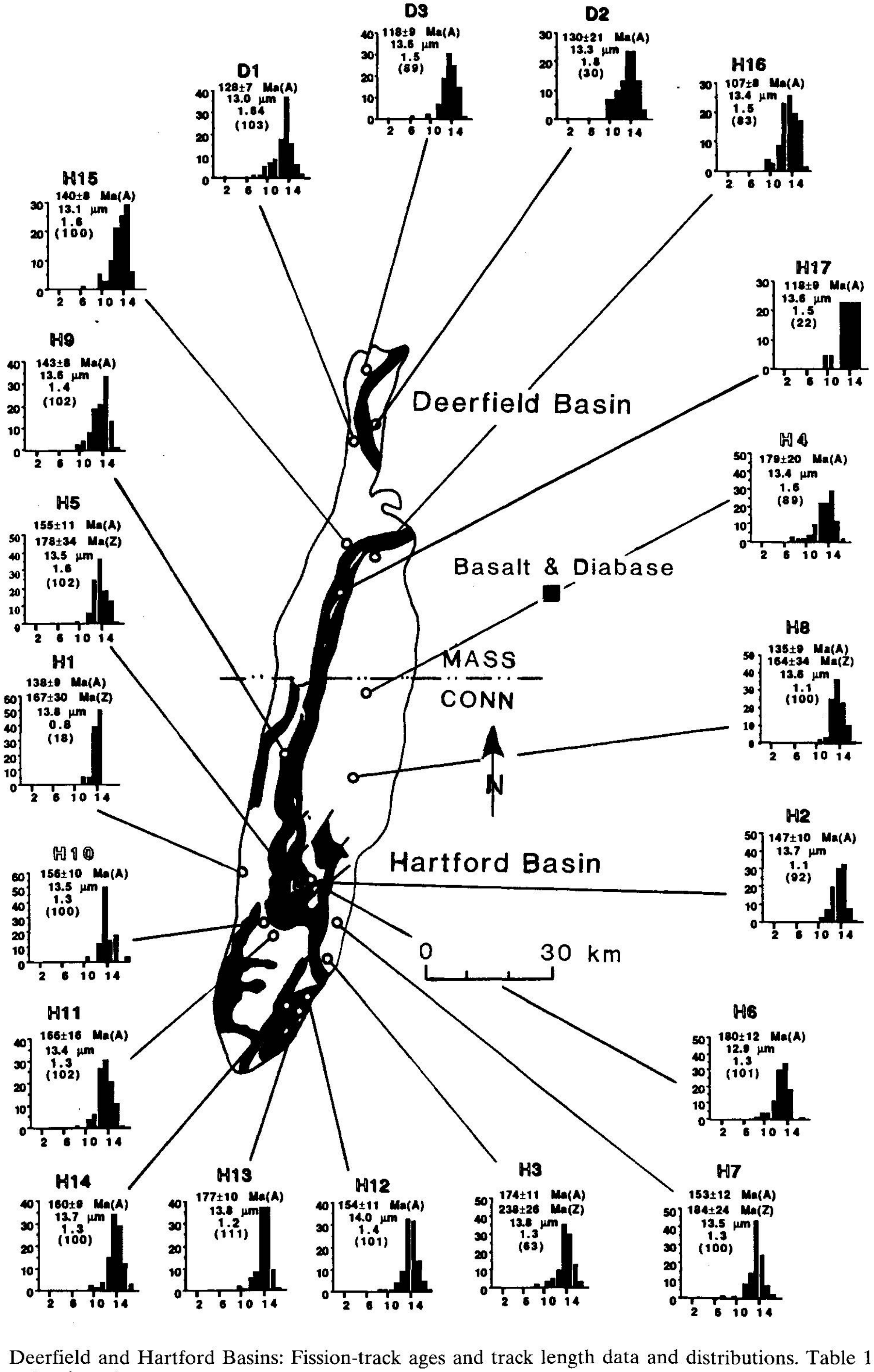

Fig. 4 Deerfield and Hartford Basins: Fission-track ages and track length data and distributions. Table 1 gives meaning of various datum.

