TRIP A4: PETROGENESIS AND TECTONICS OF PRE-, SYN-, AND POST-OTTAWAN GRANITOIDS OF THE WESTERN HUDSON HIGHLANDS, NY

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INTRODUCTION AND GEOLOGIC SETTING

The purpose of this field trip will be to examine the field relations, geochemistry, and geochronology of a diverse suite of pre-, syn-, and post-Ottawan (1090-1030 Ma) granitoid rocks exposed in the western Hudson Highlands, NY. These rocks are critically important for constraining petrogenetic processes and the tectonic history of the Grenville Orogen (1350-960 Ma) in the north central Appalachians. The Hudson Highlands, along with the physically contiguous New Jersey Highlands and similar rocks extending into eastern Pennsylvania, are collectively called the Reading Prong, one of the largest of several Grenville-age (~1350 to 1000 Ma) basement massifs within the core of the Appalachian orogenic belt of eastern North America (Figs. 1 and 2; Rankin, 1975). These basement massifs lie outboard (east) of the main Grenville Province in eastern Canada and record variable amounts of post-Mesoproterozoic metamorphic and deformational overprint (e.g., Rankin et al., 1989; Gates and Costa, 1998). The Reading Prong displays evidence of only brittle deformation concentrated along narrow, reactivated Mesoproterozoic shear zones due to late Paleozoic compression and Mesozoic rifting (Gates, 1995; 1998) and thus, have a well preserved record of Grenville-age metamorphism and deformation. Rocks of the Hudson Highlands consist of a complex assemblage of metasedimentary, metavolcanic, and quartzofeldspathic ("granitic") gneiss, and intrusive granitoid rocks that were variably deformed and metamorphosed at upper amphibolite to hornblende-granulite facies conditions during at Grenville orogenesis (Dallmeyer and Dodd, 1971; Dallmeyer, 1974; Helenek and Mose, 1984). Based on field relations and recent SHRIMP U-Pb zircon ages (Ratcliffe and Aleinikoff, 2001; Gates et al. 2004; Volkert et al., 2005; Volkert et al., 2010; Aleinikoff et al., 2012), rocks of the Hudson Highlands, and the contiguous New Jersey Highlands can be roughly divided into two groups: (1) pre-Ottawan (>1060 Ma) and (2) syn- to post-Ottawan (<1060 Ma). Pre-Ottawan rocks all have strong, penetrative, high-grade metamorphic fabrics related to the Ottawan orogeny. Syn- to post-Ottawan rocks are variably deformed, ranging from undeformed to those that locally have strong, highgrade, ductile fabrics but lack the regional-scale, penetrative fabrics that characterize the pre-Ottawan rocks. Locally, syn- to post-Ottawan rocks truncate fabric elements in pre-Ottawan rocks. The area of the field trip is located in parts of the Sloatsburg and Popolopen Lake quadrangles west of the Hudson River within the west central Hudson Highlands, New York (Figs. 2 and 3). Previous mapping in this area, divided the units by rock types (Dodd, 1965; Jaffe and Jaffe, 1973; Dallmeyer, 1974; Helenek and Mose, 1984).

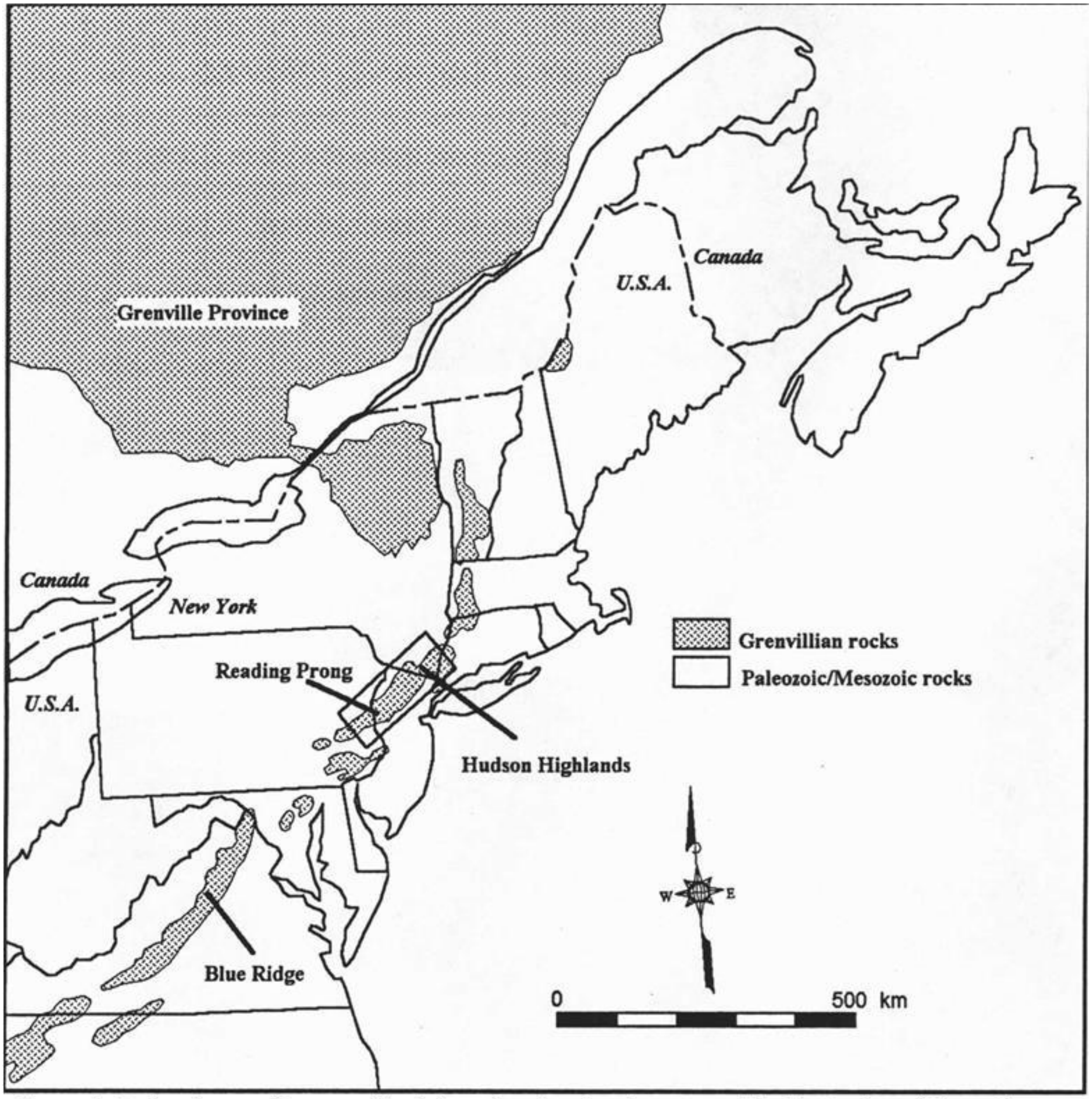

Figure 1. Regional map of eastern North America showing the geographic distribution of Grenville rocks. The area of Figure 2 is outlined by a rectangle. Map modified from Gates et al. (2001).

PRE-OTTAWAN ROCKS

Metavolcanic Lithofacies (~1350-1250 Ma)

The oldest rocks in the region are a suite of quartzofeldspathic orthogneiss which include strongly banded, interlayered, very light colored, biotite- and/or hornblende-quartz-plagioclase gneiss, charnockitic (orthopyroxene-bearing) quartz-plagioclase gneiss, and amphibolites of mafic to intermediate compositions. Mafic, intermediate, and felsic compositional banding ranges in thickness from 5 cm to 5 m with varying proportions of each rock type. There are local interlayers of quartzite and calc-silicate gneiss. Migmatites also occur locally in this unit. These rocks are interpreted to represent a

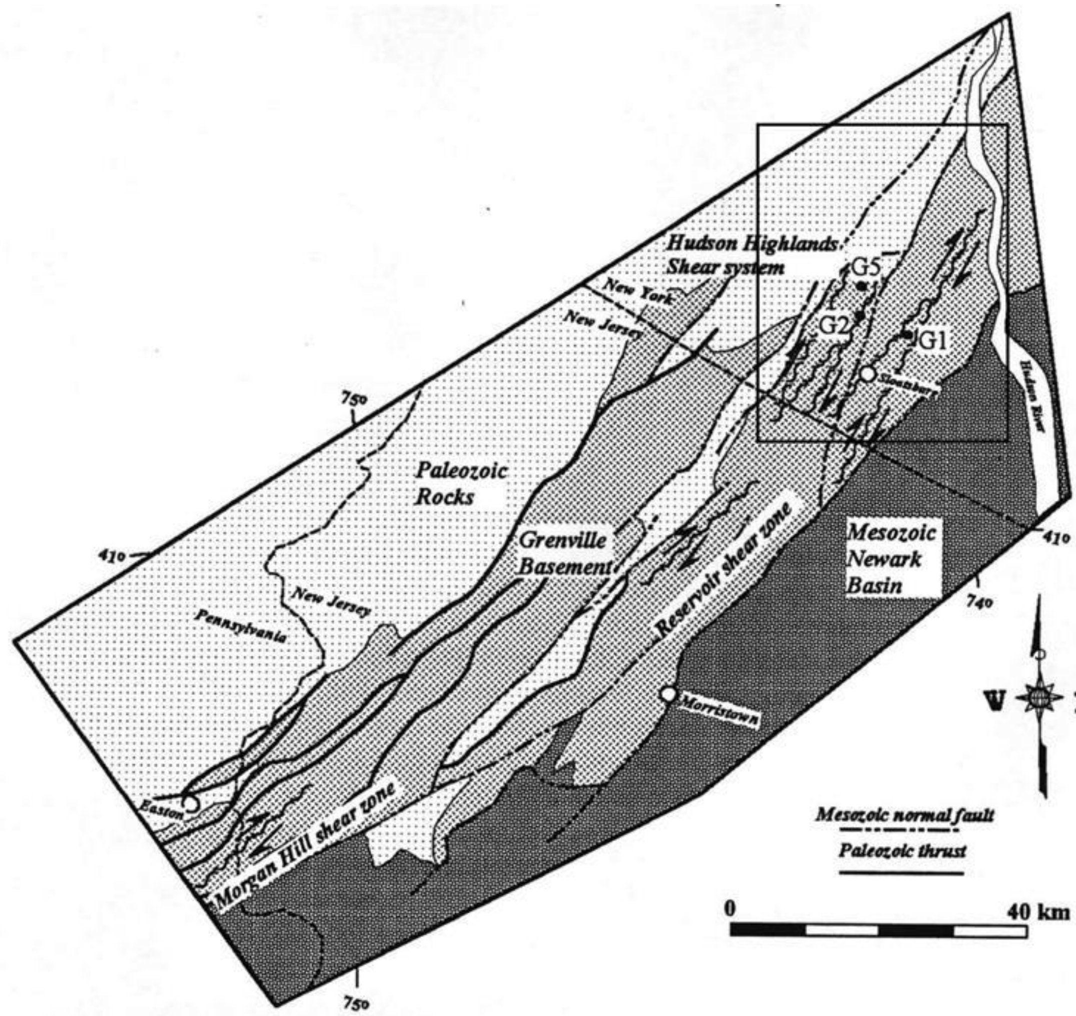

Figure 2. General geologic map of the Reading Prong and Hudson Highlands. The inset box shows the approximate area shown in Figure 3. G1, G2, and G5 are sample localities where Gates et al. (2001b; 2004) obtained SHRIMP U-Pb zircon ages. G1 is the Lake Tiorati Diorite at Stop #2 (see Fig. 6) and G2 is the sheared quartzofeldspathic gneiss at Stop #3. Map modified from Gates et al. (2001).

continental volcanic-plutonic arc suite of calc-alkaline rocks mixed with minor sediments (Ratcliffe, 1992; Gates et al., 2001c). Rocks equivalent to the metavolcanic lithofacies extends southwestward into the New Jersey Highlands where it is called the Losee Metamorphic Suite (Volkert and Drake, 1999) and northeastward into the eastern Hudson Highlands (Ratcliffe, 1992) where SHRIMP U-Pb zircon ages for these areas range from ~1.36 to ~1.25 Ga (Walsh et al., 2004; Volkert et al, 2010). Rocks of the metavolcanic lithofacies are lithologically and chemically very similar to tonalitic and charnockitic gneisses found in the southern Adirondacks (McLelland and Chiarenzelli, 1990) and to the Mount Holly Complex in the Green Mountain Massif in Vermont (Ratcliffe et al., 1991), which are dated at ~1.35 to 1.3 Ga. Overall, these rocks are interpreted to represent an Andean-type, continental arc system with northwestward-dipping subduction that existed along the entire eastern margin of the Laurentia from ~1.4 to ~1.2 Ga (see discussion in Volkert et al., 2010).

Metasedimentary Lithofacies (~1300-1200 Ma)

Throughout the western Hudson Higlands there are belts of rock considered to have sedimentary protoliths including pelitic-, psammitic-, calcsilicate-gneisses, quartzite, and marble. Belts of rock upward of a few kilometers wide may contain all or some of these rock types, interlayered at the scale of meters to 100's of meters. These rocks have been included in the metasedimentary lithofacies that is portrayed on the geologic map (Fig. 3). The metapelite consists of interlayered biotite-garnet gneiss with medium to coarse quartz, plagioclase, K-feldspar and local sillimanite, and cordierite with quartzofeldspathic layers. Within the metapelite are zones of graphite-pyrite-garnet gneiss with biotite, quartz, K-feldspar, plagioclase, and sillimanite locally. Quartzite layers of 10-50 cm thickness also occur within this unit as do rare and discontinuous layers of diopside and diopside-garnet marble to calcsilicate of 10 cm to 2 m thickness. The calc-silicate is quartzofeldspathic with salite, apatite, sphene, scapolite, and hornblende, and is commonly migmatitic. Based on the abundance of graphite-sulfide rocks and the presence of minor interlayers of amphibolite of probably volcanic origin, Gates et al. (2001c) interprets this sequence as most likely a suite of continental- to oceanic-arc extensional basin deposits. Volkert and Drake (1999) came to a similar conclusion based on field relations and whole-rock geochemical data on correlative rocks in New Jersey Highlands. Similar packages of metasedimentary rocks are common in the Adirondacks (e.g., McLelland et al., 1996) and in the Central Metasedimentary Belt in Canadian Grenville (e.g., Rivers, 1997; Carr et al., 2000).

The contacts with the quartzofeldspathic gneiss and rocks of the metavolcanic lithofacies are usually gradational such that age relations based on field relations are ambiguous due to transposition of original stratigraphic and/or cross-cutting relations. However, in the New Jersey Highlands, Volkert and Drake (1999) have recognized field evidence that indicates that the correlative metasedimentary sequence unconformably overlies the equivalent of the metavolcanic lithofacies (Losee Metamorphic Suite). Demonstrably unconformable relations between these units in the Hudson Highlands has yet to be recognized in the study area of this field trip, however, Ratcliffe (1992) also places the equivalent of the metavolcanic lithofacies in the eastern Hudson Highlands at the base of the "stratigraphy", below metasedimentary rocks. Dodd (1965) and Helenek and Mose (1984) document a few localities where metasedimentary lithofacies rocks are crosscut by metaplutonic quartzofeldspathic gneisses (e.g. Storm King granite gneiss) in the Popolopen Lake quadrangle near Bear Mountain. Thus, the age of the metasedimentary lithofacies rocks is roughly constrained to be younger (or at least contemporaneous with) than the metavolcanic lithofacies (<1300 Ma), but clearly older than quartzofeldapthic gneiss unit (see below) which has been dated ato be in the range of 1230-1160 Ma (see below; Ratcliffe and Aleinikoff, 2001; Gates et al, 2004; Volkert et al., 2010). This interpretation is also supported by SHRIMP U-Pb zircon ages of (1) detrital grains from a semi-pelite from the western Hudson Highlands (G5 in Fig. 2) which yielded a wide range of ages from 2000-1200 Ma (Gates et al., 2004) and (2) interlayered rhyolitic gneisses within the metasedimentary sequence from the New Jersey Highlands that yield ages of 1300 to 1240 Ma and thus roughly bracket the upper and lower age limit of the as well as inherited cores that range from 1390 to 1300 Ma (Volkert et al., 2010).

Quartzofeldspathic Gneiss (~1230-1160 Ma)

The quartzofeldspathic gneiss ranges from massive to layered quartz-plagioclase gneiss and quartz-K-feldspar-plagioclase gneiss with minor amounts of clinopyroxene, hypersthene, hornblende and/or biotite. Locally, this unit contains magnetite or garnet in trace amounts. Compositional layers are defined by the proportion and type of the ferromagnesian mineral component. Locally, this unit contains apparent textural gradation across the fabrics by an increase in the amount of mica and

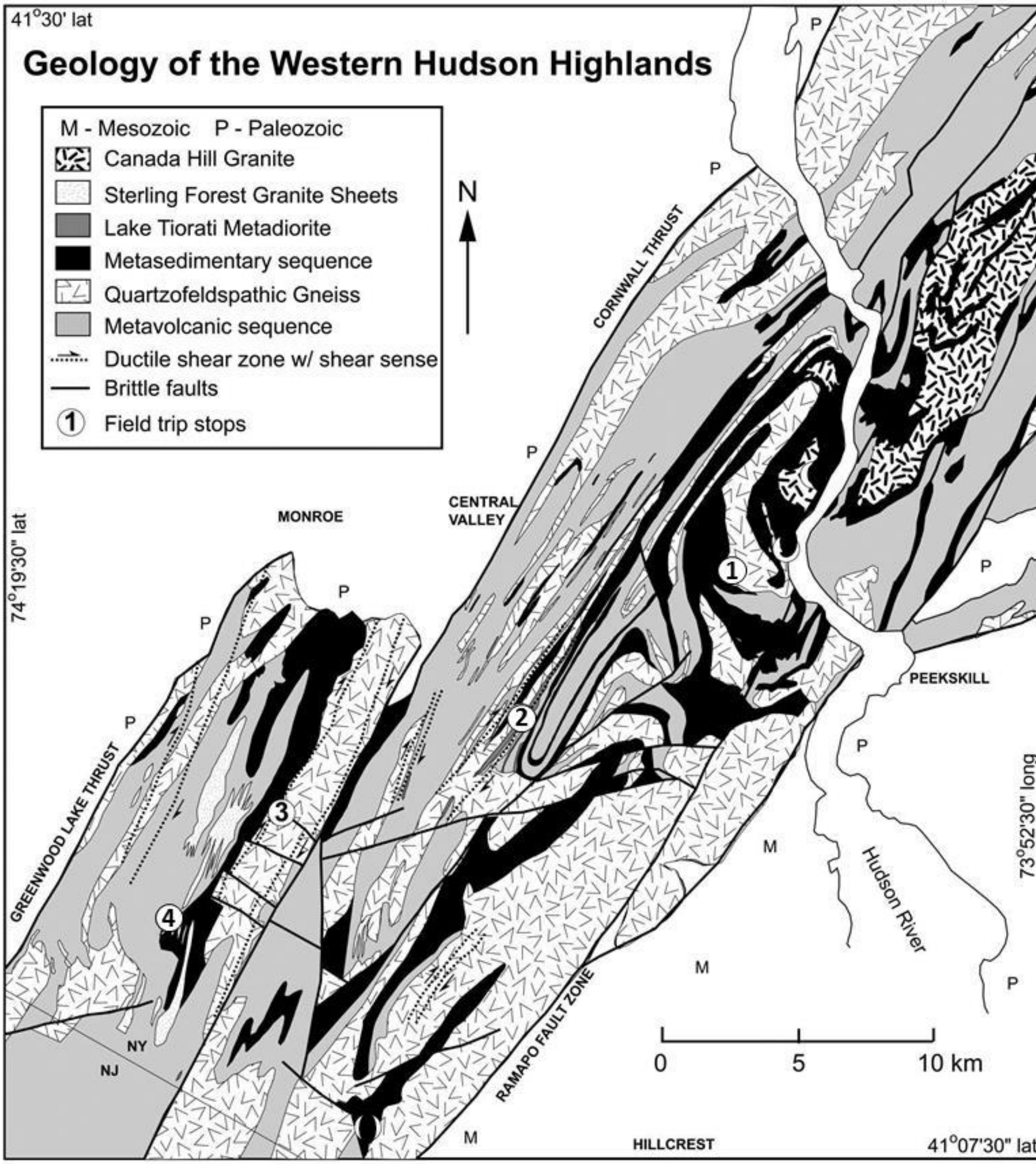

Figure 3. Generalized geologic map of the west central Hudson Highlands showing field trips stops 1-4. Based on geologic mapping of Dodd (1965), Offield (1967), Helenek (1971), Ratcliffe (1992), Valentino et al. (2001); Gates et al. (2001).

decrease in layer spacing with sharp contacts between, suggesting a relict sequence. However, such relict sequences in granulite terranes are difficult to interpret. Quartzofeldspathic gneiss is locally interlayered with quartzite and with mafic gneiss at the contact with the metavolcanic lithofacies. The gradational contacts with the metavocanic and metasedimentary lithofacies, and the internal compositional layers suggest that parts of the quartzofeldspathic units could represent a volcaniclastic sequence. However, in the more massive rocks, this unit is strongly lineated (L>S) defined by stretched hornblende prisms and rodded quartz-feldspar aggregates interspersed with large (2-4 cm) plagioclase and/or K-feldspar augen and locally contains mafic gneiss xenoliths. These features clearly support a metaplutonic origin for at least part of quartzofeldspathic gneiss. These more massive textured rocks are interpreted here to be correlative to hornblende granite gneiss mapped in the Popolopen Lake (Dodd, 1965) and West Point quadrangles (Helenek and Mose, 1984), and Oscawana Lake quadrangles (Ratcliffe, 1992) which has been historically referred to as the "Storm King Granite" (Berkey, 1907; Lowe, 1950). These rocks also correlate with similar metaplutonic hornblende granite gneiss lithologies within the Byram Intrusive Suite in the New Jersey Highlands (Volkert et al., 2000; Volkert, 2004).

