The Thermal Evolution of the Grenville Terrane Revealed through U-Pb and Fission-Track Analysis of Detrital Zircon from Cambro-Ordovician Quartz Arenites of the Potsdam and Galway Formations

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ABSTRACT

Tectonothermal studies of Precambrian terranes using detrital zircons have been the domain of U-Pb dating techniques. Advancements in technology have made it possible to study the low-temperature evolution of these terranes with the fission-track (FT) dating method, and combining these two techniques provides a unique look at the thermal evolution of Precambrian terranes. Detrital zircon grains from the upper middle Cambrian to lower middle Cambrian Potsdam and Galway formations in New York State, which uncomformably overlie the Precambrian Grenville terrane, were analyzed by U-Pb and FT dating. Approximately 90% of the U-Pb ages fall between 950 and 1200 Ma, fully consistent with the idea that these zircons are derived almost entirely from Grenville-age rock. Zircon FT (ZFT) ages from the same suite of samples have component populations of ~540, ~780, and ~1200 Ma, with single-grain ages as old as 2.1 Ga. The most important observations from the FT data are that there is no widespread resetting on either side of the Adirondacks, that the component populations are older than the age of deposition, and therefore that the principle population likely reflects the cooling ages of what was almost exclusively Grenville source rock. The ZFT component populations older than Grenville tectonic events (FT age > 1.6 Ga) suggest that these old grains and the zircon with old U-Pb ages were transported from other nearby Precambrian terranes, such as the Superior and the Yavapai-Mazatzal. These FT data show that the Potsdam and Galway formations have not undergone heating significant enough to reset fission tracks in zircon since deposition and that the heating in the source rocks at 540 Ma corresponds to cooling after the breakup of Rodinia and the rifting of the Iapetus Ocean.

Introduction

Precambrian cratons around the world are typically overlain by Phanerozoic cover strata that provide important clues about the evolution and assembly of the underlying basement terranes (Gehrels et al. 1995; Rahl et al. 2003). Many of these cover strata are Cambrian quartz arenites that sit above the Great Unconformity, and these sandstones have important detrital minerals, such as rutile, zircon, and garnet, that provide information about the source rocks. Of all these minerals, zircon ($ZrSiO_4$) is the most widely studied because it is abundant, robust, and easily dated. Typically, studies of Precambrian detrital zircon are limited to the U-Pb isotopic system (Gehrels et al. 1995), although (U+Th)/He (ZHe dating) is an emerging technique (Rahl et al. 2003; Reiners et al. 2005). Currently, ZHe dating requires the complete dissolution of zircon, a time-consuming process, before analysis for uranium and thorium (Reiners et al. 2003). Detrital studies using U/Pb dating of zircon are very useful and have dated rocks from all over the world (Gehrels et al. 1995; Fedo et al. 2003). Two notable examples are the 4.4-Ga zircon from the Yilgarn Craton in the Jack Hills of Western Australia and the 4.2-Ga zircon from northwestern Canada (Wilde et al. 2001; Iizuka et al. 2006). The key advantage of using the U-Pb method is that it reveals crystallization ages, but the downside is that this technique is unable to date subtle, low-temperature events that lack crystallization of primary datable

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minerals. Both zircon fission-track (ZFT) and ZHe methods allow us to date the low-temperature thermal history of a terrane that may be more directly related to exhumation.

For the past several years, we have been developing the technique of scanning electron microscopy–high-density fission-track (SEM-HDFT) dating, which involves using a scanning electron microscope (SEM) to date zircon grains with very high track densities. We are now able to routinely date zircon cooling ages by using fission tracks from Cambrian strata and Precambrian basement rocks (see Montario and Garver 2008). The use of the ZFT dating method in Precambrian and Cambrian terranes has been hampered by our ability to determine very high spontaneous track densities (ρ_s), which are typical in very old zircons with average uranium concentrations (or younger zircons with high uranium concentrations). In most cases, high-density track analysis has been impossible because the etching technique for grains with significant radiation damage was poorly explored and SEM imaging tools were not readily available to most researchers. New advancements in SEM technology have allowed larger sample chambers with automatic stages and simple user interfaces. The main advantage is that SEMs do not have the limits on resolution and magnification that affect optical microscopes, which are limited to a maximum of ~1250–1600 × . Until now, these limitations have prevented the study of fission tracks in zircons older than ~300–400 Ma without a significant counting bias. This counting bias means that the only datable grains have low uranium content (Bernet and Garver 2005). The SEM-HDFT technique allows for exciting new possibilities of understanding the thermal evolution of Precambrian terranes and how these terranes have evolved with time.

The Adirondack Mountains are a well-exposed massif of Grenville basement and surrounding lower Paleozoic cover strata in northern New York State (fig. 1). The Grenville rocks, and the overlying cover sequence, have been subjected to a number of distinct Paleozoic and younger thermal events. The timing and significance of these events are not well constrained and are the subjects of considerable debate (e.g., Johnsson 1986; Sarwar and Friedman 1995; Lim et al. 2005). Many thermal studies have been conducted in and around the Adirondacks to determine the timing of heating. Both high-temperature studies on the Grenville basement rocks (e.g., Miller and Duddy 1989; Mezger et al. 1991; Heizler and Harrison 1998) and low-temperature studies on Grenville rocks and Cambrian cover strata (e.g., Sarwar and Friedman 1995; Roden-Tice et al. 2000; Weary et al. 2001; Roden-Tice and Tice 2005; Smith 2006; Selleck et al. 2008) have provided insight into the thermal evolution of these rocks, but collectively the overall thermal history is poorly known.

This article focuses on dating three key samples from the Cambrian cover strata flanking the Adirondacks, using the SEM-HDFT dating technique and laser ablation U/Pb geochronology. All samples are from Cambrian quartz arenites that rest above the Great Unconformity on the Grenville basement. Sample M-07 was collected from the southern end of Lake George on the eastern side of the Adirondacks. Sample M-09 was collected near Kimball Corners on the southern end of the Adirondacks. Sample M-19 was collected near Fishers Landing, located on the western side near Lake Ontario. These sample locations reflect differences in the peak thermal evolution of overlying Ordovician carbonates, as revealed by conodont alteration index (CAI) values. The CAI is relatively well calibrated to temperatures and therefore allows determination of the maximum paleotemperature range attained (Epstein et al. 1977). There is a robust data set for CAI values in Ordovician and Devonian carbonate rocks in New York State and adjacent areas (fig. 2; Epstein et al. 1977; Weary et al. 2001). These data come from carbonate strata slightly higher in the stratigraphic section than but very close stratigraphically to the Potsdam Formation (<100 m) and therefore are useful for evaluating which cover rocks were likely heated after deposition. The east side of the Adirondacks has a CAI of 4–5 (190°–480°C) from Cambro-Ordovician cover limestones, and the west side has CAI values of 2–3 (60°–200°C; Epstein et al. 1977; Harris et al. 1978; Harris 1979; Weary et al. 2001). This case study in the Adirondacks will help to refine this technique and allow us to apply it to Precambrian terranes in other areas.

Background on ZFT Retention

Fission tracks are a damage trail produced in minerals through the spontaneous fission of ^{238}U. Tracks are retained in a crystal, provided that the crystal or host rock remains below the temperature of annealing. Effective closure temperature (T_c) is the temperature at which a system becomes closed when the mobile daughter products of a nuclear reaction become immobile and are retained in the host crystal (Dobson 1973). For the fission-track system, the daughter is an actual damage trail left by the fission decay of ^{238}U (Fleischer et al. 1975). The closure temperature of the ZFT system is principally controlled by the rate of cooling, because a

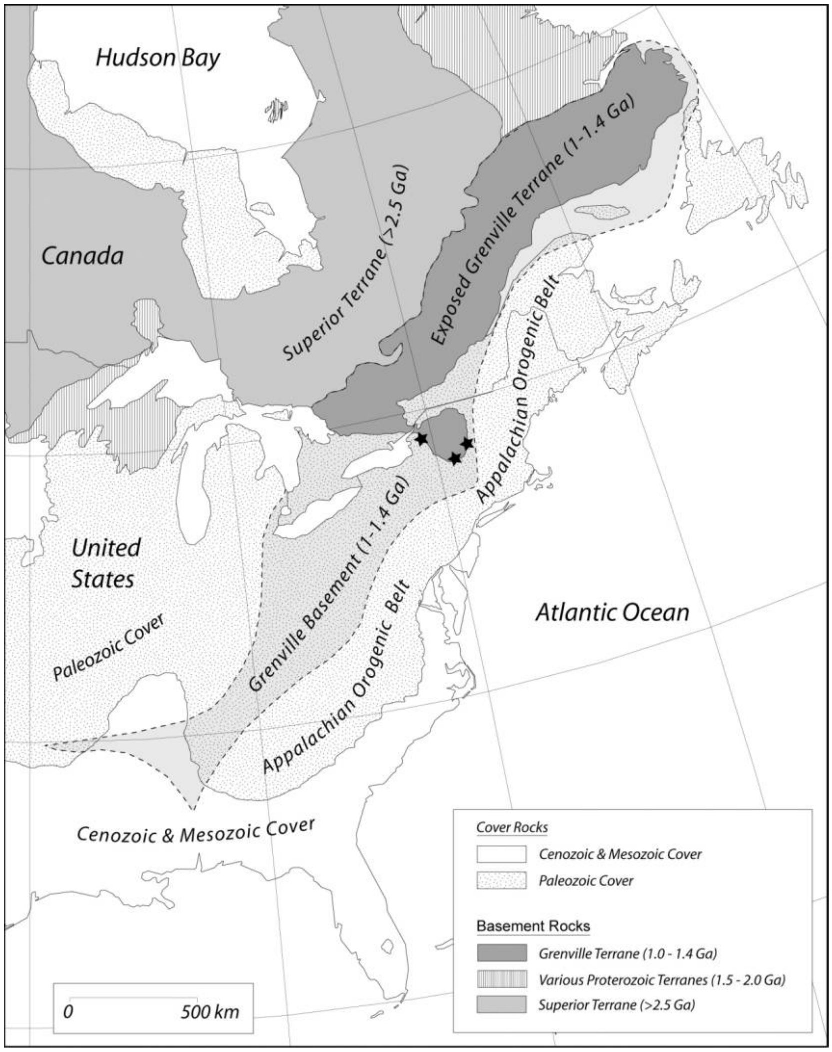

Figure 1. Distribution of Precambrian terranes and Paleozoic and Mesozoic strata of eastern North America. This study focuses on an exposure of Grenville-age basement rocks in the Adirondacks and cover strata in New York State. Stars indicate sample locations. Modified from the USGS *North America Tapestry of Time and Terrain* map (Barton et al. 2003).

fast cooling rate results in a higher T_c than does a slow cooling rate (Dobson 1973; Reiners and Brandon 2006). One way to envision closure temperature is as a simplification of the partial-annealing zone (PAZ); it is valid only for geological samples that have experienced constant cooling rates (Wagner and van den Haute 1992). If the samples have undergone relatively constant cooling, then the closure temperature corresponds to a point within the PAZ where 50% of the tracks are stable (Wagner and Reimer 1972; Wagner and van den Haute 1992).