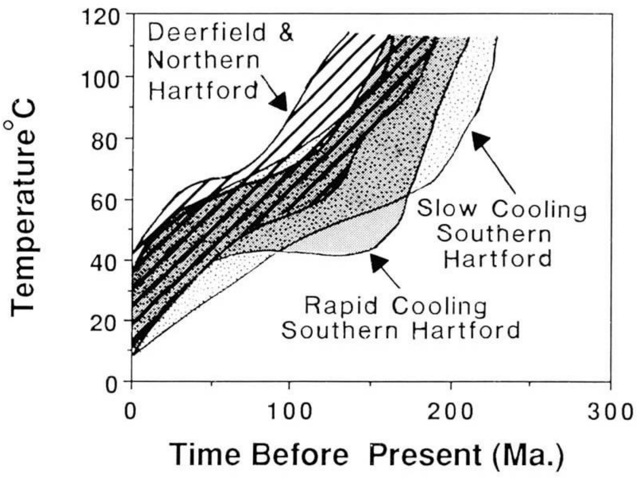

Fig. 5 Model temperature-time paths deduced from fission-track data on apatites for the Deerfield and Hartford basins.

larger standard deviations of the track length distributions suggesting slower cooling through 70–90 °C temperature range, are from scattered locations (H4, H6, H9, H11). There is no apparent correlation between these samples and thermal anomalies defined by organic geochemical indicators (PRATT et al., 1988). These samples may be recording a generalized overall basin cooling and may not have been exposed directly to a hydrothermal fluid pulse of short duration and high temperature.

Model tT paths were calculated, based on the LASLETT et al. (1987) annealing equation, for both southern Hartford Basin samples which indicate rapid cooling and those which suggest slower cooling (Fig. 5). The tT paths indicate cooling began for all southern Hartford Basin samples during the Late Triassic to Late Jurassic (~220–160 Ma). All of the rapidly cooled southern Hartford Basin samples yield calculated tT paths that remain in the 40–60 °C temperature range from ~170 Ma to < 50 Ma after initial cooling (Fig. 5). Those samples, which have track length distributions suggesting slower cooling histories, yield model tT paths that remain in the 70–90 °C temperature range for a prolonged time (~140 Ma). Slow cooling through the 70–90 °C temperature range produces short track lengths which give the track length distribution a pronounced negative skewness.

The distinction between the southern Hartford samples which experienced rapid cooling and those which experienced slower cooling is demonstrated by comparing the slopes of their respective model tT paths (Fig. 5). This difference in thermal history for samples from a limited geographic area is consistent with the interpretation of PRATT et al. (1988) that restricted areas of high thermal anomalies, probably due to the circulation of hydrothermal fluids, exist in the southern Hartford Basin.

Newark Basin. – All apatite fission-track ages for the sedimentary samples from the northern Newark Basin are reset and yield an age range from Early Jurassic to Early Cretaceous (~160–126 Ma). These apatite fission-track ages are consistent with a mean apatite fission-track age of 146 Ma for Newark Series samples and Grenville and Paleozoic crystalline rocks from the southern Newark Basin and surrounding terrain (KOHN et al., 1988a, 1988b) and those ages determined for the Hartford and Deerfield Basins. Two samples of Palisades Diabase yield apatite fission-track ages which are the same within analytical error (148 ± 16 and 153 ± 17 Ma; Tab. 1; Fig. 3), which agree with the apatite fission-track ages obtained on the sediments, and which are younger than the U–Pb crystallization age of 201 ± 1 Ma (DUNNING and HODYCH, 1990).

Confined track length distributions for the sedimentary apatite samples are negatively skewed with a range of mean track lengths (12.7 ± 1.1 to 14.8 ± 1.0 µm; Tab. 1) indicating moderate to slow cooling which allowed the accumulation of short tracks. The data from the Palisades Diabase yields a narrow track length distribution (standard deviation = 0.9 µm) with a long mean track length (13.8 ± 0.13 µm) consistent with a rapid cooling history.

