Geology of Central Park, Manhattan, New York City, USA: New geochemical insights

Steven J. Jaret*
Nicholas D. Tailby
Keiji G. Hammond
*Department of Earth and Planetary Sciences, American Museum of Natural History,
200 Central Park West, New York, New York 10024-5102, USA*

E. Troy Rasbury
Kathleen Wooton
*Department of Geosciences, Stony Brook University, 255 Earth and Space Science Building,
Stony Brook, New York 11794-2100, USA*

Denton S. Ebel
*Department of Earth and Planetary Sciences, American Museum of Natural History,
200 Central Park West, New York, New York 10024-5102, USA*

E. DiPadova
Riley Smith
Victoria Yuan
Noa Jaffe
New York City Department of Education, 52 Chambers Street, New York, New York 10007, USA

Lisa M. Smith
*Department of Earth and Planetary Sciences, American Museum of Natural History,
200 Central Park West, New York, New York 10024-5102, USA*

Lynsey Spaeth
New York City Department of Education, 52 Chambers Street, New York, New York 10007, USA

ABSTRACT

Here we present an overview of the geology of the Manhattan Prong and a specific guide for field stops in northern Central Park. This guide is intended to provide a brief introduction to these complex rocks for researchers, undergraduate students,

*sjaret@amnh.org

and teachers. Given the easy access to Central Park and numerous schools and institutions nearby, these outcrops provide ideal teaching outcrops for students of all levels. We also present new geochemical and isotopic results for the Manhattan and Hartland Schists. Previous work has focused primarily on field mapping, structural relationships, or infrastructure-related mapping, whereas our new geochemistry data allow for more detailed discussions of provenance and overall tectonic history of these rocks. Our results suggest that all of the rocks in northern Central Park (regardless of mapped unit) are derived from Laurentia.

INTRODUCTION

Teaching Geology in the Parks

This work is largely the result of an activity associated with the American Museum of Natural History's Masters of Arts Teaching (MAT) Earth Science Residency program. Since 2011, the museum has been preparing pre-service teachers and supporting them as they serve as public school teachers in high needs schools. As part of this program, the master's students engage in an intensive 7-week research program that focuses on New York City local and regional geology. The approach is to engage students through the idea that geology is place specific, and to show that our local setting is directly connected with the rocks, landforms, and other surface features around them. Additionally, we provide opportunity for teachers to gain hands-on access to rocks and associated contextual assets including geologic maps, photos, and videos, with which they then can teach in the future. This work represents six years of effort by museum scientists who are part of the MAT program faculty co-researching with the pre-service teachers and program graduates. This field guide is paired with a teachers' guide to northern Central Park, developed in partnership with the American Museum of Natural History's Education Department and alumni of the MAT program who are currently teachers in New York City. The teachers' guide will be available on the AMNH website (https://www.amnh.org/learn-teach) and is also available at https://doi.org/10.5531/sd.edu.2.

Scope of This Guide

The rest of this section presents a broad-based regional geologic context for the Manhattan Prong. We then introduce the geologic units and discuss previous work. Next, we present background and new geochemistry related to the overall tectonic setting and interpretations of Manhattan Prong. We then go on to summarize our new results for New York City. Finally, we present field stops and descriptions for r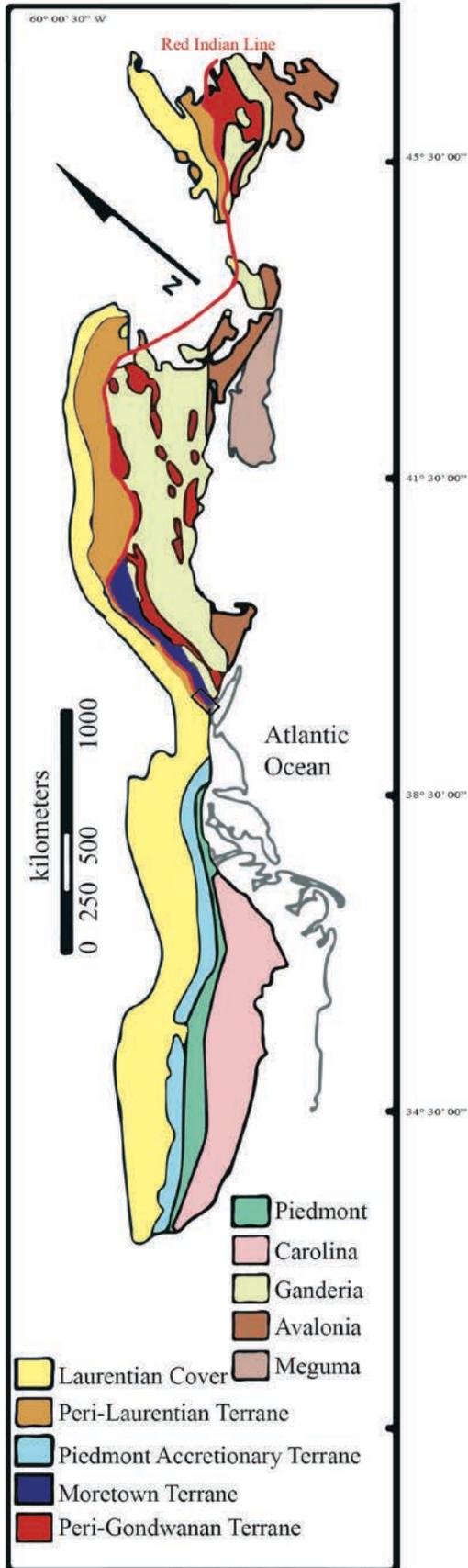ocks in Northern Central Park. **NOTE: This work was carried out in coordination with and permission from the New York City Department of Parks and Recreation and the Central Park Conservancy. Individual collecting or sampling within Central Park is strictly prohibited without prior authorization and the requisite permits.**

Background and Regional Geologic Setting

The rocks exposed within Central Park are part of a larger physiographic province, referred to as the Manhattan Prong (Long and Kulp, 1958; Hall, 1968), which includes the boroughs of New York City and much of southern Westchester County. Geologically, this region borders the older Hudson Highlands to the north, Laurentian margin metasediments to the west and northwest, exotic and accreted terrains (e.g., units correlative with the Bronson Hill Arc and/or Mooretown equivalents) to the northeast, and is overlain by Triassic and Cretaceous sediments to the west and south in New Jersey (Fig. 1). Structurally, the Manhattan Prong sits at an important junction of the Appalachian Mountain belt, as it marks the boundary between the northern and southern Appalachians (Macdonald et al., 2014; Hibbard et al., 2006; Van Staal and Barr, 2012).