The T_c for apatite is well calibrated by laboratory annealing studies, but zircon is not as well calibrated (Laslett et al. 1987). Laboratory studies and field-based studies of zircon from geological samples differ significantly in terms of calculated closure temperatures. In general, laboratory annealing studies predict higher closure temperatures than do field-based studies, with estimates of 306°–338°C for zero-damage grains (Galbraith and Laslett 1997; Tagami et al. 1998; Rahn et al. 2004). Field-based studies on rocks that have relatively well known thermal histories have produced a T_c for zircon that ranges from ~205° to ~260°C (Harrison et al. 1979; Zaun and Wagner 1985; Hurford 1986; Brandon and Vance 1992; Foster et al. 1996; Bernet 2002, 2009). Therefore, the natural examples appear to be ~50°–100°C lower than those in laboratory-based an-

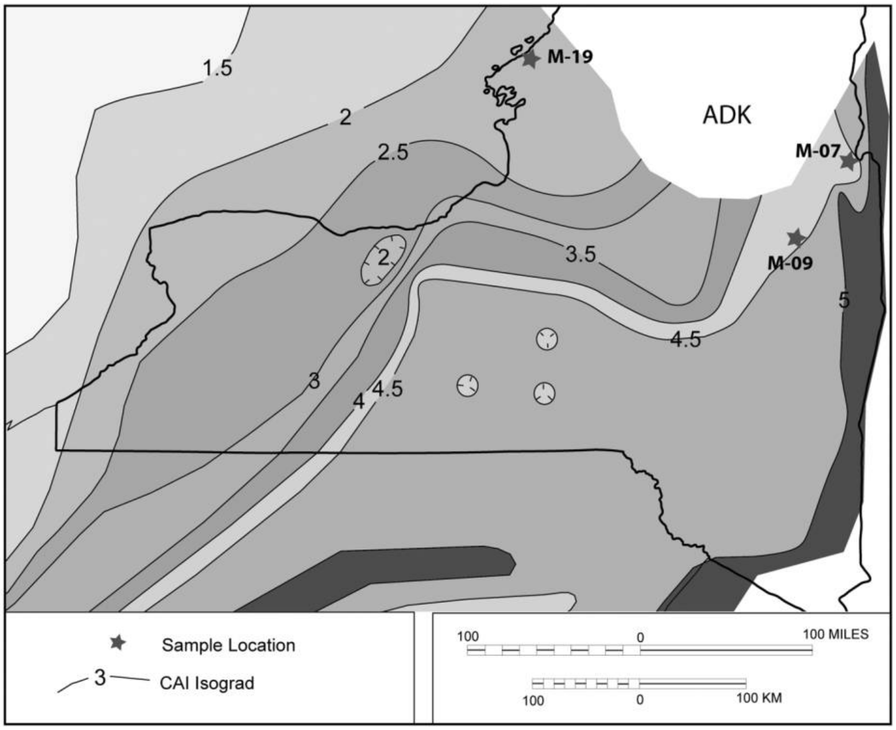

Figure 2. Location map of the study area and sample locations. Overlain on the state outline are conodont alteration index (CAI) isotherms from both surface and subsurface samples of Ordovician limestones (mainly the Trenton Group) in New York State (Weary et al. 2001) and Pennsylvania (Repetski et al. 2002). The CAI values increase from west to east across the state, with the highest values along the Taconic Orogen front. Stars indicate sample locations. ADK = Adirondack Mountains.

nealing studies. The differences between field-based and lab-determined T_c's is generally attributed to alpha damage from self-irradiation (Gleadow 1978; Naeser et al. 1987; Garver and Kamp 2002; Riley 2004; Garver et al. 2005).

Annealing results in the removal of preexisting tracks by the restructuring of atoms displaced by the ^{238}U fission event. The main factors that are inferred to affect annealing rates are time, temperature, composition, radiation damage, pressure, intergranular solutions, and ionizing radiation (see Wagner and van den Haute 1992). Annealing is a unique aspect of FT dating in that it can provide useful information about the thermal history of a rock. The PAZ (FT dating) is the temperature range at which fission tracks are partially annealed but still preserved over geologic timescales (Wagner 1972; Wagner and van den Haute 1992). Tracks formed in a crystal that resides below the PAZ are totally annealed, and tracks formed above the PAZ are fully preserved. In general, the boundaries of the PAZ are defined as 10% and 90% track retention when the temperature is held constant (Brandon et al. 1998). At the high-temperature end of the PAZ, only 10% of the tracks are preserved, and at the low-temperature end, 90% of the tracks are preserved (Brandon and Vance 1992; Wagner and van den Haute 1992). The current bounds for the radiation-damaged zircon PAZ are ~195°–250°C for 10% retention and ~150°–200°C for 90% retention over timescales of 1–1000 m.yr. (Reiners and Brandon 2006).

Annealing of fission tracks in crystals that have resided in near-surface conditions is less well studied. When a crystal with tracks is subsequently heated by burial or nearby plutonism, the tracks are shortened and annealed. We know that in these conditions the amount of internal radiation damage, other than that caused by fission, affects the ability of a crystal to retain tracks (Garver et al. 2005). Grains with low damage are less prone to track annealing than are grains with high damage. It is thought that zircons with high levels of radiation damage, those approaching the metamict state, are extremely susceptible to track annealing (Rahn et al. 2004; Garver et al. 2005), but this has not been approached quantitatively. It is possible that high-damage grains have fission tracks that are annealed at temperatures as low as 180°C over geologic timescales (see Garver et al. 2005).

Geologic Background

Grenville Terrane. The Grenville Orogenic cycle occurred during the Late Proterozoic and is made up of several tectonic events. The Elzevirian Orogeny occurred from ~1300 to 1220 Ma with the collision of the Elzevir Arc with Laurentia (Wasteneys et al. 1999; McLelland et al. 2002). The Elzevirian Orogeny was followed by ~40 m.yr. of what is assumed to be inactivity, until the anorthosite-mangerite-charnockite-granite (AMCG) suite was intruded from 1160 to 1145 Ma. The well-known Mount Marcy anorthositic massif is associated with this intrusive event. After another lull in tectonic activity, Amazonia collided with Laurentia during the Ottawan Orogeny at 1090–1030 Ma (see Moore and Thompson 1980; McLelland et al. 2001; Hamilton et al. 2004; Magnani et al. 2004; Bickford et al. 2008 for a review).

The Adirondack Mountains are a roughly circular exposure of Grenville basement rocks in New York State. The range is ~200 km across and has a peak elevation of just over 1600 m. The whole massif can be divided into two sections, the Central Highlands and the Northwest Lowlands, separated by the Carthage-Colton Mylonite Zone (Isachsen et al. 1991; McLelland et al. 1993). The Central Highlands are made up of mostly metaplutonic rocks, while the Northwest Lowlands are mainly metasedimentary or metavolcanic (Isachsen et al. 1991). A peak temperature of at least 790°C and pressures of 7–9 kbar have been estimated for rocks within the Adirondacks during the Grenville Orogeny (1350–1000 Ma; Storm and Spear 2005).

Cambrian Cover Sequence. In New York State, the Potsdam Formation is the basal unit of the Paleozoic cover strata that sit unconformably above the Grenville basement (ca. 1100 Ma), and this contact is well exposed around the Adirondack Mountains. The depositional age of the Potsdam Formation varies from upper middle Cambrian to lower upper Cambrian in New York State (Fisher 1977; Selleck 1997; Landing 2007). The depositional environments for the Potsdam Formation vary around the marine-nonmarine interface and are interpreted to be (1) local alluvial fans, (2) marine or fluvial channels, and (3) low-energy, littoral to nearshore environments (Otvos 1965; Selleck 1997).

The Galway Formation consists of interbedded carbonate and quartz clastic sandstones that overlie the Potsdam Formation, and it is equivalent to the Theresa Formation of southwestern New York and the Rose Run Formation of Ohio (Janssens 1973; Fisher 1977). These units, which grade upward into carbonates of the Beekmantown Group, represent a widespread transgressive sequence from the Late Cambrian to the Early Ordovician. Sandstones of the Galway Formation have been the focus of oil and gas exploration in New York over the past few years because of the large plays discovered in the Theresa Formation of Ohio (Hart et al. 1996). These lower units, rich in clastics, are overlain by a series of carbonate rocks of the Beekmantown Group that in turn are overlain by the Middle Ordovician Trenton and Black River groups. The majority of the rocks in the carbonate sequence have poor zircon yield and limit our ability to conduct detrital zircon studies to the lowest units, the Potsdam and Galway formations, both of which are rich in clastics. These units are all overlain by a thick Paleozoic sequence in New York State. This overlying stratigraphic sequence consists of the Taconic (Ordovician), Acadian (Devonian), and Alleghanian (Carboniferous) clastic wedges.

Thermal Events

This section is a summary of major thermal events that affected cover strata above the Grenville basement. This overview includes the heating events most likely to have affected detrital zircon in the Potsdam and Galway formations. Two items are important when evaluating a detrital signal. One is the overall tectonothermal history of the source rocks (or inferred source rocks). The other is the potential for postdepositional heating, which might anneal tracks and compromise the provenance information. A review the thermal history of the basement units (below the Potsdam Formation) and subsequent formations is given below.

Events That Predate the Great Unconformity: Rifting of the Iapetus Ocean. Two pulses of igneous activity ascribed to the opening of the Iapetus Ocean (Aleinikoff et al. 1995) would have affected the Grenville basement rocks. The older event (~750 Ma) is not recorded north of the Potomac River, nor did it lead to continental separation (Su et al. 1994; Aleinikoff et al. 1995). The second pulse, which appears widespread throughout the Grenville terrane, is represented by units with ages ranging from 588 to 544 Ma and occurs from Newfoundland to North Carolina (Aleinikoff et al. 1995).

Mafic dikes in the Adirondacks have similarities to rift-related metavolcanics in the western Appalachians of Vermont and the East African Rift system, and they are interpreted as being associated with the breakup of Laurentia and the opening of the Iapetus Ocean (Coish and Sinton 1991). The age of these dikes is not well constrained but is thought to be ~588 Ma (Isachsen et al. 1988), which is in agreement with ages of similar volcanics from the Grenville dike swarm of Ontario and Ottawa (Kumarapeli et al. 1990; Kumarapeli et al. 1990; Coish and Sinton 1991). To the north, the Tibbit Hill Formation of Vermont and Quebec may be related and is also dated at ca. 554 Ma (Kumarapeli et al. 1989; Abdel-Rahman and Kumarapeli 1998). Farther to the north, in Newfoundland, ages of ~550 Ma have been determined for the Skinner Cove Formation and the Lady Slipper Pluton (Cawood et al. 2001). To the south, the Yonkers and Pound Ridge gneisses near New York City are ca. 563 and 583 Ma, respectively (Long 1969; Mose and Hayes 1975).

Events That Postdate the Great Unconformity: Taconic, Acadian, and Alleghanian Burial. The Potsdam Formation is overlain by two and possibly three significant pulses of sedimentation in New York. These pulses are associated with the Taconic (~450 Ma), Acadian (~360 Ma), and Alleghanian (~300 Ma) orogenies. To calculate the amount of sediment cover and the burial depth of the Potsdam Formation, an estimate must be made of the sediment deposited during these pulses. This section outlines the basic attributes of the sedimentary cover that could have buried the Potsdam Formation and the underlying Grenville basement.

The Taconic Orogeny was the collision of North America with an island arc during the early Middle Ordovician to Early Silurian, and associated with it was the deposition of a synorogenic wedge of clastic sediment derived from the orogenic belt to the east (Bird and Dewey 1970; Rickard 1973; Fisher 1977; Bradley and Kidd 1991; Sarwar and Friedman 1995; Lim et al. 2005). The Mohawk and Champlain valleys have an average of ~1.25 km and a maximum of 1.75 km of Ordovician strata related to this orogenic episode. In the Hudson Valley, an average of 2 km of strata is present, with a maximum of 4 km (Fisher 1977). Thicknesses decrease to the west, to an average of 0.5 km of orogenic fill (Taconic) in north-central New York (Fisher 1977), and therefore we would predict that a tapering wedge covered the Adirondack Grenville basement rocks.

Hydrothermal fluids played a key role in the thermal history of New York (Smith and Nyahay 2004; Lim et al. 2005). These fluids appear to be localized around normal or wrench faults in the Mohawk Valley south of the Adirondacks (Smith and Nyahay 2004). The timing of hydrothermal fluid flow appears to coincide with the timing of fault movement, and most, but not all, studies indicate that these faults were active during the Taconic Orogeny (Bradley and Kidd 1991; Smith et al. 2003; Smith 2006; Lim et al. 2005). Seismic data of these faults show most of them dying out as they pass upward into the Trenton and Utica formations, which suggests that they were not reactivated during the Acadian or Alleghanian orogenies (see below); therefore, the inference is that they show Taconic displacement (Smith 2006). In the southern Champlain Valley, fluid inclusion homogenization temperatures of 250°C and Taconian authigenic monazite have been found in the Potsdam Formation (Collins-Waite 1991; Selleck et al. 2008).