Model tT paths for the northern Newark Basin samples calculated using the apatite fission-track age, track length distribution, and the mathematical model of LASLETT et al. (1987) suggest cooling through apatite fission-track closure temperature (100 ± 20 °C) began in the Middle to Upper Jurassic (180–150 Ma; Fig. 6). PRATT et al. (1988), using temperature of maximum pyrolitic yield (T_{MAX}), and KATZ et al. (1989), using vitrinite reflectance, have suggested patterns of thermal maturation for black shales from the Newark Basin that show less local variation than those for the Hartford Basin. According to these organic geochemical indicators, the Triassic strata in the southern Newark Basin are overmature for petroleum generation. In the northern Newark Basin, thermal maturity decreases from the Triassic through Jurassic strata. The Passaic Formation is overmature for petroleum generation. The Feltville Formation is fully mature and the Boonton Formation is marginally mature to immature.

We see no obvious correlation between apatite fission-track age and location in the strati-

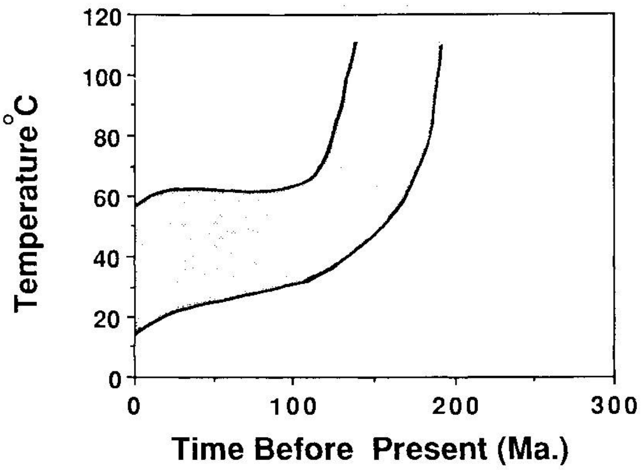

Fig. 6 Model temperature-time paths deduced from fission-track data on apatites for the Newark basin.

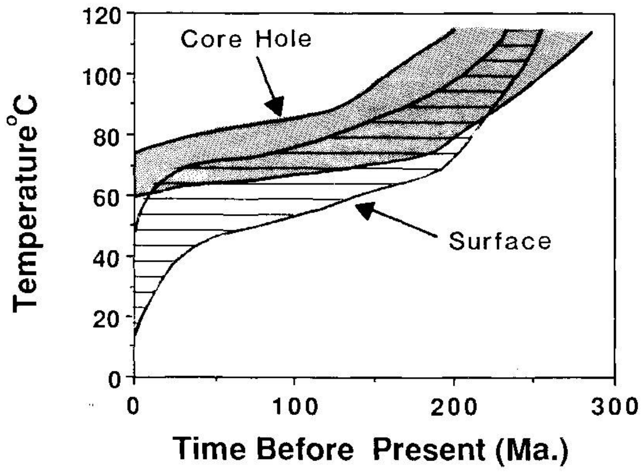

Fig. 7 Model temperature-time paths deduced from fission-track data on apatites for the Taylorsville basin.

graphic section. The youngest formation in the basin, the Boonton Formation, yields an apatite fission-track age of 150 ± 9 Ma which is within one sigma error of the age measured for the oldest formation dated, the Passaic Formation (137 ± 8 Ma).

The two zircon fission-track ages from the Passaic Formation (N2; 252 ± 37 Ma) and the Boonton Formation (N6; 338 ± 60 Ma) may be mixed ages bearing a detrital signature from their source terrain, the Precambrian basement rocks to the west of the Newark Basin. These zircon ages are not as young as those determined for the southern Newark Basin and surrounding crystalline rocks (~182 Ma; KOHN et al., 1988a, 1988b). It is possible that temperatures in this part of the Newark Basin did not exceed 200 °C during the Triassic rifting. This would be consistent with the organic geochemical indicators (PRATT et al., 1988). More zircon fission-track ages throughout the Triassic-Jurassic interval in the northern Newark Basin will help define the maximum temperature attained in this area.

