

## PROVENANCE AND TECTONIC HISTORY OF METAMORPHIC ROCKS OF CENTRAL PARK AND NEW YORK CITY

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The rocks underlying much of New York City, frequently referred to as the “Manhattan Prong”, predominately consist of a series of metasedimentary units, which were originally deposited into the Iapetus Ocean and subsequently deformed and metamorphosed during the Taconic, Acadian, and Alleghenian Orogenies (Merguerian and Merguerian, 2014, 2016; van Staal and Barr, 2012). Despite extensive field mapping in parks around Manhattan and subsurface mapping in major infrastructure sites (i.e., building foundations and tunnels), these rocks have not been studied geochemically and isotopically and interpretation within the larger tectonic framework has largely been based on correlation with presumed equivalent units in Connecticut and New England. Here we present new detrital zircon and Nd isotope provenance analyses in the broader geologic context of Northern Appalachia.

### **General Background**

The Manhattan Schist was originally defined by Hall, 1976 and has been the subject of great debate for nearly 50 years. Merguerian 2004; 2016 has subdivided the original “Manhattan Schist” of Hall into 3 subunits of schistose rocks. He correlated the third unit with the Hartland Schist in Connecticut and thus interpreted these to be fault-bounded schists which were juxtaposed during a middle Ordovician collision between the eastern margin of Laurentia and volcanic arcs (the so-called “Taconic Arc”). Generally, this fault boundary is considered a major terrane boundary, mapped as the Red Indian Line (Macdonald et al., 2014) in northern New England, and referred to in southern New England and Connecticut as Cameron’s Line (Rogers, 1958; Rogers et al., 1959). The exact location of this line however, is only definitively determined in northern New England and has been the subject of significant debate further south (see MacDonald et al., 2014). Since initial mapping of the Manhattan Prong in the 1960’s there has been significant differences in the interpretation over the unit names and lithologic units in NYC (see Stanley and Hatch, 1976; Merguerian and Merguerian 2016; Brock and Brock, 2001; Takerka, 1987; Baskerville, 1982;) as well as to where the unit boundaries lie (Figure 1).