Regionally, the rocks of New England (for the sake of adhering to regional geologic nomenclature geology we include the Manhattan Prong as situated in New England, even though New York is not a part of this political designation) represent the end result of multiple major collisional events during the assembly of the Pangea supercontinent during the Paleozoic Era. The resulting geology that we see today is a series of fault-bounded accreted terranes, each representing a specific terrane contributing to the development of the supercontinent. From west to east these terranes are referred to as the Dashwoods, Ganderia, Avalonia, and Meguma. The Dashwoods represents peri-Laurentian–derived material, whereas Ganderia, Avalonia, and Meguma all have peri-Gondwanan or Gondwanan affinities (Van Staal et al., 2009; Hatcher, 2014; Karabinos et al., 2017). The docking of each is associated with a major orogenic event: Taconic orogeny at 460–450 Ma (Dashwoods), Salinic at 450–423 Ma (Ganderia), Acadian at 420–400 Ma (Avalonia), and the Neoacadian at 395–350 Ma (Meguma). The Neoacadian was followed by another major orogenic event, the Alleghenian at 300–290 Ma. By this point, the Iapetus Ocean was largely closed, and the Alleghenian is primarily a continent-continent–style collision. The results of this event are most prominent in the southern Appalachians, although some of the Acadian and Taconic structures in New England may have been reactivated during the Alleghenian (Hatcher, 2014).

The tectonic architecture of these origins and terranes has been well documented and studied in detail in northern New England and Canada (van Staal et al., 2009; van Staal and Barr, 2012).

60° 00' 30" W

Red Indian Line

N

45° 30' 00"

41° 30' 00"

Atlantic
Ocean

38° 30' 00"

34° 30' 00"

kilometers

0   250   500   1000

Piedmont
Carolina
Ganderia
Avalonia
Meguma

Laurentian Cover
Peri-Laurentian Terrane
Piedmont Accretionary Terrane
Mooretown Terrane
Peri-Gondwanan Terrane

Particular focus has been on the main Iapetus suture, referred to as the Red Indian Line (or Cameron's Line farther south), separating the Laurentian margin from accreted terranes (Macdonald et al., 2014; Dorais et al., 2012). This boundary can be seen in detrital zircon studies where rocks of Laurentian affinity are dominated by zircons of Grenville age (1300–900 Ma), whereas accreted terranes have a Gondwanan source with ages between 630 and 535 Ma. However, the location of this boundary and its placement in southern New England remain uncertain. Faults once considered major terrane boundaries—including the mapped Cameron's Line in Connecticut—may not be true terrane boundaries (Dietsch and Ratcliffe, 2006). Importantly, the rocks of southern New England and New York have not been well studied geochemically. The assignment of units to particular terranes has been largely based on unit correlation and field mapping alone, and the assessment of whether thrust faults represent true terrane boundaries has not been the focus of detailed geochemical analysis.

Geologic map patterns and unit names and correlations change dramatically on either side of the Manhattan Prong. Specifically, Mooretown terrane and Gondwanan-derived units abruptly terminate at the northern end of the prong, and southern piedmont and Carolina terranes do not appear north of New Jersey (Fig. 1). Thus, the rocks within the Manhattan Prong are critical for linking models for the geologic history of the northern and central Appalachian Mountains. The rocks of the Manhattan Prong have been the subject of many mapping studies, particularly from a structural and geotechnical standpoint in conjunction with development of New York City infrastructure. However, there has been a lack of modern geochemical and isotopic studies of these rocks and their assumed correlative units in New England. Several questions remain regarding correlation of units, mapping, provenance of units, and petrochronology of the protolith sediments during the Taconic, Acadian, and Alleghenian orogenies. In addition to addressing these questions, we seek to understand the extent to which the map pattern of the Manhattan Prong is the result of geographic and political boundaries and the history of geologic mapping, or if the Manhattan Prong represents a true structural promontory dividing the tectonic architecture to the north and south.

DESCRIPTIONS OF AND INTRODUCTION TO THE ROCKS OF THE MANHATTAN PRONG

The rocks of the Manhattan Prong consist of the Fordham Gneiss, the Manhattan Schist, and the Hartland Schist (Hall, 1968; Merguerian and Merguerian 2004; Baskerville, 1994; Brock and

Figure 1. Generalized geologic map of the Appalachian mountain belt, modified after Macdonald et al. (2014). Major terranes and boundaries are shown, along with the outline of the U.S. coastline. Also shown is the Red Indian Line (referred to as Cameron's Line in southern New England), which is generally interpreted as the boundary between Laurentian and Gondwanan lithologies.

Brock, 2001), which are the primary units encountered in Central Park that are the subject of this field guide. Smaller units of non-schists, which are not exposed in the park, are briefly described below to provide a broader regional context.

Ultramafic Rocks

Ultramafic rocks, primarily serpentinite, occur in a narrow band along the southern end of the Manhattan Prong. Large exposures are found in Hoboken, New Jersey, and on Staten Island (Puffer, 1996), and are interpreted as being associated with the thrust faulting associated with one of the Appalachian orogenies.

Igneous Rocks

Igneous rocks in the Manhattan Prong occur as two distinct varieties: (i) in situ partial melt veins and pockets associated with metamorphism and (ii) larger coherent intrusive bodies. Partial melt veins and pockets (frequently referred to as pegmatites because they show pegmatitic textures) occur throughout the schists, both cross-cutting and following foliation. These bodies are generally small, 1–2 m wide, and have igneous textures as they are partial melts that formed in response to prograde metamorphism (see Stop 5).

The second type of igneous rocks consists of large intrusive bodies that are unrelated to in situ partial melting. The best example of this is the Ravenswood Granodiorite, occurring primarily in Long Island City just north and south of the Queensboro Bridge. This is a coarse-grained granodiorite, with large (1 m) mafic enclaves. In some cases, there is textural evidence of shearing, and this unit has been correlated with the more deformed Harrison Gneiss in Connecticut (Merrill and Magnus, 1904; Pellegrini, 1975; Ziegler, 1911).

Our reconnaissance mapping in the northern Bronx has identified an additional, previously unmapped pluton, exposed at the Bronx Zoo, in and around the bear enclosure (which we refer to as the Bear's Den Granite). This granite is extensive enough to be considered a true pluton rather than a small localized intrusion, as it occurs extensively at the bear enclosure and the facilities building, ~0.5 km apart from each other. This unit is a very coarse-grained pegmatite with notable large (15 cm, locally up to 30 cm) single crystal K-feldspar grains (Fig. 2A). K-feldspar are poikilitic with garnet, quartz, feldspar, and apatite inclusions. One exposure near the work shed at the zoo contains a several-meter-sized block of schist included in the granite as a xenolith or roof pendant. Zircon crystals in the Bear's Den Granite are distinctive: up to a millimeter in length, dark brown to black, with a very high uranium concentration, and they are not cathodoluminescent. The grains are highly metamict and discordant, and with dates of 400 Ma ± 15. This age is slightly unexpected for southern New York, but ca. 400 Ma is a commonly reported Acadian age of plutons in northern New England (De Yoreo et al., 1989).

