11-1993

Anomalous Mesozoic thermal regime, central Appalachian Piedmont: Evidence from sphene and zircon fission-track dating

B. P. Kohn
La Trobe University

M. E. Wagner
University of Pennsylvania

Tim M. Lutz
West Chester University of Pennsylvania, tlutz@wcupa.edu

G. Organist
University of Pennsylvania

Anomalous Mesozoic Thermal Regime, Central Appalachian Piedmont: Evidence from Sphene and Zircon Fission-Track Dating[1]

B. P. Kohn, M. E. Wagner[2], T. M. Lutz[3], and G. Organist[2]

Victoria Institute of Earth and Planetary Sciences, Department of Geology, La Trobe University, Bundoora, Victoria 3083, Australia

ABSTRACT

A total of 17 sphene and 45 zircon fission track ages (FTA) are reported from the Piedmont Province of Pennsylvania, Delaware, and Maryland, the Reading Prong of New Jersey, and the Newark Basin of Pennsylvania. With the exception of one sphene sample, FTA fall within a relatively restricted age range: sphene 190–217 Ma (average 199 Ma) and zircon 143–218 Ma (average 184 Ma). Near concordance of FTA over a large tract of crystalline basement (~20,000 km^2) and within Upper Triassic sediments in the Newark Basin indicates Late Triassic-Early Jurassic total resetting of the fission track clocks followed by regional cooling between sphene (~275 ± 25°C) to zircon (~220 ± 40°C) closure temperatures at rates of ~4–8°C/Ma. Fourteen Rb-Sr whole rock-mica ages, together with previously reported $^{40}Ar/^{39}Ar$ biotite and hornblende ages, generally indicate no regional Mesozoic resetting. Thus, the maximum temperature experienced by the samples was ~300°C. Sphene FTA closely match ages of ~201 Ma for Early Jurassic magmatism in the Newark Basin; hence the thermal event was probably associated with this activity. However, since most of the basement is largely devoid of such igneous rocks, the thermal effect of magmatism alone may not have been responsible for the total resetting of the FT clocks. In this respect, the role of possible regional geotherm elevation related to rift-related lithospheric thinning in Late Triassic time requires further investigation. The FTA, taken together with previously reported denudation history and thermal modeling of the Newark Basin, suggests that the thermal event proceeded under paleothermal gradients of ≥55–60°C/km. The zircon FTA pattern suggests that non-uniform cooling occurred between blocks bounded by reactivated Paleozoic faults.

Introduction

Fission track (FT) studies can provide important constraints in reconstructing thermotectonic histories at rifted continental margins (e.g., Gleadow and Brooks 1979; Kohn and Eyal 1981; Moore et al. 1986; Fitzgerald and Gleadow 1988; Omar et al. 1989). Such studies have principally concentrated on dating of apatites, because they are sensitive recorders of thermal effects typically experienced by rocks exposed in flank uplifts during rifting events (temperatures in the range of ~60–130°C). Recent developments integrating confined track length measurements and apatite ages have considerably extended the application of fission track research, allowing a more rigorous interpretation of thermal histories (e.g., Gleadow et al. 1986).

Scant attention has been paid to the possible thermal effects at rifted margins on the higher temperature sphene and zircon FT clocks, which may record older events not retained by the lower temperature sensitive apatites (e.g., Gleadow and Brooks 1979; Fitzgerald and Gleadow 1988; Kohn et al. 1988*a*, 1988*b*). The reasons are: (1) in most cases apatite FT studies suggest that rocks exposed near rift margins did not experience high enough temperatures to affect the sphene and zircon FT clocks significantly and (2) the temperature ranges and kinetics of track annealing in the two minerals are not well understood (e.g., Brandon and Vance 1992).

We report here the results of a sphene and zircon FT study, mainly on Precambrian-Paleozoic crystalline rocks of the central Appalachian Piedmont

[1] Manuscript received August 12, 1992; accepted April 13, 1993.

[2] Dept. of Geology, University of Pennsylvania, Philadelphia, PA 19104.

[3] Dept. of Geology and Astronomy, West Chester University, West Chester, PA 19383.

[The Journal of Geology, 1993, volume 101, p. 779–794] © 1993 by the University of Chicago. All rights reserved. 0022-1376/93/10106-005$1.00

(figure 1). Apart from sediments in Late Triassic-Early Jurassic rift basins that formed at the westernmost limit of Mesozoic continental break-up, the study area contains no stratigraphic or structural record of its post-Paleozoic geologic history. The FT data, combined with 14 new Rb-Sr mica ages, provide important constraints on the rift-related thermal regime and cooling history of this region and indicate the potential for similar investigations in basement flanks at other rift margins.

Regional Geology

Samples were collected from the Piedmont province of Pennsylvania, Delaware, and Maryland, the Reading Prong of Pennsylvania and New Jersey, and the Newark Basin of Pennsylvania (figure 1).

Piedmont Province. The Piedmont province is thought to have been the site of plate collision, probably between a magmatic arc and the North American continent during the Taconic orogeny in late Ordovician time (Crawford and Mark 1982; Muller and Chapin 1984; Wagner and Srogi 1987). The oldest rocks, gneisses of Grenville age (~1100 Ma), are exposed in fault blocks and nappes in southeastern Pennsylvania and the Baltimore area of Maryland (figure 1). The rocks overlying the Grenville gneisses range in age from latest Precambrian to Ordovician and were metamorphosed at the end of the Ordovician during the Taconic orogeny. They are dominantly quartzites, marbles and pelitic phyllites and schists. In figure 1 and 2 we have informally referred to all of these rock as undifferentiated Paleozoic rocks.

The Wilmington Complex of Delaware and Pennsylvania, and the James Run Formation and Baltimore Mafic Complex of Maryland all have affinities with continental magmatic arcs or possibly island arcs (Sinha et al. 1980; Wagner and Srogi 1987). Igneous rocks from these complexes have yielded Cambrian and earliest Ordovician ages (Foland and Muessig 1978; Shaw and Wasserburg 1984; Sinha et al. 1989).

The Grenville gneisses have all been affected to varying degrees of Taconic metamorphism (Wagner and Crawford 1975; Crawford and Hoersch 1984; Muller and Chapin 1984; Wagner and Srogi 1987; Hoersch and Crawford 1988). In the Honey Brook Upland, however, $^{40}Ar/^{39}Ar$ hornblende ages of 878 and 889 Ma and biotite ages of 848 and 737 Ma have been interpreted to indicate slow cooling from Grenville metamorphism, with no later disturbance (Sutter et al. 1980). A third sample near the southern margin of the Honey Brook Upland gives a biotite age of 403 Ma, and the hornblende is highly "disturbed" having lost argon post ~500 Ma.

The highest-grade Paleozoic metamorphism was in southeastern Pennsylvania and northern Delaware, where the Wilmington Complex was metamorphosed to granulite facies, probably during the Cambrian before intrusion of the ~502 Ma Arden pluton (Foland and Muessig 1978; see Wagner and Srogi [1987] for a discussion of interpretation of age data in the Wilmington Complex). The Precambrian gneisses of the West Chester Prong show evidence of a high-pressure (9–11 kb) Taconic overprint on Grenville assemblages (Wagner and Crawford 1975; Wagner and Srogi 1987). Bounding the West Chester Prong on the north is the Cream Valley fault (figure 2), which separates amphibolite-facies rocks and high pressure granulite-facies rocks on the south from greenschist-facies ones on the north.

In the Baltimore area, the Grenville gneisses are at amphibolite grade, believed by Muller and Chapin (1984) to be the result of Taconic metamorphism. Near the Susquehanna River, approximately halfway between the exposures of Grenville gneiss in Pennsylvania and those in the Baltimore area, the metamorphism is lower grade, greenschist and epidote-amphibolite facies. The intensity of metamorphism decreases toward the northwest in both areas.

The pattern of early Paleozoic metamorphism suggests that the deepest levels of crust are exposed in southeastern Pennsylvania (West Chester Prong) and that along strike the shallowest levels occur near the Susquehanna River, whereas rocks subjected to the highest temperature are in northern Delaware and adjacent parts of Pennsylvania. There is a general decrease in intensity of metamorphism toward the northwest, gradual in places, abrupt in others (i.e., the Cream Valley fault), indicating that generally shallower levels of crust are exposed in the northwest than in the southeast. Although there is post-Taconic, possibly Alleghanian deformation in the rocks of the Piedmont (Wagner et al. 1991), there is very little evidence for any Alleghanian metamorphism. Most mineral ages (e.g., many Rb/Sr ages on muscovite and biotite, this study) are interpreted as post-Taconic metamorphism cooling ages.

Reading Prong. The Reading Prong is underlain by gneisses of Grenville age. Although these rocks have been affected by Paleozoic tectonism (Drake 1969, 1970), they differ from the Grenville gneisses of the Piedmont province in that they were unaffected by Paleozoic metamorphism west of the Hudson River. $^{40}Ar/^{39}Ar$ ages on hornblende and