The Catskill "Delta" is the foreland basin fill of the Acadian Orogeny and covers a large portion of southern New York. Silurian- and Devonian-age rocks in western New York are ~1.5–2.0 km thick (Rickard 1975). In eastern New York, thicknesses increase from west to east and are ~1.5 km on the edge of the Catskill Mountains, but the section in eastern New York has been eroded by an unknown amount. Central New York has the thickest section of Devonian and Silurian strata, with an average of 2–3 km (Rickard 1975). It is reasonable to assume that a Devonian clastic wedge had covered the Adirondack Mountains because dated structures of this age occur to the east and northeast (Wintsch and Sutter 1986; Cawood 1993; Eusden and Lyons 1993; Williams 1993). Given the relative position of the Adirondacks, it is reasonable to assume that 2–3 km of Catskill Delta sediment was originally deposited in this area.

New York has virtually no strata related to the Pennsylvanian Alleghanian Orogeny, and a key question is whether these strata were deposited and then stripped away by erosion or were never deposited this far north. To the south, in Pennsylvania, maximum thicknesses reach 6–10 km. Until the 1980s, it was thought that the Alleghanian Orogeny produced a very thin sediment cover in New York (Meckel 1970). More recent studies focused on thermal maturation of Devonian strata have suggested that the sediment cover was much thicker than previously thought. Techniques used in recent studies include clay diagenesis, organic maturation, fluid inclusion, stable isotopes, and FT studies (Miller and Duddy 1989; Sarwar and Friedman 1995; Roden-Tice et al. 2000; Roden-Tice and Tice 2005; Slater 2007). Assuming average geothermal gradients, apatite FT and organic maturation data from across New York indicate almost 4 km of post-Devonian sediment cover for central and southern New York (Johnsson 1986). Estimates based on vitrinite reflectance and clay diagenesis vary from a minimum cover of 1–2 km for eastern and western New York and 3–4 km for central New York (Sarwar and Friedman 1995). Maximum post-Devonian sediment thicknesses have been estimated at ~5–6 km for western and central New York and 4–5 km for eastern New York (Sarwar and Friedman 1995). However, these estimates for the thickness of Alleghanian sediment are controversial, because they assume a typical geothermal gradient and because the timing of heating is unknown.

Totaling these estimates, sediment overburden across New York could have been anywhere from 4 to 11 km immediately after the Alleghanian Orogeny. The high estimate suggests strata thick enough to provide the burial needed to reset fission tracks in zircon in most places, given typical geothermal gradients (20°–30°C/km). The low estimate (~4 km), however, would not provide enough cover to heat the basement to temperatures sufficient to reset fission tracks in zircon.

While the Grenville basement rocks and overlying strata have had a complicated thermal history, the timing and duration of many of these events are still unclear. Detrital ages older than the deposition of the Potsdam Formation would indicate that none of the events that postdate the Great Unconformity had a significant widespread affect on ZFT ages. Detrital ages younger than the age of deposition would mean that one of the events had some effect on resetting low-retentive ZFT ages.

Methods

Sampling Locations. Bedrock samples were collected on the west, south, and east sides of the Adirondack Mountains to capture the maximum variation in paleotemperatures, as revealed by CAI values, of overlying Cambro-Ordovician carbonate rocks (fig. 2). Sample M-07 was collected from an outcrop of the Potsdam Formation near the junction of Seelye Road and Route 9L on the southern end of Lake George, New York. Sample M-19 was collected from an outcrop of the Potsdam Formation on Route 180 southeast of Fishers Landing, New York. Sample M-09 was collected from an outcrop of the Galway Formation on Route 29 near Kimball Corners, New York.

Mineral Separation. Rocks were collected from fresh, accessible outcrops in the field. About 5–10 kg of crushed sample was pulverized, and the zircon was separated by use of standard heavy liquids and magnetic separation techniques (Bernet and Garver 2005). In most samples, the dominant heavy mineral is zircon, which is generally rounded to highly rounded, spherical or ellipsoidal, frosted, and pitted (fig. 3). As a result of radiation damage effects, the grains are typically colorless, pink, brown, or yellow (i.e., Garver and Kamp 2002).

Zircon FT Dating. To estimate the number of spontaneous tracks, a sample is etched and the exposed tracks are counted. The concentration of ^{238}U is determined by use of an external detector. In this method, a mica detector with a very low uranium concentration is placed on top of a polished and etched sample. The sample is then irradiated with thermal neutrons that induce fission of ^{235}U in the sample. This neutron irradiation causes induced

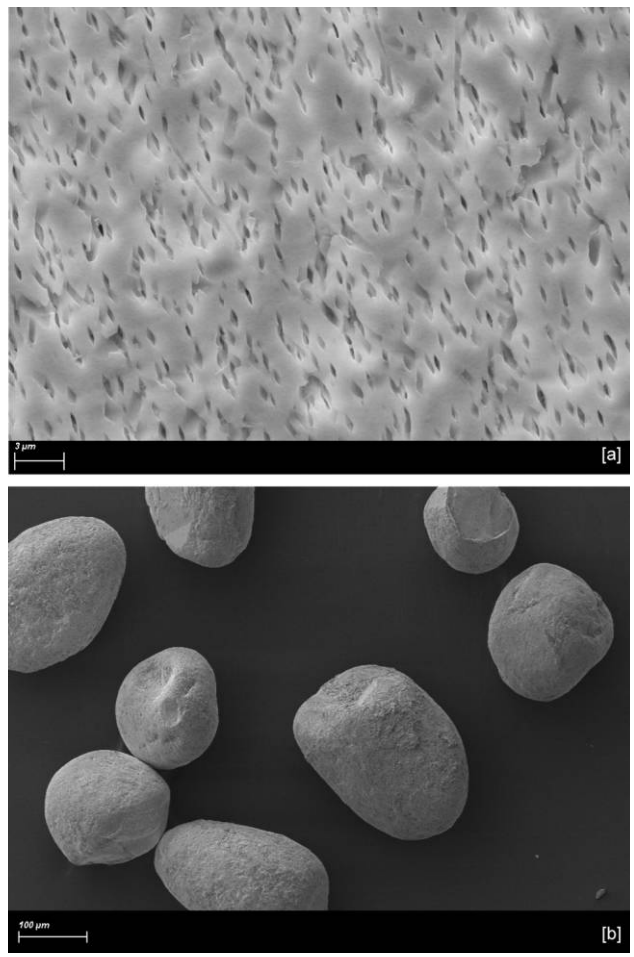

Figure 3. *a*, SEM image of etched fission tracks in zircon from the Potsdam Formation. *b*, SEM image of zircon grains from the Potsdam Formation. Zircon grains from the Potsdam Formation are generally rounded to highly rounded, spherical or ellipsoidal, frosted, and pitted. As a result of radiation damage effects, they are typically colorless, pink, brown, or yellow.

tracks to be registered in the mica detector. The newly formed tracks in the mica detector are then etched and counted to determine the concentration of ^{235}U, provided that the neutron flux is known and the ratio $^{238}U/^{235}U$ is constant in nature (see Naeser 1976; Wagner and van den Haute 1992; Gallagher et al. 1998 for a complete review). The main difference in our methodology from the traditional approach is that we image both the spontaneous and the induced tracks with an SEM and not an optical microscope.

FT Preparation. Zircon grains were mounted in PFA Teflon, ground, and polished with 9-μm and 1-μm diamond polishing liquid on Buehler AutoMet polishing machines. Samples were then etched in a KOH-NaOH eutectic for 1–30 h at 228° or 200°C. Etched samples were then covered with preannealed, fresh-cleaved, low-uranium mica. Glass monitors (CN-5), also with mica detectors, were placed at the top and bottom of the irradiation package to determine the fluence gradient. Samples were irradiated with a nominal fluence of 2×10^{15} neutrons/cm^2 at the Oregon State University nuclear reactor. After irradiation, mica was etched in 48% HF for 15–22 min. Samples and irradiated mica were mounted on glass petrographic slides for age determination.

A layer of Au-Pd ~80–100 Å (8–10 nm) thick was laid down on the samples with a sputter-coater to prevent charging. The samples were then imaged at 2000–5000× with a Zeiss Evo 50 tungsten-filament SEM (Montario and Garver 2008). Two images, secondary electron and backscatter electron, of the counting area were used to correctly identify tracks. To document grain shape and location, a secondary electron image of the dated grain was collected; this also aided in locating the grain for U-Pb analysis. Only a secondary electron image of the mica print was collected because backscatter images are unnecessary for track identification on the mica print. Tracks were counted with the photo analysis program ImageJ (National Institute of Standards), and ZFT ages were calculated with the Zeta method (Hurford 1996). A Zeta factor of 337.6 ± 9.2 was based on 12 determinations from the Fish Canyon Tuff, Buluk Tuff, and Peach Springs Tuff (all counted on the SEM). Ages were calculated with the standard age equations, and peak fitting was done with Binomfit (Brandon 1992). The SEM-HDFT dating has allowed us to count track densities of up to ~2×10^8 tracks/cm^2, or about an order of magnitude greater than the highest zircon FT densities counted optically (fig. 4).

U-Pb Geochronologic Analysis of Detrital Zircon. U-Pb geochronology of zircon was conducted by laser ablation–multicollector–inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center. The analyses in-

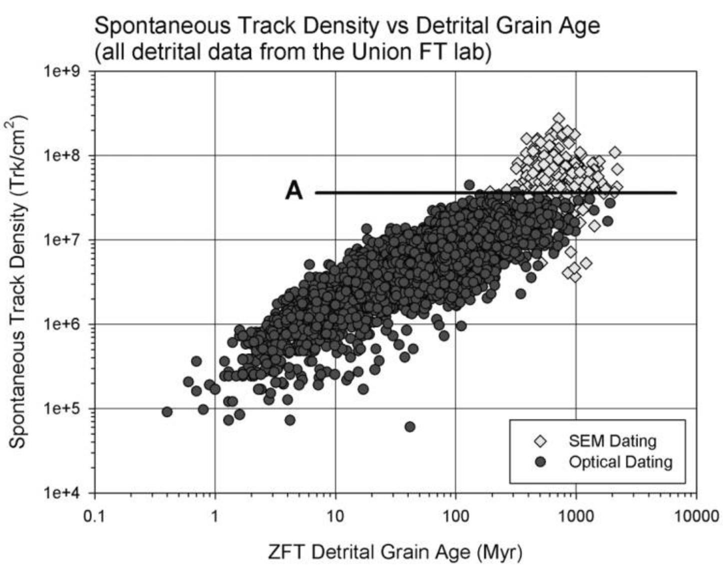

Figure 4. Spontaneous track density versus detrital grain age for more than 5000 detrital zircon grains (from various studies in the Union College fission-track [FT] lab). Circles represent grains dated via traditional identification of tracks with a light microscope at 1250×; diamonds represent track densities determined with the new SEM–high-density FT dating technique. The upper limit of track densities that can be determined by traditional zircon FT dating is about 2×10^7 tracks/cm^2 (*A*). Much older grains with higher track densities can be dated with the technique.

volved ablation of zircon with a New Wave/ Lambda Physik DUV193 Excimer laser (operating at a wavelength of 193 nm) using a spot diameter of 30 μm. The ablated material was carried in helium into the plasma source of a GVI Isoprobe equipped with a flight tube of sufficient width that U, Th, and Pb isotopes were measured simultaneously. All measurements were made in static mode, with 10e^{11}-ohm Faraday detectors for ^{238}U, ^{232}Th, ^{208}Pb, and ^{206}Pb, a 10e^{12}-ohm Faraday collector for ^{207}Pb, and an ion-counting channel for ^{204}Pb. Ion yields were ~1.0 mV/ppm. Each analysis consisted of one 20-s integration on peaks with the laser off (for backgrounds), 20 1-s integrations with the laser firing, and a 30-s delay to purge the previous sample and prepare for the next analysis. The resulting ablation pit was ~15 μm in depth.

For each analysis, the errors in determining ^{206}Pb/^{238}U and ^{206}Pb/^{204}Pb resulted in a measurement error of ~1%–2% (at 2σ level) in the ^{206}Pb/^{238}U age. The errors in measurement of ^{206}Pb/^{207}Pb and ^{206}Pb/^{204}Pb also resulted in ~1%–2% (at 2σ level) uncertainty in age for grains older than 1000 Ma, but the uncertainty for younger grains was substantially larger because of the low intensity of the ^{207}Pb signal. For most analyses, the crossover in precision of ^{206}Pb/^{238}U and ^{206}Pb/^{207}Pb ages occurred at 800–1000 Ma. Common Pb correction was accomplished by using the measured ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers (1975), with uncertainties of 1.0 for ^{206}Pb/^{204}Pb and 0.3 for ^{207}Pb/^{204}Pb. Our measurement of ^{204}Pb was unaffected by the presence of ^{204}Hg because backgrounds were measured on peaks (thereby subtracting any background ^{204}Hg and ^{204}Pb) and because very little Hg was present in the argon gas. Interelement fractionation of Pb/U was generally ~20%, whereas fractionation of Pb isotopes was generally ~2%. In-run analysis of fragments of a large Sri Lankan zircon crystal (generally every fifth measurement) with a known age of 564 ± 4 Ma (2σ error) was used to correct for this fractionation. The uncertainty resulting from the calibration correction was generally 1%–2% (2σ) for both ^{206}Pb/^{207}Pb and ^{206}Pb/^{238}U ages.