PRATT and BURRUS (1988) have suggested that the thermal anomalies present in the Newark Basin, as in the Hartford Basin, are the result of hydrothermal circulation. The evidence which supports hydrothermal circulation includes vein mineralization, particularly of barite, resulting from brine circulation in the 100–200 °C temperature range (GRAY, 1988; ROBINSON and WOODRUFF, 1988); organic geochemical analyses (PRATT et al., 1988; PRATT and BURRUSS, 1988; KATZ et al., 1989); and paleomagnetic data which indicates a major thermo-chemical event in the Newark Basin (WITTE and KENT, 1989).

Based on our limited analyses, the internally consistent apatite fission-track ages suggest that temperatures < 100 ± 20 °C were achieved in approximately the same time interval throughout the analyzed stratigraphic section (Passaic Formation through Boonton Formation). Our preliminary zircon age determinations suggest that temperatures did not exceed 175–200 °C during the Early Jurassic in the northwestern Newark Basin.

Taylorsville Basin. – In contrast to the Newark and Hartford Basins, there is no evidence of hydrothermal circulation in the Taylorsville Basin stratigraphic section (GOODWIN et al., 1985). The apatite fission-track ages determined for the surface samples, Precambrian metamorphics, Upper Paleozoic Petersburg Granite, and Triassic Vinita Sandstone, and core-hole samples are all reset and comparable to those measured for samples from the Newark, Hartford and Deerfield Basins (135 ± 7 to 200 ± 17 Ma; Tab. 1; Fig. 2).

Confined track length distributions are negatively-skewed and yield moderately short mean track lengths (11.1–13.2 µm) and a wide range of standard deviations of the track length distributions from 1.3 to 2.4 µm. Model tT paths for the surface samples, calculated in the same manner as those for the Newark, Deerfield and Hartford Basins, indicate slow cooling through 70–90 °C temperature range beginning in the Upper Triassic (~240 Ma; Fig. 7).

The core hole samples also yield calculated tT paths which suggest slow cooling from ~250 Ma to present (Fig. 7). None of the model thermal histories for the Taylorsville samples show any indication of rapid cooling as did some Hartford Basin samples.

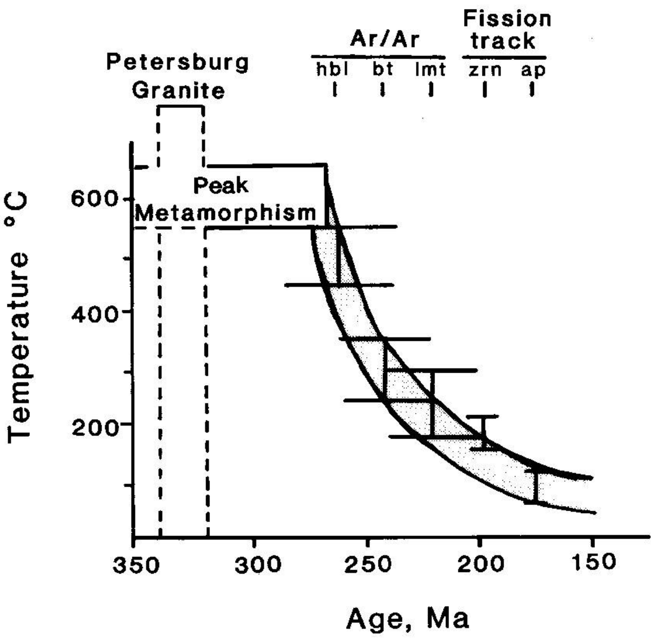

Fig. 8 Thermal history in the Taylorsville basin region, eastern Virginia Piedmont (after GATES and GLOVER, 1990, Fig. 8).