Geochemical data shows that massive-textured quartzofeldspathic gneiss, Storm King granite gneiss, and the Byram Intrusive Suite all have nearly identical chemistry characterized by metaluminous A/CNK ratios (<1.0) and A-type compositionally affinity defined by high Fe/(Fe+Mg) (~0.9), K_2O/Na_2O (1.5-2), high Ba (500-1800 ppm), Nb (20-50 ppm), Y (60-180 ppm), total REE (300-800 ppm) and low MgO (<0.7%), CaO (<2%), and Sr (80-180 ppm). REE patterns are LREE-enriched (La/Yb_n = 5-15), but have flat MREE and HREE and relatively high HREE concentrations (~20-40x chondrite) with moderately deep negative europium anomalies (Eu/Eu* = 0.20-0.50) (Figs. 4A and B). All three suites largely overlap in the "within plate granitoid" (WPG) field on tectonic discrimination diagrams (Figs. 4C and D). Similar

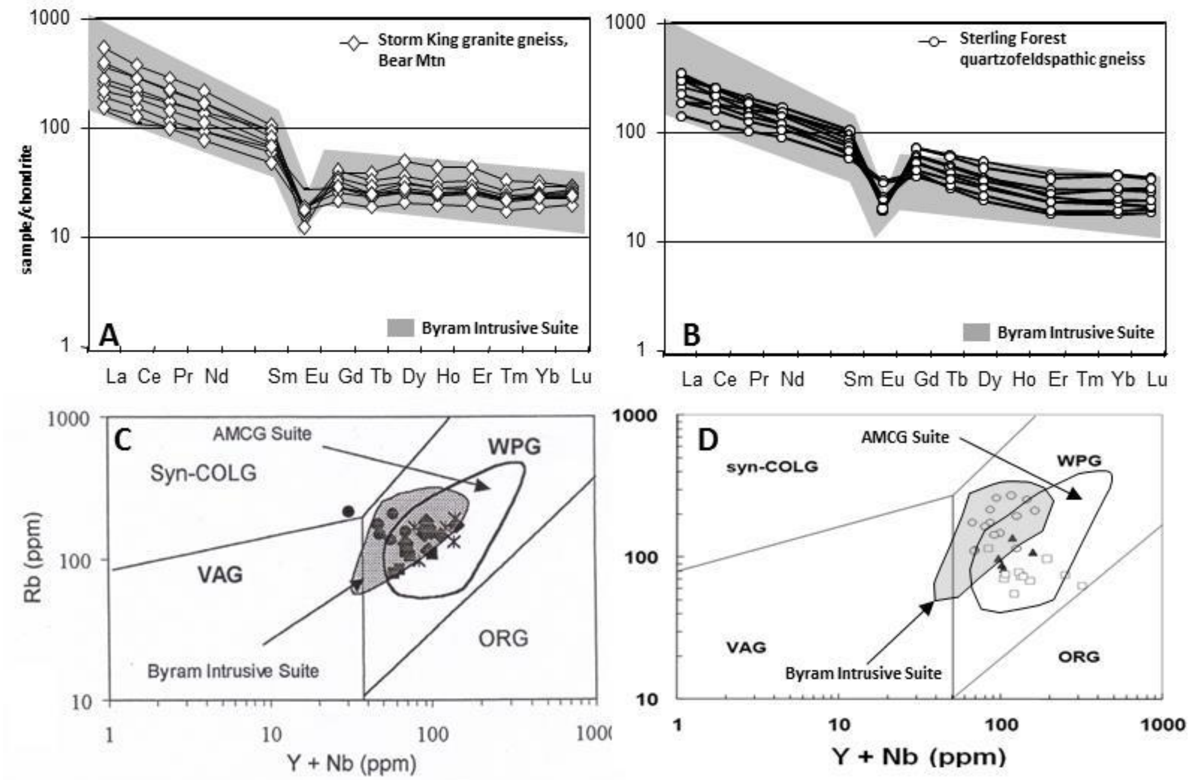

Figure 4. Geochemical plots (A) and (C) for the Storm King granite gneiss from the Bear Mountain area (including Stop #1), and plots (B) and (D) for massive quartzofeldspathic gneiss from the Sterling Forest area (including Stop #3) showing their striking geochemical similarity with each other and with correlative granite gneisses of the Byram Intrusive Suite, NJ (Volkert et al., 2000). These are rocks also similar to AMCG granitic gneisses from the Adirondacks, NY (McLelland et al., 1996). A) and (B) are REE plots and (C) and (D) are tectonic discrimination diagrams modified from Pearce et al. (1984); fields are for syn-collision (syn-COLG), volcanic arc (VAG), within plate (WPG), and ocean ridge (ORG) granitoids.

field relations and geochemical characteristics, that spans more than 150 km through the NJ Highlands northeastward into the Hudson Highland strongly supports a regional correlation and is consistent with a relatively uniform A-type granitoid protolith (Verrengia and Gorring, 2002; Peterson et al., 2011).

Current radiometric constraints on the crystallization age of these granitic metaplutonic rocks are based on SHRIMP U-Pb zircon ages that have been obtained over the last 10-15 years. Ratcliffe and Alenikoff (2001) reported a SHRIMP zircon age of 1174 ±8 Ma for the Storm King granite gneiss at Dunderberg Mountain (~10 km SE of Bear Mountain). Gates et al. (2004) obtained a broad crystallization age range of ~1160-1230 Ma by SHRIMP zircon analysis on one sample of quartzofeldspathic gneiss from within the Indian Hill Shear Zone in the Sterling Forest area (Stop #3). More recently, Volkert et al. (2010) reported SHRIMP zircon crystallization ages of 1182 ±11 and 1184 ±8 Ma from two samples of hornblende granite gneiss from the Byram Intrusive Suite. As noted by Volkert et al. (2010), the timing of this magmatism (~1180 Ma) correlates with the early stages of the Shawinigan Orogeny (1190-1140 Ma) in the Canadian Grenville Province (see Rivers, 1997 and refs. therein). Quartzofeldspathic gneisses from the New Jersey and western Hudson Highlands are chemically similar to other metaplutonic rocks of A-type chemical affinity with ages of 1210-1170 Ma from other parts of the Grenville Orogen including southeastern Canada (Easton, 1986; Lumbers et al., 1990; Davidson 1995) and the Adirondack Lowlands (Wasteneys et al., 1999; Hamilton et al., 2004; Peck et al., 2004; Heumann et. al, 2006) as well as granitic gneisses from the slightly younger AMCG suite (~1155 Ma) in the Adirondack Highlands (McLelland and Whitney, 1990; McLelland et al., 2001; 2004). The consistent A-type geochemical affinity and the large volumes of magma generated to form the protolith of the massive-textured quartzofeldspathic gneiss, Storm King granite gneiss, and the Byram Intrusive Suite supports a tectonic model that involves a major heat source to the crust. Verrengia and Gorring (2002) proposed that the Storm King granite gneiss formed from partial melting of mafic to intermediate calc-alkaline sources at mid-crustal depths with the heat source coming from asthenospheric upwelling due to gravitational collapse and delamination of an overthickened continental lithosphere produced during the final stages of Elzevirian Orogeny. Volkert et al (2010) proposed a model for Byram Intrusive Suite granitic gneisses where asthenospheric upwelling occurs by a combination of lithospheric delamination and/or slab rollback after the closure of a backarc basin that occurred post-Elzevirian (e.g <1.2 Ga).

PRE- TO SYN-OTTAWAN METAMORPHISM AND DEFORMATION

There are at least two (and perhaps three) major deformational events recorded in the crystalline rocks of the Hudson Highlands. The dominant deformational structure of the older event(s) is a penetrative gneissosity that occurs in every unit except the Lake Tiorati Diorite, Sterling Forest Granite Sheets, Canada Hill Granite, and late pegmatites (see below). This gneissosity is defined by virtually all minerals but especially by platy and elongate minerals. Biotite, amphibole, sillimanite, and pyroxene are aligned in the strongly foliated quartz-feldspar matrix. Additionally, aggregates of quartz and feldspar define layering in some lithologies. Amphibole and pyroxene clots show similar rotation textures forming sigma-porphyroclasts (Passchier and Simpson, 1986). Some pelitic rocks contain garnet-fish structures, and locally, some rocks contain intrafolial asymmetric isoclinal folds 5 to 20 cm thick. The vergence of these folds is consistent in some areas and appears to indicate westward transport. Mesoscopic and megascopic folds produced during this event are recumbent to shallowly reclined. They are tight to isoclinal and commonly asymmetric with the lower limbs sheared out. This asymmetry consistently indicates northwestward transport. The weak and sparse kinematic indicators described above support this shear sense. Thinner layers in these folds contain mesoscopic parasitic folds that are especially well developed on the upper limb. Metamorphism associated with these structures is of hornblende granulite facies and maximum P-T estimates are on the order of 700-750ºC and 4±1 kilobar based on mineral assemblages in metapelitic and mafic metavolcanic units (Dallmeyer and Dodd, 1971). Deformation and metamorphism associated with this event is most likely of Ottawan age and is interpreted to have been the result of a Himalayan-type continent-continent collision (Gates et al., 2004). However, this does not preclude the possibility of pre-Ottawan deformation events (e.g., Elzeverian, Shawinigan as defined by Rivers, 1997) that could have been obliterated by the Ottawan event. In fact, this is likely the case. Dallmeyer (1972), Helenek and Mose (1984) and Ratcliffe (1992) report structural evidence (e.g. refolded foliation) for multiple deformation events (e.g. refolded foliation) in the Bear Mountain area and in the eastern Hudson Highlands. Further evidence for a pre-Ottawan deformational history comes from U-Pb SHRIMP zircon crystallization age of 1144 ±13 Ma on the Canopus Pluton in the eastern Highlands that lacks the older fabric elements (Ratcliffe and Aleinikoff, 2001). Structural and geochronologic evidence for multiple, penetrative fabric elements that can be assigned to distinct pre- and syn-Ottawan deformation events has yet to be recognized in the western Hudson Highlands.

EMPLACEMENT AND GEOCHEMISTRY OF SYN- AND POST-OTTAWAN GRANITOIDS

Granitoids of syn- to post-Ottawan age (1060 to 960 Ma) are volumetrically minor in the Hudson Highlands compared to pre-Ottawan rocks, but are important for constraining the late geologic history of the area. Syn-Ottawan granitoids consist of two suites of leucogranites; (1) the Sterling Forest granite sheets (Gorring et al., 2002), and (2) the Canada Hill Granite (1058 ±14 Ma; Helenk and Mose, 1984; Aleinikoff et al., 2012). Post-Ottawan granitoids consist of the Lake Tiorati Diorite (1008 ±4 Ma; Gates et al., 2004) and a suite of late, crosscutting pegmatitic granite dikes. The Mount Eve Granite (1019 ±5 Ma; Drake et al., 1991; Gorring et al., 2004; Volkert et al., 2010), located in the far western New Jersey and Hudson Highlands, is also part of the post-Ottawan suite granitoids, but will not be visited on this field trip. Similar plutonic granitoid activity of syn- to post-Ottawan age has been documented elsewhere in the Adirondacks (1060-1045 Ma; Lyon Mountain granitic gneiss; 1035 Ma; Lyonsdale Bridge pegmatite; 935 Ma Cathead Mt leucogranite; McLelland et al., 2001) and in the Green Mountain Massif (ca. 960 Ma; Stamford Hill rapakivi granite; Ratcliffe et al., 1991).

<u>Sterling Forest Granite Sheets (syn-Ottawan)</u>

Mapping in the Monroe and Sloatsburg quadrangles by Valentino et al. (2001) and Linguanti et al. (2011) have identified a series of leucocratic granite sheets, primarily occurring west of the NY Thruway in the Sterling Forest section of Harriman State Park, that intrude pre-Ottawan rocks of the metavolanic and metasedimentary lithofacies and the quartzofeldspathic gneiss unit. Jaffe and Jaffe (1973) recognized these rocks in the Monroe quradrangle and mapped them as alaskite bodies. Offield (1967) also mapped isolated occurrences of this lithology immediately to the east in the Greenwood Lake quadrangle. The granite sheets are typically medium to coarse-grained, locally megacrystic (K-feldspar and plagioclase), lack penetrative deformational fabrics, and have concordant intrusive contacts with the surrounding gneisses. Currently there are no radiometric age constraints on this important unit. The granite sheets are leucocratic, with K-feldspar, quartz, plagioclase, only minor (<5%) hornblende and/or biotite, and accessory apatite, zircon, and titanite. The texture is equigranular with subhedral to anhedral interlocking grains, and locally they contain xenoliths of metasedimentary and metavolcanic lithofacies rocks. The interior of the granite sheets are not foliated, however the margins typically show high-grade ductile foliation textures that are parallel to the enclosing gneisses. The sheets range in thickness from 10’ s to 100’s of meters thick and typically strike northeast-southwest and dip moderately to steeply to the southeast parallel to foliation in the surrounding gneiss. Most are laterally continuous for several kilometers and parallel the hinge zone of fold nappes in the metavolcanic and metasedimentary sequences. In the central part of Sterling Forest, the granite sheets extend out from two large tabular shaped bodies of granite. These two bodies of granite and sheet appendages occur within core of shallowly plunging, northeast trending, parallel, open antiformal structures that can be traced from the Monroe quadrangle southward. These field relations, along with the ductile deformation textures at the sheet margins, strongly suggest a genetic relationship between granite emplacement and fold development indicating that the granite sheets were emplaced during deformation (e.g. syn-Ottawan).

The Sterling Forest granite sheets are high SiO_2 (~75%), leucocratic granites with <5% modal mafic minerals (Appendix Table 2; Fig. 5A). They are metaluminous to slightly peraluminous (ASI = 0.95 to 1.1) and have highly variable K_2O/Na_2O (0.3 to 3.3) reflecting variability in the modal abundance of K-feldspar or Na-plagioclase as the dominant feldspar. These rocks are divided into three chemically distinct groups based on REE patterns (Fig. 5C). The first group is characterized by LREE-enriched, HREE-depleted patterns with moderately negative Eu anomalies (Eu/Eu* = 0.50 to 0.7). The second group has a distinctive concave upward, "dished" MREE-depleted, HREE-enriched pattern with moderately negative to neglible Eu anomalies (Eu/Eu* = 0.35 to 1). The third group is defined by very low total REE's, strong LREE enrichment, depleted and flat MREE to HREE, extremely positive Eu anomalies (Eu/Eu* up to 3.5), and relatively high Sr and Ba concentrations (Appendix Table 2) relative to the other two groups. Group 1 granite sheets are best interpreted as partial melts of plagioclase-free source rocks with abundant residual amphibole $\pm$ garnet coupled with fractional crystallization of quartz + feldspars ± trace element-rich accessory phases (e.g., zircon, apatite, monazite, allanite). The garnet-bearing, plagioclase-free source mineralogy implies melt generation probably occurred at deep crustal levels probably involving source rocks of mafic to intermediate compositions. In comparison, Group 2 granite sheets clearly were generated by partial melting of garnet-free source rocks and hence melt generation probably occurred at shallower crustal levels. Group 3 granite sheets most likely represent rocks that accumulated feldspar, perhaps by some sort of filter pressing mechanism that extracted granitic melts during emplacement. These chemically distinctive groups of granite sheets have similar field relations and appear to be part of the same magmatic event, thus crustal melting apparently occurred at various crustal levels. On tectonic discrimination diagrams, the Sterling Forest granite sheets plot scattered along the boundary between fields for syn-collisional and volcanic arc granitoids (Figs. 5D-E).