Interpreted ages are based on ^{206}Pb/^{238}U for <1000-Ma grains and on ^{206}Pb/^{207}Pb for >1000-Ma grains. This division at 1000 Ma results from the increasing uncertainty of ^{206}Pb/^{238}U ages and the decreasing uncertainty of ^{206}Pb/^{207}Pb ages as a function of age. Analyses >30% discordant (by comparison of ^{206}Pb/^{238}U and ^{206}Pb/^{207}Pb ages) or >5% reverse discordant were not considered further. The resulting interpreted ages were plotted on relative age-probability diagrams (from Ludwig 2003). These diagrams show each age and its uncertainty (for measurement error only) as a normal distribution and sum all ages from a sample into a single curve.

Data

U-Pb analysis of sample M-07 (eastern Adirondacks), based on 94 grains, yielded component populations at 1071, 1153, 1449, and 1499 Ma (fig. 5). The component populations at 1071 and 1153 Ma make up ~90% of the entire grain population; there was one much older grain at 2700 Ma. Most grain ages are concordant, with the exception of a few of the oldest grains.

U-Pb analysis of 89 grains from sample M-09 (southern Adirondacks) yielded component ages at 1071, 1157, 1347, and 1449 Ma (fig. 5). The component populations at 1071 and 1157 Ma make up ~75% of the entire grain population. This sample had a larger population at ~2700 Ma: seven grains, as opposed to the one grain from sample M-07. Most grains are concordant, with the exception of some of the grains older than 1.5 Ga.

U-Pb analysis of 95 grains from sample M-19 (western Adirondacks) yielded component populations at 1036, 1161, 1321, 1417, and 1667 Ma (fig. 5). The largest component population, at 1036 Ma, makes up ~47% of the entire grain population, while the peak at 1071 Ma makes up ~23% of the grain population. As with the other samples, most grain ages are concordant, except for some of the grains older than ~1.5 Ga. This sample has a slightly larger percentage of grains with ages between 1.3 and 1.4 Ga than the other samples.

Peak fitting of FT grain ages for sample M-07 (Lake George), based on 50 grains, yielded two component populations, at 540 and 720 Ma (fig. 6; table 1). For this sample from the east side of the Adirondacks, the younger component population is a slightly larger percentage of the overall population. Peak fitting of grain ages for sample M-09 (Kimball Corners), based on 49 grains, yielded three component populations, at 580 and 860 Ma and 1.4 Ga (fig. 6; table 1). In this sample, the component at 860 Ma has the greatest percentage (61%) of the grain population. Peak fitting of grain ages for sample M-19 (Fishers Landing), based on 48 grains, yielded two component populations, at 550 and 800 Ma (fig. 6; table 1). For this sample from the west side of the Adirondacks, the older component population makes up the majority of the grain population.

A histogram of both U-Pb ages and FT ages shows the distribution of grain ages for each system (fig. 7). Potsdam sample M-07 has the least overlap of U-Pb and FT ages because of the larger percentage

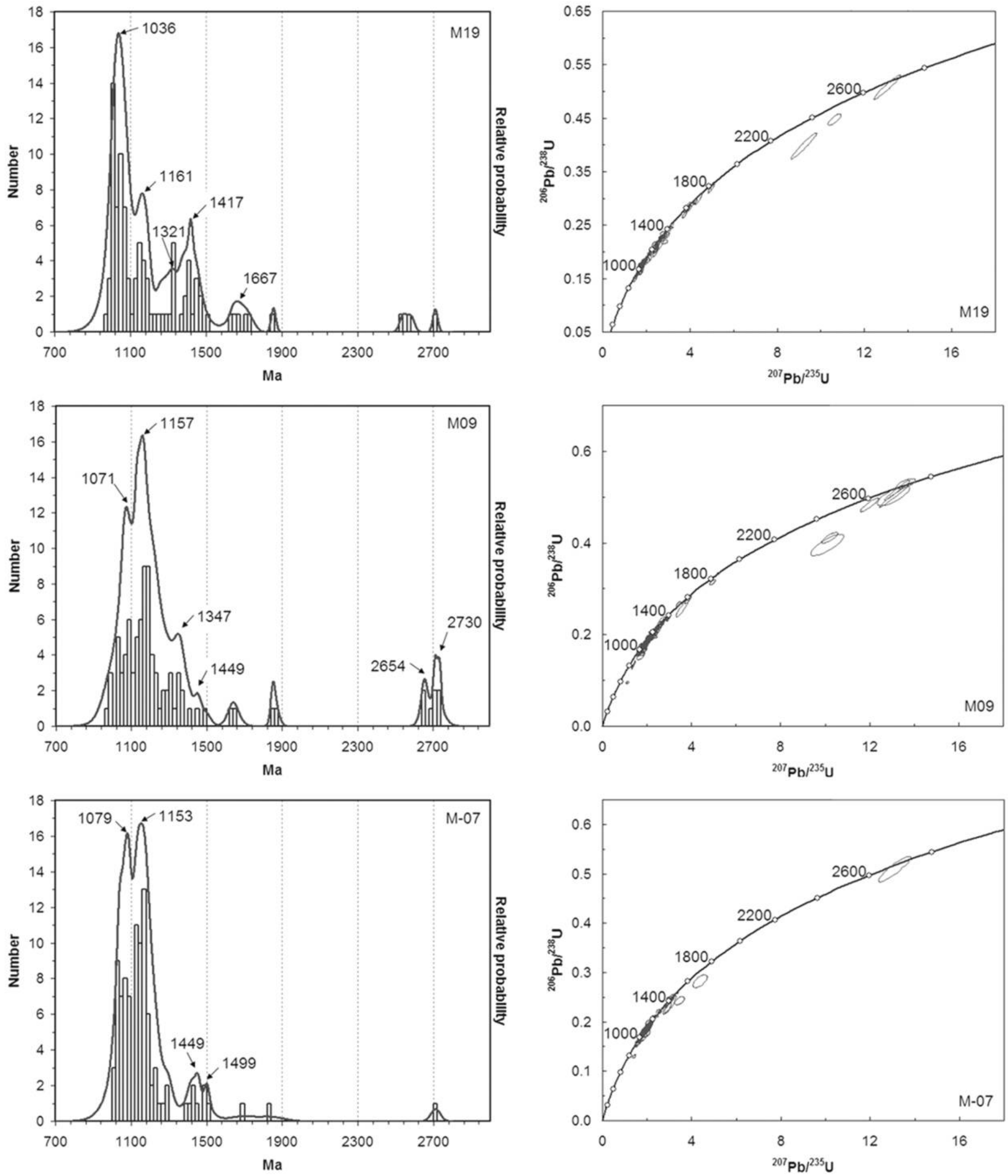

Figure 5. Probability density and concordia plots for U-Pb analysis for samples M-19, M-09, and M-07. Peak ages are labeled in the probability density plot. Data point error ellipses for the concordia plots are 68% confidence intervals.

of young grains. Sample M-09, from the Galway Formation, has some overlap due to the larger percentage of old FT grain ages.

Uranium Concentration

It is possible that the FT sample preparation and

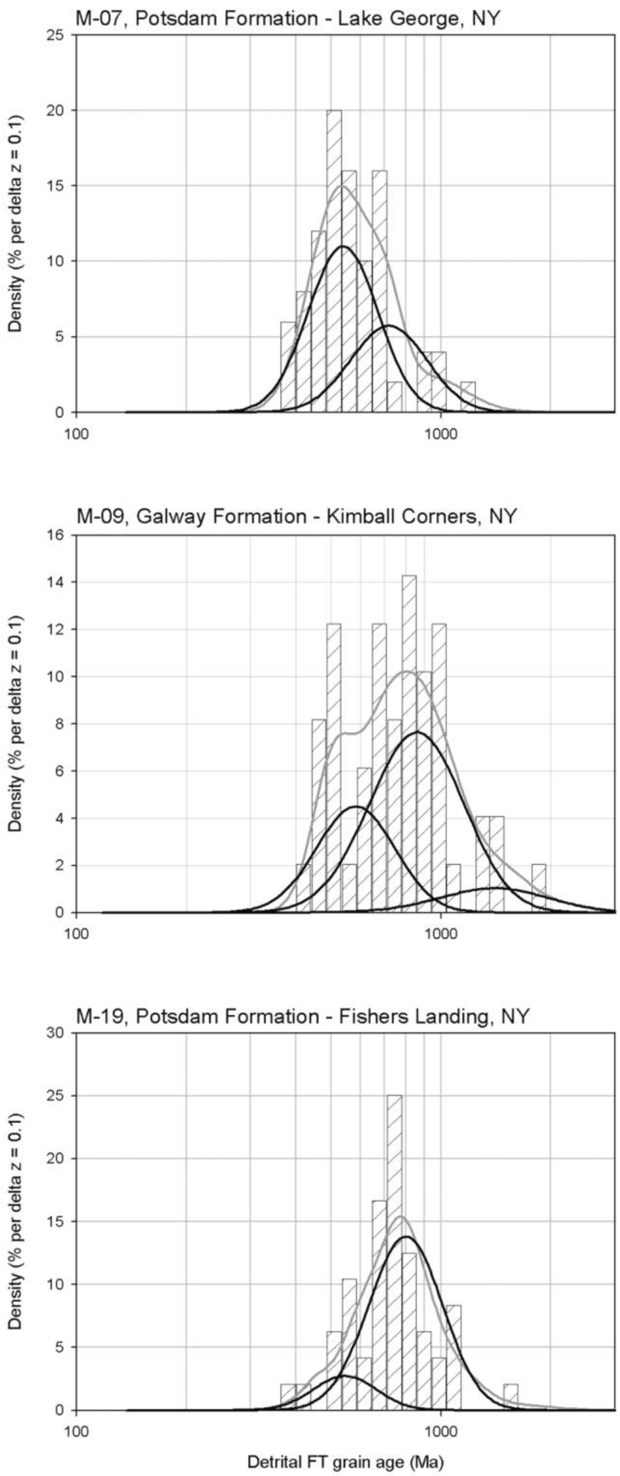

Figure 6. Statistical analysis of the fission-track (FT) ages for zircons of samples M-07 and M-19 from the Potsdam Formation and sample M-09 from the Galway Formation. Black lines represent best-fit age peaks, and gray lines represent observed data.

grain selection process influences the uranium concentrations that are counted. The main reason for this is that high–track density grains are usually avoided and older radiation-damaged grains tend to be destroyed during the etching process. This uranium bias could affect the resulting FT age if old grains are not counted. A comparison of the uranium concentrations from the U-Pb data and FT dating shows that there does not appear to be a major bias in this study. The average uranium concentration is ~213 ppm for the U-Pb ages and ~153 ppm for the FT ages, which is not surprising. The range of uranium is slightly different for the two techniques: 24–1521 ppm for the U-Pb ages and 41–345 ppm for the FT ages. While this may seem like a large difference in uranium concentrations, for the U-Pb data only 10% of the grains are over ~400 ppm and only four grains are over 1000 ppm. These high-uranium grains are all ~1.0–1.4 Ga, and no grains with U-Pb ages >1.4 Ga have uranium concentrations over ~400 ppm. With the introduction of SEM-HDFT dating, we have been able to date very old zircon with average uranium concentrations and to avoid any major uranium bias.