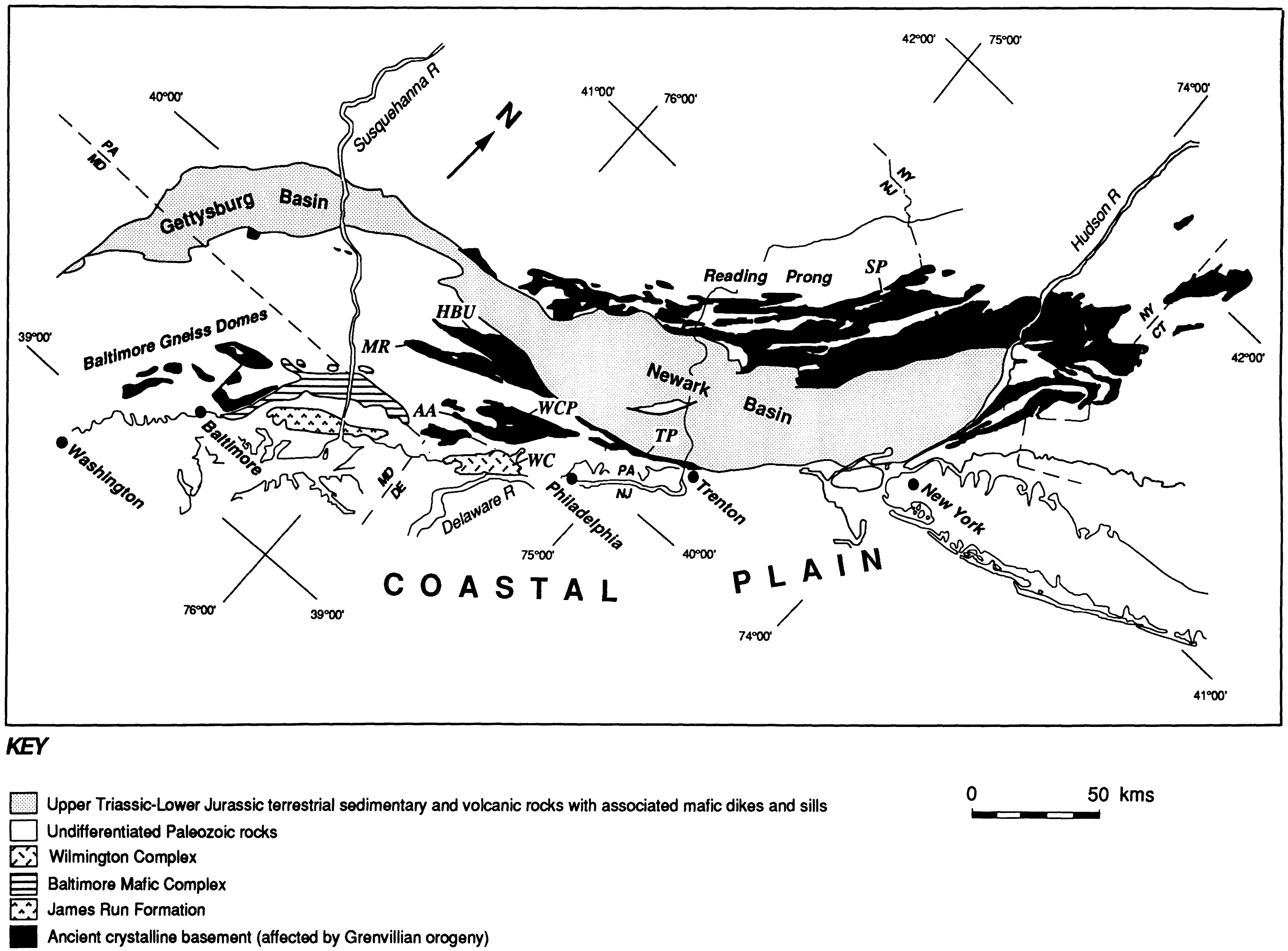

Figure 1. General locality map. WCP = West Chester Prong; AA = Avondale Anticline; MR = Mine Ridge; WC = Wilmington Complex; HBU = Honey Brook Upland; TP = Trenton Prong. SP = location of sphene sample, SP-1 (see table 1).

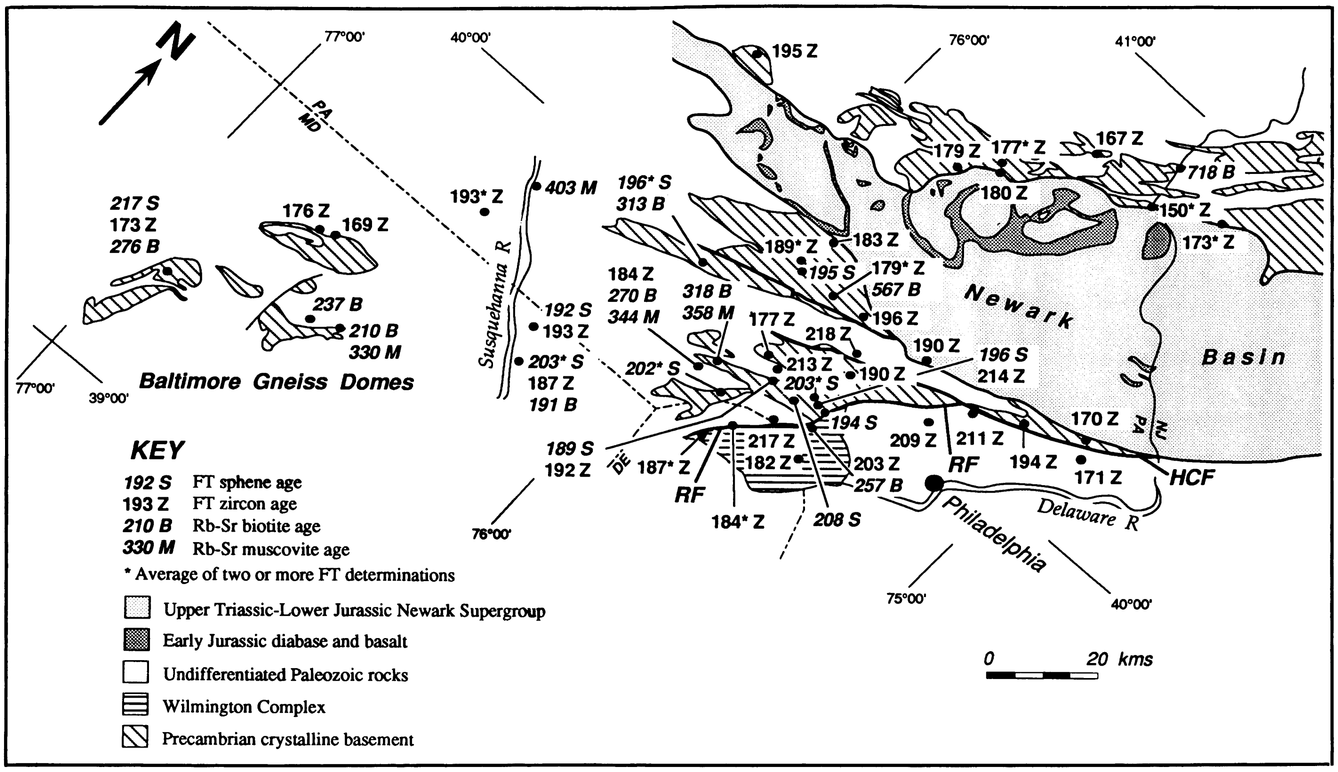

Figure 2. A real distribution of sphene and zircon fission track and Rb-Sr data. HCF = Huntingdon Valley-Cream Valley Fault; RF = Rosemont Fault. Lower Paleozoic quartzites, carbonates, phyllites and schists = undifferentiated Paleozoic rocks.

biotite reflect cooling from Grenville metamorphism west of the Hudson River (biotite 769–780 Ma; hornblende 800–940 Ma), whereas east of the Hudson, these minerals have been reset (biotite 382–393 Ma; hornblende 423–472 Ma) during Taconic (~480 Ma) metamorphism (Dallmeyer and Sutter 1976).

Newark Basin. The Newark Basin, thought to have formed during initial stages of early Mesozoic opening of the Atlantic Ocean, is a half-graben filled with ~6–8 km of Upper Triassic-Lower Jurassic non-marine sediments of the Newark Supergroup (Van Houten 1977; Olsen and Kent 1990) interlayered with Early Jurassic tholeiitic basalt flows intruded by numerous tholeiitic diabase dikes and sills. The best known intrusion is the Pallisades Sill. The basin trend generally parallels that of the Paleozoic structures, and there is strong evidence for reactivation of ancient thrust faults during its formation (Swanson 1986; Ratcliffe et al. 1986). The northwest margin of the graben is bounded by normal faults. A basin filling model with fault-controlled subsidence as the dominant mechanism has been proposed by Schlische and Olsen (1990).

Experimental Methods

Fission Track Dating. Samples weighing 2–3 kg were crushed and the heavy minerals were concentrated using a Wilfley Table. Sphenes and zircons in the 63–250 μm size range were separated using standard magnetic and heavy liquid techniques. Sphene commonly occurs in amphibolites and the more basic lithologies. It was recovered from only one Reading Prong sample. Though zircon grains were recovered from most samples, many grains proved to be metamict. Sphene and zircon concentrates were mounted in FEP teflon discs, ground and polished to an optical finish. Sphenes were etched in a solution of $6H_2O{:}3HCl{:}2HNO_3{:}1HF$ by volume (Naeser and McKee 1970) at room temperature for periods ranging from 5–30 minutes. Zircons were etched in an eutectic KOH-NaOH melt at 220°C (Gleadow et al. 1976). In order to obtain a high quality etch, each sample required a different etching period; this ranged from 5–23 hrs. Neutron irradiations were carried out in the well thermalized (high thermal/fast neutron flux ratio) RT-4 facility of the National Institute of Standards and Technology (NIST, formerly National Bureau of

Standards) reactor at Gaithersburg, Maryland. FTA were measured using the external detector method with Brazil Ruby muscovite used to record induced tracks (Gleadow 1981). The muscovite detectors were etched for 30 minutes in 48% HF at room temperature to reveal the induced tracks. Thermal neutron fluences were monitored by measuring the track density in muscovites attached to NIST SRM-962a and Corning glass CN-1 for sphene dating. The same standards, together with Corning glass CN-2, were used for zircon dating. In order to detect neutron flux gradients, grain mounts were distributed between three standard glasses along each of the five irradiation cans used in this study. As an additional check on accuracy, standard sphene from the Mt. Dromedary igneous complex (98.7 ± 0.6 Ma, see references in Green 1985) and zircon from the Fish Canyon Tuff (27.79 ± 1.4 Ma: Kunk et al. 1985) were dated (see table 1, which may be obtained from *The Journal of Geology* upon request, free of charge). In some cases samples were dated twice as a check on the precision of the calculated ages (see table 1). Counting was carried out with a transmitted light polarizing microscope using a dry ×80 objective at a total magnification of ×1250. Only tracks on grains with sharp polishing scratches were counted. Ages were calculated using the zeta calibration method, following procedures described by Hurford and Green (1983) and Green (1985). To correct for the difference between track registration geometries of sphene and zircon, internal surfaces, and the external muscovite detector, a factor of 0.5 was used (Gleadow and Lovering 1977). Errors were calculated using the "conventional method" of Green (1981) and are expressed as one standard deviation (table 1).

Rb-Sr Dating. Samples for Rb-Sr analysis were whole rocks, and biotite and muscovite grains separated from them by standard procedures. Weathered or discolored minerals were discarded. Isotope dilution measurements for Rb and Sr and $^{87}Sr/^{86}Sr$ analyses were made on samples of about 100 mg. After a mixed ^{87}Rb-^{84}Sr spike was added to each sample, Sr was separated by ion exchange chromatography. Both the Rb and Sr sample solutions were mounted on single Ta filaments for analysis.