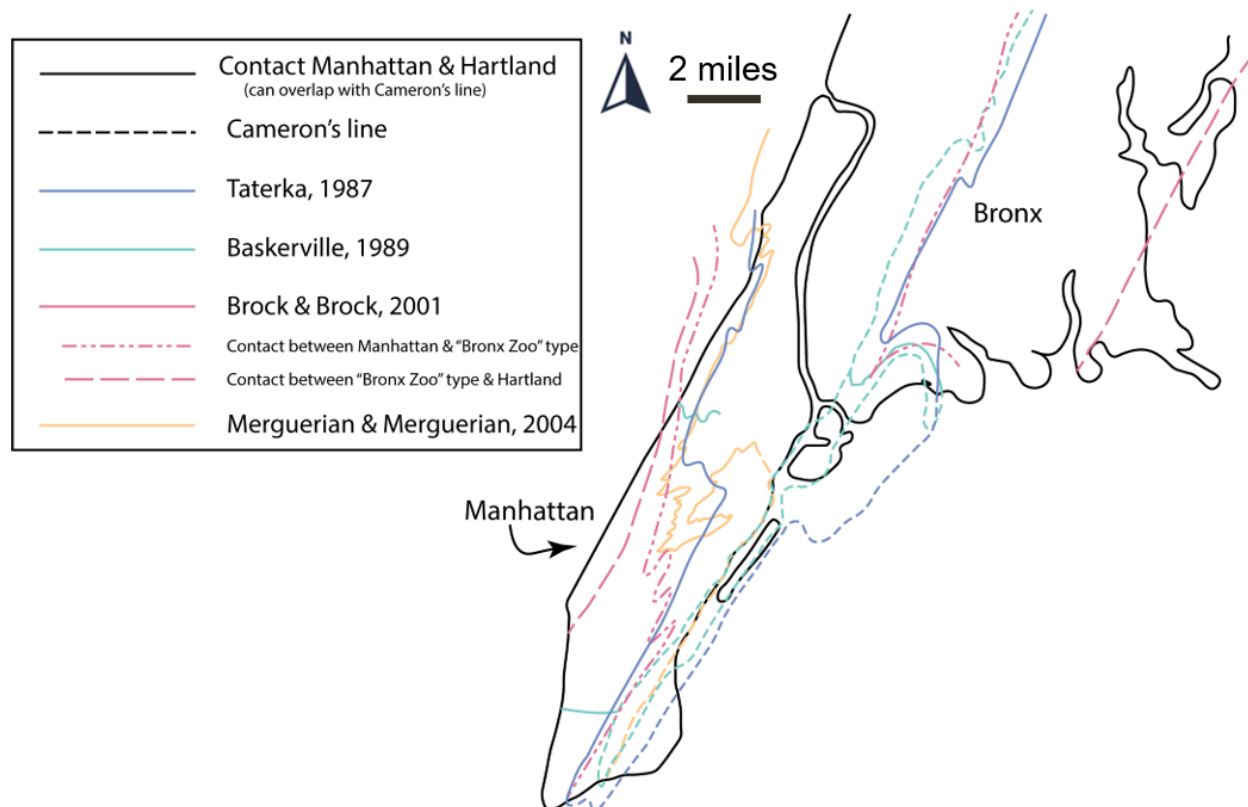


Figure 1. Compiled map of the Manhattan-Hartland boundary (Cameron's Line) showing the disagreement in mapping and complexity of these units in Manhattan and the Bronx.

The most widely recognized unit descriptions are those of Merguerian , listed below:

1) Mapped as Om and referred to as the "Tippecanoe sequence" --  
 "brown-to rusty weathering, fine- to medium-grained, typically massive, muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet schist containing interlayers centimeters to meters thick of calcite+diopside marble."

This unit is correlated (by Merguerian ) with Hall's Manhattan A and is interlayered with the Inwood Marble in places.

2) The middle Manhattan Schist (C-Om) – mapped in the bulk of Manhattan.  
 "rusty to sometimes maroon-weathering, medium- to coarse-grained, massive biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist. The middle schist unit is characterized by the presence of layers and lenses of kyanite+sillimanite+quartz+magnetite up to 10 cm thick, cm-to m-scale layers of blackish amphibolite, and subordinate quartzose granofels."

These are the equivalent of the combined Manhattan B and C of Hall (1976). These rocks, which contain calc-silicate interlayers in western Connecticut (Merguerian , 1977) are inferred to represent metamorphosed Cambrian to Ordovician sedimentary- and minor volcanic rocks

deposited in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America, and are thus considered a part of the Taconic Sequence

3) The structurally highest, upper schist unit (C - Oh) -- dominantly “gray-weathering, fine-to coarse-grained, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and thin- to massive granofels and coticule, with cm- and m-scale layers of greenish amphibolite+garnet.”

Merguerian, 1977 has interpreted these as representing “metamorphosed deep-oceanic shales, interstratified lithic sandstones, chert, and volcanic rocks, all a part of the deep-water facies of the Taconic Sequence.” Merguerian further interprets them as equivalent to the Hartland Formation in western Connecticut which he equates to the Rowe/Mooretown/Hawley belt in Western Massachusetts.

### **Tectonic interpretations**

The pelitic schists in New York City are divided into three main lithologies: the Manhattan Schist, the Hartland Schist, and the Walloomsac Schist. Of these, the Walloomsac is limited in Manhattan, occurring primarily at one exposure in Inwood Park (that is currently inaccessible due to bridge construction) and so this work focuses only on the Hartland and Manhattan schists. The Manhattan schist is interpreted to represent near shore sediments, derived primarily from Laurentia, whereas the Hartland interpreted to be deposited in the deep ocean largely derived from volcanics shedding sediment from the East into the Iapetus Ocean.

In turn, equally model dependent, the contact between these two units is widely considered a major tectonic boundary and is frequently mapped as “Cameron’s Line” (Rogers, 1958) correlated with terrain boundary faults in Connecticut and New England. Merguerian and Merguerian have noted the presence of large amphibolite lenses within the Hartland as suggestive of volcanic source, similar to the Ammonoosuc volcanics in New Hampshire. Furthermore, serpentinite bodies are exposed in Hoboken, NJ, and Staten Island and are mapped in historically in subsurface exposures in Manhattan. Therefore, based primarily on field and structural observations there has been a general assumption that the Iapetus Suture lies somewhere in the Manhattan Prong.