The uniformly reset zircon fission-track ages (186 ± 25 to 241 ± 33 Ma) from both surface crystalline rocks adjacent to the basin and bottom core hole samples within the basin suggest extensive heating > 175–200 °C at ~200 Ma. This is consistent with the zircon and sphene fission-track ages obtained for the Grenville and Paleozoic crystalline rocks and Mesozoic Newark Series from southeastern Pennsylvania and the Baltimore, MD area (KOHN et al., 1988a, 1988b).

The Taylorsville Basin does not contain the extensive volume of tholeiitic basalts and diabase intrusives present in the Newark and Hartford-Deerfield Basins. The thermal event which reset both apatite and zircon fission-track ages must be the result of other factors, such as high paleogeothermal gradient due to lithospheric extension (~50 °C/km) and/or deep burial (> 4–8 km, depending on geothermal gradient) followed by slow exhumation. Hydrothermal fluid circulation also appears to be absent in this basin precluding it as a fission-track annealing agent.

Studies on the tectonic thermal evolution of the Alleghanian Orogen by GATES and GLOVER (1989) include a cooling curve for Alleghanian metamorphism in the eastern Virginia Piedmont. The fission-track data used by these authors (DURRANT, 1979) do not agree with our analyses. It is unclear why this discrepancy exists as DURRANT (1979) followed the established fission-track techniques of Naeser (1978). When the thermal decay curve for Alleghanian metamorphism based on $^{40}Ar/^{39}Ar$ analyses (Fig. 8 after GATES and GLOVER, 1989) has been reworked by plotting our data instead of Durrant's, the new cooling curve gives a more rapid cooling in the 150 to 250 Ma range. Thus, the cooling ages obtained using our fission-track analysis are quite consistent with the thermal-tectonic history for the eastern Virginia Piedmont as proposed by GATES and GLOVER (1989).

Conclusion

Consistently reset apatite (126 ± 9 to 200 ± 17 Ma) and zircon fission-track ages (164 ± 30 to 241 ± 33 Ma) from three widely separated Early Mesozoic Basins, the Deerfield and Hartford in Connecticut, the northern Newark in New Jersey, and the Taylorsville in Virginia, suggest a regionally pervasive thermal regime > 200 °C at ~200 Ma which cooled to ~100 °C at ~175 Ma. In the Hartford and Deerfield Basins, a combination of extensive basalt extrusion and diabase intrusion, hydrothermal fluid circulation, and higher paleogeothermal gradient as a result of lithospheric extension, caused the resetting of apatite and zircon fission-track clocks.

In the northern Newark Basin, consistent apatite fission-track ages suggest that cooling through 100 ± 20 °C occurred at approximately the same time throughout the analyzed stratigraphic interval from the Passaic Formation through the Boonton Formation. Limited zircon samples from the northwestern Newark Basin yield mixed ages indicating temperatures were not > 175–200 °C during the Early Jurassic.

In the Taylorsville Basin, the fission-track cooling ages on apatite and zircon give evidence on the low temperature cooling history which occurred as part of the tectono-thermal evolution of the Hylas zone, in the Virginia Piedmont. There is no indication of rapid cooling for the Taylorsville apatite samples based on their model tT histories as there was for some of the Hartford Basin apatite samples. Because there are only minor amounts of tholeiitic diabase dikes and no evidence exists for hydrothermal fluid circulation, the reset apatite and zircon fission-track ages must be the result of high paleogeothermal gradient during Triassic extension combined with post-Alleghanian metamorphism erosional unroofing.

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Appendix 1. Fission-track age data of apatites, Deerfield, Hartford, Newark and Taylorsville Basins, eastern U.S.

