Geochemical Characterization of New York City Schist Formations

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Abstract

New geochemical analyses of bedrock from Manhattan, New York support a more widespread distribution of the Manhattan Schist than indicated on recent geologic maps of New York City including Schuberth (1967); Baskerville (1994); Merguerian and Merguerian (2004) and Brock and Brock (2001). The 39 samples of schist from outcrops and roadcuts across all of Central Park, Manhattan plot as a single coherent population on all major element and trace element variation diagrams. Plots of K_2O/Na_2O vs. SiO_2 and K_2O/Na_2O vs. SiO_2/Al_2O_3 on the tectonic setting discrimination diagrams of Roser and Korsch (1986) are consistent with a passive margin to active continental margin depositional setting. Major elements also plot within the compositional field of the Martinsburg Formation, an Ordovician, largely continental shelf meta-pellite and a probable stratigraphic correlative of Manhattan Schist. In addition, samples mapped as Hartland Formation collected west of Central Park along the Hudson River plot within the continuum of the Central Park samples. An arc detritus depositional setting as generally proposed for Hartland deposition is notably un-represented throughout Manhattan. However, east of Manhattan, particularly Pelham Bay, an arc signature is seen. Our geochemical data together with ambiguous Hartland/Manhattan schist petrology underscores the need to establish a reliable mappable criteria capable of distinguishing Hartland from Manhattan schists.

Introduction

There are currently at least four competing geologic maps of New York City that present highly differing formation distributions, particularly Manhattan Schist and Hartland Formation. In addition each of four competing maps including Schuberth (1967); Baskerville (1994); and Merguerian and Merguerian (2004) and Brock and Brock (2001) present highly differing tectonic and stratigraphic interpretations. Our chapter is not an attempt at re-mapping New York City but simply offers some overdue geochemical characterizations of Manhattan and Hartland formations that may be used to refine future mapping.

The status of New York City geology has only become more confusing during recent years. Currently there is no consensus on the age, the provenance of the sedimentary protoliths, or the formation identification of most schist outcrops in Manhattan despite good exposure and extensive studies by countless geologists. We will, therefore, be unable to provide a consensus answer to the most basic questions at some of the outcrops that we visit on this field trip, such as “What formation is this and how old is it?” However, we will be able to provide some of the first geochemical data on each of the outcrops we visit together with some geochemical based stratigraphic correlations and some geochemical constraints on the provenance of the sedimentary provenance.

The Status of NYC Mapping and Stratigraphy

It is beyond the scope of this report to contribute to complex stratigraphic issues or map detail. However, it may be instructive to point out a few of the current choices (Figure 1).

1. Hall (1968, 1976, 1980)

Hall (1968) and a series of papers published with co-authors subdivided the Manhattan Schist into member A (an autochthonous member) and members B and C (allochthonous members). Member A overlies the Inwood Marble unconformably and is a gray schist containing quartz, biotite, muscovite, garnet, and plagioclase. Near the base of member A some dolo-marble layers appear with diopside and phlogopite. Member C overthrusts member A and is thought by Hall (1968) to be Early to Middle Cambrian in age. Member C is gray schist containing biotite, muscovite, quartz, plagioclase, garnet, kyanite, sillimanite, tourmaline and magnetite with minor gneiss. Mamber B is amphibolite but is not continuous.

The Hartland Formation was mapped from southwestern Connecticut through Westchester County, New York by Hall (1968). He subsequently (Hall 1976) divided the Hartland into four members (an amphibolite member, a schist-gneiss-amphibolite member, a gray gneiss member, and a schist and granulite member). However these member designations are best applied to the White Plains New York to Glenville, Connecticut area and have not been applied elsewhere. Hall (1980) describes in some detail the overthrusting of Hartland Formation over Manhattan Schist.

2. Ratcliffe and Knowles (1969)

The Middle Ordovician age of the lower Manhattan Schist (member A) was determined by Ratcliffe and Knowles (1969) on the basis of pelmatozoan fragments they discovered in a meta-limestone interbedded with the base of the Manhattan Schist. They also correlate the lower Manhattan Schist with the Annsville Phyllite of New York, a thick meta-pellite that may also correlate with the Martinsburg shale of New Jersey.

3. Baskerville (1994)

The map of New York City created by Baskerville (1994), describes the Manhattan Schist (without members) as an allochthonous Lower Cambrian formation that was thrust over the autochthonous Walloomsac Formation (previously mapped as Manhattan A) along the Inwood Hill Thrust-fault. Baskerville (1994) also thrusts the Hartland Formation (a Middle Ordovician to Lower Cambrian) unit (with no members) over the Manhattan Schist along Cameron’s Line.

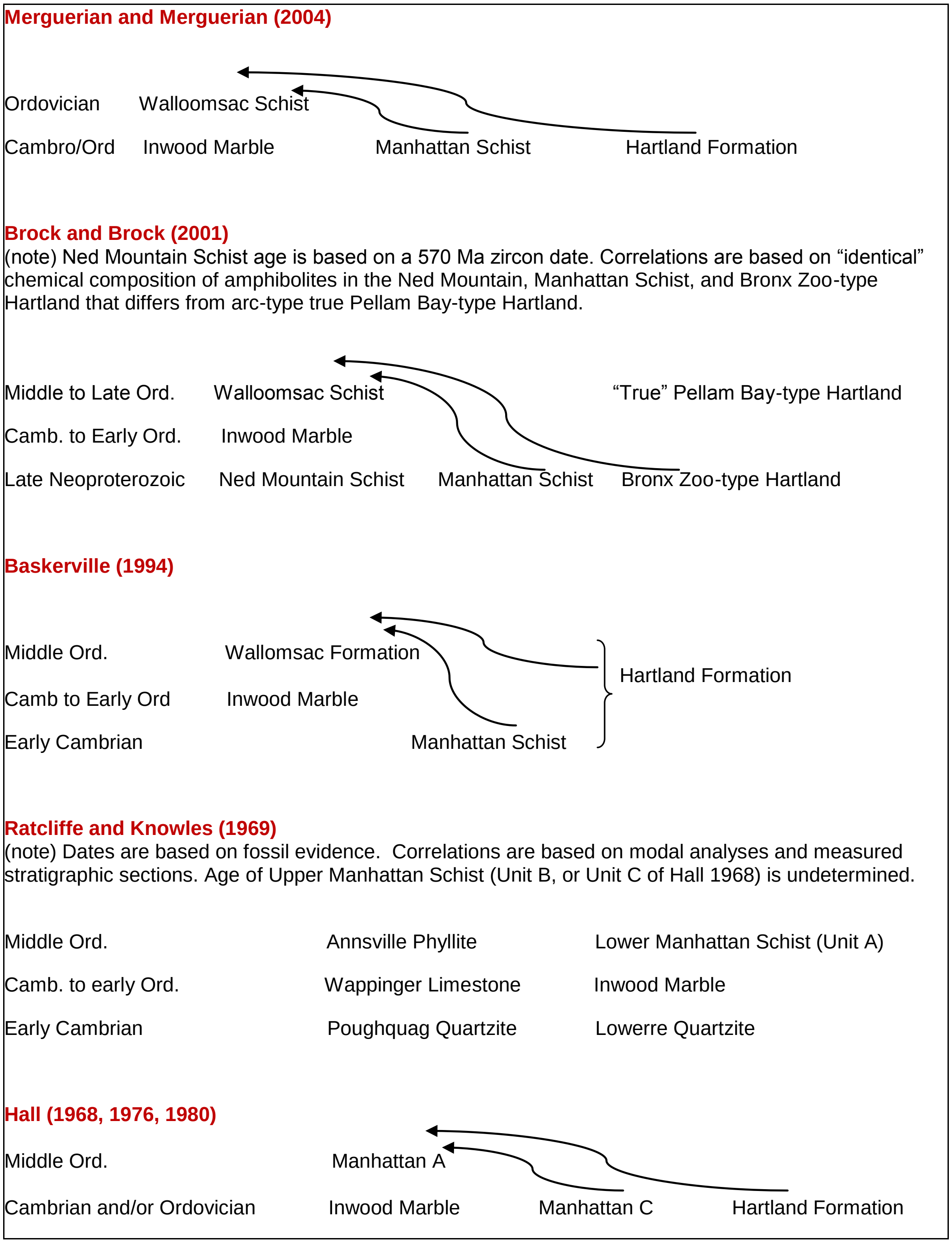
4. Brock and Brock (2001)