### **Current challenges and remaining questions:**

Importantly, much of the mapping and specifically the interpretation of New York City units comes from extensive correlation with other units in New England. However, given the high degree of structural deformation (up to as many as 4 deformation fabrics can be seen in some outcrops), several problems and questions still remain regarding the provenance and tectonic history of the Manhattan Prong.

1) The unit descriptions for the rocks here are *extremely* similar. All units are aluminous pelitic schists and therefore are dominated by muscovite, biotite, plagioclase with quartz, garnet, kyanite, and sillimanite. Locally the modal abundances can vary significantly (even thin section

to thin section) and so mineralogically it is incredibly difficult to distinguish the units and modal mineralogy is not uniquely diagnostic.

2) Tectonic and provenance interpretations should be testable by isotope geochemistry and detrital zircon geochronology. The previous interpretations – that the Manhattan schist represents metasediments derived from Laurentia whereas the Hartland schist represents sediments derived from peri-Gondwana accreted exotic terranes should stand out by distinct differences in Nd isotope geochemistry and the detrital zircon populations of these units. Sediments derived from volcanic arcs should have  $\epsilon\text{Nd}$  isotopic values within a few epsilon units of 0. Samples from the Ammonoosuc Volcanics, which have been interpreted as the equivalents of the Hartland, have  $\epsilon\text{Nd}$  values ranging between +5 and -5 (Dorais et al., 2011). On the other hand, rocks derived from Laurentia should have much more negative  $\epsilon\text{Nd}$  values, ranging between -8 to -12.

Similarly, the detrital zircon record should reflect such differences in source with Laurentian rocks being dominated by Grenville aged zircons, with potentially older recycled zircons. Arc and accreted terranes, such as Ganderia in Massachusetts and Connecticut, should not be dominated by Grenville zircons but instead should have younger, ~500-600 Ma zircons. Recent work in Western Massachusetts (MacDonald et al., 2014, Karabinos et al., 2017) have shown that detrital zircon analyses is critical to sourcing similar aged schists and have shown that there is a distinct difference in zircon populations between previously lumped Rowe and Mooretown Schists, and have thus used this technique to redefine the Iapetus suture in Massachusetts.

### **Samples**

Over the past 6 years we have undergone a systematic sampling campaign of pelitic schists in New York City. Here we present detrital zircon results from 3 outcrops and Nd isotopic results from 9 outcrops in Manhattan and the Bronx. A brief list of samples and localities is listed in Table 1.

Table 1 Sample List				
Sample Name	Location	Mapped as	Nd analyses	Zircons analyses
PB-5	Pelham Bay, Bronx	Hartland Schist	X	
TP-1	Tremont Park, Bronx	Hartland Schist	X	
TP-5	Tremont Park, Bronx	Manhattan Schist	X	
TP-6	Tremont Park, Bronx	Manhattan Schist	X	
GWB-03	George Washington Bridge, Riverside Park, Manhattan	Manhattan Schist	X	
E-79	79th St, Central Park, Manhattan	Hartland Schist	X	X
HSPB	Pelham Bay, Bronx	Hartland Schist	X	
RNH-W	"*Rock of No Hope, West", Central Park, Manhattan	Hartland Schist or Manhattan Schist		X
RNH-E	"Rock of No Hope, East", Central Park, Manhattan	Hartland Schist or Manhattan Schist		X

\*The name Rock of No Hope comes from NYC's Shakespeare in the Park. This outcrop is along path where the line for tickets forms and this outcrop is referred to as Rock of No Hope because if the line stretches beyond this rock, there is no hope of receiving a free ticket.

## Methods

### *Nd analyses*

10-15 g of sample were crushed by hand in an agate mortar and pestle to ensure homogenization. 0.070 g of each samples was dissolved in a 3 ml nitric acid + HF solution followed by 4 ml of nitric + HCl. Isolation of Nd followed standard 2-step column chemistry: TRUSpec to isolate Rare Earth Elements, followed by LNSpec for Nd separation. The Nd cut was diluted to 100 ppb and analyzed on a Nu II multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at in the Facility for Isotope Research and Student Training (FIRST) laboratory at Stony Brook University. Samples were bracketed by internal 100 ppb Nd solution and standardized with 100 jNdi solution.