Number	Number of Grains	Track Density ($10^6/cm^2$) Standard	Fossil	Induced	Correlation Coefficient	Chi Square Probability (%)	Age (Ma)	Uranium (ppm)
DEERFIELD BASIN, CONNECTICUT								
D1	21	3.99	1.83	3.09	0.94	29	128± 7*	32
		(3086)	(713)	(1207)				
D2	4					60	130± 21	13
D3	19	4.07	0.74	1.38	0.94	43	118± 9	14
		(3086)	(287)	(540)				
HARTFORD BASIN, CONNECTICUT								
H1	18	1.55	0.87	1.68	0.76	15	138 ± 9	18
		(2249)	(474)	(910)				
H2	8	1.51	2.00	3.62	0.96	92	147 ± 10	31
		(12340)	(332)	(602)				
H3	19	4.48	0.91	1.39	0.97	90	174 ± 11	17
		(8525)	(462)	(703)				
H4	12	4.12	1.60	2.05	0.76	44	179 ± 20	21
		(2521)	(164)	(211)				
H5	20	4.16	1.17	1.77	0.91	28	155 ± 11	17
		(2521)	(434)	(654)				
H6	14	4.25	1.70	2.30	0.63	<1	166±12	23
		(2521)	(495)	(669)			*180 ± 12*	
H7	10	4.29	1.54	2.41	0.91	59	153 ± 12	23
		(2521)	(303)	(475)				
H8	18	4.34	1.32	2.38	0.81	22	135 ± 9	23
		(2521)	(443)	(798)				
H9	20	4.32	1.29	2.12	0.97	61	143 ± 8	24
		(3242)	(672)	(101)				
H10	20	4.36	1.12	1.70	0.97	89	156 ± 10	19
		(3242)	(557)	(843)				
H11	20	4.41	1.15	1.80	0.95	1	152±9	20
		(3242)	(575)	(904)			*166 ± 16*	
H12	22	4.45	1.02	1.60	0.94	58	154 ± 11	15
		(3242)	(408)	(637)				
H13	20	4.49	1.60	2.20	0.87	1	178±18	23
		(3242)	(624)	(857)			*177 ± 10*	
H14	20	4.54	1.51	2.32	0.98	81	160 ± 9.	22
		(3242)	(623)	(959)				
H15	22	4.58	1.33	2.36	0.97	77	140 ± 8	23
		(3242)	(627)	(1114)				
H16	11	4.62	1.40	3.28	0.92	48	107 ± 8	29
		(3242)	(273)	(641)				
H17	15	4.11	1.16	2.20	0.94	65	118 ± 9	22
		(3086)	(328)	(624)				
NEWARK BASIN, NEW JERSEY								
N1	20	2.05	1.37	2.59	0.82	9	137±8	29
		(8525)	(474)	(893)				
N2	19	1.46	0.821	1.67	0.86	70	126±9	24
		(10091)	(322)	(657)				
N3	20	4.41	0.667	1.13	0.58	79	153±17	10
		(8525)	(137)	(233)				
N4	20	1.48	0.598	1.05	0.76	85	148±16	13
		(10091)	(145)	(254)				