Canada Hill Granite (syn-Ottawan; ~1060 Ma)

The Canada Hill Granite (Berkey and Rice, 1919; Lowe, 1950; Helenek and Mose, 1984) is a distinctively white to blue-gray, coarse-grained leucogranite that occurs as small plutons, sheets, pods, and stringers almost exclusively within metapelitic gneisses of the metasedimentary lithofacies in the northeastern part of the Hudson Highlands (Fig. 3). The largest masses of this unit occur on the eastern side of the Hudson River in the vicinity of Canada Hill in the West Point quadrangle, where it was originally mapped and defined by Berkey and Rice (1919) and again formalized as a distinct, mappable unit by Helenek (1971). Lowe (1950) and Dodd (1965) also recognized this unit to the southwest in the Popolopen Lake quadrangle as well as by Ratcliffe (1992) to the east in the Oscawana Lake quadrangle. The Canada Hill granite is almost always associated with migmatitic host rocks. The Canada Hill Granite is composed of quartz, white K-feldspar, and white to gray plagioclase in roughly equal proportions. Biotite is ubiquitous as the mafic phase with accessory amounts of sphene, apatite, and zircon. Garnet is locally abundant, especially near contacts with the enclosing migmatitic metapelite and is interpreted to represent undigested xenocrysts derived from the metapelites. It is predominantly massive textured

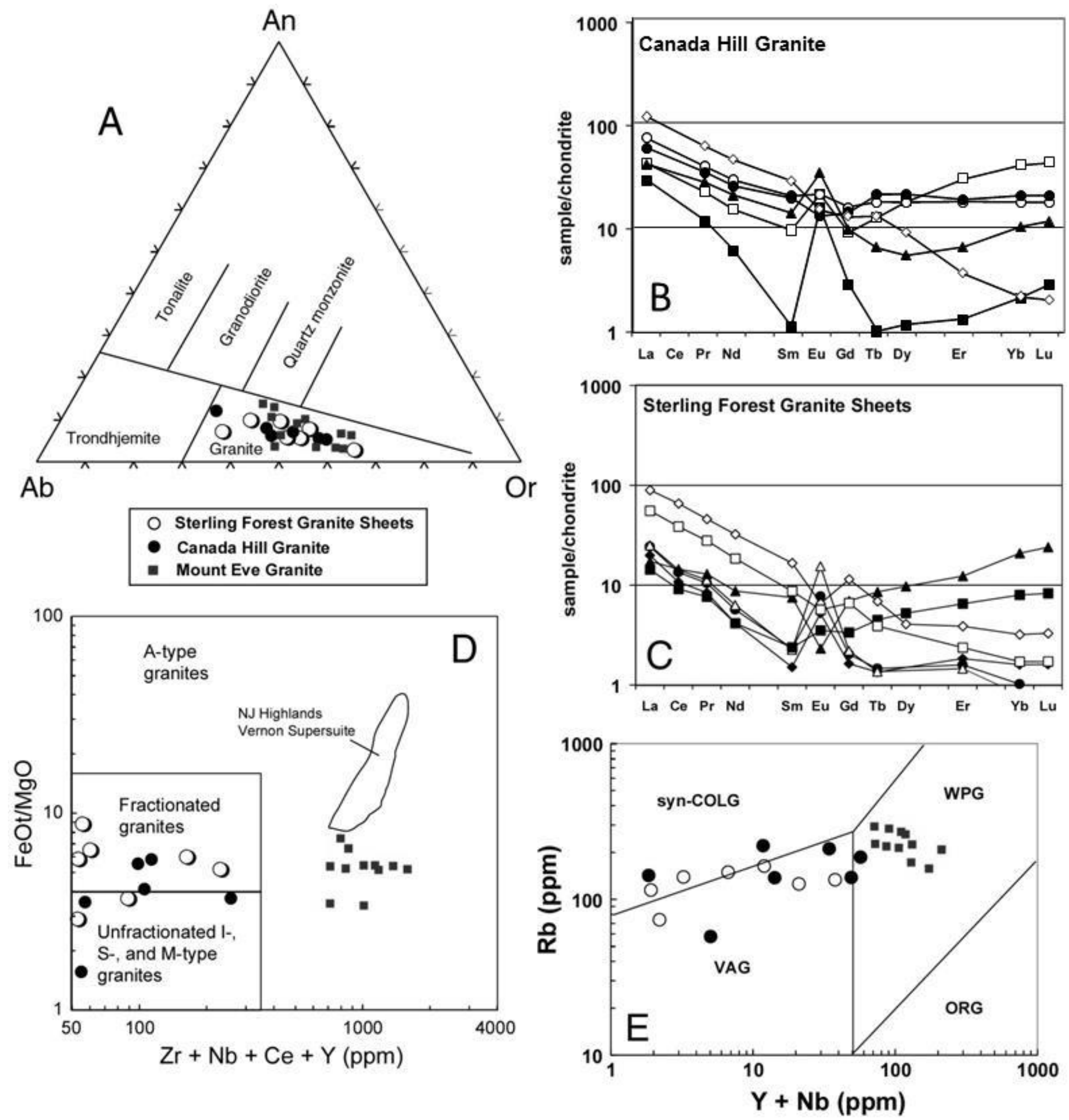

Figure 5. Geochemical plots for Sterling Forest granite sheets, the Canada Hill Granite, and the Mount Eve Granite for comparison. (A) Normative Ab-An-Or classification diagram. REE plots for (B) Canada Hill Granite and (C) Sterling Forest Granite Sheets. (D) and (E) are tectonic discrimination diagram; VAG = volcanic arc; syn-COLG = syn-collisional; WPG = within-plate; and ORG = ocean ridge granitoids.

with only local development of a weak foliation. The orientation of the sheets and pods of Canada Hill Granite parallel the foliation in the surrounding gneisses and contacts are generally gradational and migmatitic, except locally where the granite clearly truncates enclosing gneissic foliation.

Recent U-Pb SHRIMP zircon age dating by Aleinikoff et.al. (2012) indicate a crystallization age of 1058 ±14 Ma from one sample collected from roadcut exposures on NY Rte 9W located ~5 km north of Bear Mountain. The Canada Hill Granite has long been interpreted as a late, syn-metamorphic (anatectic) granite derived from partial melting of the surrounding metapelitic layers within the Metasedimentary Lithofacies (Lowe, 1950; Helenek and Mose, 1984; Ratcliffe, 1992). The intimate association of Canada

Hill Granite and the migmatites on a regional scale and the similarity of leucosome compositions and U-Pb zircon ages in migmatites with the Canada Hill support a petrogenetic link between them. The Canada Hill Granite is a high SiO_2 (71 to 75 wt%), very low FeO_T (generally <1 wt%), strongly peraluminous (ASI > 1.4) and have highly variable K_2O/Na_2O (0.3 to 3.3) reflecting variability in the modal abundance of K-feldspar or Na-plagioclase as the dominant feldspar (Appendix Table 2). REE patterns and other trace element systematics are striking similar to Sterling Forest granite sheets indicating a common petrogenetic origin for both suites (Fig. 5B). These major-element and trace element characteristics, along with a high initial $^{87}Sr/^{86}Sr$ ratio of 0.7186±0.0017 reported by Helenek and Mose (1984), provides strong support for partial melting of metapelitic sources to form the Canada Hill Granite (e.g., S-type granitoid).

<u>Lake Tiorati Diorite (post-Ottawan; ~1010 Ma)</u>

The Lake Tiorati Diorite is a coarse- to very coarse-grained black and white speckled rock composed of sodic-plagioclase, pyroxene (both clinopyroxene and orthopyroxene), hornblende, and biotite locally. The type locality and location of the largest body (~0.5 km wide and ~5 km long) is along the western shores of Lake Tiorati in the central part of Harriman State Park within the Popolopen Lake quadrangle (Fig. 3) and was originally described by Lowe (1950) and mapped by Dodd (1965) as a coarse grained amphibolite ("Amphibolite II"). A few smaller, lens-shaped bodies occur a few kilometers to the southwest in the northeast corner of the Sloatsburg quadrangle recently mapped by Valentino et al. (2001). The diorite grades to lower pyroxene, gabbroic anorthosite compositions locally. Texture ranges from granoblastic to foliated and mylonitic with S-C fabric and rotated porphyroclasts. The diorite also locally contains xenoliths of mostly mestasedimentary lithofacies rocks. SHRIMP U-Pb zircon dating of small, subhedral zircons with minimal zoning obtained from undeformed diorite from the type locality (Stop #2) yielded a cluster of concordant ages averaging 1008 ±4 Ma (Fig. 6). This is interpreted to be the crystallization age of the Lake Tiroati Diorite.

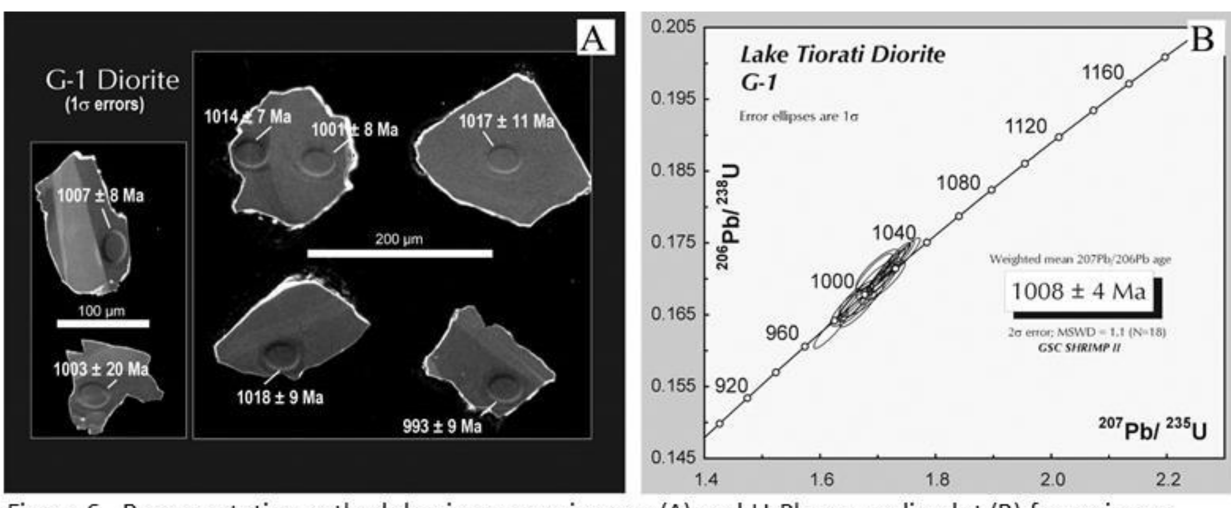

Figure 6. Representative cathodoluminescence images (A) and U-Pb concordia plot (B) from zircons extracted from the Lake Tiorati Diorite from Stop 2 analyzed using the SHRIMP II instrument at the Geological Survey of Canada (Gates et al., 2004).

Major element chemistry of coarse-grained, relatively undeformed samples of the Lake Tiorati Diorite indicate they are uniformly mafic plutonic rocks that have moderate to strong calc-alkaline geochemical signatures (Table 1; Fig. 7A). REE patterns of most samples are weak to moderately LREE-enriched

(La/Yb_N = 1.5 to 5) and slightly concave upward or "dished", MREE-depleted patterns with little to no HREE-depletion (Fig. 7B). They also have variable negative Eu anomalies (Eu/Eu* = 0.6 to 1.0). The mafic, calc-alkaline composition, relative strong negative Eu anomalies and slight MREE depletions in some samples suggests that significant plagioclase ± hornblende crystallization was important in the petrogenesis of these rocks before final emplacement. The lack of strong HREE and Y depletions relative to other trace elements indicates mantle melting occurred at relatively shallow depths above the garnet stability field (e.g. <65 km). All samples have very strong HFSE depletions and on plot well within volcanic arc fields on tectonic discrimination diagrams characteristic of calc-alkaline rocks associated with subduction zones (Figs. 7C). We interpret the arc signature in these rocks to have been inherited from lithospheric mantle sources that had been metasomatized by prior subduction events and/or

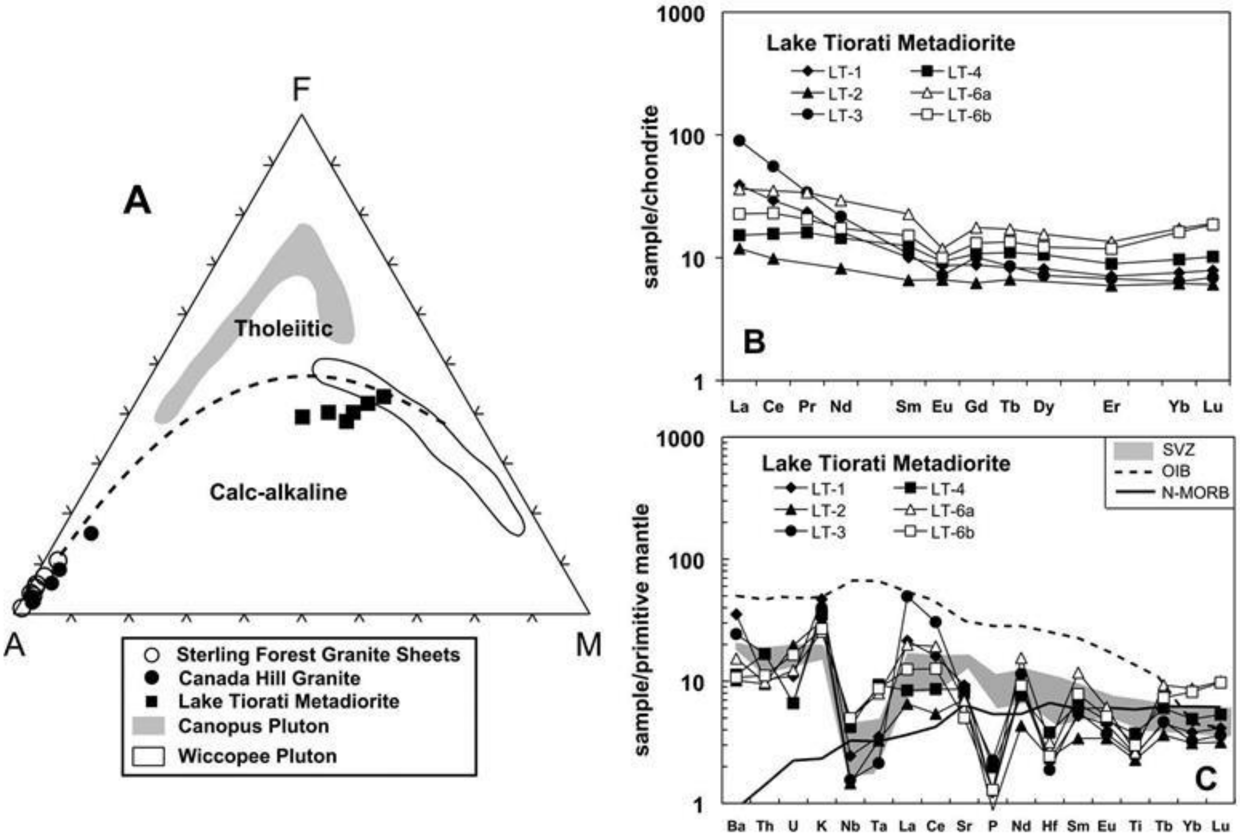

Figure 7. (A) AFM diagram showing the calc-alkaline affinity of the Lake Tiorati Metadiorite in comparison with other Mesoproterozoic mafic plutonic rocks (Canopus and Wiccopee Plutons) from the eastern Hudson Highlands (Ratcliffe, 1992). (B) REE patterns and (C) multi-element diagrams showing the strong volcanic arc chemical signature (LREE-enriched, HFSE-depleted) of the Lake Tiorati Metadiorite. OIB is average oceanic island basalt; N-MORB is average normal mid-ocean ridge basalt; and SVZ is field for Quaternary mafic lavas from the Andean Southern Volcanic Zone (Hickey et al., 1986; López-Escobar et al., 1993). OIB, N-MORB, and normalizing factors are from Sun and McDonough (1989) and Masuda et al., (1973).

extensive crustal contamination during emplacement in the crust.

<u>Late Pegmatite Dikes (post-Ottawan)</u>

The late pegmatitic dikes are pink, and very coarse grained with K-spar, quartz, and locally muscovite, hornblende, magnetite, pyroxene, titanite, and/or garnet depending upon the rock intruded. They are highly discordant, commonly within brittle faults, and contain xenoliths of fault rocks. They exhibit no deformational fabric. Thickness ranges from 1m to 10m. They are locally associated with small granite bodies. Dodd (1965), Offield (1967), Jaffe and Jaffe (1973), Ratcliffe (1992), and Volkert et al. (2005) have also described similar late, cross-cutting granite pegmatites throughout the New Jersey and Hudson Highlands. Existing radiometric age dates for these late pegmatite dikes include a hornblende $^{40}Ar/^{39}Ar$ ages of 923 ± 2.8 Ma reported by Gates and Krol (1998), and conventional TIMS U-Pb zircon ages of 965 ±10 Ma by Grauch and Aleinikoff (1985) and 986 ±4 Ma and 1004 ±3 Ma by Volkert et al. (2005). Based on limited geochemical information, Volkert et al. (2005) reported that NJ Highlands late pegmatite dikes are dominantly metaluminous, have fractionated A-type geochemical affinities, and share characteristics of the niobium–yttrium–fluorine (NYF) class of pegmatites of Cerny (1992). Based on the available geochronology and field relations, these late pegmatite dikes are interpreted to have been emplaced during a period of postorogenic extension that significantly postdates the gravitational collapse of the Ottawan Orogeny and the late- to post-Ottawan, high-grade, ductile transpressional events (e.g. Indian Hill Shear Zone).

IMPLICATIONS FOR GRENVILLE TECTONICS

The pre-Ottawan history of the western Hudson Highlands spans a ~200 Ma period of the Mesoproterozoic between ~1350 to ~1160 Ma that is strikingly similar to many events recorded in the Canadian Grenville Province, the Adirondacks, and the northern Appalachians. Important tectonomagmatic events include: (1) continental margin arc magmatism (metavolcanic unit; ~1350-1250 Ma); (2) backarc magmatism and sedimentation (metasedimentary unit; ~1300-1230 Ma) , and (3) post-orogenic lithospheric thinning and asthenospheric upwelling (quartzofeldspathic unit, ~1230-1160 Ma). The first two events correspond to the Elzevirian Orogeny in the Grenville Province which is interpreted to have been an Andean-type, continental arc-back arc system with northwestward-dipping subduction that existed along the entire eastern margin of the Laurentia between ~1400 to 1200 Ma (McLelland et al., 1996; Rivers, 1997) (Fig. 8A). The third event corresponds to post-Elzevirian magmatic processes that occurred in other parts of the Grenville Orogen between ~1210-1155 Ma that produced similar A-type metaplutonic rocks by mechanisms that involve crustal melting caused by post-orogenic lithospheric thinning and asthenospheric upwelling (Fig 8B).