Source terranes are expected to produce zircon with a typical uranium distribution, and it is unlikely that source terranes will have zircon with unusual uranium concentrations. However, in the U-Pb data presented here we see a lack of high-uranium grains (>1000 ppm) that are older than 1.4 Ga. There are two possibilities for the lack of old high-uranium grains. The first is predepositional transport and weathering. These very old grains had the opportunity to accumulate a significant amount of radiation damage at the time of deposition, putting them close to or within the metamict state (Holland and Gottfried 1955). In zircon, radiation damage causes internal disorder, volume expansion, and a decrease in density and makes grains more prone to chemical attack (Holland and Gottfried 1955). This damage would have made the grains less robust, and therefore they would not survive transport or depositional processes. The second possibility is in situ dissolution of radiation-damaged zircon. It has been shown that sufficiently radiation-damaged zircon can undergo dissolution in tropical weathering conditions (Balan et al. 2001; Delattre et al. 2007) and that hydrothermal fluids can also dissolve or alter radiation-damaged zircon by removing uranium, thorium, and radiogenic lead (Geisler et al. 2002). The grains from the Potsdam Formation that we imaged with the SEM are highly rounded, frosted, and pitted (fig. 3). Consequently, these grains have surficial textures associated with eolian transport rather than chem-

Table 1. Summary of Zircon Fission-Track Ages from the Potsdam and Galway Formations, New York State

Sample, peak	n	Population (%)	Age (Ma)	-1σ Error (Ma)	$+1\sigma$ Error (Ma)
M-07 (Potsdam, Lake George, NY)	50				
P_1		63	540	42	46
P_2		37	720	76	74
M-09 (Galway, Costanzo's Farm, NY)[a]	49				
P_1		29	580	67	75
P_2		61	860	98	110
P_3		10	1400	360	470
M-19 (Potsdam, Fishers Landing, NY)	48				
P_1		14	550	90	110
P_2		86	800	47	49
All samples combined	147				
P_1		34	540	33	35
P_2		59	780	63	69
P_3		5	1200	330	450

Note. Fission-track ages ($\pm 1\sigma$) were determined using the Zeta method, and ages were calculated with the computer program Binomfit (Brandon 1992). A Zeta factor for zircon of 337.6 ± 9.2 ($\pm 1\sigma$) is based on 12 determinations from the Fish Canyon Tuff, the Buluk Tuff, and the Peach Springs Tuff. Glass monitors (CN5 for zircon), placed at the top and bottom of the irradiation package, were used to determine the fluence gradient. All samples were counted with the methods described in Montario and Garver (2008).
[a] For M-09, a third peak was fitted to these data because of the large number of very old grains, as in the U-Pb data.

ical weathering, as described by other workers (Dott 2003). Multicycling is inferred to have driven extreme textural maturity in pre-Silurian supermature quartz sandstones (Dott 2003), and it is likely that highly radiation-damaged zircon (i.e., high-uranium grains) would be preferentially removed from the system by sedimentary fractionation because they are less robust. The grain morphology and uranium distribution may favor predepositional transport and weathering to explain the lack of old high-uranium grains.

Discussion

Detrital zircons from the Potsdam and Galway formations show a clear Grenville source with only a minor component from other sources, as indicated by the U/Pb ages. It is also clear that the dated zircons from the Potsdam and Galway formations have not had significant postdepositional resetting of fission tracks and instead record the thermal history of the underlying Grenville terrane from which most grains were derived.

This Cambrian sediment has U-Pb ages that range from 1 to 1.4 Ga and make up 90%–95% of the grain ages in both the Potsdam and Galway formations, and this result certainly demands a Grenville-aged source, as originally suggested by Gaudette et al. (1981). While all three samples almost certainly had their source in the Grenville terrane, they may have received sediment from slightly different areas within the terrane. The Potsdam Formation on the west side of the Adirondacks (sample M-19) shows a grain age distribution (~1050 Ma) from the Grenville terrane slightly younger than that of the Potsdam on the east side (M-07), which has equal amounts of grains from the two youngest sources (1050 and 1150 Ma). To the south, the Galway Formation (M-09) appears to have been derived from a slightly older part of the Grenville terrane (1.3–2.7 Ga) or a part with older, recycled material. An important finding is that no grains are dated at less than 950 Ma, and therefore these samples do not seem to record any young orogenic activity related to the rifting of Rodinia at ca. 550–600 Ma.

From the U-Pb data, it seems reasonable to assume that the source areas were similar from sample to sample with only minor differences, as discussed above. To refine our understanding of component populations, therefore, we combined all the U-Pb data into one probability density plot (fig. 8). In this plot, component ages define a peak at 1063 Ma that corresponds to the Ottawan Orogenesis (1090–1030 Ma) and a peak at 1157 Ma that corresponds to the intrusion of the AMCG suite (McLelland et al. 2001; Bickford et al. 2008). The peaks at 1368 and 1417 Ma are most likely associated with rocks from the Elzevirian Arc that collided with Laurentia at ~1300 Ma, initiating the Grenville orogenic cycle. The main point is that whether alone or combined, these U-Pb data appear to indicate a clear Grenville source similar to the Adirondack Massif.

Several explanations are possible for the oldest peaks (~1.6, 1.8, and 2.7 Ga), approximately 10% of the population, which are clearly older than the Grenville events. The oldest ages could be derived

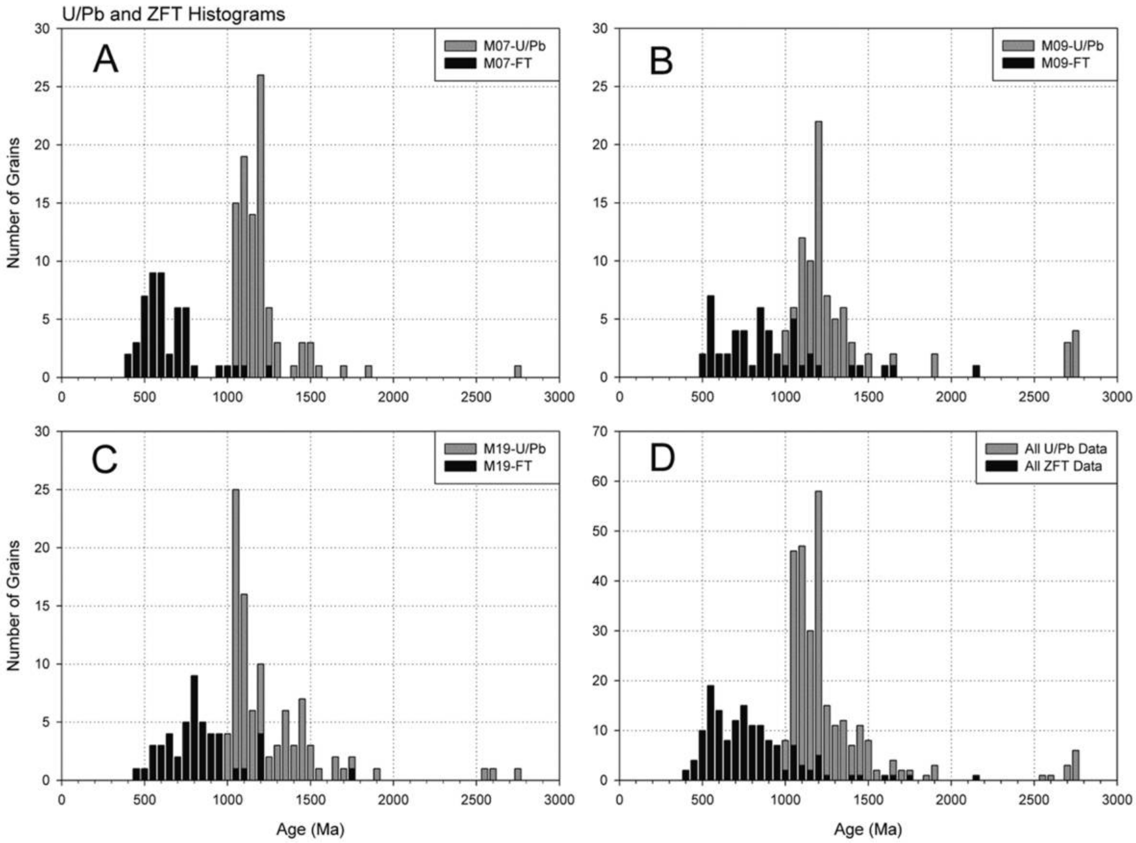

Figure 7. Histograms of U-Pb and zircon fission-track (ZFT) age data for each individual sample and all samples combined. Gray bars are for the U-Pb data, and black bars are for the ZFT data. *A*, Sample M-07 (Potsdam Formation); *B*, sample M-09 (Galway Formation); *C*, sample M-19 (Potsdam Formation); *D*, all grains.

from nearby adjacent basement terranes, such as the Superior terrane (>2.5 Ga) of Canada and the Yavapai-Mazatzal terrane (1.6–1.8 Ga) of the south-central United States (Hoffman 1997; Magnani et al. 2004; Dickinson and Gehrels 2008). However, it is also possible that these grains are from poorly studied quartzites that occur in the Adirondacks metamorphic rocks. Quartzite units, such as the Irving Pond Quartzite (McLelland et al. 2005), are known to contain zircon from older terranes and have a wide range of crystalline ages. Finally, some of these older grains are discordant and therefore could be even older than they appear, but it is still likely that they are derived from one of these sources.

There are almost no published detrital U-Pb ages for the Potsdam Formation, and there appear to be none for the Galway Formation. The U-Pb ages reported by Gaudette et al. (1981) are based on multiple-grain aliquots with a few single-grain analyses. The resulting data are in good agreement with the young component populations of our analysis, but they lack the older grains that are clearly revealed in the single-grain analysis reported here. The most likely reason for this lack of very old grains is that the oldest population is very small (~10%); several grains of Grenville age would dominate the analysis of a single older grain included with them for bulk age determination.

The ZFT ages from the Potsdam and Galway formations fall into three component populations, at ~540, ~780, and ~1200 Ma (fig. 8; table 1). The younger populations (~540–580 Ma, ~34%) are most likely related to the breakup of Rodinia and the rifting of the Iapetus Ocean. Evidence for this is seen in the significant number of dikes along the eastern seaboard of North America (Kumarapeli et al. 1990; Coish and Sinton 1991; Aleinikoff et al. 1995; Cawood et al. 2001). The percentage of grains in the young FT grain age population (ca. 540 Ma) changes slightly from the east side of the Adirondacks to the west. The fraction of grains in the

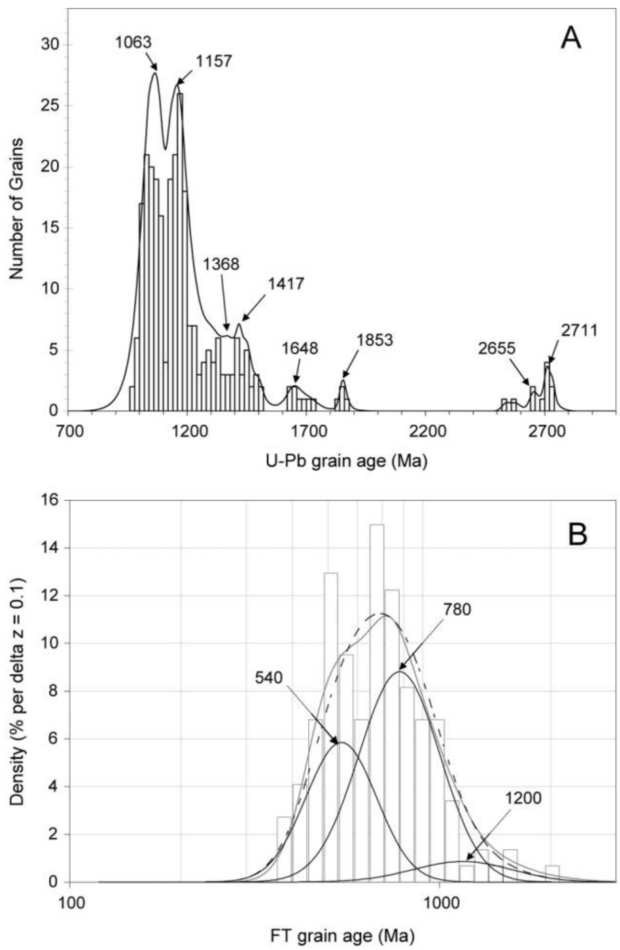

Figure 8. *A*, Probability density plot of all U-Pb data from samples M-07, M-09, and M-19. The black line shows the relative probability plot. All zircons analyzed from the Potsdam and Galway formations were older than ~950 Ma, and the majority were between 1.0 and 1.4 Ga, suggesting an almost purely Grenville source for the sandstone of the Potsdam and Galway formations of the Adirondacks. *B*, Probability density plot of all zircon fission-track (ZFT) data from samples M-07, M-09, and M-19. The ZFT ages record the postorogenic cooling of the Grenville terrane (780 Ma) and the heating associated with the rifting of the Iapetus Ocean (540 Ma), as well as the cooling ages of grains from other, older terranes (>1.2 Ga).

young population is much larger in the eastern sample (M-07): ~63% of the population, as opposed to ~14% in the western sample (M-19; fig. 6). Likewise, the opposite is true of the old population: ~37% of the grain population in the eastern sample versus ~86% of the population in the western sample. This change in the percentage of grain age populations could be explained by the nature of the immediately underlying Grenville basement rock and the distribution of Proterozoic dikes, possibly associated with the rifting of the Iapetus, within the Adirondacks.