Rb isotope dilution measurements were made on a Micromass MM30 single collector mass spectrometer; Sr measurements were made on a VG354 five collector mass spectrometer operating in a peak switching mode. Monitoring of mass 85 showed that contamination of Sr samples with ^{87}Rb did not occur. All Sr measurements were normalized to an $^{86}Sr/^{88}Sr$ ratio calculated for a mixture of spike Sr and normal Sr with an $^{86}Sr/^{88}Sr$ ratio of 0.1194. The precision of the $^{87}Sr/^{86}Sr$ ratio measurements is variable and is related inversely to the $^{87}Sr/^{86}Sr$ ratio and the concentration of Sr in the samples (table 2). Three analyses of SRM 987 run with the samples yield an average of 0.71026 ± 0.00002 (1σ).

Ages were calculated from analyses of rocks and micas assuming a two-point isochron relationship (table 2). Analytical uncertainties > ± 1% on some biotite analyses are coupled with $^{87}Rb/^{86}Sr$ ratios (>200) and $^{87}Sr/^{86}Sr$ ratios (>1.5) so that the ages are not likely to be strongly affected by the imprecision.

Fission Track Dating Results and Interpretation

Fission-track age data are presented in table 1. Sixteen sphene FTA range from 190–217 Ma (mean = 199 Ma) and show little regional variation. The seventeenth, sphene sample SP-1 from the Reading Prong (figure 1), yielded an age of 450 ± 15 Ma. Forty-five zircon FTA range from 143 to 218 Ma (mean = 184 Ma) and the older ages centered in the vicinity of the West Chester Prong and Avondale Anticline (figure 1–2).

A clearer picture of the sphene and zircon FT data can be obtained by consideration of the single grain age distributions (Hurford et al. 1984; Seward and Rhoades 1986). Single sphene and zircon grain age distributions of individual grains in representative samples from different parts of the study area are presented in figure 3 and 4 respectively. Two types of distribution diagrams are presented, those in the left-hand column show radial plots (Galbraith 1990) while those in the right hand column are histograms of single grain age distributions with a smoothed probability function (Hurford et al. 1984). For radial plots, the slope of a straight line from the origin (0) is equivalent to the FTA read off radially around the perimeter of the plot on a logarithmic scale. The abscissa measures in percent the reciprocal of the standard error. To farther to the right a point falls along the axis, the more precise the individual grain age. Grains belonging to a single age population should scatter within the ± 2σ age range shown on the Y axis and be reflected by the chi square statistic (see table 1). The sphene and zircon FT data (figures 3–4) are characterized by: (a) "mean" crystal ages falling within relatively restricted age ranges 195–210 Ma (sphenes and 165–190 Ma (zircons), and (b) most single grain data exhibiting relatively tight, unimodal distributions with high chi square probabilities. In all cases the FTA are markedly younger than the known crystallization or metamorphic

Table 2. Rb-Sr Analytical Data and Ages for Whole Rock and Micas from the Central Appalachian Piedmont

Sample number	Rock type	Location Long. (W)	Location Lat. (N)	General locality	USGS 7.5′ Quad.	Phase analyzed[a]	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$[b]	$^{87}Sr/^{86}Sr_0$	Age[c] (Ma)
5-2-4	Mica gneiss	75°44′20″	39°51′50″	Avondale Anticline	Kennett Square	R	129	112	3.337	.74245 (20)		
						M	232	24.4	27.95	.8678 (20)		
						B	535	3.9	487.1	2.930 (130)		
						R,B					.727	318
						R,M					.725	358
5-2-5	Micaceous quartzite	75°46′45″	39°49′25″	Avondale Anticline	West Grove	R	169	51	9.660	.79444 (58)		
						M	219	19.6	32.9	.9081 (30)		
						B	586	2.2	1113	5.037 (530)		
						R,B					.757	270
						R,M					.747	344
11196	Schist	72°28′05″	39°52′30″	Wilmington Complex	Media	R	79	204	1.123	.72128 (13)		
						B	507	37.6	39.63	.86232 (125)		
						R,B					.717	257
8-3-2	Felsic gneiss	75°37′40″	40°04′25″	Honey Brook Upland	Downingtown	R	43	808	0.154	.70555 (3)		
						B	357	47.3	22.23	.8841 (1)		
						R,B					.704	567
10-25-1A	Biotite gneiss	75°35′10″	39°58′55″	Mine Ridge	Parkesburg	R	66.9	641	0.3018	.70810 (3)		
						B	268	40	19.54	.79366 (83)		
						R,B					.707	313
12-11-4A	Biotite-rich gneiss	75°11′40″	40°39′40″	Reading Prong	Easton	R	148	280	1.532	.72359 (8)		
						B	598	22.5	83.37	1.5623 (81)		
						R,B					.708	718
5-17-3	Granodiorite	76°07′50″	39°37′05″	Susquehanna River	Aberdeen	R	67.7	111	1.765	.72174 (25)		
						B	1195	5.5	756.8	2.770 (83)		
						R,B					.717	191
6-11-3	Massive chlorite-rich rock	76°21′50″	39°53′30″	Susquehanna River	Conestoga	R	78	126	1.793	.73125 (16)		
						M	313	150	6.077	.75583 (17)		
						R,M					.721	403
MD85-1C	Micaceous quartzite	76°29′10″	39°27′25″	Baltimore Gneiss Domes	White Marsh	R	63.9	69.9	2.651	.73424 (43)		
						M	241	16.4	43.42	.9258 (35)		
						B	525	5.3	312.0	1.6566 (405)		
						R,B					.726	210
						R,M					.722	330
MD85-2	Mica schist	76°33′00″	39°26′15″	Baltimore Gneiss Domes	Towson	B	415	5.7	222.7	1.4918 (305)		
						B						237[d]
MD85-5	Migmatitic gneiss (Woodstock Dome)	76°52′20″	39°32′25″	Baltimore Gneiss Domes	Ellicott City	R	98	192	1.480	.73618 (15)		
						R	424	6.0	224.3	1.6114 (339)		
						R,B					.717	257

[a] R = whole rock; M = muscovite; B = biotite;
[b] The precision of the $^{87}Sr/^{86}Sr$ ratio measurements is given by numbers in brackets which indicate the uncertainties (at the 1 s.d. level) in the last given digit/s of the $^{87}Sr/^{86}Sr$ ratio.
[c] Ages calculated using an ^{87}Rb decay constant of $1.42 \times 10^{-11} y^{-1}$. Initial ratios, $^{87}Sr/^{86}Sr_0$ are intercepts of two-point isochrons.
[d] Model age based on assumed $^{87}Sr/^{86}Sr_0$ ratio of 0.725, which is typical of similar rocks.

ages of their host rocks. Similarly, zircons from Upper Triassic sediments, at the base of the section in the Newark Basin, yield FTA younger than their depositional age.

Fading of fission tracks in minerals is mainly due to heating near or above the closure temperature, whereas other factors such as pressure, shock, deformation, fluids and weathering have little or no effect on the track annealing process (Fleischer et al. 1965; Gleadow and Lovering 1974). In slowly cooled terrains, sphene FTA are usually older than coexisting zircons and sometimes concordant with K-Ar biotite ages (e.g., Harrison et al. 1979; Fitzgerald and Gleadow 1988). Although not well constrained, values reported for the effective closure temperature (i.e., the temperature of the sample at the time recorded by the FTA) are ~275 ± 25°C for sphene (Fitzgerald and Gleadow 1988 and references therein) and ~220 ± 40°C for zircon (see Hurford, 1986 and Brandon and Vance 1992 and references therein).

Levine (1986) reported burial depths during the Alleghanian orogeny of 6–9 km under a paleothermal gradient of ~33°C/km for coal-bearing strata in the Anthracite region of eastern Pennsylvania, to the north of the study area. Beaumont et al. (1988) and Jamieson and Beaumont (1988) hypothesised post-Alleghanian denudation of 8–12 km over the study area. However, the possibility that the FTA could be interpreted as transient points on a regional cooling curve during post-Alleghanian unroofing is ruled out by the concordance of zircon FTA from the crystalline basement and the Upper Triassic strata of the Newark Series; 190 ± 10 Ma from the basal conglomerate of the Stockton Fm (sample 4014, table 1), and 187 ± 36 Ma from the Passaic Fm (Roden and Miller 1989*a*). The general concordance of the FT data from a large area of crystalline basement enclosing the Newark Basin and from its basal sedimentary infill provides strong evidence for total resetting of the sphene and zircon FT clocks during a Late Triassic-Early