The map of New York City created by Brock and Brock (2001), is a major departure from previous mapping. It is based in part on a 570 Ma zircon date found in the Ned Mountain Formation that they interpret as forcing Manhattan Schist and Bronx Zoo-type Hartland Formation of “identical” chemical composition into the Late Neoproterozoic. This assumes that the host of the zircon was an ortho-amphibolite perhaps a meta-basalt and not a para-amphibolite originally composed of detritus eroded off of Late Neoproterozoic diabase exposed throughout the New Jersey Highlands and Reading Prong (Volkert and Puffer 1995). The Ned Mountain Formation includes the rocks exposed along the East River mapped by Baskerville as the Cambrian-Ordovician Ravenswood Granodiorite.

The Ned Mountain and Manhattan Schist are thrust over the Walloomsac Schist according to Brock and Brock (2001) and then Bronx Zoo type Hartland Formation is thrust over the Manhattan Schist. “True” Hartland Formation from an exotic (presumably arc) source is confined to schists associated with serpentinites (including the Staten Island Serpentinites and Castle Point Serpentinite) exposed along the Hudson River and to schists exposed well about nine Km east of Manhattan such as those of Pelham Bay.

5. Merguerian and Sanders (1994), Merguerian and Merguerian (2004)

Mapping and stratigraphic interpretations by Merguerian and Sanders (1994) and Merguerian and Merguerian (2004), agrees in most respects with earlier work by Hall. However they proposed that Manhattan Schist was thrust over Ordovician, autochthonous Walloomsac Schist instead of Ordovician, autochthonous Manhattan A. Then the Cambrian-Ordovician, allochthonous Hartland Formation was thrust over Cambrian-Ordovician, allochthonous Manhattan Schist along Cameron's Line deep into Manhattan through Central Park.



(note) Ned Mountain Schist age is based on a 570 Ma zircon date. Correlations are based on "identical" chemical composition of amphibolites in the Ned Mountain, Manhattan Schist, and Bronx Zoo-type Hartland that differs from arc-type true Pellam Bay-type Hartland.

(note) Dates are based on fossil evidence. Correlations are based on modal analyses and measured stratigraphic sections. Age of Upper Manhattan Schist (Unit B, or Unit C of Hall 1968) is undetermined.

Figure 1. Stratigraphic relationships among New York City rock units according to various authors.

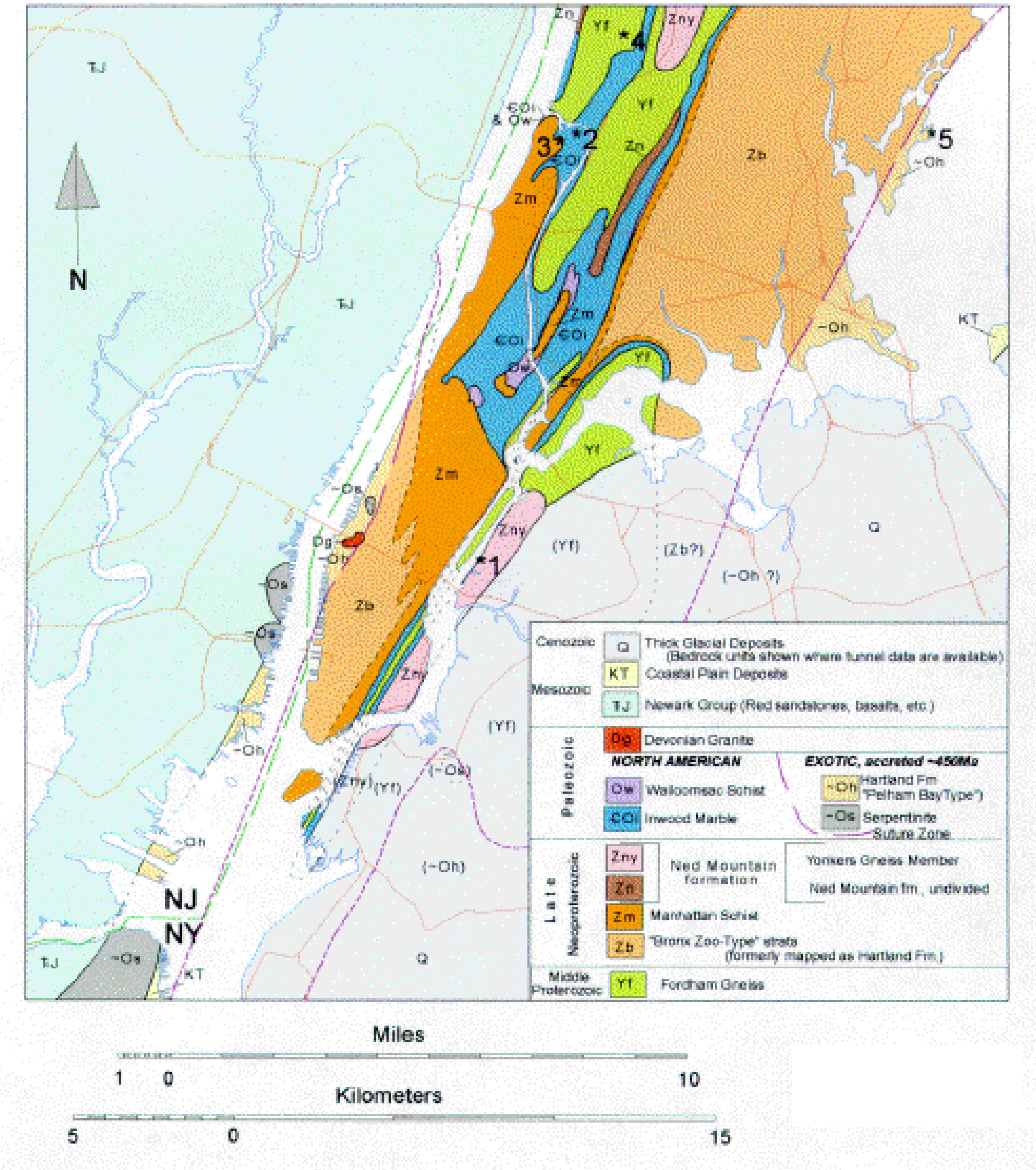


Figure 2. Geologic map of New York City (Brock and Brock, 2001)