In general, the mapped distribution of dikes shows a marked increase on the eastern side of the Adirondacks (Isachsen et al. 1988). We hypothesize that the intrusion of these dikes was a widespread low-temperature heating event that reset the ZFT system in surrounding Grenville rocks. Only a small number of these dikes have been dated by K-Ar at ca. 560–580 Ma (Isachsen et al. 1988). The youngest ZFT population is within the error of these ages. If, however, the age difference between the K-Ar and ZFT systems is real, it may be explained by slow cooling at depth after intrusion. In this case, the event may have been localized on the eastern side of the Adirondacks and the Potsdam Formation may have been derived from local sources.

With the U-Pb result in mind, we are reasonably assured that the zircon grains are largely if not exclusively Grenville derived. The most important observation in the FT data is that all the samples have peak ages older than the depositional age of the upper Cambrian to lower Ordovician Potsdam and Galway formations. These ZFT ages are likely a reflection of the low-temperature history of the Grenville terrane, the inferred source rock. A simple extrapolation of the high-temperature cooling ages from the Adirondacks shows that predicted low-temperature cooling ages (ca. 200°–300°C) for the ZFT system would fall between 600 and 800 Ma (fig. 9). The older ZFT population (~780 Ma, ~59%) determined in our data set fits within this cooling window, as predicted in our initial hypothesis. Therefore, the ZFT ages from these samples, to a first order, likely record the cooling ages of the Precambrian Grenville terrane.

The ZFT data have a small population of grain ages (~5%) that are older than the cooling ages expected (>1.0 Ga) from the Grenville terrane. This older population occurs more distinctly in the Galway Formation than in the Potsdam Formation (fig. 7). We propose that these pre-Grenville ZFT cooling ages indicate that the zircon with old U-Pb ages (>1.6 Ga) was derived from nearby Precambrian terranes and not necessarily from quartzites or other rock types in the Adirondack Mountains. However, this prediction must be proved by replicate dating with other techniques. If correct, this hypothesis suggests that these grains are likely associated with sediment shed from the Superior or Yavapai-Mazatzal terranes. One important, subtle aspect of these data is that at 1.2 Ga, these are the oldest

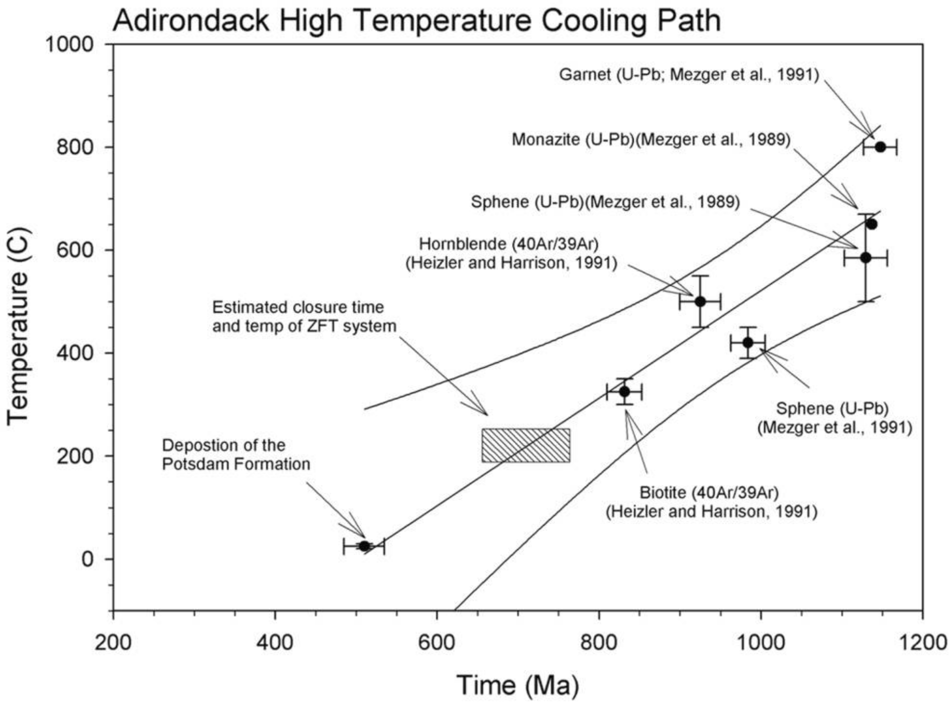

Figure 9. High-temperature data from the Adirondack Mountains, showing extrapolated cooling to surface temperatures based on the depositional age of the Potsdam Formation. The depositional age of the Potsdam Formation is upper middle Cambrian to lower upper Cambrian (Landing 2007), which means that the Potsdam Formation was deposited at surface temperatures around 500 Ma. The high-temperature data for this plot are from Mezger et al. (1991) and Heizler and Harrison (1998). Analyses include U-Pb ages for garnet, sphene, monazite, and rutile and $^{40}Ar/^{39}Ar$ ages for hornblende and biotite. The shaded area represents the approximate cooling times and temperatures for the zircon fission-track (ZFT) system based on these high-temperature data. Modified from Gombosi (2006).

detrital ZFT ages reported in the literature. In fact, one of the grains from the Galway Formation has a calculated ZFT age of more than 2 billion years. These data show that our modified ZFT dating technique should allow us to study the cooling history of Precambrian terranes elsewhere.

An issue worth considering is whether some or all of these zircon grains have been annealed or partially annealed by heating and subsequent track loss. Field-based studies have produced a closure temperature for natural radiation-damaged zircon that ranges anywhere from ~205° to 260°C, depending on the cooling rate (Harrison et al. 1979; Zaun and Wagner 1985; Hurford 1986; Brandon and Vance 1992; Foster et al. 1996; Bernet 2002). Annealing of fission tracks in some radiation-damaged zircon may occur at temperatures as low as 150°–200°C, depending on resident times (Garver et al. 2005; Reiners and Brandon 2006). Track annealing is a function of both time and temperature and varies from grain to grain, depending on radiation damage. For example, sample M-19 (Potsdam Formation) has CAI values of 2–2.5 (~60°–140°C; Epstein et al. 1977), and therefore it must have remained below temperatures required to anneal fission tracks in zircon over geologically significant periods of time. Because this sample has remained relatively cool since deposition, the ZFT distribution may be used as a baseline for comparison with samples from rocks with higher CAI values, (e.g., 4–4.5, 190°–300°C; Epstein et al. 1977). In this comparison, we note that the ZFT ages of these other samples are similar, which suggests that the rocks from the eastern sample have not undergone heating sufficient to significantly reset the ZFT system since ~540 Ma. We suspect that if a sample was heated to ~190°C for a geologically short period of time (less than ~5 m.yr.), the fission tracks could have been unannealed, including those in the highly radiation-damaged grains. Evidence of a heating event exceeding ~200°C, which has been suggested for the Potsdam Formation by fluid inclusion studies (Selleck 2008), is therefore probably the result of hot localized fluid infiltration and not a regional event. If this heating was regional, we should see clear resetting throughout the study area, but we do not, and here we explore an example of an often-cited sample that might be used to suggest that heating was regional.

A metabentonite layer in the Middle Ordovician upper Black River Group has a calculated ZFT age of ~349 Ma (Johnsson 1984) or 354 Ma (Johnsson 1986), which is younger than the depositional age (ca. 455 Ma [Mohawkian]; Ogg et al. 2008). This ZFT age has been inferred to have resulted from resetting due to burial and has been used as evidence of widespread regional heating and burial (see Johnsson 1986; Sarwar and Friedman 1995). However, we caution against overinterpretation of these data. The original sample had 14 dated grains, of which five were excluded from the final analysis because uncertainties of the single-grain ages exceeded the mean age of all the grains (Johnsson 1984). In other words, this sample has an overdispersed population. As we discuss in this article, this overdispersion is a commonly recognized phenomenon in ZFT dating with heterogeneous zircon suites with more than one component population of grains. We reanalyzed the data for this sample, using a synthetic Zeta and fluence, and the result is overdispersed grain ages that fail χ^2. Our analysis yielded two component populations at ~314 and 500 Ma (~73% and 27%, respectively). A key point is that this sample is not fully reset. We note that these ZFT ages have track densities determined optically to be $>1.0 \times 10^7$ tracks/cm^2. Track densities this high are at the limit of optical determination (fig. 4; Montario and Garver 2008) and could have resulted in a counting bias that would result in apparent ages that are too young. It is still possible that these grains are reset, but we suggest that this sample be reevaluated using the new SEM-HDFT technique.

Conclusions

1. U-Pb ages from detrital zircon of the Potsdam and Galway formations indicate derivation of these units almost entirely from the Precambrian Grenville terrane. Pre-Grenville ZFT cooling ages suggest that a small fraction (~10%) of the zircons with older U-Pb ages may have been derived from the nearby Superior or Yavapai-Mazatzal terranes. The other possibility for these pre-Grenville ZFT ages is that these zircon grains are derived from metasedimentary rocks, such as the Irving Pond Quartzite, within the Grenville terrane. This second possibility is less likely because ZFT ages from the Grenville terrane would have been reset during Ottawan Orogenesis, which we do not see.

2. The ZFT ages of detrital zircon from the Potsdam and Galway formations record the cooling history of the Grenville terrane after peak metamorphism at ca. 1.0–1.1 Ga. The two ZFT cooling ages may correspond to postorogenic exhumation (ca. 780 Ma) and rifting related to the opening of the Iapetus Ocean and the breakup of Rodinia (ca. 540 Ma). The small percentage (~5%) of older ZFT cooling ages (>1.0 Ga) probably represents grains derived from the Superior or Yavapai-Mazatzal terranes.

3. The ZFT ages presented here suggest that significant post-Devonian deposition and burial over the Adirondacks did not occur. The old ZFT ages are not consistent with widespread heating to temperatures >190°C due to 8–10 km of burial, as suggested by other workers (Johnsson 1986; Sarwar and Friedman 1995). The ZFT ages from these Adirondack samples also do not support the idea of widespread Taconic heating. However, Taconic heating events could have been the result of localized fluids. It is possible that these heating events were not long enough or hot enough to affect the annealing kinetics of fission tracks in zircon.

4. Much of our data supports the idea of a locally derived source for these units. About 90% of U-Pb ages within the Potsdam and Galway formations can be explained by source rocks from within the local Grenville basement. Proterozoic dikes, dated at ca. 580 Ma (Isachsen et al. 1988) and possibly associated with rifting of the Iapetus, occur preferentially on the eastern side of the Adirondacks. The higher percentage of younger ZFT ages (~540 Ma) in the eastern Adirondacks may indicate a locally derived source. Constant reworking in littoral or eolian environments could easily explain the frosted and pitted nature of the zircon grains from these formations, which also supports local derivation.

5. The detrital ZFT ages given here are the oldest reported in the literature (see Bernet and Garver 2005). The success of the emerging SEM-HDFT dating technique, developed for this study, suggests that we can begin to investigate the low-temperature thermal evolution of Precambrian terranes elsewhere.

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REFERENCES CITED

Abdel-Rahman, A.-F. M., and Kumarapeli, P. S. 1998. Geochemistry of mantle-related intermediate rocks from the Tibbit Hill volcanic suite, Quebec Appalachians. Mineral. Mag. 62:487–500.

Aleinikoff, J. N.; Zartman, R. E.; Walter, M.; Rankin, D. W.; Lyttle, P. T.; and Burton, W. C. 1995. U-Pb ages of metarhyolites of the Catoctin and Mount Rogers formations, central and southern Appalachians: evidence for two pulses of Iapetan rifting. Am. J. Sci. 295:428–454.