Inwood Marble

Regionally, the Inwood Marble lies unconformably between the Fordham Gneiss of the Hudson Highlands and the Hartland/Manhattan Schists. The marble is rarely exposed in New York City, but is found in Upper Manhattan near Inwood and Isham Parks (Merguerian and Merguerian, 2014). Where it is exposed, it is more typically a calcsilicate (an impure marble) rather than a true marble. It commonly contains quartz, feldspar, muscovite, and tremolite.

Metasedimentary Aluminosilicate Rocks (Hartland/Manhattan Schists)

Metasedimentary schists are the dominant rock in New York City, and certainly in Central Park are schists, primarily schists with smaller biotite schists and amphibolites occurring throughout the region. Mapping, correlation, and nomenclature of the schists have been debated in the literature for more than 60 years (Merrill, 1890; Hall, 1976, 1968; Ratcliffe, 1968; Stanley and Hatch 1976; Taterka, 1987; Brock and Brock, 2001). These schists, originally named the Manhattan Schist by Merrill (1890), are subdivided into multiple members (upper, middle, lower by Merrill; A, B, and C by Hall, 1976, and Merguerian and Merguerian, 2016). Most workers since Merrill (1890) have separated the upper member of the Manhattan Schist as a distinct named unit, the Hartland Schist, largely based on correlations with rocks in Connecticut (Merguerian and Merguerian, 2004). Brock and Brock (1999) introduced the name Ned Mountain Formation for one of the schists between the Grenvillan basement (Fordham Gneiss) and the Cambrian–Ordovician sequence schists, but it is unclear what this correlates with or how it relates to the other mapped schists. In a detailed mapping campaign of Central Park, Taterka (1987) showed that there is significant variability even within the remaining middle and lower members of the Manhattan Schist, and he subdivided these schists using location-specific members, directly related to the rocks seen in Central Park. For this guide, we will follow Taterka's mapped names since we will visit many of his mapped locations.

Brief descriptions of the Hartland and Manhattan Schists using nomenclature from Taterka (1987) are as follows:

Hartland Schist is a gray, medium- to coarse-grained muscovite-biotite-garnet schist with abundant quartz-rich layers. Large, centimeter-sized muscovite books are common throughout. The key distinguishing feature of the Hartland Schist is its weak mechanical properties as it breaks and crushes easily. This is noted when sampling, but also was instrumental in geotechnical mapping associated with tunneling for New York City infrastructure (Merguerian and Merguerian, 2004).

Manhattan Schist is subdivided into multiple member units:
- *Blockhouse Member* is a gray, medium-grained, garnet-kyanite-magnetite schist. This unit has a key distinguishing knotty texture that is the result of differential weathering between garnet-biotite layers and less resistant quartz "bootgrabbers."

Figure 2. (A) Bear's Den Granite, with large, 15–30-cm-long single K-feldspar. White notebook at lower right is 15 cm. (B) Contact between Bear's Den Granite and a block of schist.

- *East Meadow Member* is a medium-grained garnet-kyanite schist interbedded with thin quartzose layers and local amphibolites. White plagioclase grains up to 3 mm long are common.
- *110th St. Member* is a brown to red (slightly rusty) garnet schist, dominated by quartz, biotite, muscovite, and unzoned plagioclase. Garnet in this unit is abundant and up to 1 cm in size. Staurolite has been reported by Taterka (1987), although we have not encountered staurolite in any of our work.

TECTONIC OBSERVATIONS AND INTERPRETATIONS BASED ON GEOCHEMISTRY AND ISOTOPIC COMPOSITION

All the schists are extensively deformed, showing multiple generations of folds. The dominant foliation in the schists is consistent with regional trends striking NNE, but in most locations, there are at least 3-fold orientations including a prominent upright fold (seen most notably at Stops 4 and 8). The complex structures here, and in conjunction with nearby ultramafic outcrops

in Staten Island and Hoboken have led to significant focus on attempts to trace the Appalachian suture, referred to as Cameron's Line, and interpreted as a terrane boundary. Based largely on correlation with units in Connecticut, most workers consider this boundary to be separating the Hartland Schist (aka the upper Manhattan Schist) and the middle and lower members of the Manhattan Schist. That being said, the position of this boundary and the assignment of terrains have been the subject of considerable debate (Fig. 3). Tectonic interpretations are commonly conflicting. For example, whether Cameron's Line is a true terrane boundary and the distinction between Cameron's Line and other faults that are not terrane boundaries, such as the St. Nicholas fault, are treated inconsistently in the literature. Our work, for the first time, attempts to approach this from a geochemical perspective rather than from a field mapping standpoint alone. The notion that Cameron's Line is a terrane boundary separating Laurentian-derived units from those derived from exotic terranes (e.g., Ganderia, or a similar exotic micro-continent) should be testable using isotope and trace element geochemistry, because the source of these materials is both different in age and in elemental and isotopic composition.