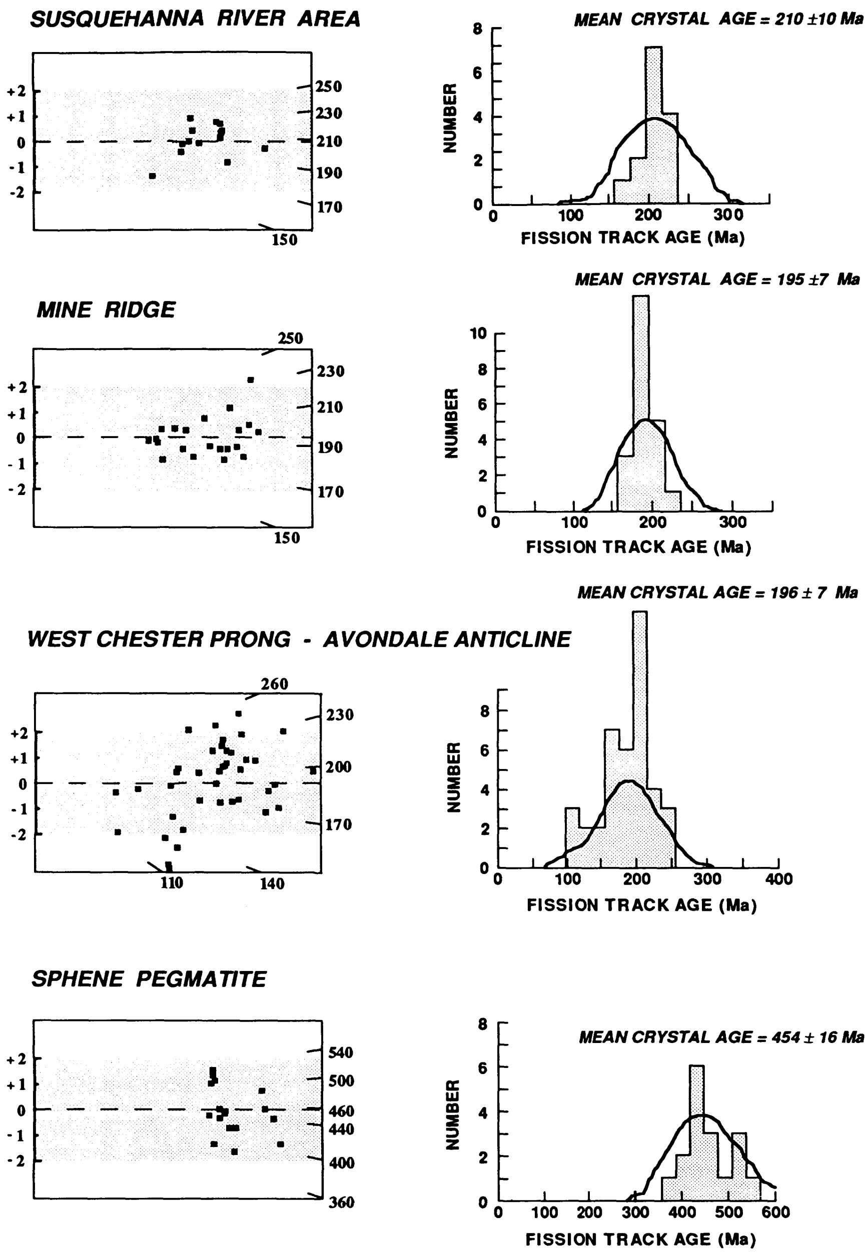

Figure 3. Radical plots of single grain age data (left) and single grain age distributions (right) for sphenes from different parts of the study area. Plot shows "pooled" data and mean crystal ages for all sphene grains dated in a particular area. Shading in radial plots indicates the $\pm 2\sigma$ range about the mean age. The relatively tight unimodal distributions of the ages for the top three plots indicate Early Jurassic cooling following total resetting of the sphene FT clocks. See table 1 for details of samples and text for further discussion of radial plots.

Jurassic regional thermal event. The Stockton Fm, the oldest formation in the Newark Basin, was deposited at ~224–228 Ma, placing a maximum constraint on the age of the event. Resetting was followed by regional cooling from sphene to zircon closure temperatures at rates of ~4°–8°C/Ma (this range takes into account errors cited for closure temperatures above), during the times indicated by the ages.

Relatively young zircon FTA ranging from 143–162 Ma were determined on two different lithologies at the same locality (samples 12-11-5A and 5B—table 1, figure 2) in the Reading prong. The samples may have been disturbed by localized hot fluids in the vicinity of the border fault. Sphene SP-1 from the Reading Prong (figure 1 and table 1) yields an age of 450 ± 15 Ma, indicating no Mesozoic resetting. This sample, located some 150 km NE of the other sphene samples, delineates the northwestern extent of the thermal anomaly and requires further investigation.

Rb-Sr Dating Results and Interpretation

Rb-Sr age data are presented in table 2. Four Rb-Sr muscovite ages range from 330 and 403 Ma and 10 Rb-Sr biotite ages from 191 to 718 Ma. Muscovite ages exceed biotite ages wherever these minerals were obtained from the same rock. In a single case (MD85-2), an age was calculated from a biotite

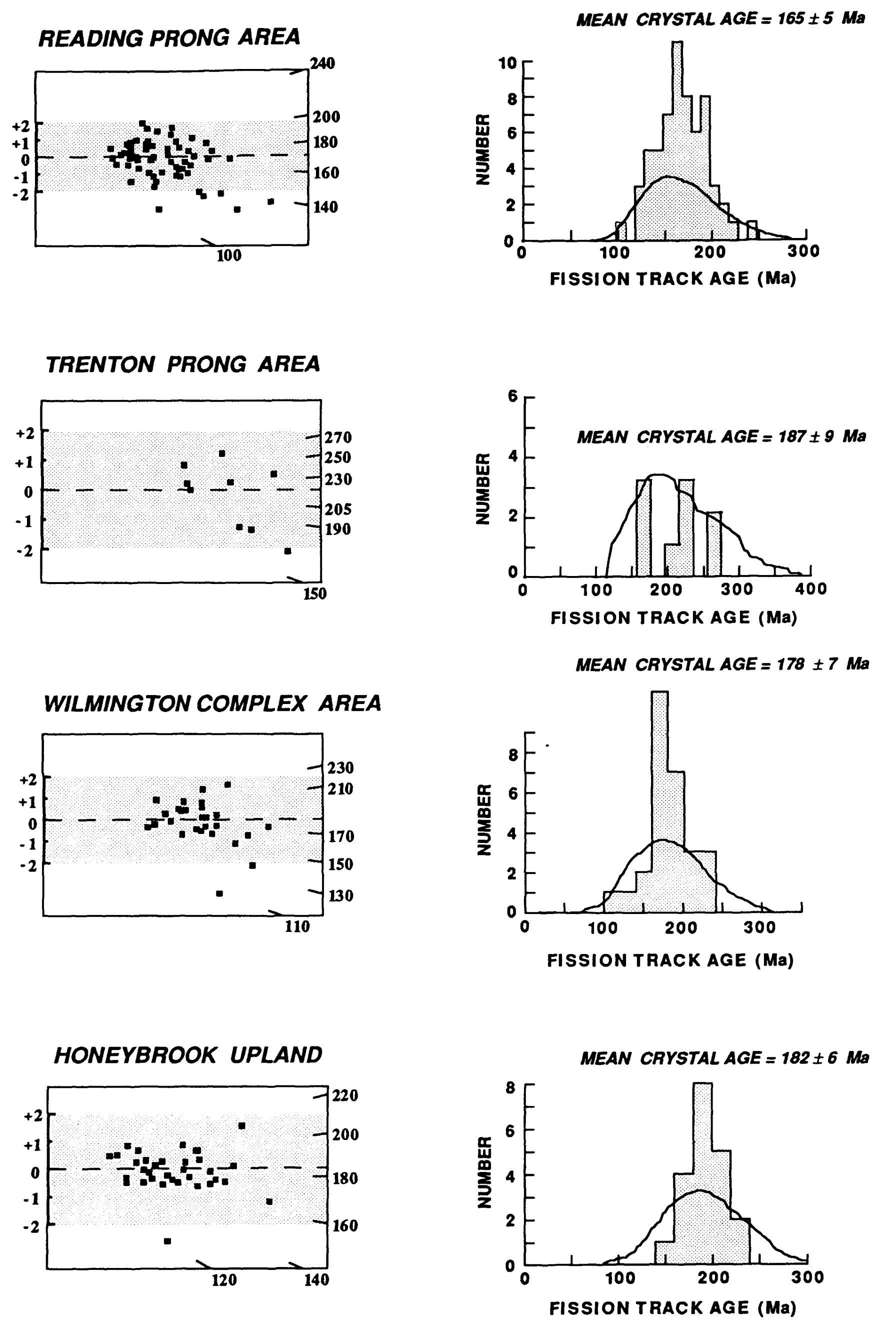

Figure 4. Radial plots of single grain age data (left) and single grain age distributions (right) for zircons from different parts of the study area. Plots show "pooled" data and mean crystal ages for grains from representative samples in a particular area. With the exception of the Trenton Prong, the relatively tight unimodal distributions of the ages indicate Early Jurassic cooling following total resetting of the zircon FT clocks. The mean zircon FTA for the Trenton Prong is similar to that for other areas but because relatively few grains were measured the data do not form a tight, unimodal distribution. See table 1 for the details of samples and text for further discussion.

measurement and an assumed initial ratio of 0.725, which seems to be typical of similar rocks from the same area. The Rb-Sr biotite data of 313 Ma from Mine Ridge is similar to biotite ages to the southeast in the Avondale Anticline area (figure 1).

Rb-Sr ages of micas from Paleozoic schists and Preambrian gneisses of the Southern Piedmont Upland are markedly younger than Rb-Sr biotite ages from the Honey Brook Upland and the Reading Prong (figures 1–2 and table 2). The Rb-Sr data broadly confirm previously reported dates that indicate little disturbance of Rb-Sr and $^{40}Ar/^{39}Ar$ systems in the Reading Prong and Honey Brook Upland during the Paleozoic. These data are consistent with the age pattern reported in a study of $^{40}Ar/^{39}Ar$ hornblende and biotite age spectra by Sutter et al. (1980). We conclude that the terrane south of the Honey Brook Upland, including Mine Ridge (figure 1), was strongly affected by Paleozoic metamorphism. By contrast, ages from the Honey Brook Upland and the Reading Prong reflect cooling ages following the Grenville Orogeny and show no apparent subsequent disturbance during Paleozoic polyphase metamorphism. Sphene and zircon FTA do not show the same regional discordances revealed by the Rb-Sr and $^{40}Ar/^{39}Ar$ data. Hence,