One of the principal tectonomagmatic events in the Grenville orogen during the late Mesoproterozoic was the Ottawan Orogeny (~1090–1030 Ma; e.g., McLelland et al., 1996; 2001). The Ottawan Orogeny is thought to have been a Himalayan-style continental collision event with associated crustal thickening, high-grade metamorphism, ductile nappe-style folding in the southeast (e.g., in the Central Granulite Terrane, Adirondack Highlands, and Appalachian massifs) and brittle northwest-directed thrusting farther west (e.g., Grenville Front Tectonic Zone and Central Metasedimentary Belt) in the orogen. This collisional event is thought to be related to the acrretion of various continental masses to form the supercontinent Rodinia (Hoffman, 1988; Dalziel, 1991; Borg and DePaolo, 1994). Although the timing of peak Ottawan orogenesis varies spatially, this event severely affected most rocks older than ~1060 Ma throughout much of the Grenville orogen (e.g., McLelland et al., 1996, 2001; Aleinikoff et al., 2000). Partial melting and migmatization of a variety of source rocks (e.g. metapelites and mafic/intermediate rocks) due to crustal thickening during peak Ottawan metamorphic conditions could explain the petrogenesis of the S-type Canada Hill granite and I-type Sterling Forest granite sheets (Figs. 5 and 8C). These magmatic events would be approximately coeval with events in the Adirondacks that produced the Lyon Mountain granite gneiss at ~1060 Ma. The age and field relations of the Lake Tiorati Diorite suggests that penetrative deformation assigned to the Ottawan Orogeny as classically defined was finished prior to ~1010 Ma in the Hudson Highlands. Supporting evidence for this statement also comes from the undeformed Mount Eve Granite suite which places a lower limit of ~1020 Ma for penetrative Ottawan metamorphism and deformation in the far western portion of the New Jersey/Hudson

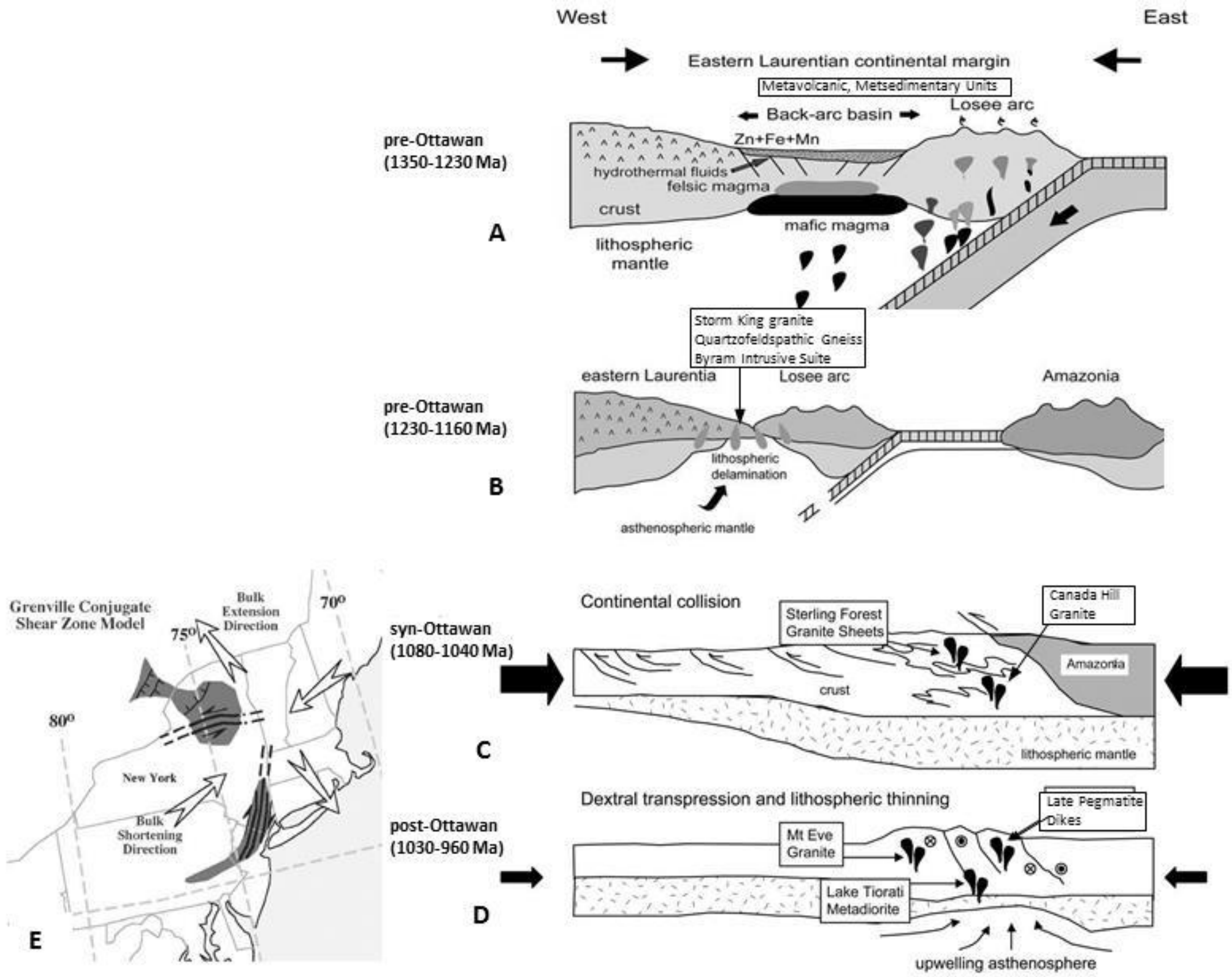

Figure 8. (A – D) Schematic cross-sectional view of model of the pre-Ottawan, syn-Ottawan, and post-Ottawan tectonics in the NJ/Hudson Highlands Diagrams modified from McLelland et al., 1996; Volkert et al., 2010). (E) Regional map view of the NE United States showing the syntaxis tectonic model for the post-Ottawan ductile shearing event that affected the NJ/Hudson Highlands and the Adirondacks (Gates et al., 2004).

Highlands. More recently, Volkert et al (2010) obtained a U-Pb SHRIMP zircon crystallization age of an undeformed granite from the NJ Highlands of 1027 ±6 Ma which pushes the lower limit of Ottawan deformation further back to ~1030 Ma.

The presence of large-scale, vertical strike-slip ductile shear zones that cross-cut rocks of ~1010 Ma indicates that the late- to post-Ottawan history in the Hudson Highlands is characterized by a high-grade, dextral transpressional shearing event that occurred between ~1010 to 925 Ma (Gates et al., 2004) (Fig. 8D). This event likely represents final adjustments of the amalgamated Rodinian supercontintent and/or another accretionary event that must have occurred far to the north of the Hudson Highlands. A collision in the area of the Canadian Appalachians and Scandinavia may have generated tectonic escape (e.g., Tapponnier et al., 1982; Burke and Sengor, 1986) of eastern Laurentia to the south along large dextral strike-slip faults (Fig. 8E). The strike-slip environment could explain the temporal association of the late- to post Ottawan granitoid suite described here (Lake Tiorati Diorite, Late Pegmatite Dikes, Mount Eve Granite). Collectively, these granitioids consist of small, dispersed plutonic bodies that form a volumetrically minor, chemically diverse group. Localized crustal heating due to upwelling asthenosphere associated with localized extension and/or transtension in the overall dextral transpressional regime could explain the small volumes and limited areal extent of these granitoids (Fig. 8D). A similar transpressional tectonic model has been proposed by Speer et al. (1994) to explain the occurrence of small volume, chemically diverse plutonic suites of Alleghenian age in the southern Appalachians. This type of model may explain similar small volume occurrences of late- to post-Ottawan (ca 1030–930 Ma) granitoids elsewhere in the Grenville orogen, particularly in the Adirondacks (e.g., Lyonsdale Bridge and Cathead Mountain pegmatites; McLelland et al., 2001) and the Green Mountain massif (e.g., Stamford Hill rapakivi granite; Ratcliffe et al., 1991). Although additional data is needed, the late pegmatite dikes in the western Hudson Highlands are interpreted to have been emplaced during a period of postorogenic extension that significantly postdates the gravitational collapse of the Ottawan Orogeny and the late- to post-Ottawan, high-grade, ductile transpressional events (e.g. Indian Hill Shear Zone).

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APPENDIX

Table 1: Representative analyses of pre-Ottawan Highland granitoids

Unit	Sterling Forest quartzofeldspathic gneiss					Storm King granite gneiss					
Sample	SF-41	SF-47	SF-48	SF-49	SF-50	SK-1	SK-2	SK-3	SK-6	SK-8	SK-9
SiO_2 (wt%)	72.17	72.60	72.69	72.75	72.29	70.19	71.77	70.77	74.03	72.44	72.83
TiO_2	0.42	0.29	0.31	0.30	0.29	0.35	0.18	0.23	0.22	0.28	0.35
Al_2O_3	13.63	12.32	12.82	12.53	12.78	13.80	12.69	11.60	11.82	11.39	11.76
$Fe_2O_{3\ (T)}$	3.50	3.20	3.54	3.47	3.36	5.06	3.19	4.43	3.61	4.21	4.39
MnO	0.04	0.02	0.04	0.05	0.04	0.05	0.04	0.05	0.04	0.05	0.05
MgO	0.20	0.69	0.23	0.18	0.20	0.11	0.09	0.08	0.09	0.12	0.20
CaO	1.41	0.72	1.29	1.25	1.06	1.69	1.42	1.11	0.96	1.05	1.19
Na_2O	3.53	2.76	2.76	3.21	3.10	3.33	3.27	3.39	3.55	3.41	3.60
K_2O	5.97	5.33	5.69	5.60	5.52	5.61	5.61	5.21	5.36	5.45	5.32
P_2O_5	0.08	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.06
Total	100.96	97.99	99.41	99.38	98.68	100.23	98.30	96.91	99.71	98.43	99.75
La (ppm)	51	68	123	80	67	55	97	208	58	154	84
Ce	108	168	233	168	148	108	201	367	123	283	180
Pr	14.7	23.1	26.5	20.4	18.0	15.6	25.6	43.2	15.0	33.7	21.9
Nd	62	99	98	83	73	66	102	154	57	121	82
Sm	12.9	21.8	17.7	16.8	14.9	15.4	22.3	24.4	11.1	19.3	15.9
Eu	2.93	1.99	2.06	2.18	2.09	2.38	1.07	1.41	1.52	1.50	1.58
Gd	12.1	18.7	16.5	15.9	13.7	8.8	12.4	12.8	6.8	10.5	9.1
Tb	1.88	2.85	2.35	2.47	2.14	1.56	2.34	1.96	1.14	1.50	1.48
Dy	10.3	15.2	12.6	14.0	12.0	12.3	19.5	14.1	8.2	10.4	11.2
Ho	2.03	2.86	2.43	2.85	2.38	2.48	3.87	2.81	1.68	2.17	2.25
Er	4.86	6.45	5.89	6.96	5.85	7.09	11.02	8.56	5.03	6.80	6.70
Tm	0.73	0.92	0.87	1.09	0.91	0.90	1.30	1.06	0.69	0.89	0.86
Yb	4.74	5.51	5.48	7.52	5.99	5.92	8.05	7.29	4.79	6.16	5.95
Lu	0.77	0.80	0.81	1.19	0.92	0.94	1.15	1.14	0.77	1.00	0.96
Sr	134	82	95	88	95	38	25	16	16	17	34
Ba	1189	634	656	772	833	439	147	129	186	174	254
Cs	0.32	0.35	0.34	1.13	1.61	0.61	0.57	0.56	0.51	0.57	0.63
Rb	125	177	214	154	177	115	171	148	130	181	166
U	0.98	1.04	2.62	3.10	1.27	2.97	6.52	4.00	1.63	4.44	3.16
Th	2.3	3.0	54	9.4	3.7	3.1	19	31	3.9	27	9.9
Y	53.6	76.0	70.6	80.1	66.0	69.2	109	78.4	47.1	61.4	62.9
Zr	550	329	344	446	440						
Hf	13.9	9.2	9.7	11.8	11.6	14.6	8.4	13.1	13.5	11.9	12.4
Nb	20.8	18.1	16.9	21.9	18.4	27.1	34.3	36.5	22.0	31.3	34.1
Ta	1.21	0.59	0.58	1.53	1.18	1.27	1.45	1.52	1.12	1.88	1.92
Sc	5.7	7.5	5.7	4.4	3.8		3.4		2.2		0.4
Cr	3.2	2.0	3.0	2.3	3.4	6.0	4.4	5.3	3.7	3.7	3.7
Ni	8.6	4.4	5.1	4.3	5.0						
Co	2.0	3.8	2.4	2.8	2.0	1.3	1.3	1.5	1.3	1.7	2.5
V	9.8	6.2	6.1	5.9	5.7	16.2	16.8	31	5.1	8.7	10.3

Major elements, Sr, Ba, Zr, Y, and Sc by ICP-OES; all other elements by ICP-MS
All analyses carried out at Montclair State University

Table 2: Representative geochemical analyses of syn- and post-Ottawan W. Hudson Highlands granitoids

Unit	Sterling Forest granite sheets					Lake Tiorati Metadiorite						Canada Hill Granite					
Sample	SF-28	SF-29	SF-31	SF-35	SF-36	LT-1	LT-2	LT-3	LT-4	LT-6a	LT-6b	CH-14	CH-16	CH-23	CH-37	CH-40	CH-42
SiO_2 (wt%)	75.57	76.01	74.97	75.25	74.83	50.66	51.02	49.71	50.94	51.78	49.09	71.66	71.18	71.06	74.38	72.62	71.64
TiO_2	0.04	0.03	0.02	0.05	0.10	0.54	0.49	0.53	0.80	0.57	0.64	0.03	0.04	0.06	0.07	0.45	0.03
Al_2O_3	14.18	13.73	13.41	13.55	13.57	15.63	15.34	14.63	18.54	13.74	12.92	15.00	14.23	15.02	15.83	14.29	15.08
$Fe_2O_{3\ (T)}$	0.41	0.51	0.17	0.47	1.18	9.09	8.36	9.34	7.99	10.12	11.48	1.64	0.77	0.38	0.51	2.35	0.17
MnO	0.02				0.02	0.14	0.16	0.15	0.10	0.16	0.18	0.05	0.02	0.00	0.00	0.01	0.00
MgO	0.10	0.07	0.05	0.07	0.20	6.90	7.40	7.91	5.42	8.59	9.90	0.29	0.19	0.26	0.20	0.69	0.06
CaO	1.06	1.32	0.80	0.87	1.39	10.61	12.27	12.41	10.00	11.77	11.86	1.20	0.99	0.47	3.90	1.16	1.64
Na_2O	4.61	3.64	2.73	3.53	3.43	3.66	3.52	3.09	4.38	2.96	2.48	3.37	2.98	1.44	3.06	3.58	4.83
K_2O	3.85	3.94	7.48	5.34	4.89	1.39	0.93	1.19	1.05	0.77	0.80	6.18	6.74	9.73	2.51	4.43	2.76
P_2O_5	0.01	0.01	0.02	0.02	0.02	0.03	0.02	0.05	0.04	0.03	0.03	0.07	0.09	0.09	0.01	0.07	0.07
Total	99.86	99.26	99.65	99.15	99.63	98.65	99.51	99.01	99.26	100.48	99.38	99.49	97.23	98.50	100.47	99.65	96.29
La (ppm)	7.2	7.5	9.2	5.9	35.0	14.7	4.5	34.0	5.8	13.7	8.6	15.6	27.2	15.2	10.5	21.7	43.5
Ce	15.5	10.5	13.2	9.9	67.1	28.6	9.6	54.1	15.3	34.3	22.5	27.2	57.6	28.6	11.3	81.4	114.2
Pr	2.1	1.3	1.6	1.3	7.3	3.5	1.7	5.1	2.4	5.1	3.1	3.3	5.8	4.1	1.7	5.1	9.1
Nd	7.0	3.0	4.1	3.4	24.8	11.6	5.8	15.5	10.3	21.0	12.4	10.7	20.4	14.7	4.3	18.0	32.1
Sm	1.94	0.35	0.54	0.64	4.19	2.31	1.51	2.47	2.87	5.22	3.48	2.18	4.60	3.20	0.26	4.44	6.51
Eu	0.23	0.45	0.67	0.35	0.64	0.75	0.57	0.62	0.81	1.03	0.86	1.82	1.80	2.87	1.33	1.12	1.29
Gd	2.43	0.51	0.63	1.20	3.94	2.72	1.93	3.14	3.35	5.47	4.09	2.80	4.87	3.01	0.89	4.37	3.98
Tb	0.56	0.08	0.09	0.30	0.46	0.49	0.39	0.50	0.65	1.00	0.79	0.74	1.03	0.38	0.06	1.23	0.77
Dy	4.22			2.32	1.82	3.16	3.04	2.79	4.13	6.06	4.75	6.94	6.77	2.15	0.46	8.18	3.50
Ho	1.08	0.06	0.06	0.61	0.36	0.64	0.54	0.60	0.89	1.40	1.19	2.06	1.54	0.49	0.11	1.69	0.51
Er	3.48	0.47	0.41	1.87	1.13	1.80	1.51	1.72	2.28	3.44	3.02	7.49	4.50	1.69	0.34	4.76	0.94
Tm	0.67	0.07	0.05	0.33	0.15	0.27	0.24	0.26	0.42	0.70	0.62	1.40	0.70	0.34	0.07	0.77	0.11
Yb	5.66	0.40	0.25	2.22	0.92	1.88	1.53	1.59	2.41	4.30	4.03	9.98	4.33	2.57	0.53	5.07	0.55
Lu	1.00	0.06	0.03	0.36	0.15	0.30	0.23	0.27	0.39	0.74	0.72	1.63	0.67	0.45	0.11	0.79	0.08
Sr	21	53	74	30	60	195	150	158	181	147	106	168	161	195	177	176	178
Ba	22	113	334	97	224	247	71	170	79	107	75	626	638	488	145	377	366
Cs	0.15	0.20	0.71	0.38	0.36	0.17	0.15	0.22	0.09	0.04							
Rb	133	74	139	125	163	27.5	10.6	22.6	13.9	8.8	8.0	175	191	220	63	161	77
U	4.88	0.96	0.67	2.45	6.42	0.23	0.41	0.14	0.14	0.26	0.35	1.57	4.06	1.73	1.87	11.9	3.42
Th	3.12	1.06	2.20	7.99	30.3	0.88	0.81	1.42	1.42	0.83	0.95	4.5	11.7	7.0	0.3	19.0	21.4
Y	33.7	1.6	3.0	20.6	11.6	18.2	14.4	16.5	24	40.2	34.7	62.5	47.7	15.0	3.3	53.9	14.0
Zr	22	50	19		134	29	22	25	43	40	28	24.1	77.1	3.7	134.7	130.1	38.2
Hf	0.29	1.72	0.19	1.14	3.67	0.69	0.73	0.58	1.17	0.98	0.75	0.94	2.76	0.26	5.48	4.32	1.35
Nb	15.1	0.6	0.2	0.5	0.4	1.7	1.0	1.1	3.0	3.5	3.5		1.3		1.3	30.8	
Ta	0.98	0.19	0.06	0.01	0.01	0.14	0.13	0.09	0.38	0.33	0.36	0.04	0.17	0.07	0.18	1.29	0.05
Sc	3.6	0.4	2.2	5.4	1.9	45.0	50.6	51.7	32.1	52.4	53.6						
Cr	1.8	1.9	2.1	2.2	3.2	41	91	135	198	137	133	1.8	3.1	1.6	8.4	16.5	5.8
Ni	4.4	2.5	2.2	1.4	2.3	56	65	160	64	73	99		5.8		7.3	0.8	0.1
Co	1.4	1.2	0.4	0.8	1.2	34	36	49	31	40	50	1.7	1.6	2.2	1.8	5.9	1.6
V	5.3	7.5	5.2	5.1	9.4	136		220	271	190	208	4.2	25.6	4.7	12.9	26.6	8.1

Major elements, Sr, Ba, Zr, Y, and Sc by ICP-OES at Montclair State University; all other elements by ICP-MS at Montclair State University

FIELD GUIDE AND ROAD LOG

Meeting Point: Lobby parking lot of DoubleTree by Hilton Hotel Nanuet. Turn right off of NYS 59 eastbound onto Rose Rd and then quick right into parking lot.