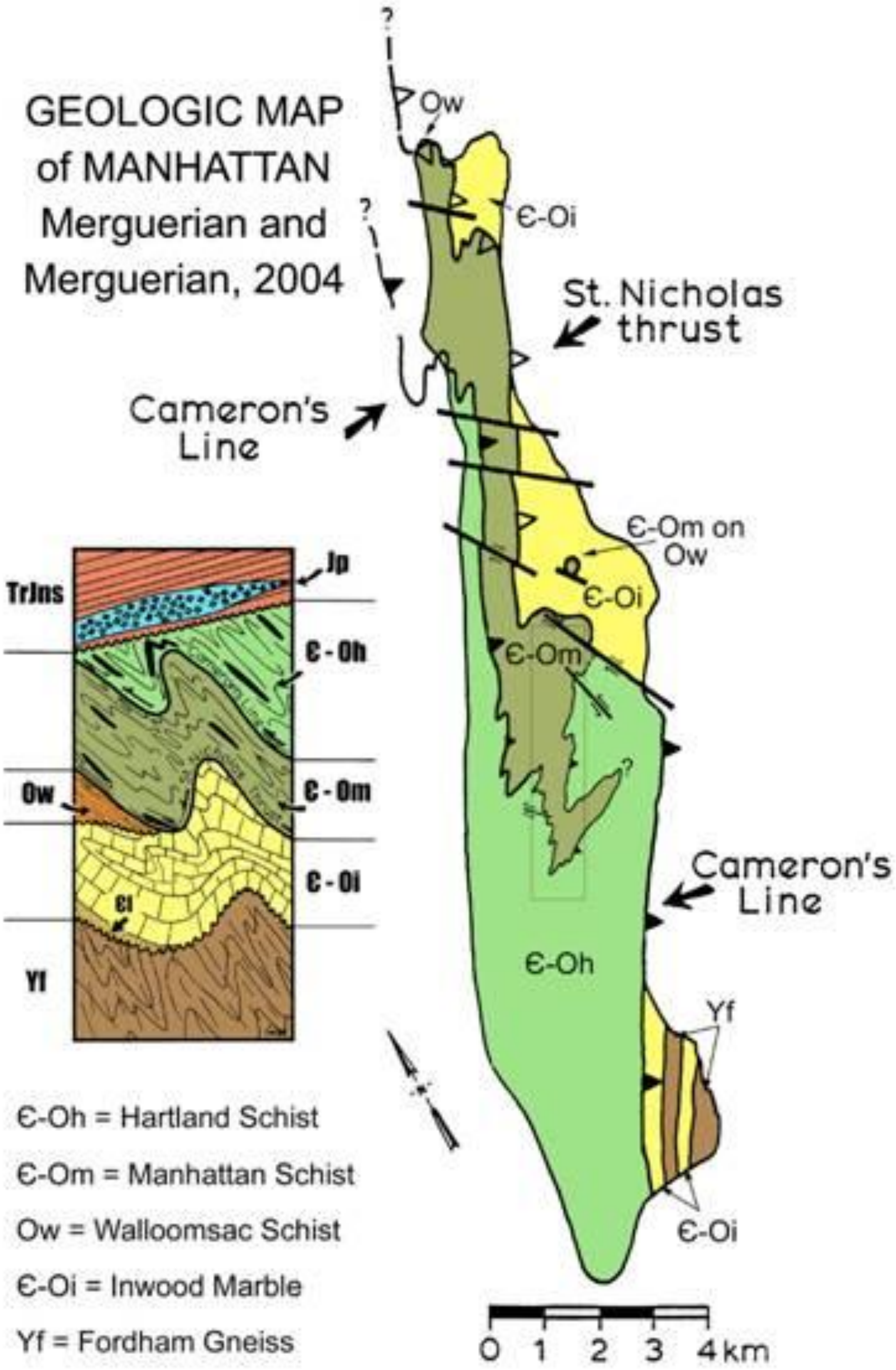


Figure 3. Geologic Map of Manhattan (Merguerian and Merguerian, 2004).

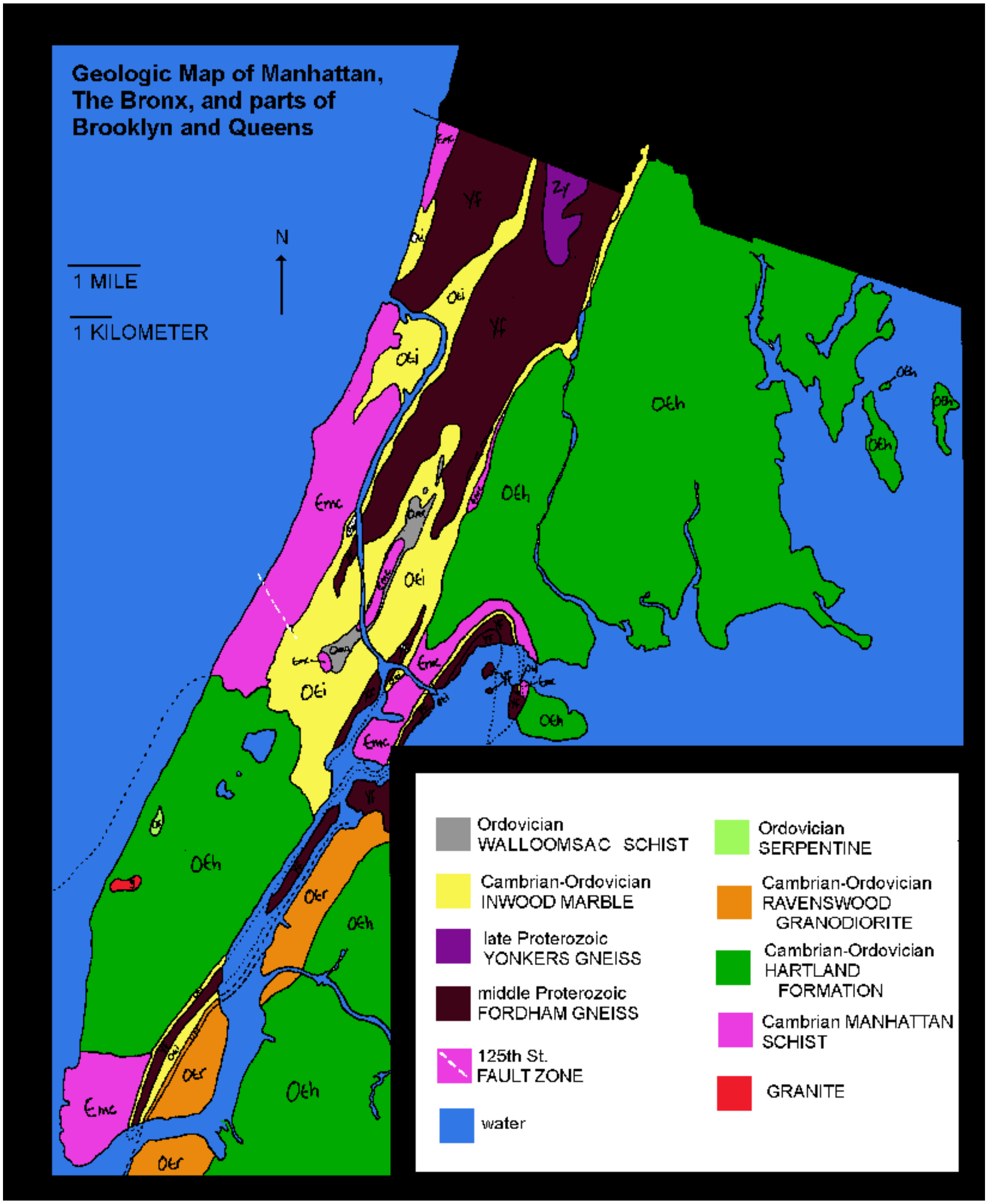


Figure 4. Geologic Map of Manhattan, The Bronx, and parts of Brooklyn and Queens by Baskerville (1994) as modified by the American Museum of Natural History (2010), New York City Geology, (Amnh.org).