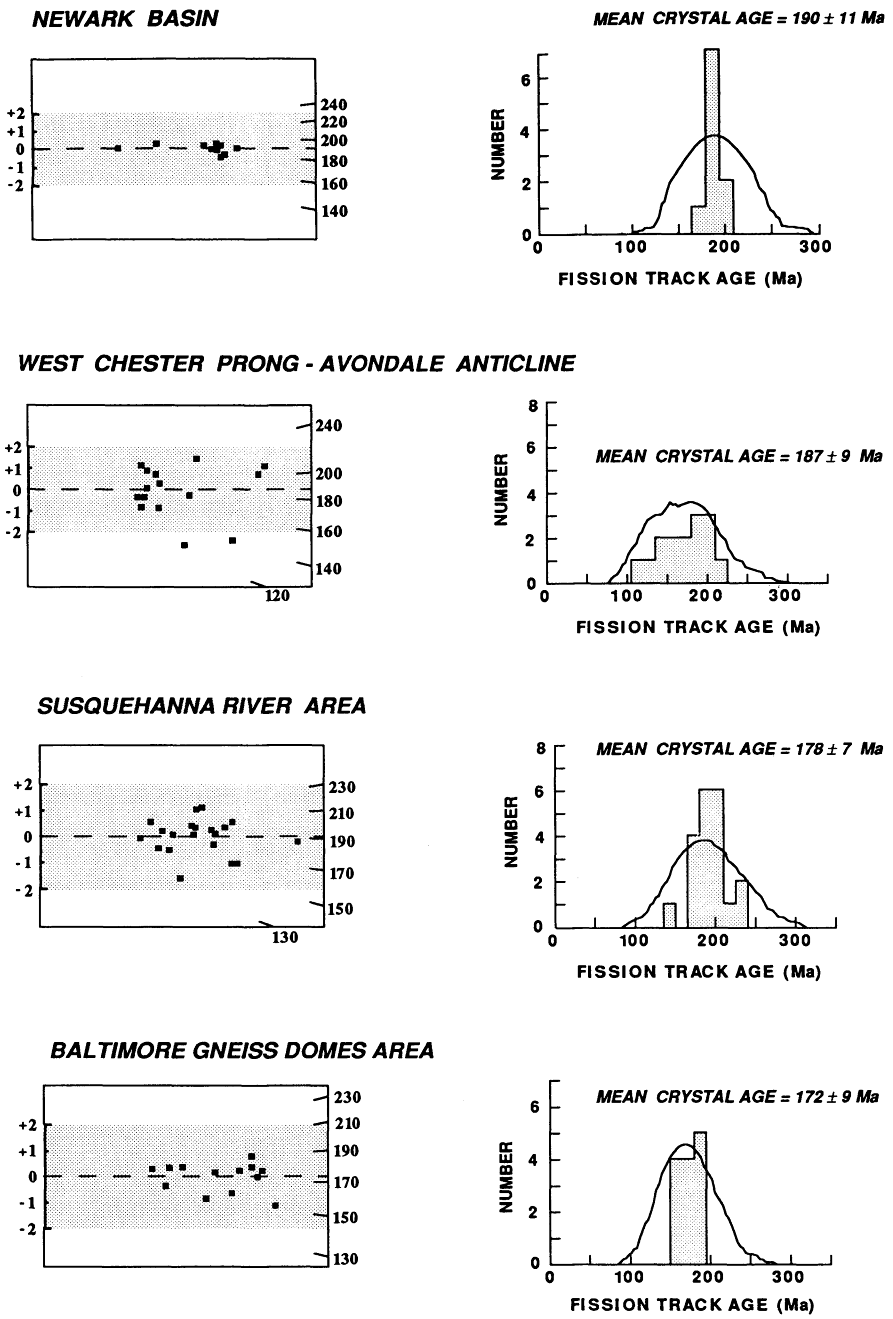

Figure 4. (*Continued*)

we conclude that Mesozoic temperatures experienced by rocks presently outcropping in the study area were ≪Rb-Sr muscovite blocking temperature ~500° ± 50°C (e.g., Wagner et al. 1977) and for the most part <Rb-Sr biotite closure temperatures, variously estimated, depending on cooling rates, at >300°C (Hanson and Gast 1967), 300° ± 50°C (Wagner et al. 1977), 320° ± 40°C (Harrison et al. 1979) and 280°C ± 40°C (Harrison and McDougall 1980). For the present study we adopt a value of ~300°–320°C for the closure temperature of Rb/Sr biotite.

Two Rb-Sr biotite ages (i.e., samples 5-17-3 and MD-85-1, table 2) deviate from the regional trend and within experimental error are close to the sphene and zircon FTA. The biotites may have been reset due to localized environmental factors, e.g., hydrothermal fluids, during the regional Mesozoic heating. Despite the above exceptions, we conclude that, in general, presently exposed central Appalachian Piedmont rocks attained Late Triassic-Early Jurassic maximum temperatures exceeding the effective closure temperature of sphene (~275 ± 25°C) and ≤Rb-Sr biotite closure temperature (~300°320°C). The proposed regional pattern of cooling history based on all available radiometric data is shown schematically in figure 5.

Independent Evidence for Heating of the Newark Basin

Evidence for high heat flow within the Newark Series of the Newark Basin is indicated by a number of independent studies. (a) An illite crystallinity study by Bermingham (1989) has shown that the lower sediments in the basin have been subjected to anchizone metamorphism ~300°C. The high degree of illite crystallinity is widespread and bears no relationship to proximity to diabase intrusions or basalt flows. (b) Base metal mineralization and hydrothermal minerals, including barite, zeolites and hematite cements are common throughout the basin. The former are associated with the Early Jurassic intrusions or faults and fractures, while the latter are commonly found as infillings within fracture systems. Studies of the mineralization indicate their association with 100°–250°C brines (Gray 1988; Robinson and Woodruff 1988). (c) Organic geochemical studies by Pratt and Burruss (1988), Pratt et al. (1988), and Katz et al. (1989) indicate that the levels of maturity of the Triassic section are greater than could be explained by conductive heat transfer alone, while Jurassic shales are mature to immature. (d) $^{40}Ar/^{39}Ar$ data of K-feldspars from granophyres and contact zones of database sheets emplaced ~201 Ma yield plateau ages of 175–178 Ma, which may date a hydrothermal heating pulse within the basin (Sutter 1988). (e) Paleomagnetic data reported from the lower sediments in the basin are interpreted as indicating an intense secondary magnetization representing a chemical component with blocking temperatures between ~300°–680°C, which was acquired relatively rapidly at ~175 Ma (Witte and Kent 1989).

Studies (b–e) have been used to argue for a discrete heating pulse during a hydrothermal event within the basin (Sutter 1988; Karner et al. 1990). A hydrothermal mechanism is unlikely to have caused the observed regional resetting, because it would require that fluids simultaneously reset crystalline masses at distances up to 60 km from the Newark Basin (figure 2). However, some of the zircon FT data, especially when considered at the 2σ error level, could reflect localized resetting and cooling associated with a hydrothermal event at ~175 Ma which overprinted the earlier regional resetting postulated above. In such a case, it would not be possible to resolve the two discrete events by FT dating alone.

Discussion

The regional thermal event could have resulted from either of two fundamental processes or a combination of both: (1) lithospheric thinning during the early stages of Mesozoic rifting and basin formation in Late Triassic Time, or (2) Early Jurassic tholeiitic magmatism within the Newark Basin and other Mesozoic rift basins.

During Mesozoic rifting, eastern North America was the site of a large thermal dome associated with extension and crustal thinning that subsequently subsided as sea-floor spreading and cooling occurred (e.g., Watts and Stecker 1979). The study area is located several hundreds of kilometers west of that site. A gravity modeling study by Bell et al. (1988) indicated that extension of the Newark Basin was small (<10 km) and could not have caused or been directly associated with a significant thermal event. Such a small amount of extension was probably too low to produce basaltic magma by decompression melting of the upper mantle (White et al. 1987), posing problems for the origin of the Early Jurassic magmatism. Bell et al. (1988) proposed that the magma could have had a source external to the basin, which would also explain the lack of a significant thermal subsidence phase in the basin. An alternative explanation (Nelson 1992) raised the possibility that the time interval between Alleghanian lithospheric delamination and collapse and onset of Triassic rifting may have been sufficiently short to prevent the lithosphere from becoming fully reestablished; hence the lower than normal amount of Triassic extension may have been sufficient to initiate melting on an already relatively thin, hot, lithosphere.

Lack of a thermal subsidence phase in the Newark Basin is also evident from zircon FTA by Roden and Miller (1991) of 338 ± 60 Ma for the youngest sedimentary unit in the Newark Basin, the Lower Jurassic Boonton Fm, with a depositional age of ~198–199 Ma (Schlische and Olsen 1990). The zircon FTA, located near the basin depocenter, is interpreted as an undisturbed detrital age (Roden and Miller 1991). This interpretation suggests that temperatures did not exceed ~220°C during the Early Jurassic in the uppermost units preserved in the northern Newark Basin. This finding is in accordance with the marginally mature to immature nature of the formation indicated by vitrinite reflectance studies (Pratt et al. 1988 and Katz et al. 1989). These workers estimated some 2–3 km of post-Boonton Fm section had been eroded from the Newark Basin. This estimate was confirmed by the thermal history modeling of the basin by Huntoon