Meeting Point Coordinates: 41° 5'24.84"N, 73°59'43.90"W; address = 425 State Route 59; Nanuet, New York 10954

Meeting Time: 8:00 AM

Distance in miles (km)

Cumu-lative	Point to Point	Route Description
0.0 (0.0)	0.0 (0.0)	Assemble in the lobby parking lot of DoubleTree by Hilton Hotel Nanuet. Leave parking lot and turn left onto Rose Rd. and immediately right onto NY-59 and proceed east.
0.5 (0.8)	0.5 (0.8)	Use the right lane to the ramp for Palisades Interstate Pkwy North and then merge and proceed north the Palisades Interstate Pkwy.
17.1 (27.4)	16.6 (26.6)	Use the right lane to the ramp for Palisades Interstate Pkwy North and then merge onto Palisades Interstate Pkwy North.
17.4 (27.8)	0.3 (0.5)	Bear slightly right at Exit 18 continue northeastward on US-6 East/ Palisades Interstate Pkwy North and then take Exit 19 Sevens Lakes Drive and merge onto Seven Lakes Drive.
17.9 (28.6)	0.5 (0.8)	Proceed southeastward on Seven Lakes Drive. At 0.5 miles, turn right at unmarked dirt road and pull into small informal parking lot (Stop 1). If you drive by the AT crossing or intersection of with Perkins Memorial Drive (on left), you have gone too far east and need to turn around and go west 0.25 mi on Seven Lakes Drive.

STOP 1: Bear Mountain, NY

Location Coordinates: (41°18'16.37"N, 74° 0'54.94"W)

The next series of substops will require a moderately strenous hike (~5-6 miles roundtrip; 600 vertical feet of elevation change) mostly along the Appalachian Trail and the Perkins Memorial Drive (paved) to the summit of Bear Mountain. On the way, we will examine very nice exposures of not only the Canada Hill granite and Storm King granite gneiss, but also take the opportunity to look at outcrops of the “rusty” metapelitic gneisses of the Metasedimentary Lithofacies and the quartz-plagioclase-biotite-Opx (“charnockitic”) gneiss of the Metavolcanic Lithofacies. We will examine the field relations between these units and discuss the current U-Pb zircon age constraints and whole-rock geochemical data to understand the petrogenesis and implications for Grenville tectonics in the region. Bring food and water. We will be out all morning and will have lunch at the summit of Bear Mountain.

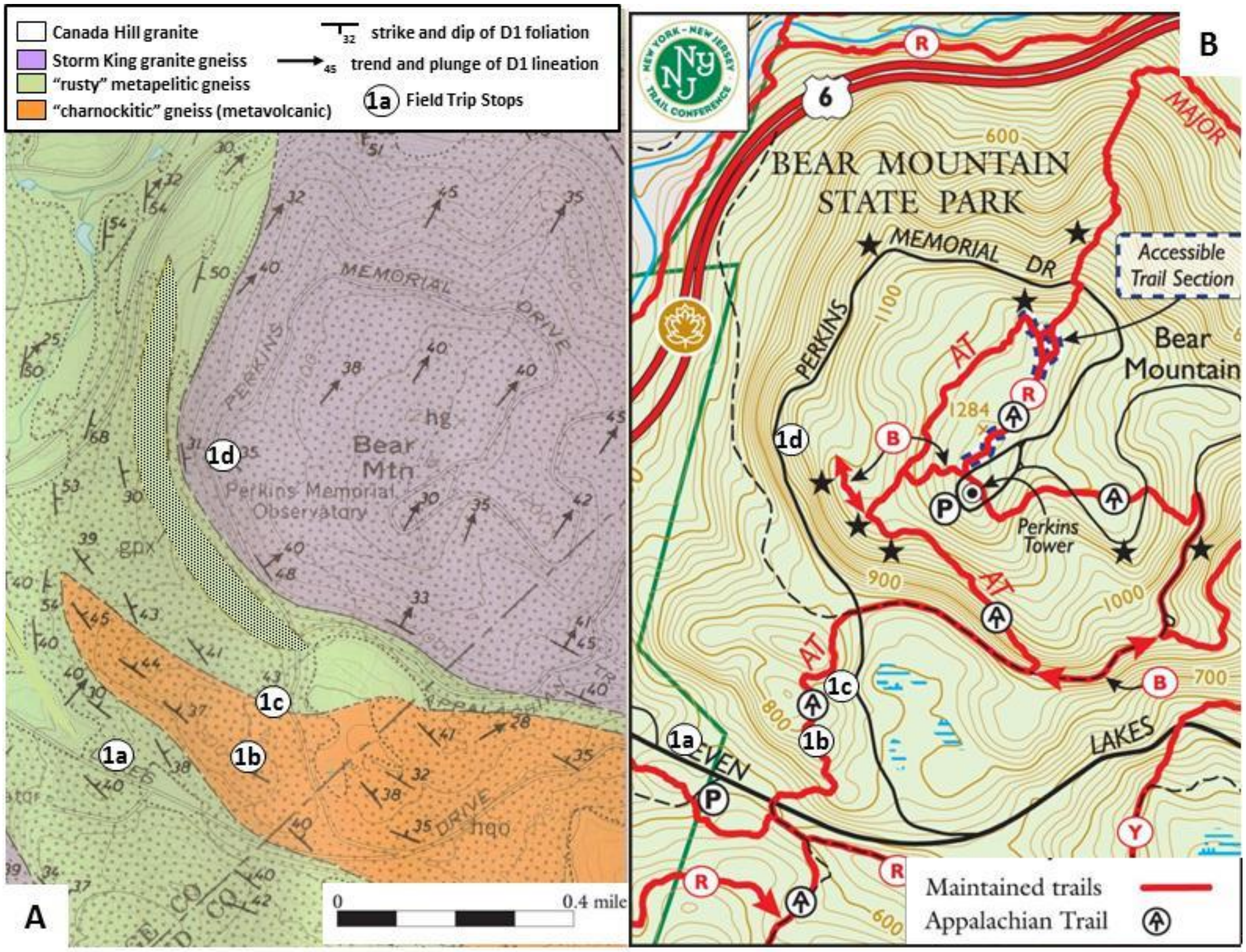

Figure 9. (A) Geologic and (B) topographic map showing the location of Stops 1a-1d at Bear Mountain, NY. Geologic map modified from Dodd (1965).

Stop 1a: The first of several stops during our hike is a very nice roadcut exposure of the "rusty" metapelitic gneiss unit of the Metasedimentary Lithofacies. The distinctive "rusty" weathering of this unit is from the alteration and breakdown of accessory Fe-sulfides (pyrite and/or marcasite?). At this locality, the metapelite has a fairly common assemblage of garnet-biotite-quartz-K-feldspar ± plagioclase ± sillimanite and has a strong foliation that is moderately NE-dipping. Metamorphism is of hornblende granulite facies and maximum P-T estimates are on the order of 700-750ºC and 4±1 kilobar based on mineral assemblages in metapelitic and mafic metavolcanic units (Dallmeyer and Dodd, 1971). Deformation and metamorphism associated with this event is most likely of Ottawan age.

Stop 1b: On the southwest flanks of Bear Mountain along the Appalachian Trail there are a series of excellent natural outcrops of the quartz-plagioclase-biotite-Opx ("charnockitic") gneiss of the Metavolcanic Lithofacies with a strong foliation that is moderately NE-dipping. We will make a quick stop to examine one of these outcrops. These rocks are significant because they presumably the oldest rocks in Hudson Highlands. Based on a U-Pb SHRIMP zircon core ages ranging from ~1360-1250 Ma (Volkert et al., 2010) on the correlative Losee Metamorphic Suite rocks in the NJ Highlands and whole-rock geochemical analysis (Volkert and Drake, 1999; Gorring et al., 2001; Volkert et al. 2004) these rocks represent a calc-alkaline, continental arc suite related to subduction off the eastern margin of Laurentia during the Elzevirian Orogeny.

Stop 1c: At this locality, there is a spectacular, glacially plucked outcrop of the distinctively blue-gray to white, leucocratic Canada Hill granite that is commonly found in the Bear Mountain area and extending northeastward into the West Point and eastern Hudson Highlands region. The Canada Hill granite at this locality is a coarse- to very coarse-grained equigranular rock composed of quartz, K-feldspar, plagioclase, and biotite ± garnet. It forms a sheet-like body ~15-20 m thick and ~300-400m in length that has concordant contacts with the surrounding metavolcanic "charnockitic" quartz-plagioclase-biotite-Opx and "rusty" metapelitic gneisses (Fig. 10). Foliation in the surrounding gneisses is moderately NE-dipping (~N45W, 40NE). The contact between the Canada Hill granite and the "charnockitic" gneiss is well exposed for about ~100m along strike where small rafts and xenoliths of "charnockitic" gneiss are observed within the Canada Hill granite. Similar crosscutting relations have been documented elsewhere in the Hudson Highlands. For example, Helenek and Mose (1984) and Ratcliffe (1992) observed the Canada Hill granite cutting gneissic fabric elements within the Storm King granite gneiss, metapelitic, and metavolcanic rocks in the Popolopen Lake and Oscawana Lake quadrangles to the south and east. In the Bear Mountain area, Helenek and Mose (1984) found xenoliths of Storm King granite gneiss enclosed in Canada Hill granite along the southern margin of the Brooks Lake Pluton. Helenek and Mose (1984) also noted a weak axial planar foliation and the location of Canada Hill granite in the hinges of large-scale, broad, open, upright, plunging folds (e.g., Bear Mountain synform) and interpreted this to indicate that the Canada Hill Granite was syntectonic to and slightly deformed during a late-stage Grenville orogenic event. Based on a recent U-Pb SHRIMP zircon core age of 1058 ±14 Ma (Aleinikoff et.al., 2012) and whole-rock geochemical analysis (Kulick and Gorring, 2004), the Canada Hill Granite represents a syn-tectonic, S-type granitoid produced by partial melting of metapelitic gneisses and emplaced during the Ottawan Orogeny (Fig. 5 and 8C).

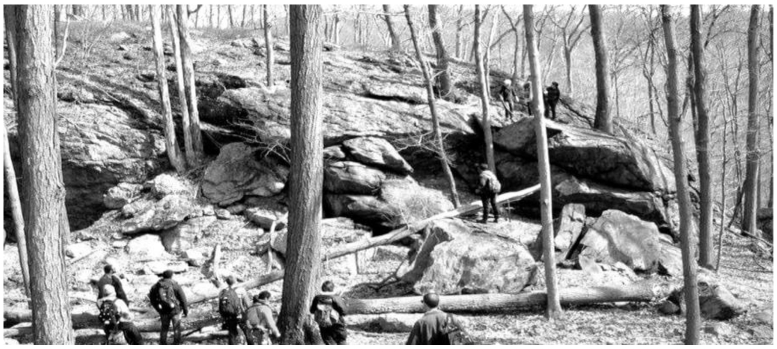

Figure 10. Canada Hill granite outcrop at Stop 1c

Stop 1d: Roadcuts along Perking Memorial Drive on the southwest side of Bear Mountain expose excellent examples of the Storm King granite gneiss. Here, the Storm King is a coarse-grained, quartz-K-feldspar-plagioclase-hornblende gneiss that is strongly lineated (L>S) rock (Fig. 11). The fabric is defined by stretched hornblende prisms and rodded quartz-feldspar aggregates interspersed with large (2-4 cm) plagioclase and/or K-feldspar augen. Based on U-Pb SHRIMP zircon age of 1174 ±8 Ma (Ratcliffe and Aleinikoff, 2001) and whole-rock geochemical analysis (Verrengia and Gorring, 2002), the Storm King granite gneiss is interpreted to represent a pre-Ottawan., A-type granitoid produced by partial melting of intermediate igneous source rocks during an early

Figure 11. Lineated Storm King granite gneiss outcrop at Stop 1d

stage of AMCG-related lithospheric thinning that affected this part of the Grenville Orogen (Fig. 4A, C and Fig 8B).

Distance in miles (km)

Cumu-lative	Point to Point	Route Description
17.9 (28.6)	0.0 (0.0)	Leave informal parking lot and immediately turn left onto Seven Lakes Drive and proceed northwest.
18.4 (29.4)	0.5 (0.8)	Keep left and follow signs for Seven Lakes Drive and merge onto US-6 West.
18.8 (30.1)	0.4 (0.6)	Use the right 2 lanes to take Exit 18 for US-6 toward NY17/I-87/Central Valley/Seven Lakes Drive.
19.1 (30.6)	0.3 (0.5)	At the traffic circle, stay in right lane and take the 2nd exit (right) onto Seven Lakes Drive.
23.4 (37.4)	3.7 (5.9)	Proceed southwest on Seven Lakes Drive.
23.5 (37.6)	0.1 (0.2)	At the Lake Tiorati circle, take first exit (right) onto Arden Road and then an immediate left into the public park/picnic area (Stop 2). This stop requires an additional ~1 km walk south on Seven Lakes Drive to the first set of low road cuts on the west side of the road.

STOP 2: Lake Tiorati, NY

Location Coordinates: (41°16'31.34"N, 74° 5'18.73"W)

We will examine the field relations and chemistry of a sheared mafic granitoid, referred to as the Lake Tiorati Diorite at its type locality near the eastern margin of the Fingerboard Mountain Shear Zone (Gates et al., 2001c; 2004). This particular outcrop is part of a relatively large body of Lake Tiorati Diorite that is ~200-300 m thick and is ~5-6 km in length located on the west side of Lake Tiorati (Fig. 12A). At the southern end of the outcrop, the rock is essentially undeformed with igneous texture (Fig. 12C). The diorite is composed mostly of plagioclase, hornblende, and clinopyroxene with minor orthopyroxene, magnetite and ilmenite. The orthopyroxene occurs as brown cores surrounded by coronas of clinopyroxene and/or hornblende. There is also a large xenolith of well-foliated biotite-plagioclase-quartz (metasedimentary) gneiss in the upper part of the outcrop. In the central and northern parts of the exposure, the diorite is cut by several anastomosing mylonite bands (Fig. 12 B). The mylonite here is part of the Fingerboard Mountain Shear Zone which is one of several late- to- post-Ottawan ductile shear zones that occur in the western Hudson Highlands (Figs. 3 and 13A) that were mapped and described by Gates et al. (2004); the details of which will be the subject of trip B-3 on Sunday, October 2, 2016, led by Michael Kalczynski and Alexander Gates. U-Pb SHRIMP dating of small, subhedral zircons with minimal zoning from the undeformed diorite from this outcrop yielded a cluster of concordant ages averaging 1008 ±4 Ma (Fig. 6). Since this body is clearly cut by ductile shear zones, this age provides an upper limit on the ductile deformation event that produced the mylonitic fabric. Whole-rock major and trace element chemistry of samples from this outcrop indicate a mafic (~50% SiO_2, see Table 1) calc-alkaline, arc-like affinity for these rocks (Figs. 7A and C). We interpret the arc signature in these rocks to have been inherited from the continental lithosphere during magma generation and emplacement, and thus they do not indicate that there was active subduction zone in

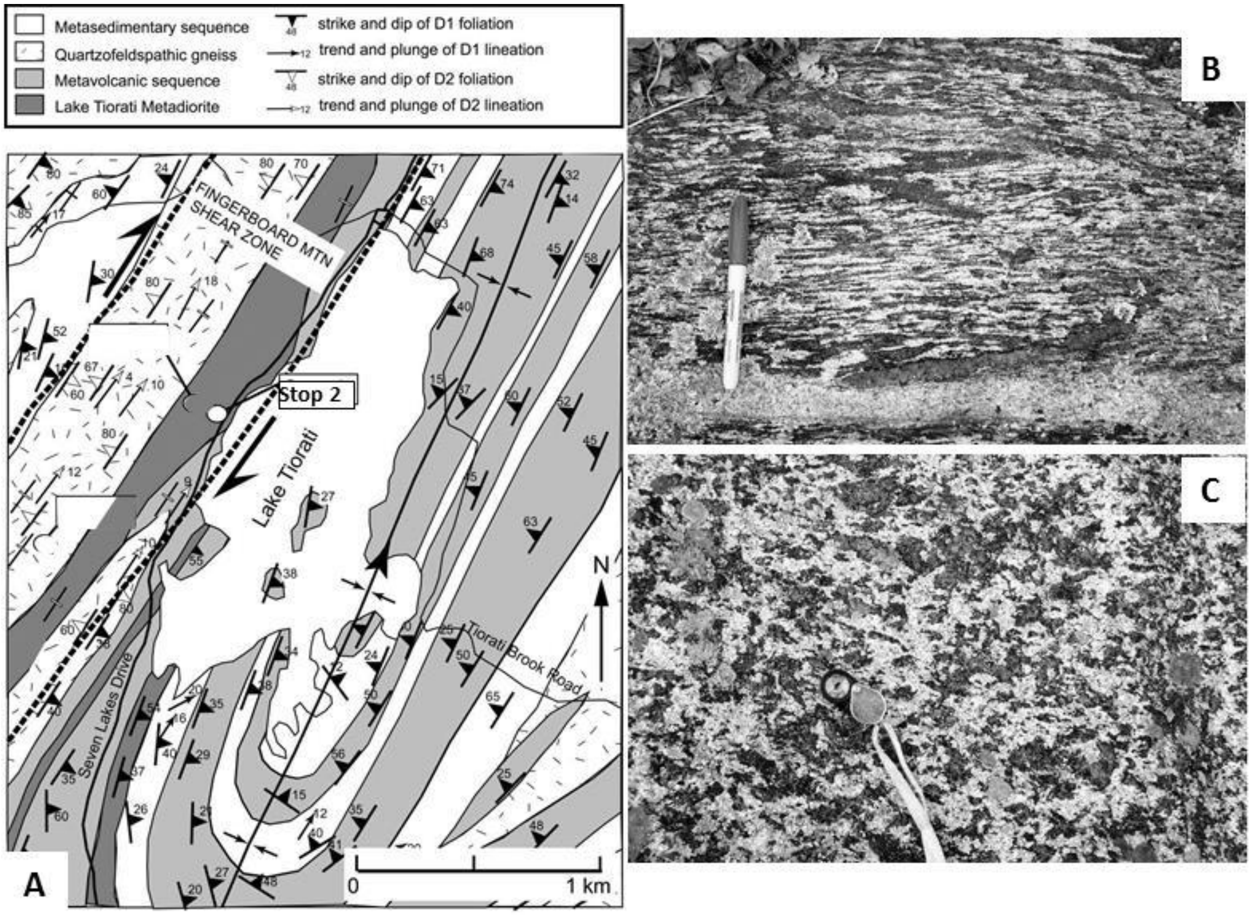

Figure 12. (A) Geologic map (modified from Dodd, 1965) showing the location of Stop 2. (B) Pavement surface of sheared Lake Tiorati Diorite from the summit of Blackrock Mountain ~5 km southeast of Stop 2. Pen is oriented NW-SE. (C) Undeformed diorite from Stop 2; hand lens for scale.

this part of the Grenville at the time. Based on field relations, geochronology, and geochemistry, the Lake Tiorati Diorite is best interpreted as a post-Ottawan mafic plutonic rock that was emplaced just prior to or synchronously with a major ductile shearing event that occurred ~1000 Ma (Fig. 8D).

Distance in miles (km)

Cumu- lative	Point to Point	Route Description

23.5 (37.6) 0.0 (0.0) Leave Lake Tiorati parking lot and immediately turn left onto Arden Road and proceed west.

28.5 (45.6) 5.0 (8.0) Turn left onto NY17 South.