Garnet Geochemistry

The geochemistry of garnet has proven to be a particularly useful tool for distinguishing different units throughout the Manhattan Prong. The composition of a garnet will reflect the complex interactions between the whole rock composition and the pressure-temperature path taken by a sample during metamorphism, combined with the types and stability of coexisting phases and the rate of change observed in the system. When garnets are sampled from within schists at different locations within the Manhattan Prong, distinct zonation styles are apparent, but they only correspond somewhat to the field mapping–based unit assignments. While large differences in garnet major element chemistry would suggest that different units have notably different whole rock composition and source, bulk analyses from the metasedimentary schists (at least among the outcrops observed in this study) are remarkably consistent. These differences in trace elements and zonation patterns within garnets from very similar schists more likely represent diffusion-based elemental changes to the garnets based on the specific pressure-temperature-time (*P-T-t*) paths that these packages of metasediments took during deformation. By analyzing many outcrops, clusters of similar garnets can be identified. For example, samples from the North Meadows (northern Central Park), Morningside Park, and Inwood Park all show a "dogleg" pattern in Mn-Ca and Fe-Mg space (Fig. 4B). In direct contrast to these "dogleg" samples, another distinct cluster of samples (largely from the Bronx and southern sections of Central Park) shows near-constant Mn and high variations in Ca (Fig. 4A). In this regard, samples from different regions of Central Park have been a useful tool in terms of hunting for major lithological boundaries—some of which we will cross during this trip.
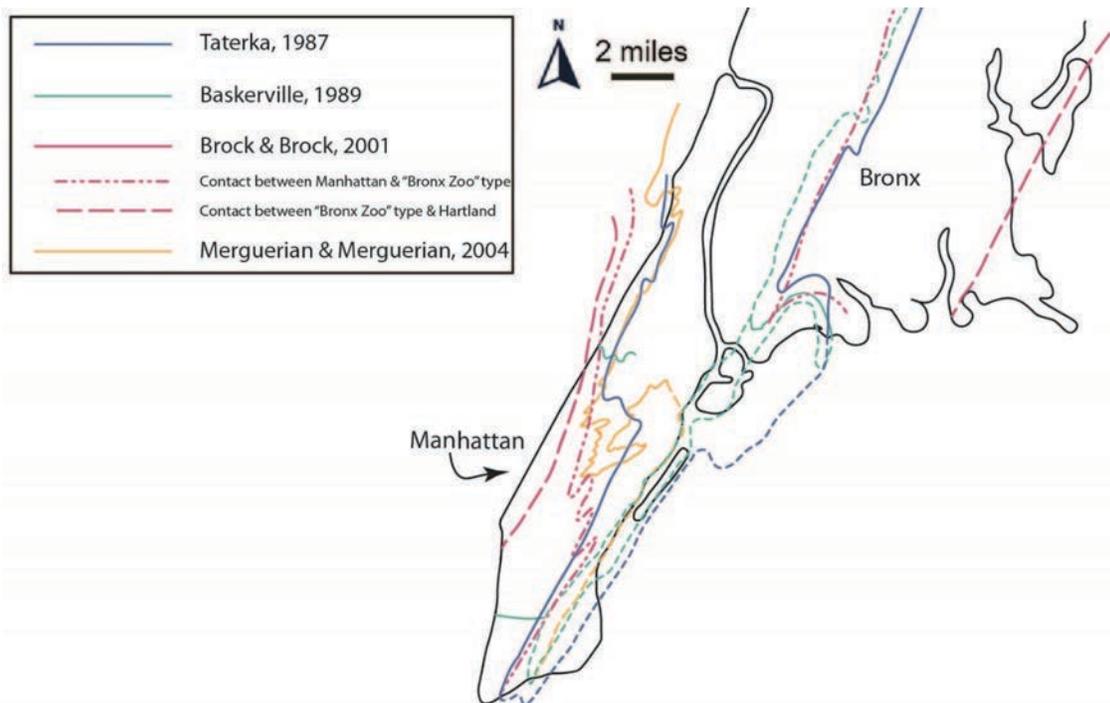

Figure 3. Compilation map showing the boundary between the Hartland and Manhattan Schists as determined by each mapper. This boundary is sometimes interpreted as Cameron's Line by some mappers/geologists.

As has been well documented from various experimental/theoretical and natural studies into garnet zonation (Spear, 1993, 2014), the geochemistry of numerous phases found coexisting with garnet in the Central Park samples—namely biotite, muscovite, plagioclase, and hornblende—can also be used to evaluate the *P-T* of the mineral assemblage. This includes thermodynamic methods where exchange thermometers (e.g., garnet-biotite, garnet-hornblende) are combined with net transfer barometers (e.g., garnet-aluminosilicate-quartz-plagioclase, garnet-muscovite-biotite-plagioclase) to define conditions at which these phases equilibrated. Direct comparison of *P-T* estimates made from the two different garnet groups presented in Figure 4B show very similar metamorphic conditions despite the different core-to-rim zonation patterns. This can be used to suggest that while the two different groups have notably different zonation patterns, their respective mineral assemblages record common peak metamorphic conditions. Here it should also be noted that by combining different barometers and thermometers, particularly where the thermodynamic considerations are based on different mineral reactions, researchers can evaluate how equilibrated the bulk mineral assemblage is (i.e., whether specific phases are nucleated during peak metamorphism versus crystallizing on the retrograde path). These evaluations, at least among the phases used to estimate metamorphic grade (garnet, biotite, muscovite, plagioclase, quartz, and aluminosilicates), indicate the mineral assemblage is equilibrated.

Isotope Geochemistry

Nd Provenance

Nd isotope ratios from eight samples across the Manhattan Prong from both the Manhattan and Hartland Schists have
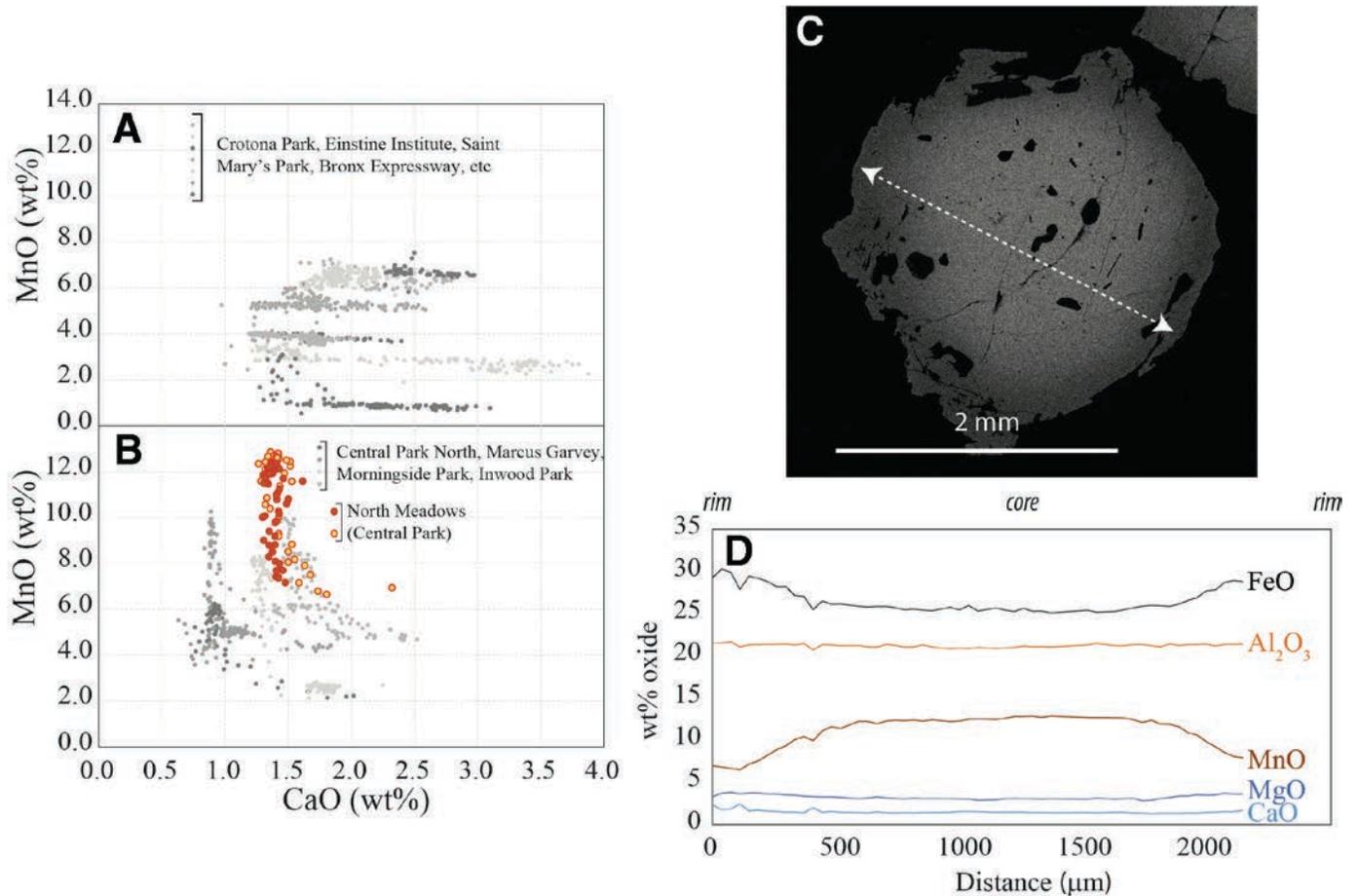