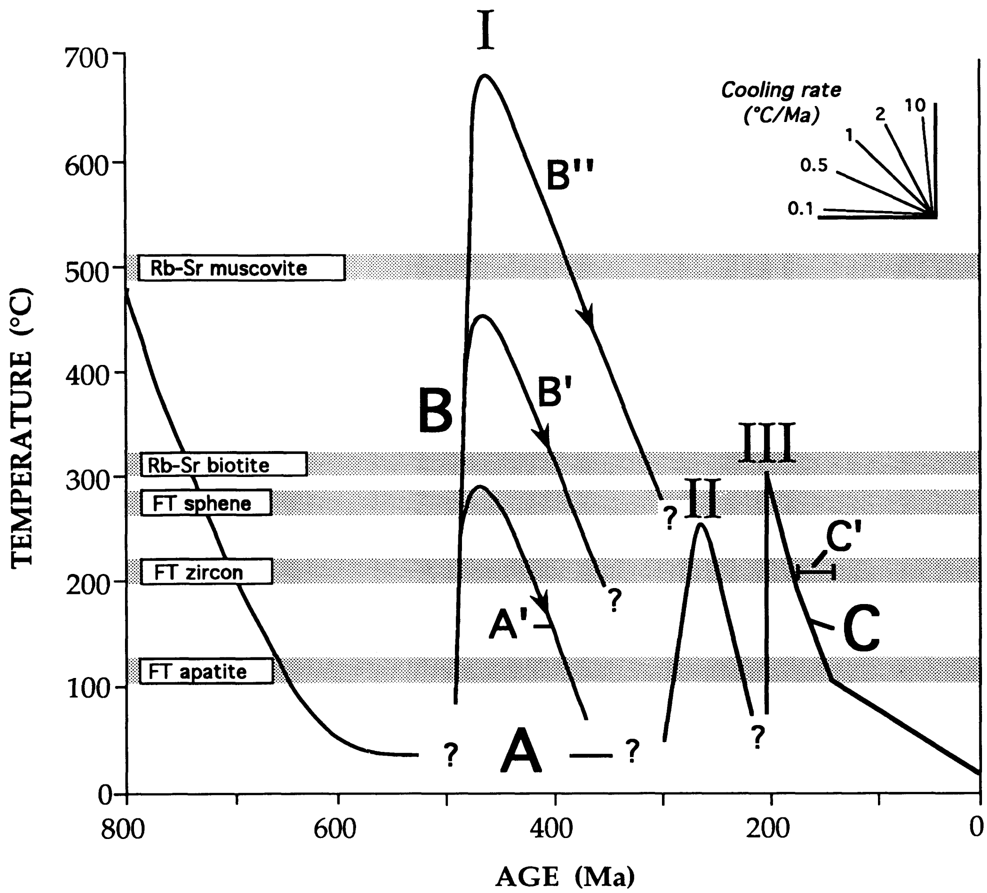

Figure 5. Schematic cooling history for study area. For geochronological data and peak metamorphic conditions shown see references in Levine (1986), Beaumont et al. (1988), Jamieson and Beaumont (1988), and also Regional Geology and Discussion section in text. Closure temperatuers (shaded areas) of the various radiometric clocks are approximate; see text for sources. Two main Paleozoic collision events are recognized: the mid-Ordovician-early Silurian–Taconic orogeny (event I) and Pennsylvanian-early Permian–Alleghanian orogeny (event II). Relatively slow post-Grenville metamorphism (~1100 Ma—Dallmeyer and Sutter 1976) cooling history was probably similar over most of the study area. However, Taconic metamorphism affected the region to varying degrees. Path **A** = Reading Prong—indicates relatively slow cooling post-Grenville metamorphism with no general resetting of radiometric clocks following Taconic orogenesis, except possibly sphene FT clocks-sample SP-1 (path **A'**). Path **B** = other areas of Piedmont Province affected by Taconic metamorphism, to the south and west of Reading Prong (**A**). Cooling segment **B'** = Honey Brook Upland and Mine Ridge (Sutter et al. 1980; Crawford and Hoersch 1984; Hoersch and Crawford 1988; Crawford, pers comm. March 1992). Cooling segment **B''** = West Chester Prong, the Avondale Anticline area (Wagner and Srogi 1987) and Baltimore gneiss domes (Muller and Chapin 1984). The study area experienced temperatures ~300°C between <228 Ma and ≥201 Ma (event III) during which sphene and zircon FT clocks were totally reset. This thermal event totally overprinted any post-Alleghanian orogeny cooling history potentially detectable by sphene and zircon FT dating. Path **C** represents the generalized post early-Jurassic cooling path of the entire study area (segment **C'** indicates that some zircon FT clocks in the Reading Prong show later cooling than that recorded for the rest of the study area—see text).

and Furlong (1992) who also found no evidence for a thermal event related to lithospheric thinning coincidental with the initial formation of the basin.

Olsen and Fedosh (1988) proposed that Early Jurassic tholeiitic magmatism along much of the eastern North American margin was confined to a short pulse, about 0.5 Ma in duration. Best available estimates for the timing of this pulse in the central Appalachian Piedmont area are: (a) a range of 200–202 Ma (Sutter 1988) from $^{40}Ar/^{39}Ar$ dating of (1) hornblende from a granophyre within a diabase, (2) an unaltered diabase, and (3) biotite from a recrystallized sedimentary xenolith within a diabase, and (b) 201 ± 1 Ma based on U/Pb dating of zircon and baddeleyite within diabases (Dunning and Hodych 1990). The sphene FTA are concordant within analytical errors, with the age of tholeiitic magmatism in the Newark Basin. This coincidence strongly suggests that the FT data record regional cooling following total annealing during a short-lived magmatic event, thus supporting alternative (2)—Newark Basin (Early Jurassic tholeiitic magmatism. Huntoon and Furlong (1992) preferred such a scenario and suggested that a brief episode of elevated heat flow in the basin was associated with the igneous activity. However, the concentration of early Jurassic tholeiitic magmatism in the Newark Basin and its general absence in the surrounding central Appalachian Piedmont crystalline rocks raises the possibility that magmatism alone may not have been responsible for the extensive resetting recorded by the sphene and zircon FT clocks. In addition, the cooling to temperatures of <300°C following Early Jurassic magmatism at ~201 Ma would have been relatively rapid (Sutter 1988) yet zircon FTA average 184 Ma. Acceptance of alternative 2) would constrain the timing of the thermal event to <~228 Ma and ≥ 201 Ma. To shed further light on the possible role of a regionally elevated geotherm due to rift-related lithospheric thinning a focused $^{40}Ar/^{39}Ar$ study of basement and detrital K-feldspars using diffusion-domain size theory (Lovera et al. 1989) is being implemented. Such a study may serve to elucidate: (1) the time of onset and extent of the thermal event, and (2) the extent of the postulated ~175 Ma hydrothermal event (Sutter 1988) over the central Appalachian Piedmont, and (3) provide important information relevant to the debate over the North American Jurassic apparent polar wandering path. (e.g., Hagstrum 1993).

For the following discussion we adopt 300°C as the maximum Mesozoic temperature attained by our samples. Under conditions similar to the present day geothermal gradient in the New Jersey Coastal Plain area, averaging ~14°C/km (based on measurements of ~31–51 mW/m^2 by Costain et al. 1986, and assuming a thermal conductivity of 3 W/mK and a 20°C surface temperature), early Jurassic burial of some 20 km would be required to reset totally the sphene FT clocks. There is no geological evidence to support this amount of Mesozoic denudation/erosion in the study area. Post-Alleghanian orogeny unroofing of at least ~8–12 km has been estimated for the Pennsylvania and Maryland Piedmont (Beaumont et al. 1988; Jamieson and Beaumont 1988). However, the Late Triassic-Early Jurassic thermal event has erased any cooling record potentially detectable by fission track dating in the interval between the end of the Alleghanian orogeny (~260 Ma) and the onset of Triassic rifting (~230 Ma). Because the crystalline basement exposed over much of the study area contains no stratigraphic or structural record of its post-Paleozoic geologic history, any estimates of post-thermal event denudation can only be related to studies of the Newark Basin. Huntoon and Furlong (1992) proposed a pulse of high heat flow (~130 mW/m^2) for the period of Early Jurassic igneous activity in the Newark Basin. Assuming an average thermal conductivity of ~2.25 W/mK for basin rocks and a surface temperature of 20°C yields an average paleothermal gradient of ~58°C/km, indicating a burial depth of ≥4.8 km at the time the sphene and zircon fission track clocks in our samples were totally reset. This depth is in broad agreement with estimates of removal of 2–3 km of post-Boonton Fm section from the Newark Basin based on organic maturity studies by Pratt et al. (1988) and Katz et al. (1989) and ≥2.5 km based on thermal modeling by Huntoon and Furlong (1992). These are similar to denudation estimates of ≥3.1–3.4 km calculated from apatite FTA in the Appalachian Basin of Pennsylvania and Maryland (Roden and Miller 1989*b*; Roden 1991), and ≥2–3 km post-Early Jurassic from the central Appalachians based on offshore sedimentation history (Slingerland and Furlong 1989). In light of the above we tentatively conclude that Mesozoic resetting of sphene and zircon clocks in the central Appalachian Piedmont proceeded under average paleothermal gradients of ≥55–60°C/km. Finally, the amount of post-Early Jurassic denudation indicated for the study area demonstrates that up to ~7 km of the post-Alleghanian orogeny overburden (assuming up to 12 km based on Beaumont et al. 1988) was removed prior to the initiation of rift related extension at ~230 Ma. This amount independently corroborates the estimates of Slingerland and Furlong (1989).

Zircon from the Precambrian Ponagansett gneiss in the vicinity of the Honey Hill Fault zone, Connecticut, some 100 km east of the Hartford rift basin, yields a FTA of 191 ± 17 Ma (BPK, unpublished data). Zircon FTA in the range of 164–238 Ma in the Hartford Basin, Connecticut, and 186–241 Ma in the Taylorsville Basin, Virginia, were reported by Roden and Miller (1991). Roden (1991) also attributed a mean apatite FTA of 176 ± 11 Ma in southwestern Virginia to cooling following tectono-thermal disturbances related to Mesozoic Atlantic margin extension. It is notable that some of these areas do not contain the extensive tholeiitic magmatics present in the Newark Basin. The above ages are also concordant with $^{40}Ar/^{39}Ar$ evidence for low temperature heating at 180–185 Ma in North Carolina slates (Noel et al. 1988). In light of the above, we suggest that the Late Triassic-Early Jurassic heating recorded in the study area was extensive along the eastern U.S. rifted margin and invites further detailed sphene and zircon FT dating to delineate the extent of the thermal anomaly.

Zircon FTA in the West Chester Prong area (figure 2) largely fall within the upper quartile of zircon ages, suggesting that this area cooled through the zircon closure temperature earlier than in the Baltimore Gneiss Domes and the eastern parts of the study area (figure 6). We consider this zircon FTA pattern to be geologically significant despite the 5–10% analytical errors associated with individual ages. Because sphene FTA are relatively uniform over the entire study area, the pattern in zircon age reflects localized variations in cooling rates from sphene to zircon closure temperature. We speculate that this pattern may have resulted from non-uniform cooling between blocks bounded by reactivated Paleozoic faults.

Conclusions

1. Sphene and zircon FTA from Grenville and Lower Paleozoic rocks of the Piedmont Province of Pennsylvania, Delaware and Maryland, the Reading Prong of New Jersey, and the Newark Mesozoic Series of Pennsylvania fall within a relatively restricted Mesozoic age range; sphene averaging 199 Ma and zircon averaging 184 Ma.

2. The near concordant FTA record Early Jurassic regional cooling at rates of ~4°–8°C/Ma following a widespread thermal event during which sphene and zircon fission track clocks were totally reset.

3. Rb-Sr whole rock-mica ages, together with previously reported $^{40}Ar/^{39}Ar$ biotite and hornblende ages, indicate no widespread regional Mesozoic resetting. Thus, the maximum temperature experienced by the samples was ~300°C.

4. The FTA data, taken together with previously determined denudation history and thermal modeling of the Newark Basin, suggest an Early Jurassic paleothermal gradient of >55–60C/km in the study area.

5. The cooling recorded by the sphene FT clocks is close in time to that of tholeiitic magmatism in the Newark Basin, suggesting that the heating was related to igneous activity. However, lack of such igneous rocks in most of the basement raises the possibility that magmatism alone may not have been sufficient to elevate the regional geotherm for total resetting of the FT clocks. Further, predicted cooling following magmatism at ~201 Ma would have been relatively rapid, yet zircon FTA average 184 Ma.