31.4 (50.2) 2.9 (3.2) Bear right to take the NY-17A/CR-106 Exit..

31.6 (50.6) 0.2 (0.3) Turn right onto NY-17A West and proceed westward.

33.0 (52.8) 1.4 (2.2) Turn right onto Clinton Road and immediately park on the right shoulder (Stop 3). This stop requires an additional ~0.5 km walk east on NY-17A to the first set of road cuts that includes rock in the median strip.

STOP

3: Indian Hill Shear Zone, road cuts on NYS 17A

Location Coordinates: (41°14'15.29"N, 74°12'6.32"W)

Road cuts on north side and in median of NY Rte 17A afford an excellent view of a post-Ottawan pegmatitic granite dike that cuts mylonitc quartzfeldspathic gneiss (correlative to Storm King granite gneiss). The mylonite here is part of the Indian Hill Shear Zone which is one of several late- to- post-Ottawan ductile shear zones that occur in the western Hudson Highlands (Fig. 3 and 13A) that were mapped and described by Gates et al. (2004) and the details of which will be the subject of trip B-3 on Sunday, October 2, 2016, led by Michael Kalczynski and Alexander Gates. The pegmatitic dike is ~2-3 m thick, vertical dike that is composed of coarse-grained granite with large crystals of hornblende that

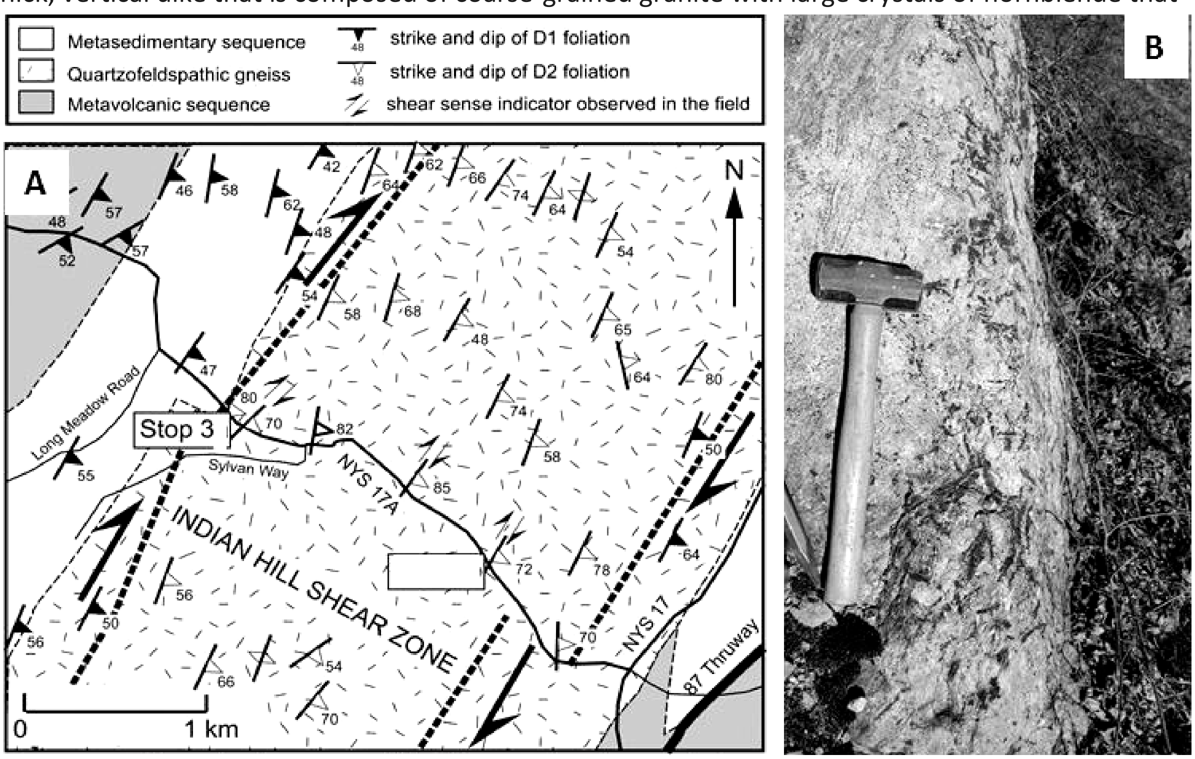

Figure 13. (A) Geologic map modified from Valentino et al., (2001) showing the location of Stop 3. (B) Pavement surface showing sharply discordant contact of pegmatitic granite dike with large sprays of hornblende (right) with mylonitic quartzofeldpathic gneiss (left). Hammer oriented NNW-SSE.

form radiating and linear aggregates. It is exhibits no deformation fabric and cross-cuts the mylonite at a high angle, and thus clearly postdates the ductile deformation of the quarztofeldspathic gneiss (Fig. 13B). Unfortunately, there are no radiometric age constraints or geochemical data for this particularly pegmatite dike, but field relations, texture, and mineralogy of this dike are very similar to pegmatitic granite dikes from the NJ Highlands (Volkert at al., 2005) and elsewhere in the Hudson Highlands (Grauch and Aleinikoff, 1985) that have U-Pb zircon ages in the range of ~1000 to ~960 Ma. Volkert et al. (2005) reported that NJ Highlands pegmatites are dominantly metaluminous, have fractionated A-type geochemical affinities, and share characteristics of the niobium–yttrium–fluorine (NYF) class of pegmatites of Cerny (1992). These late pegmatite dikes are interpreted to have been emplaced during a period of postorogenic extension that significantly postdates the gravitational collapse of the Ottawan Orogeny and the late- to post-Ottawan, high-grade, ductile transpressional events (Fig. 8D).

Distance in miles (km)

Cumu-lative	Point to Point	Route Description
33.0 (52.8)	0.0 (0.0)	Turn around on Clinton Road and immediately cross over NY-17A and proceed south on Long Meadow Road (CR-84).
36.6 (58.6)	3.6 (5.8)	Noticeable pink granite outcrop on the right (west) side of road (Stop 4). Park on the other side (east) of road where there is more gravel shoulder. If you come to Old Forge Road, you have gone past the locality by ~200m.

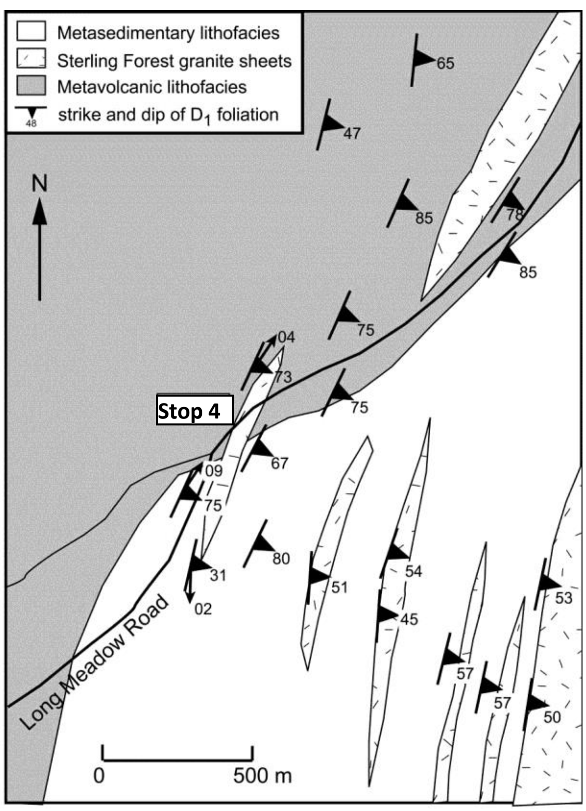

Figure 14. Geologic map showing the location of Stop 4.

STOP 4: Sterling Forest Granite Sheets, road cuts on Long Meadow Road (CR 84)

Location Coordinates: (41°12'9.28"N, 74°14'52.67"W)

This roadcut along northwest side of Long Meadow Road exposes a fine example of the syn-Ottawan Sterling Forest granite sheets found in the western Hudson Highlands (Fig. 14). These pink granite sheets are very leucrocratic (~75 wt% SiO_2) (Appendix Table 2), composed of almost entirely quartz, K-feldspar, and plagioclase, with only small amounts (<5%) of hornblende ± biotite with accessory apatite, titanite, and zircon. At this locality, the sheet has a medium-grained, equigranular igneous texture and shows no evidence of deformational fabric. However, locally these granite sheets are foliated where intersected by late-stage, ductile shear zones and thus, are clearly pre- or syntectonic with the shearing event. This particular sheet is one of several, 10-100 m thick, finger-like bodies that extend both southward and northward several kilometers from the main plutonic masses at Hogback Mountain (to the north) and Bill White Mountain (to the south). Here, the sheet is about 20 m thick, strikes N20E and dips ~65° to the southeast and has intruded parallel to foliation in the surrounding gneisses. It intrudes amphibolites and intermediate gneisses of the metavolcanic unit (contact observed at the north end of the outcrop) and metapelitic gneisses of the metasedimentary lithofacies. The granite sheet exposed here (sample SF-28) has a distinctly "dished" MREE pattern, a moderately strong negative Eu anomaly (Eu/Eu* = 0.35), high HREE contents (~20x chondritic) and very low Ba and Sr concentrations (~20 ppm) (Fig. 5C and Appendix Table 2). These chemical characteristics indicate that amphiboles and feldspars were important phases in the petrogenesis of this particular granite. The data is consistent with partial melting of garnet-free, mafic amphibolitic source rocks and/or fractional crystallization of amphibole + plagioclase ± K-feldspar at shallower crustal levels. The Sterling Forest granite sheets represents a syn-tectonic, I-type granitoid produced by partial melting of mafic/intermediate igneous sources and were emplaced during the Ottawan Orogeny (Fig. 5 and 8C).

Distance in miles (km)

Cumu-lative	Point to Point	Route Description
36.6 (58.6)	0.0 (0.0)	Proceed southwest (turn around, if necessary) on Long Meadow Road (CR-84).
40.9 (65.4)	4.3 (6.9)	Turn left on Sterling Mine Road.
43.6 (69.8)	2.7 (4.3)	Use the right lane to take the ramp for NY-17 South, then merge onto NY-17 South and proceed southeast.
45.0 (72.0)	1.4 (2.2)	Use the right lane to take the ramp for NY-17 S/I-87 S/New York Thruway ramp to I-287, then merge onto I-87 South/NY-17 South and proceed south..
53.0 (84.8)	8.0 (12.8)	Keep left to continue on I-87 South.
54.9 (87.8)	1.9 (3.0)	Take Exit 14 for NY-59 toward Spring Valley/Nanuet. Use the left 2 lanes to turn left onto NY-59 and proceed southeast on NY-59.
54.9 (87.8)	0.1 (0.2)	Turn right onto Rose Road and then immediate right into parking lot of DoubleTree by Hilton Hotel Nanuet. (End of trip)

TRIP A5: STRATIGRAPHY, STRUCTURE, AND TECTONICS OF NEW YORK CITY AS VIEWED THROUGH ITS PARKS

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INTRODUCTION

Geological Setting

NYC is situated at the extreme southern end of the Manhattan Prong (Figure 1), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward into the crystalline terrains of New England. Southward from NYC, the rocks of the Manhattan Prong plunge nonconformably beneath predominately buried Mesozoic rocks, younger Cretaceous strata, and the overlying Pleistocene drift found capping much of the region including all of Long Island and much of Staten Island. This NYSGA paper and allied Trip A-5 field guide are intended to prepare and expose participants to our subdivisions of the venerable Manhattan Schist into three separable units by utilizing exposures in NYC parks including Isham, Inwood Hill and Central parks.

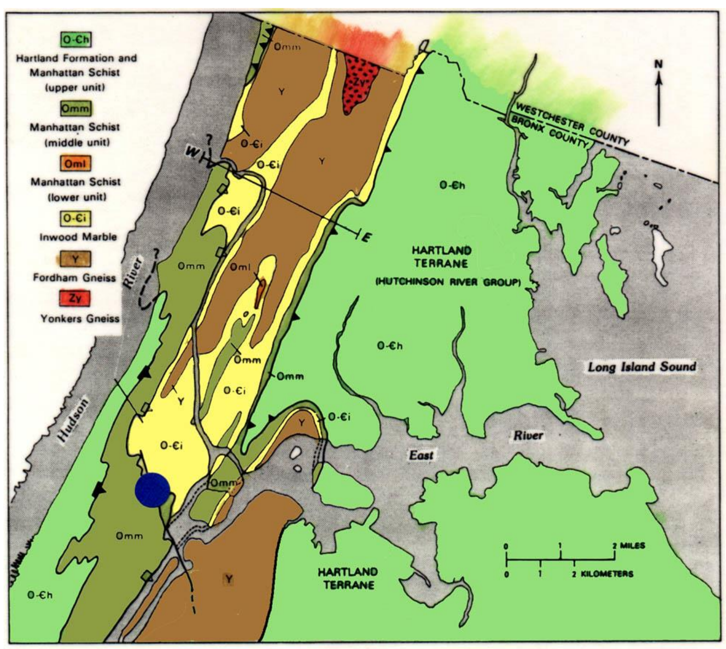

Figure 1 – Geological map of New York City showing the generalized structural geology of the region using older terminology of upper, middle, and lower units of the Manhattan Schist of Merguerian and Baskerville (1987) and Merguerian and Merguerian (2004). Triangles show the dip of Cameron's Line (solid) and the St. Nicholas thrust (open) and the flagged triangles indicate overturned thrusts. Most faults and intrusive rocks have been omitted. Blue dot is epicenter of 21 January 2001 magnitude 2.4 earthquake that occurred along Manhattanville fault.

Previous Investigations

A detailed history of NYC bedrock investigations appears elsewhere (Merguerian and Sanders 1991) so the following is simply a brief excerpt and overview. In 1890 (p. 390), Merrill named the Manhattan Schist for the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of Professors W. W. Mather (1843) and J. D. Dana (1880), that they represent metamorphosed equivalents of the lower Paleozoic strata of southern Dutchess County, New York. Merrill (1890) confides that "the name Manhattan Group was proposed by naturalist R. P. Stevens, Esq., to include the rocks of New York Island".

Despite this acknowledgement, Merrill and others (1902) produced the United States Geological Survey New York City Folio (#83) and following Dana chose to use the name Hudson Schist (rather than Manhattan Schist) for the schistose rocks of NYC. This pioneering work by Merrill and coworkers set the stage for a series of detailed investigations by many geologists in the 1900's that helped define the details of NYC bedrock units and use of the term Manhattan Schist as the name locality for the unit. Merrill also extended "Group" status to include the Manhattan Schist, the Inwood "limestone" and the Fordham and Yonkers gneisses and correctly correlated the Fordham with Proterozoic sequences of the Hudson Highlands. Formal removal of the significantly older Fordham and Yonkers gneisses from the "Manhattan Group" had to await the refinement and application of radiometric dating techniques and detailed mapping in the 1960's by Leo M. Hall (1968a; b). Formal "de-Grouping" of the "Manhattan Group" took place after spirited debate at a Symposium on the New York City Group of Formations at the 1968 meeting of the New York State Geological Association at Queens College, Queens, New York. Our studies of the metamorphic rocks of NYC since 1972 have benefited from these early works and access to surface and subsurface construction sites.

NYC BEDROCK STRATIGRAPHY

Based on study of over 1,000 natural exposures and a multitude of drill core and construction excavation geotechnical analyses our joint investigations of the bedrock geology of NYC have portrayed a complex structural history and suggests that the Manhattan Schist formation exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three separable map units now known as the **Hartland, Manhattan, and Walloomsac** formations (Figure 1). These subdivisions agree with designations proposed by Hall (1976; 1980) but suggest the presence of a hitherto unrecognized structurally higher unit that is a direct correlative of the Hartland Formation (= Rowe and Ratlum Mountain schists) of western Connecticut (Merguerian 1983a; 1987; 2016). The three schistose units are juxtaposed along imbricate ductile faults known as the St. Nicholas thrust and Cameron's Line (Merguerian 1994; 1996a) as indicated in a simplified cross section across the northern tip of Manhattan into the Bronx (Figure 2).

Keyed to Figure 1, the W-E section of Figure 2 shows the general structure of NYC and how the St. Nicholas thrust and Cameron's Line overthrusts position the Manhattan and Hartland formations above the Walloomsac formation and the underlying Inwood- Fordham cover+basement sequence. Late stage regional F_3 folds produce digitations of the structural- and stratigraphic contacts that dip gently south, downward out of the page toward the viewer. The N-S section illustrates the southward topping of tectonostratigraphic units exposed in central Manhattan and the effects of the yet younger NW-trending asymmetric folds. The structural geology of NYC is detailed in a later section and the proposed new stratigraphic interpretation is diagrammed in Figure 3.

<u>Hartland Formation</u>. The structurally high Hartland formation (OЄh) is dominantly gray-weathering, fine- to coarse-textured, well-layered (cm- and m-scale) muscovite-quartz-biotite-plagioclase-kyanite-garnet-staurolite schist, gneiss, and migmatite with layers of gray quartzose granofels, greenish amphibolite±garnet and scarce coticule. *(Note: Minerals listed in descriptions are in decreasing order of abundance.)* The schistose facies is lustrous and consists of dense, aligned fine- to coarse-textured muscovite and lesser biotite that splits readily along the foliation (Figure 4). The gneiss and granofels lithotypes are massive, commonly more feldspathic, migmatitic and may or may not show pronounced foliation. Gray quartzites are also found as discrete interlayers up to 0.5 m thick. Although typically not exposed at the surface, the Hartland underlies most of the central and southern portions of Manhattan and the eastern half of the Bronx. Because it is lithologically identical to the Cambrian (?) to Ordovician Hartland Formation of western Connecticut and Massachusetts, the Hartland name has been extended into NYC (Merguerian 1983b) where it is considered part of the allochthonous **Taconic Sequence**.

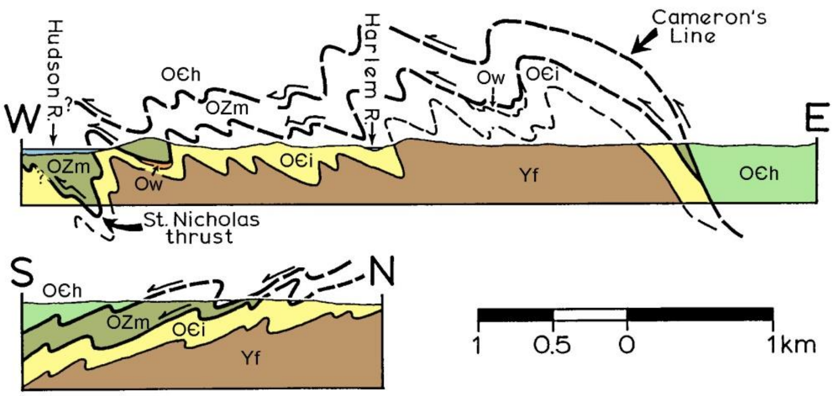

Figure 2 - Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). See Figure 1 for the line of the W-E section. The N-S section runs through the east edge of Central Park.