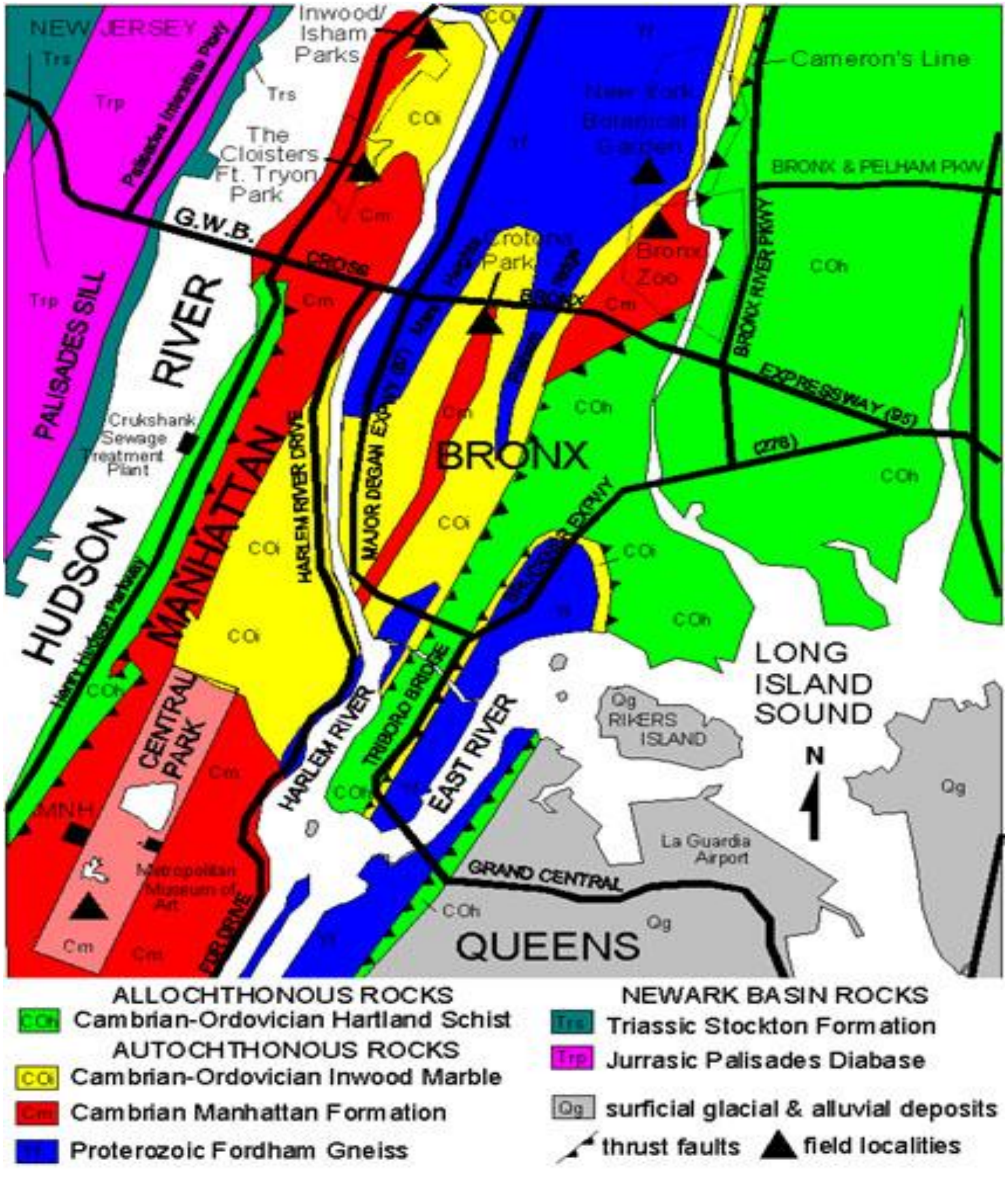


Figure 5. Geologic Map of northern New York City area by Schuberth (1967) as modified by the United States Geological Survey (2010) (3dparks.wr.usgs.gov).

Where is Cameron's Line ?

A recent Wikipedia definition of Cameron's Line is "… an Ordovician suture fault in the Northeast United States which formed as part of the continental collision known as the Taconic orogeny around 450 Mya. Named after Eugene F. Cameron, who first described it in the 1950's it ties together the North American continent, the prehistoric Taconic Island volcanic arc, and the bottom of the Iapetus Ocean." The NYC portion of the Northeast the "American continent" is the Manhattan Schist, the "volcanic arc" is the Hartland Formation and the "bottom of the Iapetus Ocean" is represented by a series of serpentinite units such as the Staten Island and Castle Point serpentinites . If the serpentinites of the NYC area were a continuous unbroken unit they would define Cameron's Line. However since this is not the case it is located at the boundary of the Manhattan Schist and the Hartland Formation along the stretches where serpentinite is missing.

One reason why it may be important to find Cameron's line is because as defined by Wikipedia it is a major fault and earthquakes typically occupy fault-plains. Since it appears that Cameron's line cuts through one of the most densely populated urban centers on earth it is all the more important. Strong local earthquakes are rare but not unheard of. It is somewhat likely that the focus of the next quake to strike NYC will be on Cameron's line although this is a subject that needs considerable additional study.

Petrological Characterization of Manhattan and Hartland Formations

A major obstacle faced by previous studies of New York City is the lack of any reliable petrologic criteria that can be used to distinguish the Hartland Formation from the Manhattan Schist in the field. Both formations are biotite-schists with similar accessory minerals including muscovite- garnet amphiboles, sillimanite, and magnetite. Some samples of Manhattan Schist also contain kyanite or tourmaline although these are not reliable or mappable characteristics. A few geologists including Merguerian and Merguerian (2004) have found weathered outcrop color useful. They find that the weathered surface of most outcrops of Manhattan Schist are reddish brown in contrast to the gray color of most Hartland weathered surfaces although exceptions are not rare.

Contrasting Provenances of Hartland and Manhattan Protoliths

There is a consensus among each of the principal geologists who have studied the New York City area that the protolith of the Manhattan Schist was pelitic sediment eroded off the North American continental craton and deposited on the continental shelf. The timing of metamorphic conversion into schist, however is in dispute. Bed-rock sources of sediment included widespread Proterozoic potassic granites, quartz-oligoclase gneiss including those of the New Jersey Highlands and shallow Neoproterozoic alkalic diabase intrusions and probable basaltic extrusions (Volkert and Puffer, 1995; Puffer, 2004)

In contrast, the Hartland Formation is generally interpreted as an exotic arc terrain composed of calc-alkaline volcanic rock and vocanogenic sediments that was accreted onto Laurentia during the Taconic Orogeny during the Ordovician period.

One objective of this project, therefore, is to examine the extent to which any geochemical distinction can be identified among sediments eroded off such contrasting sources.