6. The thermal event erased any cooling record of denudation in the study area potentially detect-

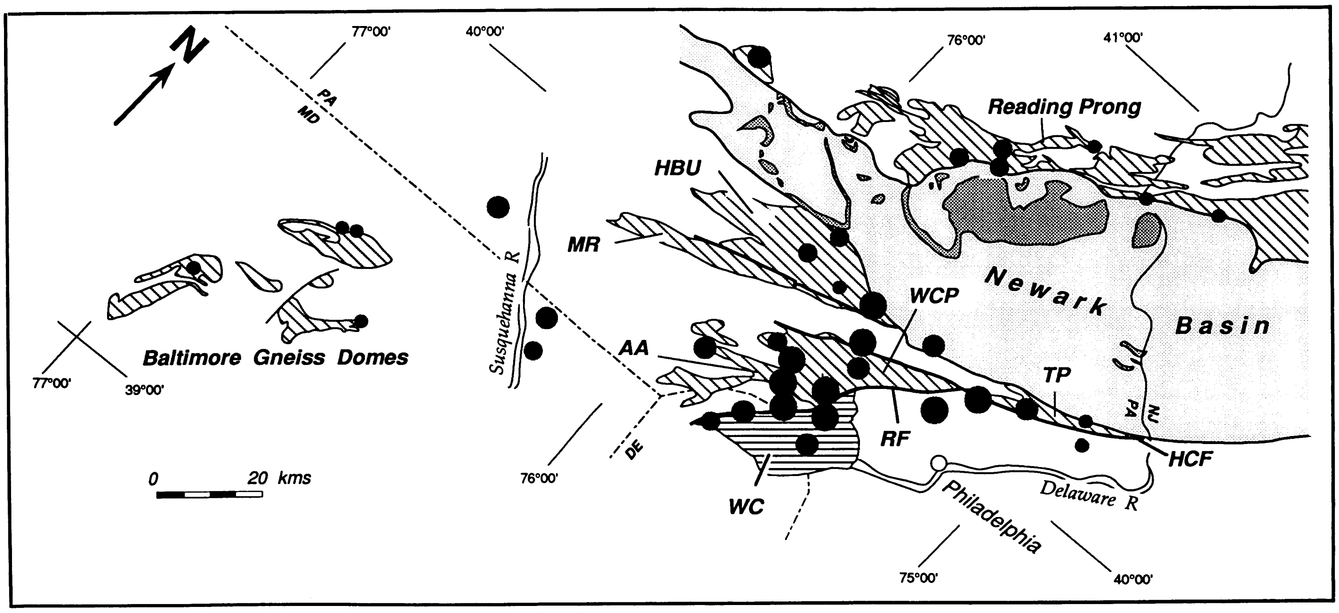

Figure 6. Distribution of zircon FTA data over the study area. The upper quartile of ages, (i.e., older ages = largest circles) are largely centered in the West Chester Prong (WCP)–Avondale Anticline (AA) area, suggesting that this area cooled more rapidly after Early Jurassic heating than other parts of the study area. The pattern of cooling may indicate non-uniform uplift along reactivated major Paleozoic faults (HCF and RF—see figure 2) bounding the WCP-AA area.

able by fission track dating, of the interval spanning the end of the Alleghanian orogeny and the onset of Triassic rifting.

7. The zircon FTA pattern indicates non-uniform cooling between blocks bounded by reactivated Paleozoic faults.

ACKNOWLEDGMENTS

We are deeply indebted to Dr. B. S. Carpenter of the National Institute of Standards and Technology (NIST, formerly National Bureau of Standards) Gaithersburg, Maryland for supervising the irradiation of our samples. We thank W. L. Griffin, formerly of the Geological Museum, Oslo for allowing us to perform Rb/Sr measurements at that Institute and T. Enger and A. S. Stabel for their technical assistance. R. Volkert (via A. Drake) and A. Goldstein provided samples from the Reading Prong and the Ponagansett Gneiss respectively. Colin Howard and Bud Alcock assisted with mineral separations. Two anonymous reviewers provided constructive criticism of an earlier draft of the paper. This study was supported by the National Science Foundation Grant EAR-8313739.

REFERENCES CITED

Beaumont, C.; Quinlan, G.; and Hamilton, J., 1988, Orogeny and stratigraphy: numerical models of the Paleozoic in the eastern Interior of North America: Tectonics, v. 7, p. 389–416.

Bell, R.; Karner, G. D.; and Steckler, M. S., 1988, Early Mesozoic rift basins of eastern North America and their gravity anomalies: the role of detachments during extension: Tectonics, v. 7, p. 447–462.

Bermingham, D., 1989, Illite crystallinity in the Newark Basin of southeastern Pennsylvania and northern New Jersey: Unpub. M.S. dissertation, Univ. of Pennsylvania, 117 p.

Brandon, M. T., and Vance, J. A., 1992, Tectonic evolution of the Cenozoic Olympic subduction complex, Washington State, as deduced from fission track ages for detrital zircons: Am. Jour. Sci., v. 292, p. 565–636.

Costain, J. K.; Speer, J. A.; Glover, L., III; Perry, L.; Dashevsky, S.; and McKinney, M., 1986, Heat flow in the Piedmont and Atlantic coastal plain of the southeastern United States: Jour. Geophys. Res., v. 91B, p. 2123–2135.

Crawford, M. L., and Mark, L., 1982, Evidence from metamorphic rocks for overthrusting, Pennsylvania Piedmont: Can. Mineral, v. 20, p. 333–347.

Crawford, W. A., and Hoersch, A. L., 1984, The geology of the Honey Brook Upland, southeastern Pennsylvania, *in* Bartholomew, M. J., ed., The Grenville event in the Appalachians and related topics: Geol. Soc. America Spec. Paper 194, p. 111–125.

Dallmeyer, R. D., and Sutter, J. F., 1976, $^{40}Ar/^{39}Ar$ incremental-release ages of biotite and hornblende from variably retrogressed basement gneisses of the northeasternmost Reading Prong, New York: their bearing on early Paleozoic metamorphic history: Am. Jour. Sci., v. 276, p. 731–747.

Drake, A. A., Jr., 1969, Precambrian and Lower Paleozoic geology of the Delaware Valley, New Jersey-Pennsylvania, *in* Subitzky, S., ed., Geology of Selected Areas in New Jersey and Eastern Pennsylvania and Guidebook of Excursions: Rutgers Univ. Press, New Brunswck, N.J., p. 51–131.

———, 1970, Structural geology of the Reading Prong, *in* Fisher, G. W., et al., eds. Studies of Appalachian Geology: Central and Southern: New York, Wiley Interscience, p. 271–291.

Dunning, G. R., and Hodych, J. P., 1990, U/Pb zircon and baddeleyite ages for the Palisades and Gettysburg Sills of the northeastern United States: implications for the age of the Triassic-Jurassic boundary: Geology, v. 18, p. 795–798.

Fitzgerald, P. G., and Gleadow, A. J. W., 1988, Fission-track geochronology, tectonics, and structure of the Transantarctic Mountains in northern Victoria Land, Antarctica: Chem. Geol. (Isotope Geosc. Sect.), v. 73, p. 169–198.

Fleischer, R. L.; Price, P. B.; and Walker, R. M., 1965, Effects of temperature, pressure, and ionization on the formation and stability of fission tracks in minerals and glasses: Jour. Geophys. Res., v. 70, p. 1497–1502.

Foland, K. A., and Muessig, K. W., 1978, A Paleozoic age for some charnockitic-anorthositic rocks: Geology, v. 6, p. 143–146.

Galbraith, R. F., 1990, The radial plot: graphical assessment of spread in ages: Nucl. Tracks, Radiat. Meas., v. 17, p. 207–214.

Gleadow, A. J. W., 1981. Fission track dating methods: what are the real alternatives?; Nucl. Tracks, v. 5, p. 169–174.

———, and Brooks, C. K., 1979, Fission track dating, thermal histories, and tectonics of igneous intrusions in east Greenland: Contrib. Mineral. Petrol., v. 71, p. 45–60.

———; Duddy, I. R.; Green, P. F.; and Lovering, J. F., 1986, Confined fission track lengths in apatite: a diagnostic tool for thermal history analysis: Contrib. Mineral. Petrol., v. 94, p. 405–415.

———; Hurford, A. J.; and Quaife D. R., 1976, Fission track dating of zircon: improved etching techniques: Earth Planet. Sci. Lett., v. 33, p. 273–276.

———, and Lovering, J. F., 1974, The effect of weathering on fission track dating; Earth Planet. Sci. Lett., v. 22, p. 163–168.

———, and ———, 1977, Geometry factor for external detectors in fission track dating: Nucl. Track Detection, v. 1, p. 99–106.

Gray, N. H., 1988, The origin of copper occurrences in the Hartford Basin, *in* Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of the early Mesozoic basins of the eastern U.S.: U.S. Geol. Surv. Bull. 1776, p. 341–349.

Green, P. F., 1981. A new look at statistics in fission track dating; Nucl. Tracks, v. 5, p. 77–86.

———, 1985, Comparison of zeta calibration baselines for fission-track dating of apatite, zircon, and sphene: Chem. Geol. (Isotope Geosc. Sect.), v. 58, p. 1–22.

Hagstrum, J. T., 1993, North American Jurassic APW: the current dilemma: EOS (Trans. Am. Geophys. Union), v. 74, p. 645.

Hanson, G. N., and Gast, P. W., 1967, Kinetic studies in contact metamorphic zones: Geochim. Cosmochim, Acta., v. 31, p. 1119–1153.

Harrison, T. M., and McDougall, I., 1980, Investigations of an intrusive contact, northwest Nelson, New Zealand, I. Thermal, chronological, and isotopic constraints: Geochim. Cosmochim. Acta, v. 44, p. 1985–2003.

———; Armstrong, R. L.; Naeser, C. W.; and Harakal, J. E., 1979, Geochronology and thermal history of the Coast Plutonic complex, near Prince Rupert, B.C.: Can. Jour. Earth Sci., v. 16, p. 400–410.

Hoersch, A. L., and Crawford, W. A., 1988, The Mine Ridge of the S.E. Pennsylvania Piedmont: Northeastern Geology, v. 10, p. 181–194.

Huntoon, J. E., and Furlong, K. P., 1992, Thermal evolution of the Newark Basin: Jour. Geology, v. 100, p. 579–591.

Hurford, A. J., 1986, Cooling and uplift patterns in the Lepontine Alps, south-central Switzerland, and an age of vertical movement on the Insubric fault line: Contrib. Mineral. Petrol., v. 92, p. 413–427.

———, and Greene, P. F., 1983, A guide to fission track dating calibration: Chem. Geol. (Isotope Geosc. Sect.), v. 1, p. 285–317.

———; Fitch, F. J.; and Clarke, A., 1984, Resolution of the age structure of the detrital zircon populations of two Lower Cretaceous sandstones from the Weald of England by fission track dating: Geol. Mag., v. 121, p. 269–396.