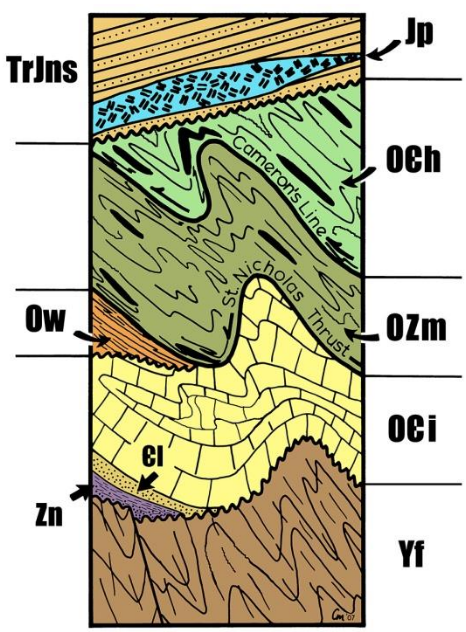

Figure 3 - Bedrock stratigraphy of New York City as described in text and noted in figures. Note that the polydeformed bedrock units are nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive (Jp).

Manhattan Formation. The Manhattan formation (OZm) consists of very massive rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite-magnetite-tourmaline gneiss, migmatite, and to a lesser degree, schist (Figure 5). The unit is characterized by a lack of internal layering except for the presence of kyanite+sillimanite+quartz+ magnetite layers and lenses up to 10 cm thick, cm- to m-scale layers of black amphibolite, and scarce thin, quartzose granofels. The unit is a major ridge former in northern Manhattan, a testament to its durability to weathering owing to the lack of layering and presence of resistant minerals quartz, garnet, kyanite, and sillimanite. Owing to the localized concentration of individual crystals and zones of disseminated magnetite some parts of the formation are strongly magnetic.

The Manhattan Formation forms the bulk of the "exposed" Paleozoic metamorphic rocks of northern Manhattan including most northern Central Park exposures and the bulk of the highlands of Inwood Park. The Manhattan is lithologically identical to Hall's Manhattan B and C and the Waramaug and Hoosac formations of Late Proterozoic (?) to Ordovician age in New England (Hall, 1976; Merguerian, 1977; 1983a; 1985; 2016). These rocks, which contain calc-silicate and quartzose interlayers in western Connecticut are inferred to represent metamorphosed sedimentary- and minor volcanic rocks deposited in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America. As such, they are considered, along with the Hartland Formation, a part of the allochthonous **Taconic Sequence**.

Walloomsac Formation. Found interlayered at the top of the Inwood Marble in New York City, this discontinuous unit (Ow) is composed of fissile brown- to rusty-weathering, fine- to medium-textured, biotite-muscovite-quartz-plagioclase-kyanite-sillimanite-garnet-pyrite-graphite schist and migmatite. The formation contains interlayers centimeters to meters thick of plagioclase-quartz-muscovite granofels, layers of ("Balmville") calcite marble, and hard diopside±tremolite±phlogopite calc-silicate rock. Pinkish garnet occurs as porphyroblasts up to 1 cm in size and amphibolite is absent. As shown in the photomicrograph of Figure 6, strongly pleochroic reddish biotite, pinkish garnet, graphite, and pyrite are diagnostic mineralogical features of the former pelitic portions of the formation.

Exposed Walloomsac Formation can be found interlayered with the underlying Inwood at five localities in Manhattan - (1) at the northern edge of Inwood Hill Park in Manhattan, (2) beneath the St. Nicholas thrust on the north and east sides of Mt. Morris Park (Merguerian and Sanders, 1991), and (3) in the northern edge of Central Park (Merguerian and Merguerian, 2004). The Walloomsac has also been detected sheared against Hartland rocks in numerous borings and building excavations from (4) northern and (5) southern Manhattan (Merguerian and Moss, 2006; 2007) including the World Trade Center site (Merguerian, 2010).

In the Bronx, four areas of Walloomsac rocks have been found; (1) on the Grand Concourse and I-95 overpass (Merguerian and Baskerville, 1987), (2) beneath the St. Nicholas thrust in the western part of Boro Hall Park (Fuller et al., 1999), (3) below the St. Nicholas thrust in the northwest and southeastern part of the New York Botanical Garden (Merguerian and Sanders, 1998 and unpublished data), and (4) in the western and northeastern part of Crotona Park (unpublished data). Because it is interpreted as being autochthonous (depositionally above the Inwood Marble and underlying Fordham Gneiss) it is assigned a middle Ordovician age. The lack of amphibolite and the presence of graphitic schist and quartz-feldspar granofels and calc-silicate layers enables the interpretation that the Walloomsac Schist is the metamorphosed equivalent of middle Ordovician carbonaceous shale and interlayered greywacke and calcareous strata of the Tippecanoe Sequence and is therefore considered correlative with parts of the Annsville and Normanskill formations of SE New York and the Martinsburg formation of eastern Pennsylvania.

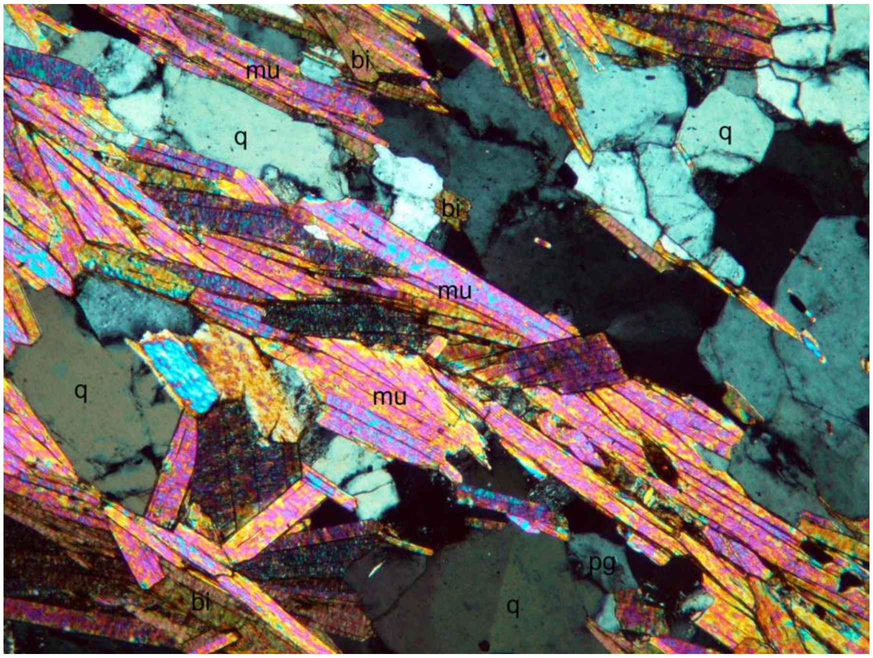

Figure 4 - Photomicrograph in cross-polarized light of Hartland schist (Ꞓ-Oh) showing a penetrative mica foliation consisting of intergrown and oriented muscovite (mu), biotite (bi), in a matrix of flattened quartz (q), and minor plagioclase feldspar (pg). Note the high mica content and prevalence of muscovite and quartz, diagnostic mineralogical characteristics of the Hartland. (CM Sample N125; 112th Street and Riverside Drive, Manhattan; 2 mm field of view.)

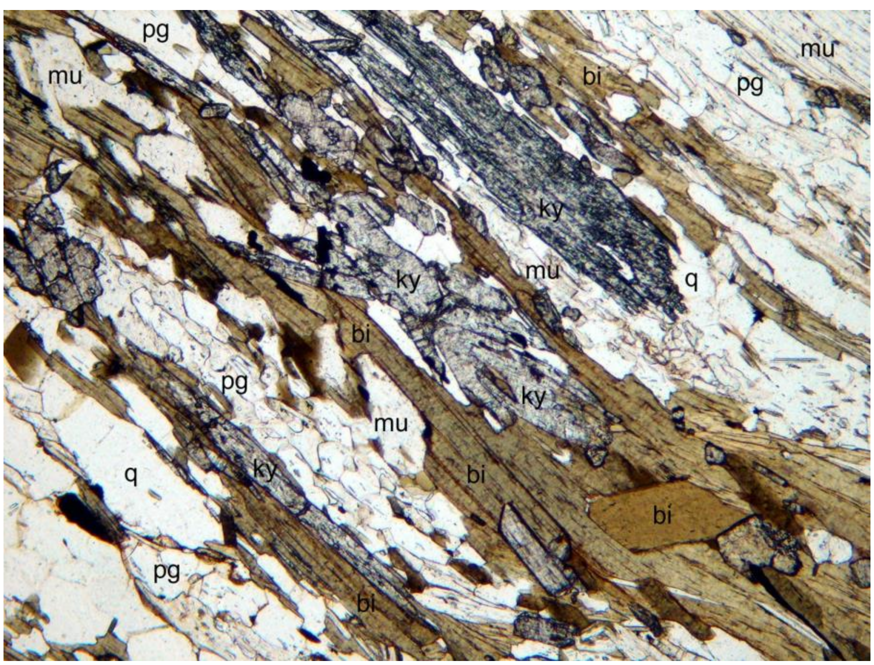

Figure 5 - Photomicrograph in plane-polarized light of the Manhattan Schist (OZm) showing an aligned intergrowth of biotite (bi), kyanite (ky), and muscovite (mu) in a fine-textured matrix of intergrown plagioclase (pg) and quartz

(q). The penetrative foliation in this view, which consists of aligned micas and kyanite as well as flattened quartz and feldspar, is diagonal across the image and marks a structural discontinuity that may split readily. (CM Sample N217; South of George Washington Bridge approach, Manhattan; 2 mm field of view.)

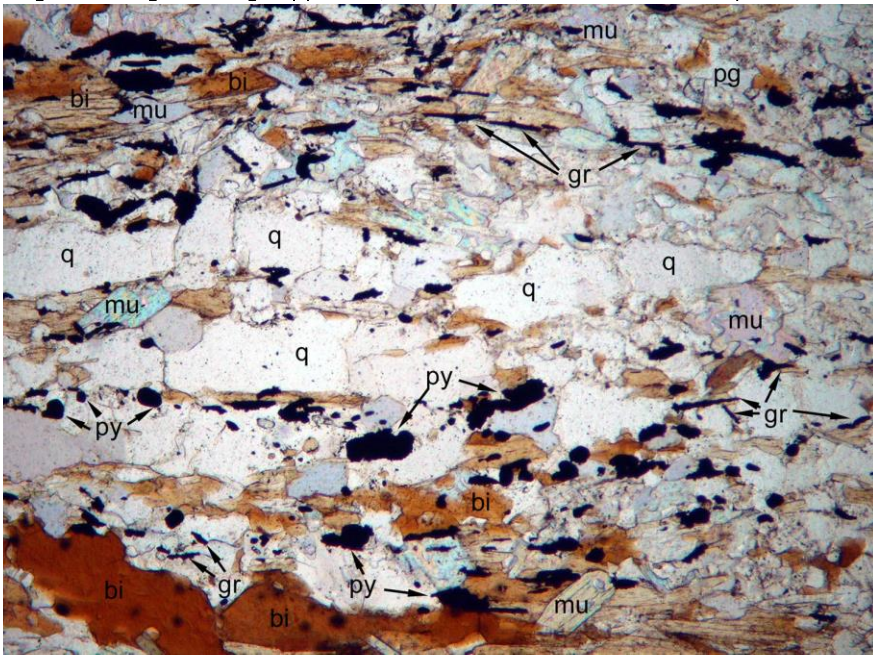

Figure 6 - Photomicrograph in plane-polarized light of the Walloomsac Schist (Ow) displaying a penetrative foliation (subhorizontal) defined by aligned biotite (bi), muscovite (mu), lenticular quartz (q), graphite (gr), and pyrite (py). Late idioblastic muscovite crystals overgrow the foliation. Diagnostic petrographic characteristics of the Walloomsac include the presence of graphite and pyrite and strongly pleochroic red-brown biotite. (CM Sample N113-3L; Inwood Hill Park, at south footing of Henry Hudson Bridge, Manhattan; 2 mm field of view.)

Origins of the Hartland, Manhattan, and Walloomsac Formations

Metamorphosed to amphibolite facies grade and then retrograded to biotite facies grade the exposed metamorphic cover rocks of NYC (Hartland, Manhattan, and Walloomsac Formations) were originally deposited as sediment and intercalated clastic, volcanic and volcaniclastic materials, though in vastly different depositional environments (Figure 7). The Hartland Formation was originally deposited in a deep ocean basin floored by oceanic lithosphere and fringed by offshore volcanic islands. The marginal ocean basin was the receptor of a huge influx of terrigenous and volcanogenic material. This produced a thick well-layered sequence of clay, silt, sand, and interlayered volcanogenic strata which resulted in a variable lithologic sequence. Even after protracted Paleozoic deformation and metamorphism, compositional layering was preserved in the Hartland, forming a dominantly well-layered metamorphic rock mass consisting of interlayered and locally migmatitic schist, gneiss, granofels, and amphibolite.

The Manhattan Formation originated along the edge of the former North American continental margin as thick clay-rich sediment with occasional sand interlayers and mafic igneous injection or flows. (See Figure 7.) As a result, the Manhattan is often more massive in character than the Hartland although some subunits appear similar. By contrast, the Walloomsac Formation is mineralogically unique since it originated under restricted oceanic conditions and consisted of thick accumulations of carbonaceous, sulphidic, and clay-rich sediment with occasional sandy and calcareous interlayers. This has resulted in a mineralogically distinct schistose rock enriched in biotite, graphite, garnet and pyrite together with layers of calcite marble and calc-silicate rock. The contrast in internal compositional layering and mineralogy allows for separation of the three units in the field and also during routine core examination and petrographic analysis.

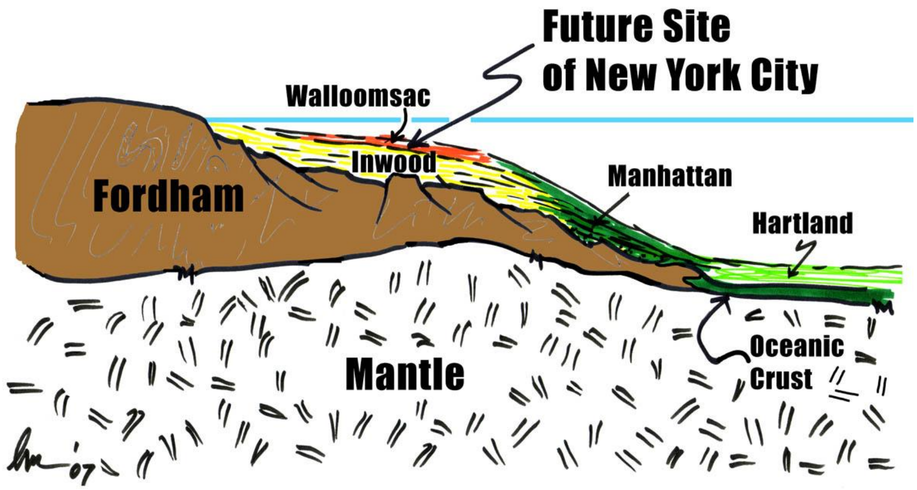

Figure 7 - Diagrammatic cartoon of eastern North America after rifting from Rodinia and during deposition of the Paleozoic strata that are to become the Hartland, Manhattan, and Walloomsac formations. Note the correlation of units and their relationships to the underlying units of the partly coeval Inwood and older Fordham.

NYC Bedrock Formations Found Beneath the Hartland, Manhattan, and Walloomsac Formations

The metamorphic rocks described above are in structural or unconformable contact with the predominately older units as described below.

Inwood Marble. The Inwood Marble (OЄi in Figures 1-3) consists of white to bluish-gray fine- to coarse-textured dolomitic and lesser calcitic marble locally with siliceous interlayers containing diopside, tremolite, phlogopite, muscovite (white mica) and quartz (Figure 8) together with accessory graphite, pyrite, tourmaline (dravite-uvite), chlorite and zoisite according to our investigations (Merguerian, et al., 2011). Layers of calc-schist, calc-silicate rock and fine grained gray quartzite with a cherty appearance are also locally present. The unit is exposed in the Inwood section of northern Manhattan, the Harlem lowland NE of Central Park, in thin belts in the East River channel, in the subsurface of southeastern Manhattan, and also crops out in the Bronx and Westchester County. The Inwood is correlative with a continuous outcrop belt of non-metamorphosed Cambro-Ordovician carbonate rocks (Sauk Sequence) found along the entire Appalachian chain of North America.

Fordham Gneiss. The Fordham Gneiss (Yf in Figures 1-3) constitutes the oldest underpinning of rock formations in NYC and consists of a complex assemblage of Proterozoic Y ortho- and paragneiss, granitoid rocks, metavolcanic- and metasedimentary rocks. In NYC, only a few attempts have been made to decipher the internal stratigraphic relationships, hence, the three-dimensional structural relationships remain obscure. Based on detailed studies in the Queens and Brooklyn NYC water tunnels (Merguerian, 2000; Merguerian et al., 2001; Brock et al., 2001), the Fordham consists of predominately massive mesocratic, leucocratic, and melanocratic orthogneiss with subordinate schistose rocks. They are Grenvillian in age (1.1 Ga) and were metamorphosed to the high pressure granulite facies which has produced a tough, anhydrous interlocking mineral texture consisting of primary clino- and lesser orthopyroxene, plagioclase, and garnet that has partially resisted Paleozoic hornblende and biotite grade retrograde regional metamorphism (Figure 9).

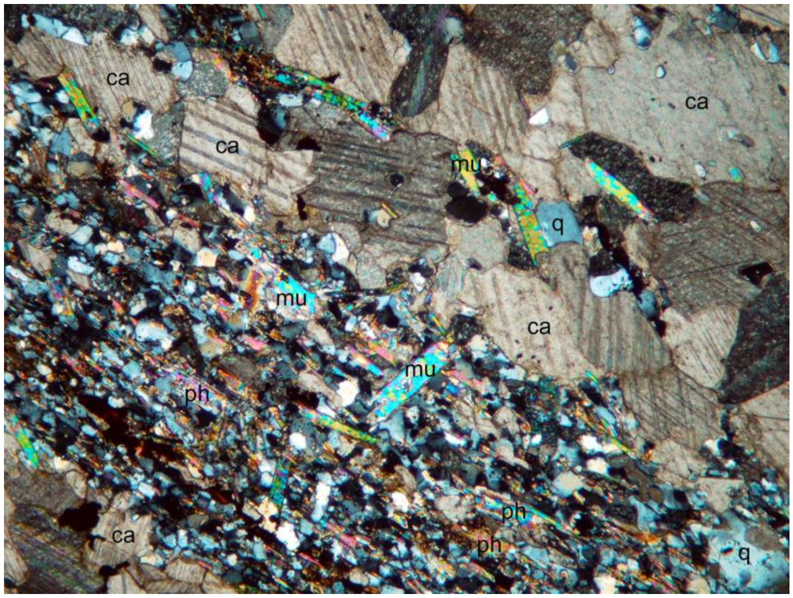

Figure 8 - Photomicrograph in cross-polarized light of the Inwood Marble near the contact with the Walloomsac showing the granoblastic texture produced by recrystallized twinned calcite (ca). A fine-textured mica-rich zone cutting diagonally across the slide defines a foliation which here consists of aligned muscovite (mu) and phlogopite (ph) in a matrix of recrystallized quartz (q), calcite, and biotite (bi). Normally the Inwood is quite pure and consists of coarse textured granoblastic calcite or dolomite. (CM Sample N113-4; Inwood Hill Park, at south footing of Henry Hudson Bridge, Manhattan; 2 mm field of view.)