Figure 4. Trace element geochemistry of garnets. (A and B) MnO versus CaO plots for garnets showing two distinct patterns where (A) shows a "near constant" MnO concentration across the garnets, whereas (B) shows a "dogleg pattern." Analyses from dozens of outcrops across the entire Manhattan Prong fall into one or the other of these patterns, allowing for clustering of outcrops with similar garnet geochemistry. (C) Mn-Kα X-ray map showing "normal" core to rim zonation pattern observed in North Meadows garnet 1 and trajectory of analytical traverse. (D) Quantitative major element traverse from North Meadows garnet 1. (C and D) are representative examples of the methodology and shown as an example across all patterns and clusters.
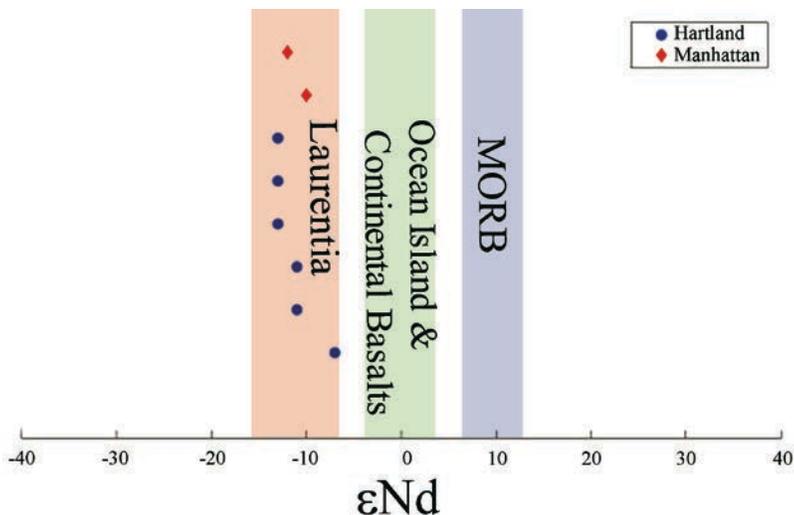
Figure 5. Nd isotope values for schists. Units mapped as Hartland Schist are indicated by circles, whereas Manhattan units are indicated by diamonds. Both Manhattan and Hartland units fall in the Laurentian field and are not different, despite previous interpretations that would suggest the Hartland is not Laurentia-derived. Y-axis is arbitrary, and data points are offset vertically by sample. MORB—mid-oceanic ridge basalt.

remarkably consistent εNd values and suggest both units are derived from Laurentia (or have the same source). No evidence of exotic terranes has been found in the Manhattan Prong (Fig. 5). Similarly, the detrital zircon record from Hartland units in Central Park (Stops 5 and 6) indicates these rocks are derived primarily from Laurentia (Fig. 6).

Detrital Zircons

Interestingly, however, the detrital zircon population is not purely Laurentian, but also shows a small population of younger ca. 600 Ma grains, particularly at E 79th St. We interpret this to reflect an origin in the Iapetus Ocean that is off the coast of Laurentia, as indicated by the dominance of Grenville-aged zircon

grains. However, the small population of younger ca. 600 Ma grains suggests some amount of mixing, and that it was not entirely isolated from input from exotic terrains.

SYNTHESIS AND CONCLUSIONS

The rocks of Central Park and the broader Manhattan Prong represent a very complex and complicated set of units in a tectonically complex setting, and much more work remains to be done in order to fully understand exactly how these units fit into the larger regional geologic history. Our work attempts to attack this problem from a geochemical standpoint, addressing provenance of only a few outcrops that are separated by lack of outcrop and by many faults. Our work suggests that all rocks of both
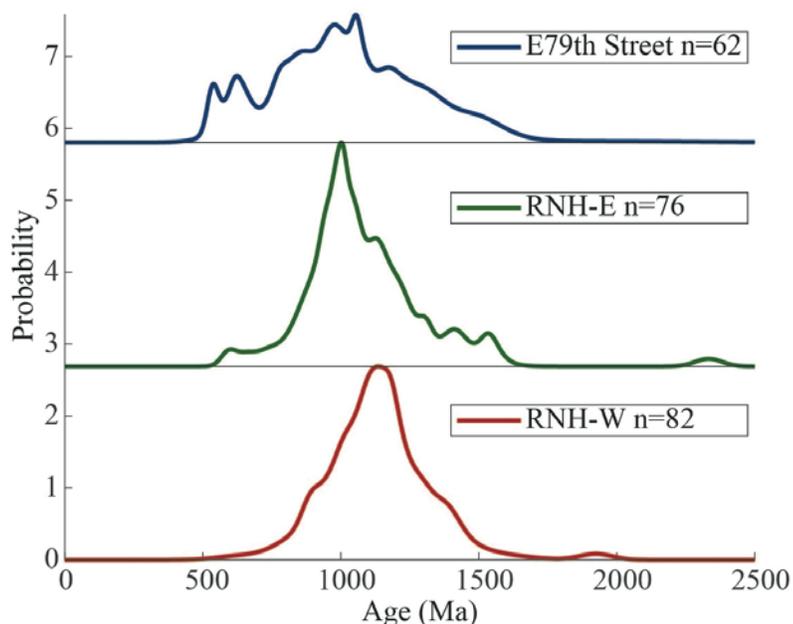