### *Zircon analyses*

2-3 kilograms of sample were crushed by hand and using a Bilco disc pulverizer. The sample was then washed to remove fines and dry-seived into four sizes: >63 mm, 63-125 mm, 125-250 um, and greater than 250 um. The 125-250 size fraction was used for these analyses. Zircons were separated using sodium polytungstate (SPT, density 2.9) and hand-picked under a reflected light microscope. Zircons were mounted in uv-curing epoxy, and polished with 1200 grit sheets. Zircon analyses were conducted in the FIRST lab at Stony Brook University using a 213 New Wave laser attached to an Agilent 7500ce quadrupole mass spectrometer using argon plasma gas and He carrier gas at 1.21 L/min. U, P, Ti, La, Ce, Pr, Hf, and Zr were measured using a 40 micron spot with a 30 second dwell time. Each analysis began with 4 reference

analyses (Mud Tank, age = 732 Ma) and Mud Tank was measured every 5 zircons for standardization, interspersed with Plesovice (age = 337 Ma). Zircon ages were calculated using the Iolite software (version 3) and the U-Pb\_Geochron4 data reduction scheme.

## Results

### *Nd Results*

All samples have  $\epsilon\text{Nd}$  values between -1 and -13 (Figure 2, Table 2) consistent with metasediments having been derived from Laurentia.  $\epsilon\text{Nd}$  values for those units previously mapped as Manhattan Schist are indistinguishable from those mapped as Hartland Schist.

Sample #	$\epsilon\text{Nd}$
PB5-4	-7
TP1-1	-10
TP5-1	-13
TP5-2	-11
TP6-1	-13
TP6-2	-13
GWB03	-12
E79	-13
HSPB	-11

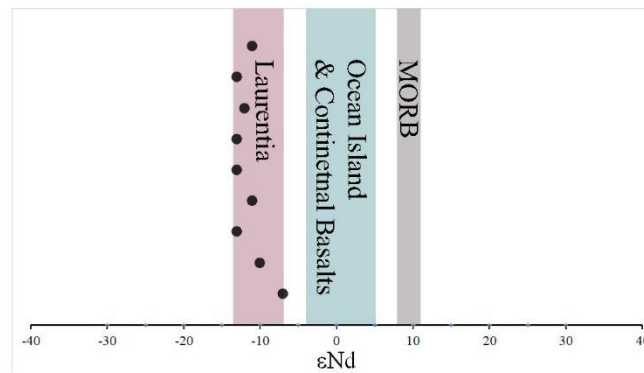


Figure 2. Whole-rock  $\epsilon\text{Nd}$  values for the schists in Manhattan and the Bronx. All samples are consistent with being derived from Grenvillian terrane.

### *Detrital Zircon Results*

Age probability histograms for detrital zircons of RNH-W, RNH-E, and E79th Street are dominated by zircons near 1000 Ma (Figure 3). However, the pattern and distribution of ages varies. RNH-W shows peaks at 1150, 950, 1800 and 2800 Ma. RNH-E shows peaks at 1000, 600, and 1500 Ma. E79<sup>th</sup> Street shows a broad peak between 1000 and 1100 Ma, as well as a broad peak at 600 Ma. There is also a difference in youngest zircon age. RNH-W has a youngest zircon of  $872 \text{ Ma} \pm 80 \text{ Ma}$ , whereas the youngest zircon in RNH-E is  $593 \pm 27 \text{ Ma}$  and the youngest zircon is E79th St is  $534 \pm 36 \text{ Ma}$ .