Number	Number of Grains	Track Density (10⁶/cm²) Standard	Fossil	Induced	Correlation Coefficient	Chi Square Probability (%)	Age (Ma)	Uranium (ppm)
N5	18	1.51	2.42	4.28	0.78	51	150±9	67
		(10091)	(433)	(764)				
N6	6	1.54	2.45	3.37	0.98	98	196±23	
		(12340)	(131)	(180)				
N7	17	1.55	0.664	1.12	0.93	85	161±12	14
		(12340)	(274)	(462)				
TAYLORSVILLE BASIN, VIRGINIA								
T1	20	3.93	3.13	4.24	0.90	65	172±9	76
		(3810)	(708)	(959)				
T2	18	3.97	1.00	1.35	0.84	30	174±10	34
		(3810)	(536)	(722)				
T3	14	3.99	1.35	1.91	0.98	99	167±18	27
		(3810)	(161)	(227)				
T4	20	4.01	1.09	1.44	0.89	30	180±10	21
		(3810)	(587)	(773)				
T5	10	1.29	2.13	2.39	0.84	25	200±17	25
		(6401)	(289)	(324)				
T6	20	3.81	1.37	2.27	0.86	30	137±9	39
		(2107)	(420)	(694)				
T7	10	1.31	1.47	2.53	0.91	88	135±9	26
		(6401)	(386)	(665)				
T8	20	4.53	1.29	2.58	0.92	50	135±7	40
		(10536)	(632)	(1260)				
T9	18	3.88	1.41	1.85	0.94	40	171±10	31
		(6401)	(538)	(706)				
T10	20	4.55	0.879	1.55	0.92	22	154±9	32
		(10536)	(466)	(819)				
T11	20	4.57	1.13	1.72	0.86	75	179±11	26
		(4633)	(469)	(712)				
T12	20	3.78	1.63	2.51	0.54	<1	146±8	44
		(2107)	(623)	(958)			*152±13*	
T13	20	4.55	0.810	1.27	0.90	70	171±11	16
		(6736)	(396)	(622)				
T14	20	3.80	1.41	2.17	0.73	1	146±8	37
		(2107)	(610)	(941)			*153±11*	
T15	20	4.55	0.794	1.16	0.61	30	185±13	17
		(4633)	(349)	(509)				
T16	20	3.76	0.671	0.851	0.90	99	175±15	11
		(2107)	(273)	(346)				

Mean ages are given in italics for samples which failed the chi-square test. Parentheses enclose the number of tracks counted. Standard and induced track densities measured in mica external detectors and fossil track densities on internal mineral surfaces. Ages calculated using the zeta method and standard glasses SRM612 and/or CN1. *± 1 sigma.

Appendix 2 Fission-track age data of zircons, Hartford, Newark and Taylorsville Basins, eastern U.S.

Number	Number of Grains	Track Density ($10^6/cm^2$) Standard	Fossil	Induced	Correlation Coefficient	Chi Square Probability (%)	Age (Ma)	Uranium (ppm)
HARTFORD, CONNECTICUT								
H1	10	0.239	0.855	2.73	0.21	<1	129±17	406
		(1006)	(316)	(101)			*167±30*	
H3	10	0.353	10.7	2.92	0.92	91	238±26	378
		(1296)	(438)	(120)				
H5	5	0.251	14.8	3.53	0.13	28	178±34	549
		(1006)	(159)	(38)				
H7	7	0.246	11.1	2.76	0.56	10	184±24	430
		(1006)	(343)	(85)				
H8	10	0.239	17.2	5.11	0.17	<1	137±17	835
		(1006)	(370)	(110)			*164±34*	
NEWARK BASIN, NEW JERSEY								
N2	10	3.07	1.46	2.97	0.89	99	252±37	377
		(1616)	(300)	(61)				
N5	7	3.50	1.58	2.71	0.58	85	338±60	302
		(1296)	(227)	(39)				
TAYLORSVILLE BASIN, VIRGINIA								
T3	12	3.57	1.21	3.34	0.56	73	217±27	370
		(1296)	(349)	(96)				
T6	7	3.01	1.45	3.20	0.38	9	229±38	415
		(1616)	(209)	(46)				
T8	10	3.64	1.23	3.99	0.69	40	188±21	466
		(1296)	(378)	(123)				
T10	10	3.46	9.62	2.31	0.96	94	241±33	285
		(1296)	(316)	(76)				
T12	10	3.71	1.13	4.04	0.47	<1	175±17	467
		(1296)	(536)	(191)			*186±25*	
T14	12	3.04	9.19	2.40	0.66	68	195±26	354

Mean ages are given in italics for samples which failed the chi-square test. Parentheses enclose the number of tracks counted. Standard and induced track densities measured in mica external detectors and fossil track densities on internal mineral surfaces. Ages calculated using the zeta method and standard glasses SRM612, CN1 and/or CN5. *± 1 sigma.