Figure 6. Detrital zircon populations of three Hartland Schist outcrops shown from west (bottom graph) to east (top graph) across the middle of Central Park. All three are dominated by Laurentian grains; however, there are subtle differences. As you move east, the age of the main age peak gets slightly younger, and the proportion of 600 Ma age grains increases. One sample is from E 79th St. and two samples are from the Rock of No Hope, taken from the eastern side (RNH-E) and western side (RNH-W) of the outcrop.
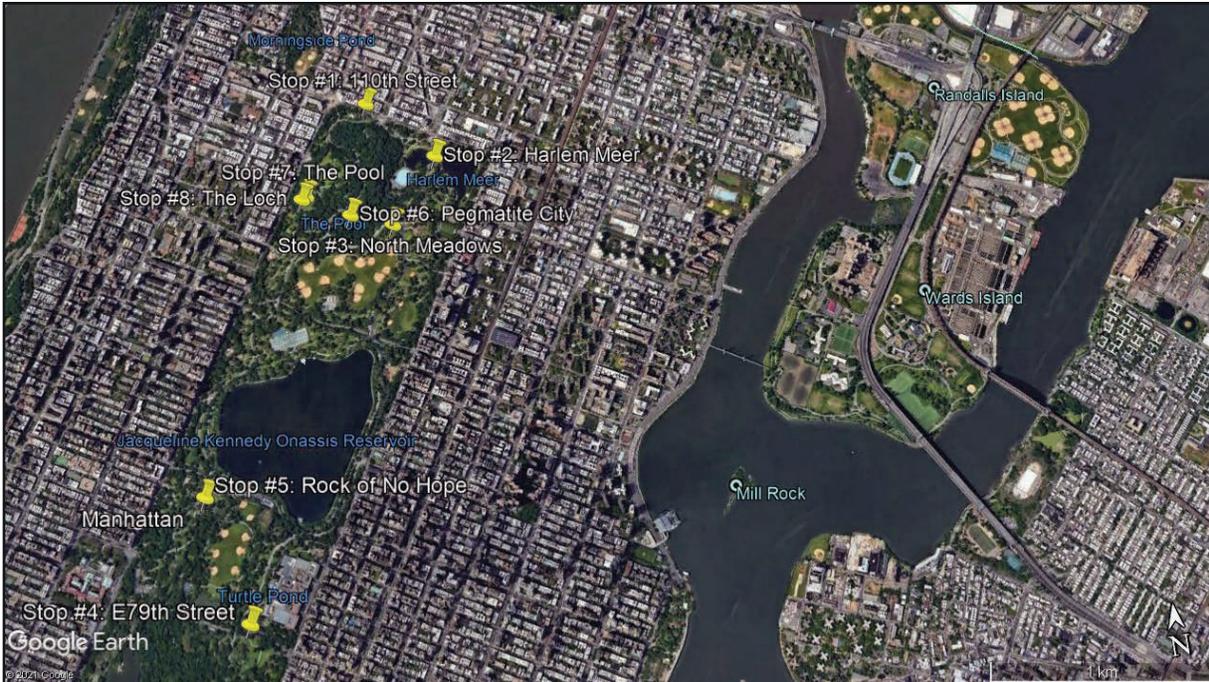
Figure 7. Map of the field stops. This map is available as a GoogleEarth file in the GSA Supplemental Material[1].

Manhattan and Hartland Schists are derived primarily from Laurentia, and that the boundary between these schists (sometimes called Cameron's Line) is not a terrane boundary based on trace element and geochemical results. How these data relate to other ongoing studies remains to be analyzed. Particularly, the nature of the boundary between Laurentian rocks and rocks of Gondwanan affinities remains a major question both in New York City and other parts of New England.

FIELD STOPS

Field stops: N.B. This entire trip is a no-hammer and no-sampling trip.

Central Park has many paths and routes, so we are providing GPS coordinates for each outcrop in addition to the map (Fig. 7), but we are not including step-by-step directions. In short, the stops go in a roughly clockwise direction.

Stop 1: NW Corner 110
(40° 47′ 58″ N, 73° 52′ 23″ W)

Here we see schists of the Blockhouse Member of the Manhattan schist (Fig. 8) as mapped by Taterka (1987). Bedding is

slightly difficult to see but is visible on the edges of the outcrop where fold hinges are exposed and show bedding planes. Subtle graded bedding is visible particularly near the large quartz layers, which parallel bedding. Bedding has a strike of 045 and dip of 50° to the SSE. Multiple orientations of foliation are visible as well as upright folds, and one set trending to the S-SW (trend of 230°). The outcrop has a distinctive knobby texture, due to differential weathering with resistant quartz lenses standing out prominently. Lastly, there are several large glacial striations visible, trending 135°.

Stop 2: Harlem Meer
(40° 47′ 48″ N, 73° 57′ 10″ W)

At this location, we observe an outcrop described by Taterka (1987) as the "110th Street Member" of the Manhattan schist (Fig. 9), a unit broadly defined as a brown-weathering garnet schist. This was originally distinguished from the Blockhouse Member due to samples in and around the southwestern edge of the Harlem Meer displaying a "lack of magnetic signature," because the Blockhouse Member contains abundant magnetite. Subsequent electron microprobe analyses from select samples obtained from this location confirm a general lack of magnetite, although it remains unclear if this is a definitive characteristic. This location, like later stops in the Loch (and as observed around the prong—see Stop 6), displays prominent pegmatites in outcrops at the southwestern end of the meer (Dutch for "lake").

Figure 8. Blockhouse Member, showing knobby texture (bottom of image) and glacial striations.

Stop 3: North Meadows
(40° 47′ 37″ N, 73° 57′ 20″ W)

This outcrop was mapped as the Blockhouse Member of the Manhattan Schist (Fig. 10) by Taterka (1987). The outcrops observed in and around the North Meadows of Central Park likely are close to a structural boundary within the prong. Samples acquired immediately north of "Softball Field 8" show garnet geochemistry of the dogleg pattern (Fig. 4B), Some sections made from this location also produce mineralogy common to this group, including small tourmaline and aluminosilicate grains.

Samples acquired from locations toward the southeast, essentially between the North and East Meadows, show geochemical characteristics of the near constant pattern (Fig. 4A).

Stop 4: E 79th St. near 5th Ave.
(40° 46′ 37″ N, 73° 57′ 55″ W)

This outcrop is mapped as Hartland Schist by Taterka (1987) and consists of a large exposure with felsic schist and amphibolite layers, which may appear as alternating layers. However, close inspection of the outcrop reveals upright folds (Fig. 11)

Figure 9. Harlem Meer exposure.