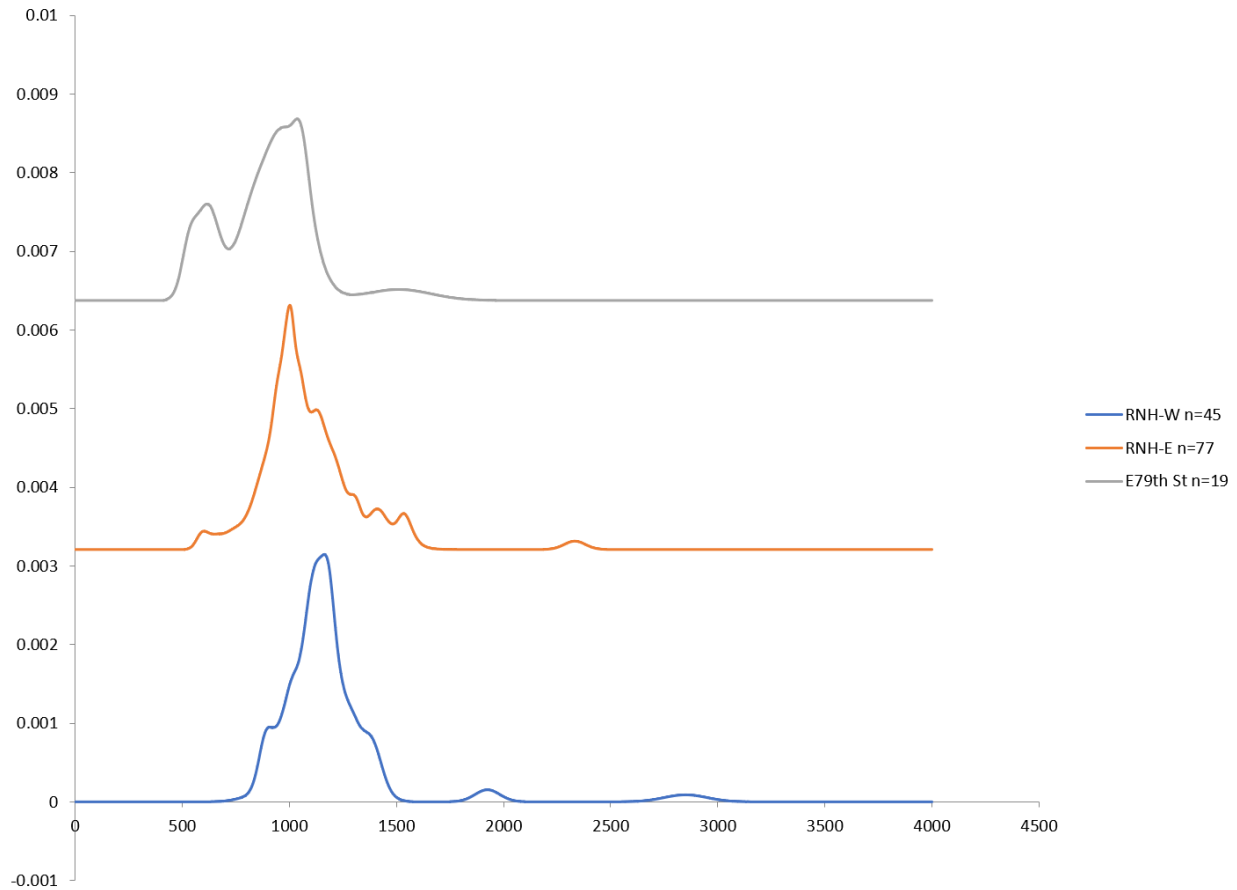


Figure 3. Age probability histograms for concordant zircons from E79th Street, Rock of No Hope-E and Rock of No Hope West.

### *Discussion and Conclusions*

All samples from the Manhattan and Hartland Schists have both Nd isotopic values and detrital zircon age populations consistent with dominant derivation from Laurentia, and thus all samples appear to be located west of the Iapatus suture (Cameron's Line). The Hartland schist sample, particularly those from E79th Street and Pelham Bay were previously correlated with the Hartland Terrane in Connecticut and the Ammonoosuc Volcanics in New Hampshire and interpreted as derived from arc volcanics, largely due to the presence of amphibolites in these units. Our results do not support this interpretation, despite their outcrop appearance as similar in composition and texture to the Ammonoosuc suite. Rather, these samples appear more similar to the Rowe and Western Cover in New England (MacDonald et al., 2014).

Interestingly, there are subtle differences, particularly in the detrital zircon ages, which suggest these samples may still be distinguishable from one another. It appears that as you move from west to east across Central Park, there is an increase in the number of younger, peri-Gondwanan zircons (~500-600 Ma). This could be due to difference in facies of the metasediments and distance from the Laurentian margin. While all samples appear to have a significant fraction of sediment shed off Laurentia, the E79th Street sample shows substantially more influence from arc volcanics to the east.

Thus far, we have not identified any samples that are geochemically representative of arc-derived sediment with a Ganderia or exotic terrane signature. Presumably the terrane boundary seen in Connecticut, Massachusetts, and northern New England does still occur in southern NY, but at present, it does not appear to cross through New York City, likely lying farther to the East.

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