Jamieson, R. A., and Beaumont, C., 1988, Orogeny and metamorphism: a mode for deformation and pressure-temperature-time paths with applications to the central and southern Appalachians: Tectonics, v. 7, p. 417–455.

Karner, G. D.; Steckler, M. S.; Omar, G. I; and Kohn, B. P., 1990, Fission-track results from the Newark Basin: implications for hydrothermal events: EOS (Trans. Am. Geophys. Union), v. 71, p. 1606.

Katz, B. J.; Robison, C. R.; and Jorjorian, T., 1989, The level of organic maturity within the Newark Basin and its associated implications, *in* Manspeizer, W., ed., Triassic-Jurassic Rifting; Continental Breakup, and the Origin of the Atlantic Ocean and Passive Margins North America, Part B: Amsterdam Elsevier, p. 683–696.

Kohn, B. P., Eyal, M., 1981, History of uplift of the crystalline basement of Sinai and its relation to opening of the Red Sea as revealed by fission track dating of apatites: Earth Planet. Sci Lett., v. 52, p. 129–141.

———; Wagner, M. E.; Lutz, T. M.; and Organist, G., 1988*a*, Regional thermal overprinting during Mesozoic rifting recorded by sphene and zircon fission-track dates, central Appalachian Piedmont, USA: Abs. 6th Int. Conf. Fission Track Dating, C2–11.

———; Wagner, M. E.; Lutz, T. M.; Organist, G.; and Omar, G. I., 1988*b*, Mesozoic rift-related and post-rift uplift of the central Appalachian Piedmont: constraints from fission-track analysis: Geol. Soc. America, Abs. with Prog., v. 20, p. A387.

Kunk, M. J.; Sutter, J. F.; and Naeser, C. W., 1985, High precision $^{40}Ar/^{39}Ar$ ages of sanidine, biotite, hornblende, and plagioclase, from the Fish Canyon Tuff, San Juan volcanic field, south-central Colorado: Geol. Soc. America Abs. with Prog., v. 17, p. 636.

Levine, J. R., 1986, Deep burial of coal-bearing strata, Anthracite region, Pennsylvania: sedimentation or tectonics?: Geology, v. 14, p. 577–580.

Lovera, O. M.; Richter, F. M.; and Harrison, T. M., 1989, The $^{40}Ar/^{39}Ar$ thermochronometry for slowly cooled samples having a distribution of diffusion domain sizes: Jour. Geophys. Res., v. 94, p. 17,917–17,935.

Moore, M. E.; Gleadow, A. J. W.; and Lovering, J. F., 1986, Thermal evolution of rifted continental margins; new evidence from fission tracks in Basement apatites from southeastern Australia: Earth Planet. Sci. Lett., v. 78, p. 255–270.

Muller, P. D., and Chapin, D. A., 1984, Tectonic evolution of the Baltimore Gneiss anticlines, Maryland, *in* Bartholomew, M. J., ed., The Grenville Event in the Appalachians and Related Topics: Geol. Soc. America Spec. Paper 194, p. 127–148.

Naeser, C. W., and McKee, E. H., 1970, Fission-track and K-Ar ages of Tertiary ash flow tuffs, north-central Nevada: Geol. Soc. America Bull., v. 81, p. 3375–3384.

Nelson, K. D., 1992, Are crustal thickness variations in old mountain belts like the Appalachians a consequence of lithospheric delamination?: Geology, v. 20, p. 498–502.

Noel, J. R.; Spariosu, D. J.; and Dallmeyer, R. D., 1988, Paleomagnetism and $^{40}Ar/^{39}Ar$ ages from the Carolina slate belt, Albemarle, North Carolina: implications for terrane amalgamation into North America: Geology, v. 16, p. 64–68.

Olsen, P. E., and Fedosh, M., 1988, Duration of Early Mesozoic extrusive igneous episode in eastern North America determined by use of Milankovitch-type lake cycles: Geol. Soc. America Abs. with Prog., v. 20, p. 59.

———, and Kent, D. V., 1990, Continental coring of Newark rift: EOS (Trans. Am. Geophys. Union), v. 71, p. 385.

Omar, G. I.; Steckler, M. S.; Buck, W. R.; and Kohn, B. P., 1989, Fission track analysis of basement apatites at the western margin of the Gulf of Suez rift, Egypt:

evidence for synchroneity of uplift and subsidence: Earth Planet. Sci. Lett., v. 94, p. 316–328.
Pratt, L. M., and Burruss, R. C., 1988, Evidence for petroleum generation and maturation in the Hartford and Newark Basins, *in* Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of Early Mesozoic basins of the eastern U.S.: U.S. Geol. Survey Bull. 1776, p. 74–79.
———; Shaw, C. A.; and Burruss, R. C., 1988, Thermal histories of the Hartford and Newark Basins inferred from maturation indices of organic matter, *in* Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of Early Mesozoic basins of the eastern U.S.: U.S. Geol. Survey Bull. 1776, p. 58–63.
Ratcliffe, N. M.; Burton, W. C.; D'Angelo, R. M.; and Costain, J. K., 1986, Low-angle extensional faulting, reactivated mylonites, and seismic reflection geometry of the Newark basin margin in eastern Pennsylvania: Geology, v. 14, p. 766–770.
Robinson, G. R., Jr., and Woodruff, L. G., 1988, Characteristics of base-metal and barite vein deposits associated with rift basins, with examples from some early Mesozoic basins of eastern North America, *in* Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of Early Mesozoic basins of the eastern U.S.: U.S. Geol. Survey Bull. 1776, p. 377–390.
Roden, M. K., 1991, Apatite fission-track thermochronology of the southern Appalachian basin: Maryland, West Virginia, and Virginia: Jour. Geology, v. 99, p. 41–53.
———, and Miller, D. S., 1989*a*, Thermal history of Hartford, Newark, and Taylorsville basins using fission track analysis: Geol. Soc. America Abs. with Prog; v. 21, p. 266.
———, and ———, 1983*b*, Apatite fission-track thermochronology of the Pennsylvania Appalachian Basin: Geomorphology, v. 2, p. 39–51.
———, and ———, 1991, Tectono-thermal history of Hartford, Deerfield, Newark, and Taylorsville Basins, eastern United States, using fission-track analysis: Schweiz. Mineral. Petrogr. Mitt., v. 71, p. 187–203.
Schlische, R. W., and Olsen, P. E., 1990, Quantitative filling model for continental extensional basins with applications to early Mesozoic rifts of eastern North America: Jour. Geology, v. 98, p. 135–155.
Seward, D., and Rhoades, D., 1986, A clustering technique for fission track dating of fully to partially annealed minerals and other non-unique populations: Nucl. Tracks Radiat. Meas., v. 11, p. 259–269.
Shaw, H. F., and Wasserburg, G. J., 1984, Isotopic constraints on the origin of Appalachian mafic complexes: Am. Jour. Sci., v. 284, p. 319–349.
Sinha, A. K.; Hanan, B. B.; Sans, J. R.; and Hall, S. T., 1980, Igneous rocks of the Maryland Piedmont: indicators of crustal evolution, *in* Wones, D. R., ed., Caledonide orogen: the Caledonides in the USA: Proc. IGCP Proj. 27, p. 131–135.
———; Hund, E.; and Hogan, J. P., 1989, Paleozoic accretionary history of the North American plate margin (central and southern Appalachians): constraints from the age, origin, and distribution of granitic rocks, *in* Hillhouse, J. W., ed., Deep structure and past kinematics of accreted terranes: Am. Geophys. Union Geophys. Mon. 50, p. 219–238.
Slingerland, R.; and Furlong, K. P., 1989, Geodynamic and geomorphic evolution of the Permo-Triassic Appalachian Mountains: Geomorphology, v. 2, p. 23–37.
Sutter, J. F., 1988, Innovative approaches to the dating of igneous events in the early Mesozoic basins of the eastern U.S., *in* Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of Early Mesozoic basins of the eastern U.S.: U.S. Geol. Survey Bull. 1776, p. 194–200.
———; Crawford, M. L.; and Crawford, W. A., 1980, $^{40}Ar/^{39}Ar$ age spectra of coexisting hornblende and biotite from the Piedmont of S.E. Pennsylvania: their bearing on the metamorphic and tectonic history: Geol. Soc. America Abst. with Prog., v. 12, p. 85.
Swanson, M. T., 1986, Pre-existing fault control for Mesozoic basin formation in eastern North America: Geology, v. 14, p. 419–422.
Van Houten, F. B., 1977, Triassic-Liassic deposits of Morocco and eastern North America: a comparison: AAPG Bull., v. 61, p. 79–94.
Wagner, G. A.; Reimer, G. M.; and Jäger, E., 1977, Cooling ages derived by apatite fission-track, mica Rb/Sr and K/Ar dating: the uplift and cooling history of the central Alps: Mem. Ist. Geol. Mineral. Univ. Padova 30, 27 p.
Wagner, M. E., and Crawford, M. L., 1975, Polymetamorphism of the Precambrian Baltimore Gneiss in southeastern Pennsylvania: Am. Jour. Sci., v. 275, p. 653–682.
———, and Srogi, L. A., 1987, Early Paleozoic metamorphism at two crustal levels and a tectonic model for the Pennsylvania-Delaware Piedmont: Geol. Soc. America Bull., v. 99, p. 113–126.
———; Srogi, L. A.; Wiswall, C. G.; and Alcock, J., 1991, Taconic collision in the Delaware-Pennsylvania Piedmont and implications for subsequent geologic history, *in* Schultz, A., and Compton-Gooding, E., eds. Geologic Evolution of the Eastern United States, Field Trip Guidebook, NE-SE GSA: Virginia Museum Nat. Hist. Guidebook, 2, p. 91–119.
Watts, A. B., and Steckler, M. S., 1979, Subsidence and eustasy at the continental margin of eastern North America, *in* Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment (Maurice Ewing Series, Vol. 3): Washington, DC, Am. Geophys. Union, p. 218–234.
White, R. S.; Spence, G. O.; Fowler, S. R.; McKenzie, D. P.; Westbrook, G. K.; and Bowen, A. N., 1987, Magmatism at rifted continental margins: Nature, v. 230, p. 439–444.
Witte, W. K., and Kent, D. W., 1989, A middle Carnian to early Norian (~225 Ma) paleopole from sediments of the Newark Basin, Pennsylvania: Geol. Soc. Am. Bull., v. 101, p. 1118–1126.