Figure 10. Exposure of the Blockhouse Member of the Manhattan Schist. Note the knobby "bootgrabbers" of resistant quartz at the far end of the outcrop (top of the photo).
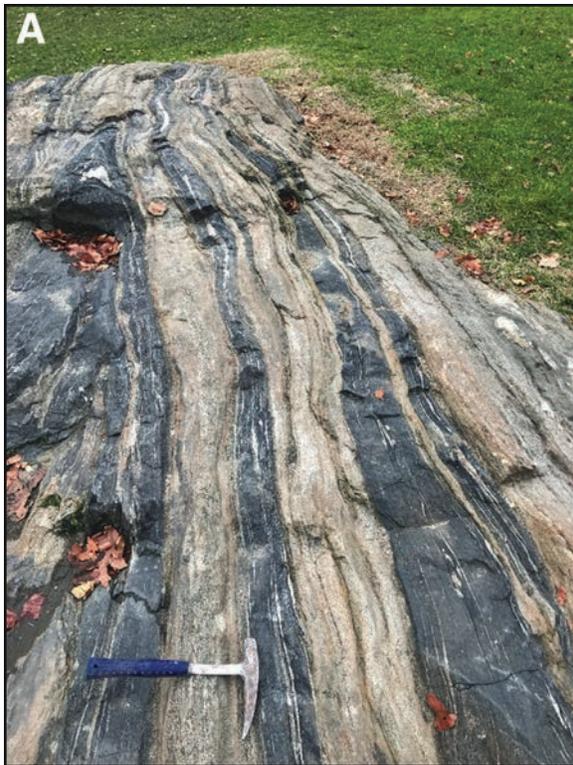

Figure 11. Upright folds in amphibolite seen from two different orientations. (A) Plan-view of the outcrop taken looking down onto the surface. (B) Looking edge-on to the side of the outcrop showing a steeply dipping axial plane.

(one well-preserved fold in the amphibolite is usually visible on the edge near the walkway, if the grass is not too high). Like other Hartland Schist outcrops, this rock is extremely friable and easy to crush. Interestingly, detrital zircon and Nd isotopic results suggest the rocks are derived primarily from Laurentia, not arcs or Ganderia-like exotic terranes. However, the zircon populations do contain a small proportion of 600 Ma grains, suggesting the original sediment was not entirely absent of grains arriving from the east.

Stop 5: Rock of No Hope
(40° 46′ 54″ N, 73° 58′ 7″ W)

Rock of No Hope is mapped as Hartland Schist (Fig. 12) by Taterka (1987). It includes a large outcrop (RNH-E) and a smaller one to the west (RNH-W) just west of the jogging path. This outcrop gets its name from the New York City theater world. During summers when they offer free Shakespeare in the Park shows, the line for tickets stretches along this pathway. Once the line reaches this outcrop, however, there is no hope of getting tickets.

Here we are close to one of the proposed Manhattan–Hartland Schist boundaries, and as you will see, this unit is difficult to assign to a specific unit. It is muscovite- and kyanite-rich, but garnets are less abundant, and it does not exbibit the same

mechanical weakness of the exposure at E 79th St. Garnet geochemistry (Fig. 4) suggests this may be a separate unit, because detrital zircon populations are dominated by Laurentian grains but contain a small fraction of 600 Ma grains (Fig. 6). This outcrop remains an area of geochemical study.

Structurally, the rocks are heavily deformed and exhibit up to three generations of folding. Additionally, there are several pegmatites here, those parallel to foliation, and those that cross-cut foliation, suggesting multiple melting events. At the southern end of the outcrop there is a large pegmatite dike with well-defined chilled margins that cross-cuts all of the foliation. RNH-W is slightly more granular in texture with less muscovite and lacks intrusions.

Stop 6: Pegmatite City
(40° 47′ 40″ N, 73° 57′ 30″ W)

Here we see a different generation of pegmatites than elsewhere in the park or within New York City (Fig. 13). These are distinct in appearance from the Bear's Den Granite found at the Bronx Zoo, and lack the large K-feldspar that dominate the Bear's Den locality. Instead, this pegmatite is dominated by white and tan albite with large muscovite books (crystals that can be split into sheets) up to 2 cm in length. The relationships to other igneous rocks and to the schist are still being studied and are

Figure 12. Hartland Schist showing multiple orientations of folds and a pegmatite dike (left).

Figure 13. Large muscovite books in the pegmatite.

complicated by lack of exposed contact between the pegmatite and schist.

Stop 7: The Pool
(40° 47′ 44″ N, 73° 57′ 38″ W)

This outcrop was mapped as Hartland Schist by Taterka (1987). This stop shows strong structural deformation in felsic schists and amphibolite (Fig. 14). Folding style here is similar to E 79th St. (Stop 4), again highlighting the importance of perspective when looking at highly deformed rocks. However, unlike the E 79th St. outcrop, which is composed of Hartland Schist, this unit is geochemically Manhattan Schist. Take a minute to explore the outcrop from multiple angles to see the upright folds.

Stop 8: The Loch
(40° 47′ 43″ N, 73° 57′ 39″ W)

This outcrop was mapped as Hartland by Taterka (1987). Here we see a large (~2 m high) pegmatite dike, clearly cross-cutting the foliation and with a large (2.5-cm-wide) chilled margin (Fig. 15). The texture of this dike, particularly the presence of ~20 cm knobby single crystals of K-feldspar present in the dike are reminiscent of the Bears' Den Granite exposed at the Bronx Zoo. We interpret this dike as a feeder dike to the larger stock to the north.

ACKNOWLEDGMENTS

Figure 14. Tightly folded amphibolite in Manhattan Schist. On the other side of this outcrop, you will find a glacial erratic perched on the schists.

Figure 15. Pegmatite dike cutting across the schists. Note the chilled margin (indicated by N.D.T.'s finger) along the edge of the dike and a large single feldspar at the base of the dike (fls). The texture and composition of this dike is the same as the Bear's Den Granite exposed at the Bronx Zoo, and we interpret this as a feeder dike cutting across the schist.

REFERENCES CITED

Baskerville, C.A., Nocholas K. Coch, N.K., Horenstein, S., Prinz, M., Puffer, J.H., Roberts-Dolgin, G.R., and Weiss, D., eds., 1989, Geology and Engineering Geology of the New York Metropolitan Area: 28th International Geological Congress Field Trip Guidebook T361, Washington: American Geophysical Union, https://doi.org/10.1029/FT361.

Brock, P.C., and Brock, P.W.G., 1999, The birth of Iapetus: Geochemical evidence for Late Neoproterozoic rifting from the metaigneous rocks of the Ned Mountain formation, Manhattan Prong: 6th Annual Conference on Geology of Long Island and Metropolitan New York Program with Abstracts, SUNY Stony Brook, New York, Long Island Geologists, April 24, 1999: SUNY Stony Brook, Stony Brook, New York, p. 13–15.

Brock, P.C., and Brock, P.W.G., 2001, Bedrock Geology of New York City: More Than 600 m.y. of Geologic History: Field Guide for Long Island Geologists Field Trip, October 27, 2001, 10 p.