Balan, E.; Neuville, D. R.; Trocellier, P.; Fritsch, E.; Muller, J.-P.; and Calas, G. 2001. Metamictization and chemical durability of detrital zircon. Am. Mineral. 86:1025–1033.

Barton, K. E.; Howell, D. G.; and Vigil, J. F. 2003. The North America tapestry of time and terrain. U.S. Geol. Surv. Geol. Invest. Ser. I-2781.

Bernet, M. 2002. Exhuming the Alps through time: clues from detrital zircon fission-track ages. PhD dissertation, Yale University, New Haven, CT.

———. 2009. A field-based estimate of the zircon fission-track closure temperature. Chem. Geol. 259:181–189.

Bernet, M., and Garver, J. I. 2005. Fission-track analysis of detrital zircon. Rev. Mineral. Geochem. 58:205–237.

Bickford, M. E.; McLelland, J. M.; Selleck, B. W.; Hill, B. M.; and Heumann, M. J. 2008. Timing of anatexis in the eastern Adirondack Highlands: implications for tectonic evolution during ca. 1050 Ma Ottawan orogenesis. Geol. Soc. Am. Bull. 120:950–961.

Bird, J. M., and Dewey, J. F. 1970. Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen. Geol. Soc. Am. Bull. 81:103–136.

Bradley, D. C., and Kidd, W. S. F. 1991. Flexural extension in collisional foredeeps. Geol. Soc. Am. Bull. 103:1416–1438.

Brandon, M. T. 1992. Decomposition of fission-track grain-age distributions. Am. J. Sci. 292:535–564.

Brandon, M. T.; Roden-Tice, M. K.; and Garver, J. I. 1998. Late Cenozoic exhumation of the Cascadia accretionary wedge in the Olympic Mountains, NW Washington State. Geol. Soc. Am. Bull. 110:985–1009.

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. J. Sci. 292:565–636.

Cawood, P. A. 1993. Acadian Orogeny in west Newfoundland: definition, character and significance. *In* Roy, D. C., and Skehan, J. W., eds. The Acadian Orogeny: recent studies in New England, maritime Canada, and the autochthonous foreland. Geol. Soc. Am. Spec. Pap. 275, p. 135–152.

Cawood, P. A.; McCausland, P. J. A.; and Dunning, G. R. 2001. Opening Iapetus: constraints from the Laurentian margin in Newfoundland. Geol. Soc. Am. Bull. 113:443–453.

Coish, R. A., and Sinton, C. W. 1991. Geochemistry of mafic dikes in the Adirondack Mountains: implications for late Proterozoic rifting. Contrib. Mineral. Petrol. 110:500–514.

Collins-Waite, D. 1991. Diagenesis of the Cambro-Ordovician Beekmantown Group: a petrographic and fluid inclusion study. MS thesis, SUNY Binghamton.

Delattre, S.; Utsunomiya, S.; Ewing, R. C.; Boeglin, J.-L.; Braun, J.-J.; Balan, E.; and Calas, G. 2007. Dissolution of radiation-damaged zircon in lateritic soils. Am. Mineral. 92:1978–1989.

Dickinson, W. R., and Gehrels, G. E. 2008. Sediment delivery to the Cordilleran foreland basin: insights from U-Pb ages of detrital zircons in upper Jurassic and Cretaceous strata of the Colorado Plateau. Am. J. Sci. 308:1041–1082.

Dobson, M. H. 1973. Closure temperature in cooling geochronological and petrological systems. Contrib. Mineral. Petrol. 40:259–274.

Dott, R. H., Jr. 2003. The importance of eolian abrasion in supermature quartz sandstones and the paradox of weathering on vegetation-free landscapes. J. Geol. 111:387–405.

Epstein, A. G.; Epstein, J. B.; and Harris, L. D. 1977. Conodont color alteration: an index to organic metamorphism. U.S. Geol. Surv. Prof. Pap. 995, 27 p.

Eusden, J. D., Jr., and Lyons, J. B. 1993. The sequence of Acadian deformations in central New Hampshire. *In* Roy, D. C., and Skehan, J. W., eds. The Acadian Orogeny: recent studies in New England, maritime Canada, and the autochthonous foreland. Geol. Soc. Am. Spec. Pap. 275, p. 51–66.

Fedo, C. M.; Sircombe, K. N.; and Rainbird, R. H. 2003. Detrital zircon analysis of the sedimentary record. Rev. Mineral. Geochem. 53:277–303.

Fisher, D. W. 1977. Correlation of the Hadrynian, Cambrian, and Ordovician rocks in New York State. N.Y. State Mus. Map and Chart Ser. 25.

Fleischer, R. L.; Price, P. B.; and Walker, R. M. 1975. Nuclear tracks in solids. Berkeley, University of California Press, 605 p.

Foster, D. A.; Kohn, B. P.; and Gleadow, A. J. 1996. Sphene and zircon fission-track closure temperature revisited: empirical calibrations from $^{40}Ar/^{39}Ar$ diffusion studies on K-feldspar and biotite. International Workshop on Fission-Track Dating (University of Ghent, Aug. 26–30), Abstr. 37.

Galbraith, R. F., and Laslett, G. M. 1997. Statistical modelling of thermal annealing of fission tracks in zircon. Chem. Geol. 140:123–135.

Gallagher, K.; Brown, R.; and Johnson, C. 1998. Fission track analysis and its applications to geological problems. Annu. Rev. Earth Planet. Sci. 26:519–572.

Garver, J. I., and Kamp, P. J. J. 2002. Integration of zircon color and zircon fission-track zonation patterns in orogenic belts: application to the Southern Alps, New Zealand. Tectonophysics 349:203–219.

Garver, J. I.; Reiners, P. R.; Walker, L. J.; Ramage, J. M.; and Perry, S. E. 2005. Implications for timing of Andean uplift based on thermal resetting of radiation-damaged zircon in the Cordillera Huayhuash, northern Peru. J. Geol. 113:117–138.

Gaudette, H. E.; Vitrac-Michard, A.; and Allegre, C. J. 1981. North American Precambrian history recorded in a single sample: high-resolution U-Pb systematics of the Potsdam sandstone detrital zircons, New York State. Earth Planet. Sci. Lett. 54:248–260.

Gehrels, G. W.; Dickinson, W. R.; Ross, G. M.; Stewart, J. H.; and Howell, D. G. 1995. Detrital zircon reference for Cambrian to Triassic miogeoclinal strata of western North America. Geology 23:831–834.

Geisler, T.; Pidgeon, R. T.; van Bronswijk, W.; and Kurtz, R. 2002. Transport of uranium, thorium, and lead in metamict zircon under low-temperature hydrothermal conditions. Chem. Geol. 191:141–154.

Gleadow, A. J. W. 1978. Comparison of fission track dating methods: effects of anisotropic etching and accumulated α-damage. *In* Zartman, R. E., ed. Short papers of the Fourth International Conference on Geochronology, Cosmochronology and Isotope Geology (Snowmass, CO). U.S. Geol. Surv. Open File Rep. 78-701, p. 143–145.

Gombosi, D. J. 2006. (U+Th)/He systematics in rutile through empirical calibration from examples in the Western Gneiss Region (Norway), Bronson Hill Anticlinorium (New Hampshire), and the Adirondacks (New York). BS thesis, Union College, Schenectady, NY.

Hamilton, M. A.; McLelland, J.; and Selleck, B. 2004. SHRIMP U-Pb geochronology of the anorthosite-mangerite-charnockite-granite (AMCG) suite, Adirondack Mountains, New York: ages of emplacement and metamorphism. *In* Tollo, R. P.; Corriveau, L.; McLelland, J.; and Bartholomew, M. J., eds. Proterozoic tectonic evolution of the Grenville Orogen in North America. Geol. Soc. Am. Mem. 197:337–356.

Harris, A. G. 1979. Conodont color alteration, an organo-mineral metamorphic index and its application to Appalachian Basin geology. *In* Scholle, P. A., and Schluger, P. R., eds. Aspects of diagenesis. Soc. Econ. Paleontol. Mineral. Spec. Publ. 26:3–16.

Harris, A. G.; Harris, L. D.; and Epstein, J. B. 1978. Oil and gas data from Paleozoic rocks of the Appalachian Basin: maps for assessing hydrocarbon potential and thermal maturity (conodont color alteration isograds and overburden isopachs). U.S. Geol. Surv. Miscell. Geol. Invest. Map I-917E, 5 sheets, scale 1 : 250,000.

Harrison, T. M.; Armstrong, R. L.; Naeser, C. W.; and Harakal, J. E. 1979. Geochronology and thermal history of the Coast Plutonic Complex, near Prince Rupert, British Columbia. Can. J. Earth Sci. 16:400–410.

Hart, B.; Copley, D.; and Loewenstein, S. 1996. Chasing the Rose Run play with 3D seismic in New York. Oil Gas J. 94:88–91.

Heizler, M. T., and Harrison, M. 1998. The thermal history of New York basement determined from the $^{40}Ar/^{39}Ar$ K-feldspar studies. J. Geophys. Res. 103:29,795–29,814.

Hoffman, P. F. 1997. Tectonic genealogy of North America. *In* van der Pluijm, B. A., and Marshak, S., eds. Earth structure: an introduction to structural geology and tectonics. New York, McGraw-Hill, p. 459–464.

Holland, H. D., and Gottfried, D. 1955. The effect of nuclear radiation on the structure of zircon. Acta Crystallogr. 8:291–300.

Hurford, A. J. 1986. Cooling and uplift patterns in the Lepontine Alps south central Switzerland and age of vertical movement on the Insubric fault line. Contrib. Mineral. Petrol. 92:413–417.

———. 1996. Zeta: the ultimate solution to fission track analysis calibration or just an interim measure? *In* van den Haute, P., and De Corte, F., eds. Advances in fission-track geochronology. Dordrecht, Kluwer Academic, p. 19–32.

Iizuka, T.; Horie, K.; Komiya, T.; Maruyama, S.; Hirata, T.; Hidaka, H.; and Windley, B. F. 2006. 4.2 Ga zircon xenocryst in an Acasta gneiss from northwestern Canada: evidence for early continental crust. Geology 34: 245–248.

Isachsen, Y. W.; Coish, R.; Sinton, C.; Heisler, M.; and Kelley, B. 1988. Dikes of the northeast Adirondack region: their distribution, orientation, mineralogy, chronology, chemistry and mystery. *In* Olmsted, J. F., ed. Field trip guidebook, N.Y. State Geol. Assoc., p. 215–243.

Isachsen, Y. W.; Landing, E.; Lauber, J.; Rickard, L. V.; and W. Rogers, W. 1991. The geology of New York: a simplified account. N.Y. State Mus. Education Leaflet 50, 300 p.

Janssens, A. 1973. Stratigraphy of the Cambrian and lower Ordovician rocks in Ohio. Ohio Div. Geol. Surv. Bull. 64, 197 p.

Johnsson, M. J. 1984. The thermal and burial history of south central New York: evidence from vitrinite reflectance, clay mineral diagenesis and fission track dating of apatite and zircon. MS thesis, Dartmouth College, Hanover, NH.

———. 1986. Distribution of maximum burial temperatures across northern Appalachian Basin and implications for Carboniferous sedimentation patterns. Geology 14:384–387.

Kumarapeli, P. S.; Dunning, G. R.; Pintson, H.; and Shaver, J. 1989. Geochemistry and U-Pb zircon age of comenditic metafelsites of the Tibbit Hill Formation, Quebec Appalachians. Can. J. Earth Sci. 26:1374–1383.

Kumarapeli, P. S.; Seymour, K. S.; Fowler, A.; and Pintson, H. 1990. The problem of the magma source of a giant radiating mafic dike swarm in a failed arm setting. *In* Parker, A. J.; Rickwood, P. C.; and Tucker, D. H., eds. Mafic dikes and emplacement mechanisms. Rotterdam, Balkema, p. 163–171.

Landing, E. 2007. Ediacaran-Ordovician of East Laurentia: geologic setting and controls on deposition along the New York Promontory region. *In* Landing, E., ed. Ediacaran-Ordovician of East Laurentia: S. W. Ford Mem. Vol. N.Y. State Mus. Bull. 510, p. 5–24.