Sampling and Analysis of New York City Schists

Sampling for this project was confined to schists, the chief component of NYC bedrock. Although amphibolites are also widespread throughout the NYC area they are petrogenically ambiguous and beyond the scope of this study. The MgO/CaO ratio of NYC schists is much higher than any common volcanic rock and are therefore is interpreted as meta-sediments. In contrast, NYC amphibolites resemble meta-diabase which may have intruded into the bedrock after it was deposited and resemble common meta-volcanic rocks which may have extruded from sources that differ from the sedimentary source of the schists.

Each schist sample was collected at a different large outcrop. Each sample, to the extent possible, represents the most common lithology of the outcrop from which it was sampled. Float samples were not collected.

Each sample collected from Boro Hall Park, and Central Park tables 1-2 was analyzed with a Rigaku x-ray fluorescence wavelength dispersive spectrophotometer. Samples from Riverside Park, the campus of The City College, and Pelham Bay were analyzed commercially at ALS Chemex using ICP-MS techniques. Care was taken to avoid damage to outcrops and wherever possible small loose samples were lifted from existing cracks then cleaned and trimmed of weathered material.

1. Central Park, Manhattan

Thirty two schist samples representing 32 of the largest outcrops in Central Park were collected and analyzed (Table 1). The analytical data appearing in Table 1 has not been previously published although averages were published by Puffer et al (1994) that included some amphibolite samples. As a test of Taterka's (1987) placement of Cameron's Line (the plate suture at the base of the Hartland Terrain) through the center of Central Park, 19 schist samples from the northern half of Central Park were collected north of his line placement and geochemically compared with 20 samples from the southern half. Puffer et al (1994). It was anticipated that if the schist samples collected from the northern half were Manhattan Schist they might display some geochemical distinction when compared to Hartland Schist samples from the southern half. Sample locations appear on the Map of Central Park by Puffer et al (1994).

Table 1, Chemical Composition of Schist Samples from Central Park

A. 18 samples from north of Taterka's placement of Cameron's Line (Manhattan Formation ?)

Sample #	CK-5	CK-8	CK-11	CK-13	CK-19	CK-20	CK-21	CK-22	CK-30	CK-32	CK-33	CK-34
SiO_2	70.08	63.41	68.42	61.98	59.91	58.07	66.34	53.08	62.41	52.19	55.95	53.27
TiO_2	0.99	1.22	0.81	1.2	1.24	1.18	1.03	1.47	1.28	1.49	1.4	1.79
Al_2O_3	12.77	16.14	13.56	15.08	16.39	20.21	14.11	20.34	16.69	21.36	18.09	16.53
FeO_t	5.51	7.61	5	8.1	7.19	7.73	5.07	8.06	6.87	8.92	7.29	10.81
MnO	0.09	0.1	0.08	0.15	0.07	0.14	0.05	0.12	0.13	0.19	0.09	0.19
MgO	2.92	3.35	2.51	3.86	3.78	3.91	2.56	4.29	3.44	4.2	4.01	4.35
CaO	1.58	1.13	1.89	1.85	1.31	1.29	1.01	0.93	1.63	1.12	1.99	2.01
Na_2O	2.68	1.52	3.26	2.13	1.62	2.78	1.28	1.74	2.34	2.01	1.92	1.89
K_2O	2.54	3.62	2.24	3.46	3.99	4.31	3.41	4.73	3.26	4.82	4.31	5.09
P_2O_5	0.14	0.24	0.12	0.25	0.23	0.13	0.18	0.14	0.17	0.1	0.18	0.22
LOI	1.32	1.7	1.98	3.2	3.35	1.42	3.56	4.5	1.76	2.6	3.42	2.97
Total	100.62	100.04	99.87	101.26	99.08	101.17	98.6	99.4	99.98	99	98.65	99.12
Cr	80	105	85	151	131	91	50	110	80	80	121	90
Cu	30	109	109	95	101	94		97	101			
Ni	31	59	62	42	64	51	15	60	40	50	49	43
Rb	97	112	89	114	118	119	83	114	96	120	110	112
Sc	9	14	9	16	12	10		15				
Sr	192	160	218	226	172	200	163	131	158	212	201	122
V	144	180	123	178	165	171	92	194	163	171	138	179
Y	26	25	24	24	26	25	26	26	24	21	25	22
Zr	319	248	263	243	225	203	344	199	268	244	183	206

Sample #	CK-37	Blockh	EMeadow	Red	3	2
SiO_2	62.36	66.5	64	49.43	47.01	75.72
TiO_2	1.09	1.1	1.12	1.38	1.78	0.66
Al_2O_3	18.8	14.9	12.95	20.01	19.42	10.9
FeO_t	6.21	4.99	6	10.79	11.58	3.72
MnO	0.09	0.08	0.08	0.11	0.14	0.08
MgO	3.21	2.2	3.04	3.21	4.63	1.5
CaO	0.99	1.31	1.92	0.17	1.01	1.32
Na_2O	1.24	2.12	1.92	0.31	1.62	2.25
K_2O	3.7	2.71	3.1	6.35	6.21	1.23
P_2O_5	0.23	0.19	0.17	0.07	0.34	0.12
LOI	1.8	2.61	2.96	5.68	5.29	2.18
Total	99.72	98.71	97.26	97.51	99.03	99.68
Cr	98	80	150	102	210	49
Cu	112					
Ni	40	18	20	15	60	37
Rb	107			153	148	77
Sc	14					
Sr	78	151	135		85	155
V	179	88	120	210	195	67
Y	27			26		
Zr	240	454	338	158		

B. 13 samples from south of Taterka's placement of Cameron's Line (Hartland Formation ?)

Sample #	CK-1	CK-2	A1	B1	B2	B3	C1	D1	G1	H	I2	Z1	7
SiO_2	57.22	73.94	61.11	55.85	47.85	60.21	61.42	58.35	68.4	61.92	65.31	53.22	56.83
TiO_2	1.73	1.18	1.12	1.17	1.48	0.95	1.35	1.14	0.79	1.04	0.99	1.36	1.41
Al_2O_3	14.88	10.69	19.86	19.8	23.01	17.85	17.11	18.99	14.52	16.99	16.32	18.41	17.61
FeO_t	8.21	4.49	6.07	7.91	9.08	6.28	8.44	8.11	4.71	7.03	5.82	8.29	7.71
MnO	0.13	0.08	0.08	0.11	0.11	0.14	0.13	0.12	0.08	0.12	0.09	0.12	0.1
MgO	4.88	2.35	2.99	5.56	3.92	4.41	3.33	1.19	1.97	4.42	2.79	4.38	4.2
CaO	2.21	1.82	1.97	0.52	1.29	0.3	0.61	0.62	1.02	0.22	1.18	2.09	1.03
Na_2O	2.47	2.63	2.52	1.01	1.73	0.48	0.96	1.45	1.24	0.68	1.87	2.27	1.25
K_2O	3.85	1.42	2.99	5.94	6.69	5.34	5.37	5.63	3.61	5.54	3.86	4.46	5.09
P_2O_5	0.4	0.21	0.22	0.13	0.23	0.18	0.22	0.11	0.09	0.07	0.12	0.23	0.27
LOI	3.7	1.5	1.48	2.88	3.21	2.73	1.39	3.32	3.21	1.94	2.9	4.39	3.97
Total	99.68	100.31	100.41	100.88	98.6	98.87	100.33	99.03	99.64	99.97	101.25	99.22	99.47
Cr	145	149	85	195	110	90	95	52	45	89	80	83	133
Cu	92	107	106	90	87		92	90		94	107		
Ni	50	30	39	63	43	60	42	32	36	71	37	54	51
Rb	102	65	99	179	158	177	131	173	113	174	123	131	150
Sc	16	8	15	15	16	14	14	14		13	14		
Sr	187	107	171	42	132	10	22	72	100	2	129	123	109
V	230	75	169	177	227	112	207	171	85	124	172	160	150
Y	24	24	25	28	26	26	26	25	25	25	27	26	
Zr	268	456	230	178	185	139	163	213	278	163	269	223	