De Yoreo, J.J., Lux, D.R., Guidotti, C.V., Decker, E.R., and Osberg, P.H., 1989, The Acadian thermal history in western Maine: Journal of Metamorphic Geology, v. 7, p. 169–190, https://doi.org/10.1111/j.1525-1314.1989.tb00583.x.

Dietsch, C., and Ratcliffe, N.M., 2006, 40Ar/39Ar metamorphic ages from the Manhattan Prong and Rowe-Hawley Zone of New York and Connecticut: Geological Society of America Abstracts with Programs, v. 38, no. 2, p. 20.

Dorais, M., Atkinson, M., Kim, J., West, D.P., and Kirby, G.A., 2012, Where is the Iapetus suture in northern New England? A study of the Ammonoosuc Volcanics, Bronson Hill terrane, New Hampshire: Canadian Journal of Earth Sciences, v. 49, p. 189–205, https://doi.org/10.1139/e10-108.

Hall, L.M., 1968, Bedrock geology in the vicinity of White Plains, New York, Trip A, *in* Finks, R.M., ed., Guidebook to Field Excursions: New York State Geological Association Annual Meeting, 40th: Flushing, New York, Queens College Department of Geology, p. 7–31.

Hall, L.M., 1976, Preliminary correlation of rocks in southwestern Connecticut, *in* Page, L.R., ed., Contributions to the Stratigraphy of New England: Geological Society of America Memoir 148, p. 337–349, https://doi.org/10.1130/MEM148-p337.

Hatcher, R.D., Jr., 2014, The Appalachian orogen, *in* Reference Module in Earth Systems and Environmental Sciences: Amsterdam, Elsevier, ISBN 9780124095489, https://doi.org/10.1016/B978-0-12-409548-9.09096-5.

Hibbard, J.P., Van Staal, C.R., Rankin, D.W., and Williams, H., 2006, Lithotectonic Map of the Appalachian Orogen: Canada–United States of America: Geological Survey of Canada, "A" Series Map 2096A, 2 sheets, scale 1:1,500,000, https://doi.org/10.4095/221912.

Karabinos, P., Macdonald, F.A., and Crowley, J.L., 2017, Bridging the gap between the foreland and hinterland I: Geochronology and plate tectonic geometry of Ordovician magmatism and terrane accretion on the Laurentian margin of New England: American Journal of Science, v. 317, p. 515–554, https://doi.org/10.2475/05.2017.01.

Long, L.E., and Kulp, J.L., 1958, Age of the metamorphism of the rocks of the Manhattan Prong: Geological Society of America Bulletin, v. 69, p. 603–606, https://doi.org/10.1130/0016-7606(1958)69[603:AOTMOT]2.0.CO;2.

Macdonald, F.A., Ryan-Davis, J., Coish, R.A., Crowley, J.L., and Karabinos, P., 2014, A newly identified Gondwanan terrane in the northern Appalachian Mountains: Implications for the Taconic orogeny and closure of the Iapetus Ocean: Geology, v. 42, no. 6, p. 539–542, https://doi.org/10.1130/G35659.1.

Merguerian, C., and Merguerian, J.M., 2004, Geology of Central Park—From rocks to ice, *in* Hanson, G.N., chm., Eleventh Annual Conference on Geology of Long Island and Metropolitan New York, 17 April 2004: Long Island Geologists Program with Abstracts: New York, State University of New York at Stony Brook, 24 p.

Merguerian, C., and Merguerian, J.M., 2014, Field Trip Guidebook for Isham and Inwood Parks, NYC: Lamont Doherty Earth Observatory Manhattan Prong Workshop, 06–07 September 2014, 59 p.

Merguerian, C., and Merguerian, J.M., 2016, Stratigraphy, structure and tectonics of New York City as viewed through its parks, *in* Gates, A.A., and Bennington, J.B., eds., Geologic Diversity in the New York Metropolitan Area: New York State Geological Association, 88th Field Conference (Joint Conference with Friends of the Grenville), p. 142–162.

Merrill, F.J.H., 1890, On the metamorphic strata of southeastern New York: American Journal of Science, 3rd series, v. 39, p. 383–392.

Merrill, F.J.H., and Magnus, H.C., 1904, Distribution of Hudson Schist and Harrison Diorite in the Westchester County Area of the Oyster Bay Quadrangle: New York State Geologist's Annual Report, v. 23, p. 193–194.

Pellegrini, T.L., 1975, Lower Paleozoic Stratigraphy and Structure of the Mamaroneck Area, New York, *in* New York State Geological Association Field Guide: Hempstead, New York, p. 179–194.

Puffer, J.H., 1996, Serpentinites of New York City and vicinity, *in* Benimoff, A.I., and Ohan, A.A., eds., Field Trip Guide for the 68th Annual Meeting, New York State Geological Association, Staten Island, New York, The College of Staten Island/CUNY, p. 1–52.

Ratcliffe, N.M., 1968, Trip H: Stratigraphic and structural relations along the western border of the Cortlandt intrusives, *in* Finks, R.M., ed., Guidebook to Field Excursions: New York State Geological Association, 40th Annual Meeting, New York, p. 197–220.

Spear, F.S., 1993 Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths: Washington, D.C., Mineralogical Society of America, 799 p.

Spear, F.S., 2014, The duration of near-peak metamorphism from diffusion modelling of garnet zoning: Journal of Metamorphic Geology, v. 32, no. 8, p. 903–914, https://doi.org/10.1111/jmg.12099.

Stanley, R.S., and Hatch, N.L., Jr., 1976, Discussion: Early Paleozoic stratigraphy of western Massachusetts and Connecticut and southeastern New York, *in* Page, L.R., ed., Contributions to the Stratigraphy of New England: Geological Society of America Memoir 148, p. 351–356, https://doi.org/10.1130/MEM148-p351.

Taterka, B.D., 1987, Bedrock geology of Central Park, New York City [M.S. thesis]: Amherst, Massachusetts, University of Massachusetts Department of Geology and Geography, Contribution 61, 84 p. plus maps.

van Staal, C., and Barr, S.M., 2012, Lithospheric architecture and tectonic evolution of the Canadian Appalachians and associated Atlantic margin, *in* Percival, J., Cook, F., and Clowes, R., eds., Tectonic Styles in Canada: The LITHOPROBE Perspective: Geological Association of Canada Special Paper, v. 49, p. 55.

van Staal, C., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N., 2009, Pre-Carboniferous, episodic, accretion-related, orogenesis along the Laurentian margin of the northern Appalachians Murphy, *in* Murphy, J.B., Keppie, J.D., and Hynes, A.J., eds., Ancient Orogens and Modern Analogues: Geological Society, London, Special Publication 327, p. 271–316, https://doi.org/10.1144/SP327.13.

Ziegler, V., 1911, The Ravenswood granodiorite: New York Academy of Sciences Annals, v. 21, p. 1–10.