Laslett, G. M.; Green, P. F.; Duddy, I. R.; and Gleadow, A. J. W. 1987. Thermal annealing of fission tracks in apatite. 2. A quantitative analysis. Chem. Geol. Isotope Geosci. Sect. 65:1–13.

Lim, C.; Kidd, W. S. F.; and Howe, S. S. 2005. Late shortening and extensional structures and veins in the western margin of the Taconic Orogen (New York to Vermont). J. Geol. 113:419–438.

Long, L. E. 1969. Whole-rock Rb-Sr age of the Yonkers Gneiss, Manhattan Prong. Geol. Soc. Am. Bull. 80: 2087–2090.

Ludwig, K. R. 2003. User's manual for Isoplot 3.00: a geochronological toolkit for Microsoft Excel. Spec. Publ. 4. Berkeley, CA, Berkeley Geochronology Center, 70 p.

Magnani, M. B.; Levander, A.; Miller, K. C.; Eshete, T.; and Karlstrom, K. E. 2004. Seismic investigation of the Yavapai-Mazatzal Transition Zone and the Jemez Lineament in northeastern New Mexico. *In* Karlstrom, K. E., and Keller, G. R., eds. The Rocky Mountain region—an evolving lithosphere: tectonics, geochemistry and geophysics. Am. Geophys. Union Geophys. Monogr. 154, p. 227–238.

McLelland, J.; Bickford, M. E.; and Selleck, B. 2005. SHRIMP U/Pb study of zircons from the Adirondacks and adjacent Grenville Province of Canada: a preliminary report. Geol. Soc. Am. Abstr. Program 37(1):21.

McLelland, J.; Hamilton, M.; Selleck, B.; McLelland, J.; Walker, D.; and Orrell, S. 2001. Zircon U-Pb geochronology of the Ottawan Orogeny, Adirondack Highlands, New York: regional and tectonic implications. Precambrian Res. 109:39–72.

McLelland, J.; Isachsen, Y.; Whitney, P.; Chiarenzelli, J.; and Hall, L. 1993. Geology of the Adirondack Massif, New York. *In* Reed, J. C., Jr.; Bickford, M. E.; Houston, R. S.; Link, P. K.; and Van Schmus, W. R., eds. Precambrian: conterminous U.S. (Geology of North America, Vol. C-2). Boulder, CO, Geol. Soc. Am., p. 338–353.

McLelland, J.; Storm, L. C.; and Spear, F. S. 2002. Geology and geochronology of the southern Adirondacks. *In* McLelland, J., and Karabonis, P., eds. 94th Annual meeting of the New England Intercollegiate Geological Conference and 74th Annual meeting of the New York State Geological Association (Lake George, NY, September 27–29, 2002). Guidebook for fieldtrips in New York and Vermont, p. A1.1–A1.20.

Meckel, L. D. 1970. Paleozoic alluvial deposition in the central Appalachians: a summary. *In* Fisher, G. W.; Pettijohn, F. J.; Reed, J. C., Jr.; and Weaver, K. N., eds. Studies of Appalachian geology: central and southern. New York, Interscience, p. 49–67.

Mezger, K.; Rawnsley, C. M.; Bohlen, S. R.; and Hanson, G. N. 1991. U-Pb garnet, sphene, monazite, and rutile ages: implications for the duration of high-grade metamorphism and cooling histories, Adirondack Mts., New York. J. Geol. 99:415–428.

Miller, D. S., and Duddy, I. R. 1989. Early Cretaceous uplift and erosion of the northern Appalachian Basin, New York, based on apatite fission track analysis. Earth Planet. Sci. Lett. 93:35–49.

Montario, M. J., and Garver, J. I. 2008. Using scanning electron microscopy for high track-density fission-track dating. *In* Garver J. I., and Montario, M. J., eds. FT2008: 11th International Conference on Thermochronometry, Abstracts, p. 171–173.

Moore, J. M., and Thompson, P. H. 1980. The Flinton Group: a late Precambrian metasedimentary succession in the Grenville Province of eastern Ontario. Can. J. Earth Sci. 17:1685–1707.

Mose, D. G., and Hayes, J. 1975. Avalonian igneous activity in the Manhattan Prong, southeastern New York. Geol. Soc. Am. Bull. 86:929–932.

Naeser, C. W. 1976. Fission track dating. U.S. Geol. Surv. Open File Rep. 76–190, 86 p.

Naeser, C. W.; McKee, E. H.; Johnson, N. M.; and MacFadden, B. J. 1987. Confirmation of a Late Oligocene-Early Miocene age of the Deseadan Salla Beds of Bolivia. J. Geol. 95:825–828.

Ogg, J. G.; Ogg, G.; and Gradstein, F. M. 2008. The concise geologic time scale. Cambridge, Cambridge University Press, 176 p.

Otvos, E. G. 1965. Sedimentary structures and depositional environments, Potsdam Formation, upper Cambrian. Bull. Am. Assoc. Pet. Geol. 50:159–165.

Rahl, J. M.; Reiners, P. W.; Campbell, I. H.; Nicolescu, S.; and Allen, C. M. 2003. Combined single-grain (U-Th)/He and U/Pb dating of detrital zircons from the Navajo Sandstone, Utah. Geology 31:761–764.

Rahn, M. K.; Brandon, M. T.; Batt, G. E.; and Garver, J. I. 2004. A zero model for fission-track annealing in zircon. Am. Mineral. 89:473–484.

Reiners, P. W., and Brandon, M. T. 2006. Using thermochronology to understand orogenic erosion. Annu. Rev. Earth Planet. Sci. 34:419–166.

Reiners, P. W.; Campbell, I. H.; Nicolescu, S.; Allen, C. M.; Hourigan, J. K.; Garver, J. I.; Mattinson, J. M.; and Cowan, D. S. 2005. (U-Th)/(He-Pb) double dating of detrital zircons. Am. J. Sci. 305:259–311.

Reiners, P. W.; Zhou, Z.; Ehlers, T. A.; Xu, C.; Brandon, M. T.; Donelick, R. A.; and Nicolescu, S. 2003. Post-orogenic evolution of the Dabie Shan, eastern China, from (U-Th)/He and fission-track analysis. Am. J. Sci. 303:489–518.

Repetski, J. E.; Ryder, R. T.; Harper, J. A.; and Trippi, M. H. 2002. Thermal maturity patterns (CAI and $\%R_o$) in the Ordovician and Devonian rocks of the Appalachian Basin in Pennsylvania. U.S. Geol. Surv. Open File Rep. 02-302, 60 p.

Rickard, L. V. 1973. Stratigraphy and structure of subsurface Cambrian and Ordovician carbonates of New York. NY. State Mus. Map and Chart Ser. 18.

———. 1975. Correlation of Silurian and Devonian rocks in New York State. N.Y. State Mus. Map and Chart Ser. 24.

Riley, B. C. D. 2004. Laramide exhumation and heating in southeastern Arizona: low-temperature thermal history and implications for zircon fission-track systematics. PhD dissertation, University of Texas, Austin.

Roden-Tice, M. K., and Tice, S. J. 2005. Regional-scale mid-Jurassic to Late Cretaceous unroofing from the Adirondack Mountains through central New England based on apatite fission-track and (U-Th)/He thermochronology. J. Geol. 113:535–552.

Roden-Tice, M. K.; Tice, S. J.; and Schofield, I. S. 2000. Evidence for differential unroofing in the Adirondack Mountains, New York State, determined by apatite fission-track thermochronology. J. Geol. 108:155–169.

Sarwar, G., and Friedman, G. M. 1995. Post-Devonian sediment cover over New York State: evidence from fluid inclusion, organic maturation, clay diagenesis, and stable isotope studies. Lecture Notes in Earth Sciences 58. Berlin, Springer, 109 p.

Selleck, B.; Williams, M.; and Jercinovic, M. 2008. In-situ U-Th-Pb microprobe dating of authigenic monazite and xenotime in the Potsdam Sandstone, eastern New York: a new approach to dating hydrothermal fluid flow and dolomitization. Eastern Section of the American Association of Petroleum Geologists Meeting Abstracts, p. 14.

Selleck, B. W. 1997. Potsdam Sandstone of the southern Lake Champlain valley: sedimentary facies, environments and diagenesis. *In* Grover, T. W.; Mango, H. N.; and Hasenohr, E. J., eds. New England Intercollegiate Geological Conference, 89th Annual Meeting (Killington-Pico, VT, September 19–21, 1997). Guidebook for fieldtrips in Vermont and adjacent New Hampshire and New York, p. C3-1–C3-16.

———. 2008. Stratigraphy, sedimentology and diagenesis of the Potsdam Formation of the southern Lake Champlain Valley. *In* New York State Geological Association, 80th Annual Meeting (Lake George, NY, September 26–28, 2008). Fieldtrip guidebook, p. 144–156.

Slater, B. E. 2007. Outcrop analog for lower Paleozoic hydrothermal dolomite reservoirs, Mohawk Valley, NY. MS thesis, University of Albany.

Smith, L. B., Jr. 2006. Origin and reservoir characteristics of upper Ordovician Trenton–Black River hydrothermal dolomite reservoirs in New York. Am. Assoc. Pet. Geol. Bull. 90:1691–1781.

Smith, L. B., Jr.; Lugert, C. M.; and Nyahay, R. E. 2003. Integrated characterization of hydrothermal dolomite reservoirs in Trenton–Black River carbonates of New York. Am. Assoc. Pet. Geol. Annual Meeting (Salt Lake City, May 11–14, 2003) Abstracts, p. A160.

Smith, L. B., Jr., and Nyahay, R. 2004. Fault-controlled hydrothermal dolomite reservoirs in Ordovician Trenton–Black River carbonates of New York. Geol. Soc. Am. Abstr. Program 36:118.

Stacey, J. S., and Kramers, J. D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet. Sci. Lett. 26:207–221.

Storm, L. C., and Spear, F. S. 2005. Pressure, temperature and cooling rates of granulite facies migmatitic pelites from the southern Adirondack Highlands, New York. J. Metamorph. Geol. 23:107–130.

Su, Q.; Goldberg, S. A.; and Fullagar, P. D. 1994. Precise U-Pb zircon ages of Neoproterozoic plutons in the southern Appalachian Blue Ridge and their implications for the initial rifting of Laurentia. Precambrian Res. 68:81–95.

Tagami, T.; Galbraith, R. F.; Yamada, R.; and Laslett, G. M. 1998. Revised annealing kinetics of fission tracks in zircon and geological implications. *In* van den Haute, P., and De Corte, F., eds. Advances in fission-track geochronology. Dordrecht, Kluwer Academic, p. 99–112.

Wagner, G. A. 1972. The geological interpretation of fission track ages. Trans. Am. Nucl. Soc. 15:117.

Wagner, G. A., and Reimer, G. M. 1972. Fission track tectonics: the tectonic interpretation of fission track apatite ages. Earth Planet. Sci. Lett. 14:263–268.

Wagner, G. A., and van den Haute, P. 1992. Fission-track dating. Dordrecht, Kluwer Academic, 285 p.

Wasteneys, H.; McLelland, J.; and Lumbers, S. 1999. Precise zircon geochronology in the Adirondack Lowlands and implications for revising plate-tectonic models of the Central Metasedimentary Belt and Adirondack Mountains, Grenville Province, Ontario and New York. Can. J. Earth Sci. 36:967–984.

Weary, D. J.; Ryder, R. T.; and Nyahay, R. 2001. Thermal maturity patterns in New York State using CAI and $\%R_o$. Northeast. Geol. Environ. Sci. 23:356–376.

Wilde, S. A.; Valley, J. W.; Peck, W. H.; and Graham, C. M. 2001. Evidence from detrital zircons for the existence of continental crust and oceans on Earth 4.4 Gyr ago. Nature 409:175–178.

Williams, H. 1993. Acadian Orogeny in Newfoundland. *In* Roy, D. C., and Skehan, J. W., eds. The Acadian Orogeny: recent studies in New England, maritime Canada, and the autochthonous foreland. Geol. Soc. Am. Spec. Pap. 275, p. 123–134.

Wintsch, R. P., and Sutter, J. F. 1986. A tectonic model for the Late Paleozoic of southeastern New England. J. Geol. 94:459–472.

Zaun, P. E., and Wagner, G. A. 1985. Fission-track stability in zircons under geological conditions. Nucl. Tracks 10:303–307.