2. Boro Hill Park, Manhattan

Fifteen schist samples from Boro Hall Park, at locations that appear on a map by Cadmus et al. (1996), were collected and chemically analyzed (Table 2). Preliminary analyses of the same samples plus some amphibolite analyses appear on Table 1 of Cadmus et al (1996). Samples M-5 through M-9 and H-1 through H-4 were collected along Third Avenue road cuts at the southern edge of the park at locations spaced at least 10 m apart. As a test of Baskerville's (1989) placement of Cameron's Line through the center of Boro Hill, 8 schist samples from the southwestern portion of Boro Hill Park were collected west of his line placement and geochemically compared with 7 samples from the east of his placement of Cameron's Line. It was anticipated that if the schist samples collected from the western half were Manhattan Schist they might display some geochemical distinction when compared to Hartland Schist samples from the eastern half. Baskerville (1989) proposed that the swale separating the east side of the park from the west side defines Cameron's Line.

Table 2, Chemical Composition of Schist Samples from Boro Hall Park

A. Boro Hall west of Baskerville's placement of Cameron's Line (Manhattan Formation?)

Sample #	MS-1	MS-3	MS-4	MS-6	MS-7	M-7	M-8	M-9
SiO_2	67.31	61.24	53.86	61.72	55.72	60.16	58.84	58.32
TiO_2	0.87	0.68	1.09	1.2	1.51	0.9	1.09	1.02
Al_2O_3	12.48	15.68	16.46	19.25	16.8	16.4	17.02	17.87
FeO_t	5.32	7.01	7.03	6.26	7.78	6.25	7	7.02
MnO	0.05	0.08	0.07	0.06	0.1	0.1	0.04	0.06
MgO	1.81	1.73	2.62	1.72	2.45	3.72	4.34	4.02
CaO	3.02	4.82	5.92	0.85	1.24	4.16	3.9	3.95
Na_2O	1.18	0.88	1	0.49	1.34	0.95	0.6	0.65
K_2O	2.33	1.8	4.33	4.17	5.11	4.26	3.28	3.32
P_2O_5	0.2	0.19	0.21	0.23	0.27	0.22	0.22	0.23
LOI	5.21	5.11	4.92	4.85	5.83	3.42	4.01	4.32
Total	99.78	99.53	97.51	100.8	98.15	100.54	100.34	100.78
ppm								
Ni	16	18	15	15	18	67	66	65
Rb	133	148	160	148		89	83	78
Sr	630	85	622	320		760	219	358
Zr	257	188	177	256		216	208	202

B. Boro Hall Park east of Baskerville's placement of Camerons Line (Hartland?)

Sample #	H-1	H-2	H-3	H-4	Hart-1	Hart-3	Hart-5
SiO_2	51.45	62.51	40.32	62.06	54.61	58.75	58.95
TiO_2	1.62	1.61	2.25	1.63	1.74	1.29	1.93
Al_2O_3	16.43	13.83	24.04	15.77	19.48	19.82	15.07
FeO_t	9.92	8.48	13.4	9.13	10.04	8.67	8.67
MnO	0.1	0.14	0.15	0.17	0.16	0.13	0.14
MgO	5.52	4.03	5.74	3.65	2.38	2.1	3.07
CaO	2.5	1.42	0.75	1.04	0.82	0.79	0.36
Na_2O	2.36	1.91	0.91	1.6	0.58	0.46	0.33
K_2O	4.53	3.92	6.58	3.49	4.89	3.45	6.19
P_2O_5	0.31	0.12	0.32	0.25	0.19	0.2	0.22
LOI	5.02	2.64	5.31	2.11	4.52	4.22	4.75
Total	99.76	100.61	99.77	100.9	99.41	99.88	99.67
Ni	73	65	79	73	17	18	20

Rb	92	86	104	81	145	128	176
Sr	328	277	132	192	223	221	175
Zr	146	314	232	358	287	180	219

3. West-side, Manhattan, along Hudson River

Thirteen schist samples were collected along the west side of Manhattan of which 5 were chemically analyzed (Table 3). From south to north analyzed samples were collected at a city park on 53rd Street and 11th Ave (Sample H3), at a large outcrop just north east of the Boat Basin near 82nd Street and 11th Ave, at another large outcrop in Riverside Park at 91st Street along the Hudson River, and on the campus of The City College at 135th Street. Of these samples only the sample from The City College has been consistently mapped as Manhattan Schist. Each of the remaining west-side samples are highly controversial.

Table 3, Chemical Composition of Schist Samples from the West Side of Manhattan

location	82nd & 11	91st & H	91st & H	53rd & 11	City College
Sample #	H1D	H2A	H2C	H3	M1
SiO2	61.92	83.51	46.29	63.76	58.13
TiO2	0.96	0.62	1.51	0.81	0.95
Al2O3	18.9	7.76	23.98	15.4	18.52
FeOt	7.87	2.81	13.68	6.42	7.76
MnO	0.1	0.05	0.17	0.11	0.22
MgO	1.81	0.59	3.36	3.33	3.26
CaO	0.59	0.96	0.35	2.61	3.46
Na2O	0.81	1.46	0.62	3	2.47
K2O	4.61	1.24	6.92	3.02	3.21
P2O5	0.13	0.06	0.05	0.27	0.12
LOI	1.8	0.56	2.71	0.81	1.67
Total	99.5	99.62	99.64	99.54	99.77
Ba	0.1	0.03	0.12	0.05	0.08
Cr	79	26	118	42	99
Sr	119	125	92	246	292
Zr	269	483	282	215	194

4. Pelham Bay, Bronx

In order to collect schist samples from a New York City location that has been consistently mapped as Hartland Formation we chose Pelham Bay. Similar reasoning was provided by Brock and Brock (2001) who identified the schist there as “True Hartland Formation” and as Pelham Bay-type Hartland Formation. Seven schist samples were collected there at large representative outcrops of which four were chemically analyzed (Table 4). Each of these sample locations were mapped by Seyfert and Leveson (1968) as part of the “Felsic Unit” which represents about 85% of the exposed rock of the Bay. Some of the Felsic Unit is described as felsic gneiss but the samples that we collected each contain at least 20 volume percent biotite and display a schistose texture. Table 4 also includes the average chemical composition of 2 “sillimanite schists” and the average of 2 “plagioclase-biotite gneisses” (interpreted here as schists with 35 % biotite) chemically analyzed by Seyfert and Leveson (1968).

Additional samples of schist and gneiss from the Brooklyn – Queens water tunnel complex were also sampled by Jeff Steiner and chemically analyzed (Table 4).

Table 4, Chemical Composition of Schist Samples from Pelham Bay Park and Brooklyn

			Pelham Bay Park				Brooklyn Tunnel Complex	
	Seyfert and Leveson (1968)		new	new	new	new	gneiss	schist
Sample #	4	14	OB-1	OB-3	OB-4	OB-5	b12	b13
SiO2	48.1	50.7	65.2	54.8	69.4	68.5	73.03	55.93
TiO2	1.7	1.6	0.87	1.2	0.79	0.94	0.19	1.42
Al2O3	23.1	20.3	14.15	19.1	13.3	14.1	11.99	14.58
Fe2O3	2.6	2.7	7.55	9.21	4.79	6.43	4	12.11
FeO	9.5	6.8						
MnO			0.4	0.17	0.07	0.14	0.09	0.06
MgO	4.4	3.5	2.07	3.07	1.57	1.23	1.89	5.01
CaO	2	4	1.07	2	2.39	3.4	0.79	1.89
Na2O	2.3	5.1	2.67	2.19	2.82	2.65	1.55	2.88
K2O	4.5	3.6	4.54	4.9	1.96	1.29	6.23	3.44
P2O5	n.d.	n.d.	0.1	0.14	0.16	0.39	0.02	0.09
LOI	n.d.	n.d.	0.39	0.79	0.68	0.2	0.5	1.52
Total	98.2	98.3	99.01	97.57	97.93	99.27	100.28	98.93
Ba			623	949	445	342	1158	524
Cr			60	70	40	50	0	275
Cu			7		17	16	11	71
Ni			39	37	10	14	0	100
Rb			163	151	62	48	102	120
Sr			111	106	97	159	75	129
V			69	97	64	79	0	305
Y			27	42	29	37	226	52
Zr			179	169	365	356	617	220

Bktl 12 run 45 BTL 13 run

Geochemical Results:

1. Geochemical resemblance of schist samples from Manhattan to an active continental margin

About half of the samples collected throughout Manhattan were collected at locations mapped by various authors as Hartland Formation and about half were collected at locations mapped as Manhattan Formation. However, anticipated bimodal distributions are not apparent on any plot of element distributions and both sample populations display overlapping distributions of all elements analyzed. In particular, plots of the K_2O/Na_2O vs. SiO_2 composition of schist samples from Manhattan (Tables 1, and 3) onto Figure 6 define a single population within the "active continental margin" field of Roser and Korsch (1986). Sedimentary rock collections from well defined tectonic settings on a global basis were plotted onto a K_2O/Na_2O vs. SiO_2 discrimination diagram and successfully separated by Roser and Korsch (1986) into 3 fields with minimal overlap. The "passive continental margin" tectonic setting is described as sediment deposited in plate interiors at stable continental margins or intracratonic basins. Sediment sources are dominated by recycled quartz-rich sediment derived from adjacent continental terrains. Sediment deposited into an "active continental margin" setting is described as derived from a tectonically active continental margin on or adjacent to active plate boundaries. Sediment are dominated by quartzo-feldspathic continental derived trench deposits deposited into an accretionary wedge or complex active margin basins. The "oceanic island arc" field of Figure 6 represents quartz poor volcanogenic sediments derived from oceanic island arcs and deposited in a variety of tectonic settings including forearc, intraarc, and backarc basins and trenches (Roser and Korsch, 1986).

An active continental margin setting is consistent with several tectonic models that describe sedimentation preceding the Taconic Orogeny including the "Cross Sections of Eastern North America" (USGS, 2003). An active continental margin setting is also consistent with the consensus description of Manhattan Schist sedimentation.

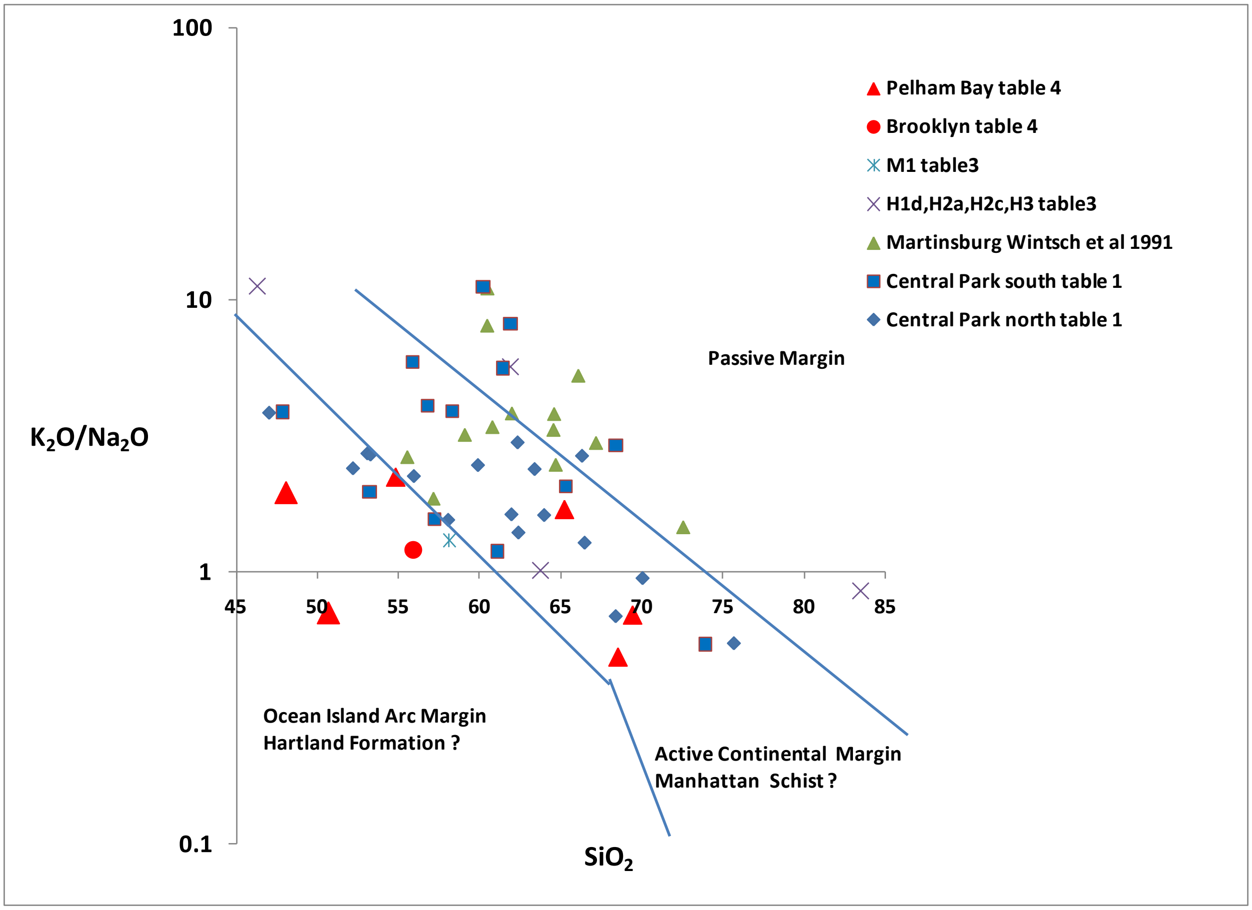


Figure 6. Plot of schist samples from Manhattan (tables 1-4) plotted onto diagram developed by Roser and Korsch (1986).

2. Geochemical resemblance of schist samples from Manhattan to Martinsburg shale

The Martinsburg Formation (Group) represents a second met sediment that was probably deposited in an active continental margin setting. McBride (1962) on the basis of his interpretation of sedimentary structures typical of the Martinsburg Formation suggested a turbidity current depositional setting and interpreted the chemical composition of the Martinsburg as indicative of a sedimentary to low-grade metamorphic rock provenance with granitic rocks as a secondary source. He also interpreted the turbidity currents as having flowed down the sub-sea slope of Appalachia toward the southeast.

The geochemical data of Wintch et al (1991) can be used to compare the Martinsburg with the schists of Manhattan. They collected 48 mudstones and 26 greywacke samples from a 3500 m thick section through the Martinsburg at Lehigh Gap Pennsylvania, 65 km west of Manhattan. They found that during greenschist-facies metamorphism of greywacke/metagraywacke assemblages Na_2O was lost and K_2O was gained. They also found that these changes were balanced by opposite changes in adjacent mudstone/slate assemblages resulting in minimal formation-wide net changes in either component. The K2O/Na2O and SiO2 data of Wintsch et al (1991) is plotted onto Fig. 6 and overlaps the field of schist from Manhattan. Figure 6, therefore, indicates that the schists of Manhattan and the metasediments of the Martinsburg Formation were probably deposited in a similar depositional setting and supports a correlation of two very thick Ordovician metasediment formations exposed 65 km from each other on the opposite sides of the Newark rift basin.

3. Geochemical resemblance of schist samples from Pelham Bay and Queens New York to volcanogenic arc detritus

In contrast to the schists of Manhattan, a schist sample collected from Brooklyn/Queens and the schist samples collected at Pelham Bay Park (including those chemically analyzed by Seyfert and Leveson, 1968) plot within or close to the "oceanic island arc" field of Figure 6. Although there is some overlap into the "active continental margin" field this result is consistent with the consensus view that the metasediments of Pelham Bay Park were derived from an island arc source.

More geochemical data is clearly needed but it appears that the Roser and Korsch (1986) diagram or similar as yet to be developed criteria may provide a basis for distinguishing between Manhattan Schist and Hartland Formation.

Field Trip Stops:

Stop 1. Central Park

No rock collecting is permitted so don't even bother to bring your rock hammer. However feel free to pick up loose samples and examine them with your hand lens. We will spend one hour at this stop. The bus cannot wait for stragglier.

The outcrops near 59th Street. along the southern portion of Central Park have been described as Cambrian Manhattan Formation by Schuberth (1967), (Fig. 1); as Cambrian-Ordovician Hartland Formation by Baskerville (1994), Fig. 2); as Cambrian-Ordovician Hartland Schist by Merguerian and Merguerian (2004), (Fig. 3); and as Late Proterozoic Manhattan Schist by Brock and Brock (2001), (Fig. 4). Still other options have been published and we encourage lively debate, but please leave your rock hammers in the bus.

Most of the outcrops of Central Park are roche moutonnée that were cut by a thick ice sheet into bedrock during the Pleistocene. Glacial polish and striations are clearly visible.

The large outcrop near 59th Street is a biotite-muscovite-garnet-plagioclase-sillimanite schist that is intersected by common pegmatites and amphibolite layers that are approximately conformable to the rock foliation.

Please note the mineralogy and texture of this rock because we will compare it with outcrops from further north into Central Park and elsewhere on the trip. But please be mindful of the time and try not to wander too far north into the park.

Stop 2. Riverside Park (Boat Basin)

The outcrops near 82nd Street just north east of the Boat Basin have been described as Cambrian Hartland Formation by Schuberth (1967), (Fig. 1); as Cambrian-Ordovician Hartland Formation by Baskerville (1994), Fig. 2); as Cambrian-Ordovician Hartland Schist by Merguerian and Merguerian (2004), (Fig. 3); and as Ordovician Pelham Bay-Type Hartland Formation by Brock and Brock (2001), (Fig. 4). The exact outcrop location appears on the map by Baskerville (1994) and includes strike and dip data as do all of his outcrop locations.

Stop 3. City College Campus and St. Nicholas Park (lunch)

Box lunches will be provided for all that have ordered them. While you are eating please examine any of the excellent exposures of Manhattan Schist throughout St. Nicholas Park adjacent to the campus of The City College but please don't wander too far off.

There is a general consensus that the outcrops exposed on the campus of the City University of New York (The City College) and along the St. Nicholas Park hill-side adjacent to the campus are Manhattan Schist (Figs 1-4). Samples observed here can, therefore, be thought of as a Manhattan Schist standard for comparison with other field trip stops.

St. Nicholas Avenue at the base of St. Nicholas Park marks the boundary between the Manhattan Schist on the west and the Inwood Marble on the East. The topography marking the highlands, locally Sugar Hill, has long been considered the result of differential erosion that sculpted the softer marble unit at the base. However, the downward-stepping outcrops that can easily be traced in the Park may represent an imbricate structural system that down-drops the schistose unit eastward.

Stop 4. Pelham Bay (Bronx, NY) Park in Beach Parking Lot , walk to north end of the beach and outcrops are at shoreline at Latitude 40.870095°; Longitude -73.783833°

The structural geology and petrology of Pelham Bay Park has been described by Seyfert and Leveson (1968). They used the New York State geological map by Fisher et al (1961) as their source of stratigraphy which had designated the Pelham Bay rocks as "…undivided schists and gneisses of unknown age". Seyfert and Leveson (1968) divided the Pelham Bay rocks into a "Felsic Unit" consisting of felsic quartz-plagioclase-biotite-gneisses and biotite-sillimanitic schists and a "Mafic Unit" consisting of amphibolites, plagioclase-biotite gneiss and minor calcite-rich layers and plagioclase-rich layers. They also describe several pegmatites within both units.

Some of this wide range of lithologies including pegmatites, pegmatite border zones, and the unusual calcite-rich layers were chemically analyzed with accompanying mineral modes (Seyfert, 1968). However, about 85% of their map of Pelham Bay Park consists of the "Felsic Unit". It is difficult to determine which lithology typifies the Felsic Unit but seems to fall somewhere close to an undefined boundary between schist and gneiss In general the Felsic Unit is largely a biotite- plagioclase-quartz-sillimanite-muscovite-garnet rock that mineralogically overlaps most of the schists of Manhattan. Microcline is notably absent or only a minor component of most of the rock but is a major component of some of the pegmatites. The microcline rich pegmatites appear to be discordant intrusions that intersect the foliation of the host rocks. A plagioclase rich generation of pegmatites is approximately equally common but is generally concordant to the foliation of host rocks that are also plagioclase rich and depleted in microcline.

Chemical analyses of the felsic unit members including plagioclase-biotite gneiss containing 64 % plagioclase and 35 % biotite and sillimanite schist containing 27 % plagioclase 43 % biotite and 11.5 % sillimanite (Seyfert, 1968) appear in Table 4.

Most of the exposed rock of Pelham Bay is a lighter shade of gray and not as reddish compared to Manhattan Schist. However, we find that fresh broken surfaces are difficult to distinguish from Manhattan Schist and are equally difficult to distinguish petrographically in thin section. We therefore invite all field trippers to carefully compare Pelham Bay rock with Manhattan rock. If any of you find any consistent mappable distinctions please share them with the rest of us.

One possible distinction may be contrasting plagioclase/biotite ratios. In general the plagioclase/biotite ratio of the average Pelham Bay rock is higher than typical of the schists of Manhattan. This elevated ratio is reflected in the contrasting (although overlapping) Na/K ratio of the analyzed rocks (Fig. 6). The plagioclase/biotite ratio may, therefore, be one of the few ways to map Hartland/Manhattan boundaries although, again, overlapping values do not permit definitive conclusions. As previously stated, sodic enrichment is an important characteristic of calc-alkaline lithologies such as the andesitic volcanic-arc lithology proposed for the protolith of the Hartland Formation.

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