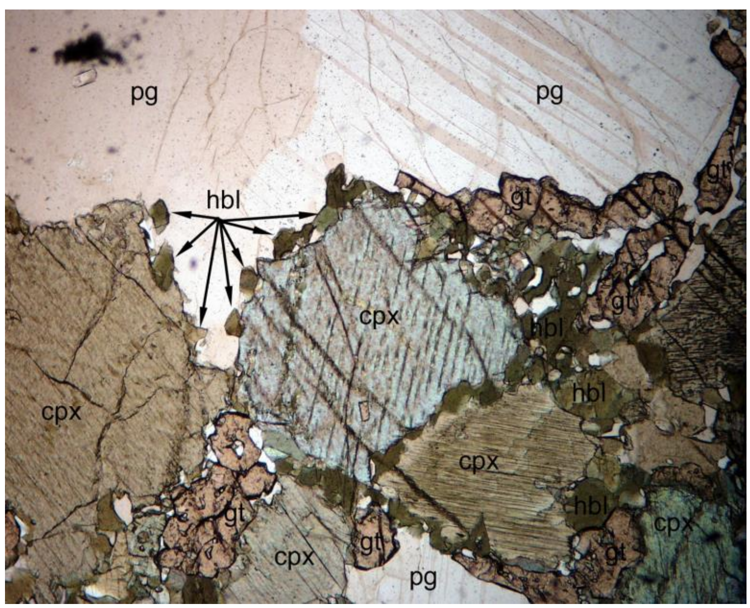

Figure 9 - Photomicrograph in plane-polarized light of Proterozoic mafic orthogneiss showing a coarse-textured granular intergrowth of clinopyroxene (cpx), plagioclase (pg), and garnet (gt) produced during Grenvillian metamorphic recrystallization of a former mafic igneous rock. Granular hornblende (hbl) was produced during a secondary Paleozoic metamorphism but the older interlocking granoblastic metamorphic texture has prevailed. (CM Sample Q114; Queens Tunnel Station 015+90; 2 mm field of view.)

The Fordham is exposed in the Bronx, in the subsurface of SE Manhattan, the East River channel, and western Queens and Brooklyn (City Water Tunnel #3, Stage 2) and presumably underlies most the region at greater depth (Figure 7). Occurring locally between the Inwood and Fordham, are two minor units that are poorly understood and somewhat controversial. One is the very local Lowerre Quartzite (unit Ꞓl in Figure 3) of Norton (1959) and the other a late Proterozoic unit known as the Ned Mountain Formation (unit Zn in Figure 3) of Brock (1989; 1993). The Ned Mountain is correlative with Proterozoic Z rocks mapped as the Yonkers Gneiss (Scotford, 1956) and the Ravenswood Granodiorite Gneiss (Ziegler, 1911) found in Westchester County and in western Queens, respectively. They have little bearing on the primary focus of this paper and field trip and are here referenced for sake of completion.

Other Rocks Associated with the Bedrock Series

Serpentinite. In addition to the famous Staten Island serpentinite, many scattered bodies of serpentine rock have been encountered in NYC (Figure 10). In addition to a few bodies known in Manhattan near 59th Street and 10th Avenue, the Bruckner Boulevard/Cross Bronx Expressway/Hutchinson River Parkway interchange at the north end of the Bronx-Whitestone Bridge approach in the Bronx, and a few bodies that were penetrated during construction of the Brooklyn Water Tunnel (Schnock, 1999) and the Manhattan Water Tunnel, serpentinite has also been found in a building construction site at 43rd Street and Sixth Avenue in midtown Manhattan (Merguerian and Moss, 2005) and in northern Manhattan (Merguerian and Moss, 2007). These sheared masses are interpreted as ophiolitic scraps and are commonly found in ductile fault contact with enclosing Hartland rocks or near the Manhattan-Hartland contact (Merguerian, 1979). The serpentinites are black to greenish fine-textured rocks containing serpentine group minerals including chrysotile, chromite, magnetite, orthoamphibole, magnesite, talc, calcite, chlorite together with relict olivine and pyroxene.

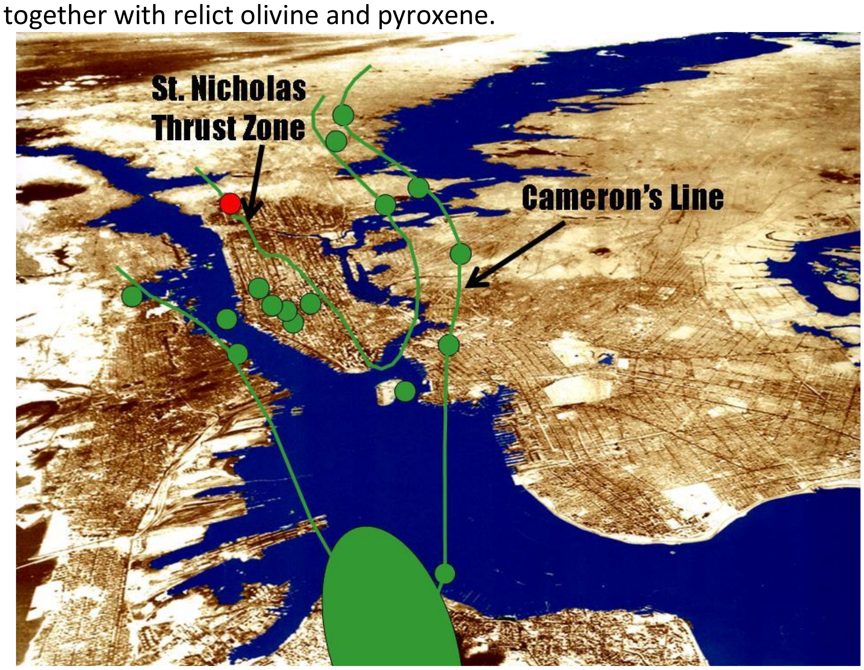

Figure 10 - Cartoon showing distribution of 18 known areas of serpentinite in the New York City area. The green lines surround areas of serpentinite defining a zone of sheared rock broadly coincident with the St. Nicholas thrust and Cameron's Line, two important elements of the Taconian suture zone in New York City. The red dot shows the location of a serpentinite in northern Manhattan described by Merguerian and Moss (2007).

Granitoid. All units of the NYC bedrock described above have been intruded by granitoids that range from foliated and internally sheared pre- and syn-tectonic intrusives to post-tectonic bodies. They range from fine-textured to pegmatitic and occur as dikes, sills, stocks, and small plutons consisting of essential K-feldspar, quartz, plagioclase, biotite, hornblende, muscovite, and subordinate garnet. Minor tourmaline and beryl are also locally found.

Rhyodacite. Found exclusively beneath the area of Woodside, Queens a swarm of five thin sub-parallel rhyodacite dikes, all displaying pristine igneous textures, were penetrated during construction of the Queens Tunnel (Merguerian, 2000; 2001). They occur as tabular, discordant injections roughly oriented N53°W and average roughly 3 m in thickness. The larger dikes vary from 5.3 m down to 1 m and taper off to thinner dikelets. The rhyodacites are reddish, glassy to aphanitic igneous rocks with no metamorphic fabric and low average density (2.58 g/cm^3).

The unique devitrified texture of the groundmass and the presence of vesicles unequivocally identify the Queens Tunnel rhyodacite as a hypabyssal rock. The dikes are Permian in age (~295 Ma) and crosscut folded Proterozoic Y granulite facies rocks of the Queens Tunnel Complex with which they are genetically and temporally unrelated. The injection of a suite of Permian rhyodacite dikes that are chemically, texturally, and temporally unrelated to their bedrock hosts, mark an anomalous geological formation that adds a new chapter to the evolution of the NYC area.

Alkalic and Mafic Dike Rocks. Mapping in conjunction with construction of NYC Water Tunnels # 1 and 2 also defined alkalic and mafic dike rocks (Berkey; 1911; 1933; 1948) and I have seen mafic dikes in the Queens Tunnel and elsewhere in NYC. Some of them are foliated and of presumable middle Ordovician age and others contain pristine igneous textures and are most likely associated with the early Jurassic Palisades intrusive epoch.

STRUCTURAL GEOLOGY

Deformational Episodes

All bedrock units in NYC have shared a complex Paleozoic structural history which involved three superposed phases of deep-seated deformation (D_1-D_3) followed by three or more episodes of open- to crenulate folds (D_4-D_6). The synmetamorphic juxtaposition of the various units occurred very early in their structural history ($D_1 + D_2$) based upon crosscutting relationships. The Fordham harbors a more complex history as a result of its great age. It has experienced deformation and metamorphism during the Grenville orogeny (~1.1 Ga) in addition to the three Paleozoic orogenies (Taconian, Acadian, and Allegenian) experienced by the overlying Inwood, Walloomsac, Manhattan, and Hartland rocks. Below, we will restrict our discussion to the Paleozoic deformation.

The obvious map scale folds in NYC are those with steep N- to NE-trending axial surfaces (S_3) and variable but typically shallow plunges toward the S and SW (Figures 1 and 2). The folds are typically overturned to the NW with a steep SE-dipping schistosity (Figure 11). Shearing along S_3 axial surfaces typically creates a transposition foliation of S_1, S_2, and S_3 that is commonly invaded by granitoids to produce migmatite both during the D_2 and subsequent D_3 events. The third-generation structures deform two earlier structural fabrics (S_1 and S_2). The older fabrics trend roughly N50°W and dip gently

toward the SW (except along the limbs of overturned F_3 folds). We suspect that all of these structures (D_1, D_2, and D_3) are products of the protracted middle Ordovician Taconic orogeny.
During D_2, the rocks acquired a penetrative S_2 foliation consisting of oriented mica and intergrown sillimanite and kyanite with flattened quartz together with staurolite and garnet porphyroblasts. Distinctive layers and lenses of kyanite+quartz+magnetite developed in the Manhattan formation and very locally in the Hartland during D_2. Near ductile fault contacts the S_2 fabric is highly laminated with frayed and rotated mica and feldspar porphyroclasts with and without fine-textured tails, ribboned and locally polygonized quartz, lit-par-lit granitization, and quartz veins all developed parallel to the axial surfaces of F_2 folds. The D_3 folding event, a period of dominantly L-tectonism, smeared the previously flattened kyanite+quartz layers and lenses into elongate shapes stretched parallel to F_3 axes. In addition, porphyroblasts of tremolite pseudomorphic after diopside also show alignment parallel to F_3 hingelines in the bounding Inwood Marble (Merguerian and Merguerian, 2012).

Although the regional S_2 metamorphic grain of the NYC bedrock trends N50˚W, the appearances of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25˚. (See Figure 11.) S_3 is oriented N30˚E and dips 75˚SE and varies from a spaced schistosity to a transposition foliation often with shearing near F_3 hinges. The F_3 folds and related L_3 lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz and kyanite lenses and layers into elongate shapes. Metamorphism was of identical grade with D_2 which resulted in kyanite overgrowths and annealing of former mylonitic textures (Merguerian 1988).

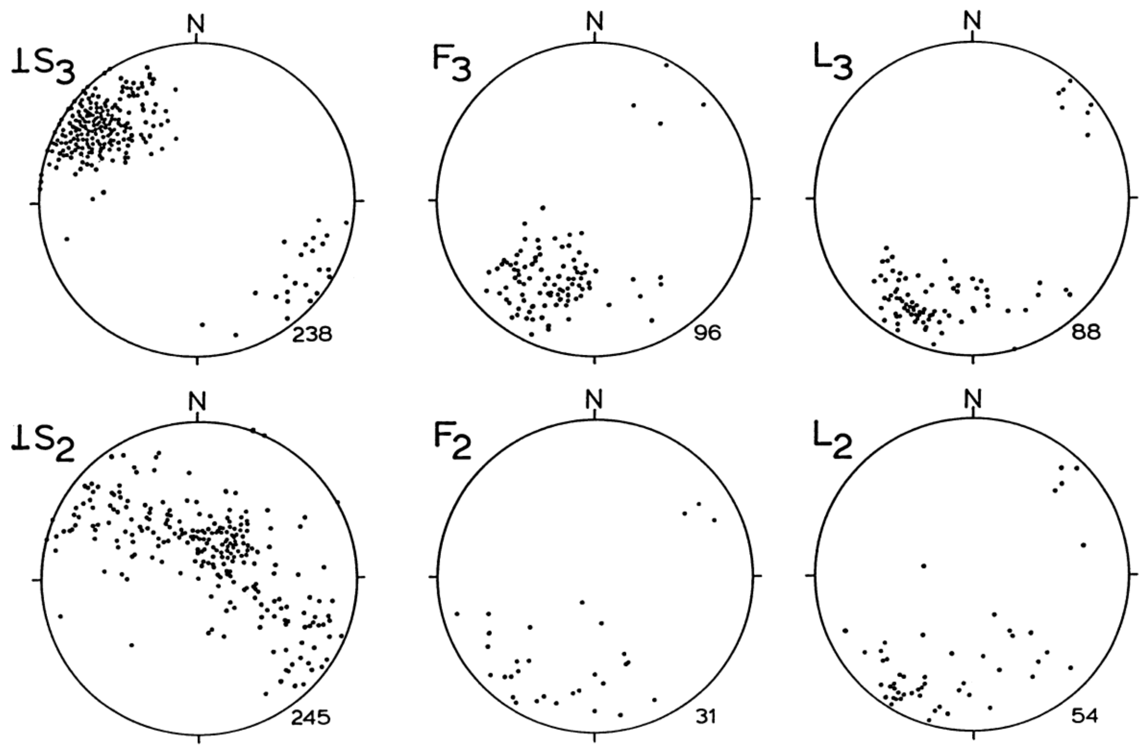

Figure 11 - Equal area stereograms showing the distribution of poles to S_2 and S_3, the orientation of F_2 and F_3 fold hingelines, and the orientation of L_2 and L_3 lineations. The number of plotted points indicated to the bottom right of each stereogram. (Adapted from Merguerian and Sanders, 1991, Figure 26, p. 113.)

<u>Second Ave Subway Mapping</u>

The long-delayed Second Avenue Subway project in NYC has provided us an opportunity for a thorough three-dimensional study of the stratigraphy, structure, and metamorphism of the Hartland formation in NYC. Between 83rd and 87th streets on Second Avenue twin TBM-bored tunnels and ground-down ancillary station complex excavations indicate that the Hartland in this part of NYC is a migmatitic amphibolite facies rock mass that is well-layered at the scale of 0.5 cm to 1.0 m. The project exposes a schistose to gneissic rock consisting of the assemblage muscovite-quartz-plagioclase-biotite±kyanite± staurolite±garnet with interlayers of quartz-plagioclase-mica granofels, greenish amphibolite±biotite± garnet, subordinate gray quartzite and coticule. The schistose facies is lustrous and consists primarily of aligned fine- to coarse-textured muscovite and thus splits readily along the foliation and lithologic contacts. The mica gneiss, granofels, amphibolite, and quartzite interlayers are typically massive and hard, contain much less mica than the schist and may not show pronounced foliation.

In 2012-13, we had the opportunity to observe and record the F_2 recumbent fold phase in large-scale fresh exposures during our site inspections and mapping of the 86th street station complex of the Second Avenue subway excavation (Merguerian and Merguerian, 2014). Figure 12 provides a south facing view of the main station cavern excavated below 86th street in NYC. The cavern was advanced by traditional drill and blast technology using access shafts at 87th and 83rd streets and by excavating in a series of top down slashes to open the cavern down to the level of existing TBM-bored north and southbound tunnels mined earlier.

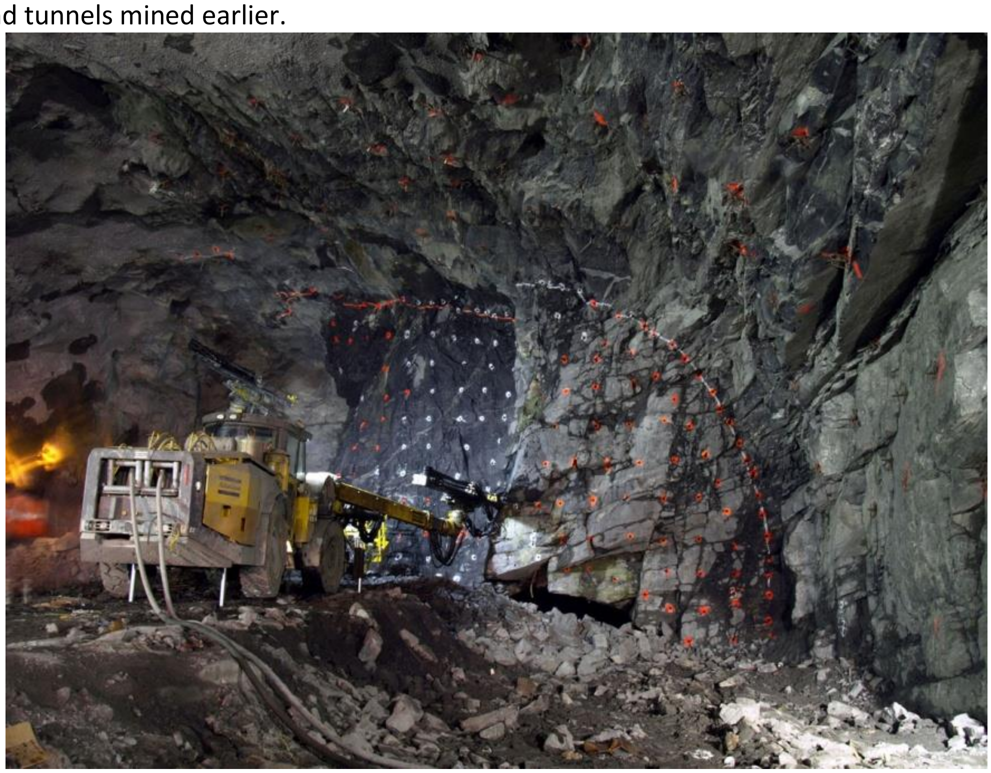

Figure 12 - View from north of west (R) and center (L) slashes of North Cavern excavation at 86th Street Station for Second Avenue Subway. West (southbound) TBM tunnel crown at +77.2’ exposed in right center of image below area of intersecting joints, faults and resulting overbreak. The center (wet. blackish area) and western (right of center) slashes are discussed in text. (Digital image taken 19 December 2012.)

<u>Center Slash</u>. Exposed in late 2012, the center slash of the 86th street north main station cavern for the Second Avenue Subway project in the vicinity of Station 1205+00 (below 85th street) exposed highly fractured and jointed Harland schist, granofels, and amphibolite in a series of top down excavations that ultimately breached through existing TBM-bored tunnels. The map and image of the center slash (Figure 13) shows SE-plunging F_2 reclined isoclinal recumbent folds of early SE-dipping gently inclined penetrative foliation and deformed grantoid sill (g). Another foliated granitoid is injected along a moderately inclined reverse shear showing 0.5 m of offset. Recrystallization during folding and shearing produces penetrative mica foliation (Feature 10.) that has formed parallel to compositional layering and the S_2 axial surface. Gently inclined foliation joints are prominent discontinuities (J_1) that formed parallel to the foliation and parallel compositional layering. Listed below Figure 13, these are intersected by steep NNE-trending (J_2) and NW-trending (J_3) joints and faults producing overbreak seen at top of image.

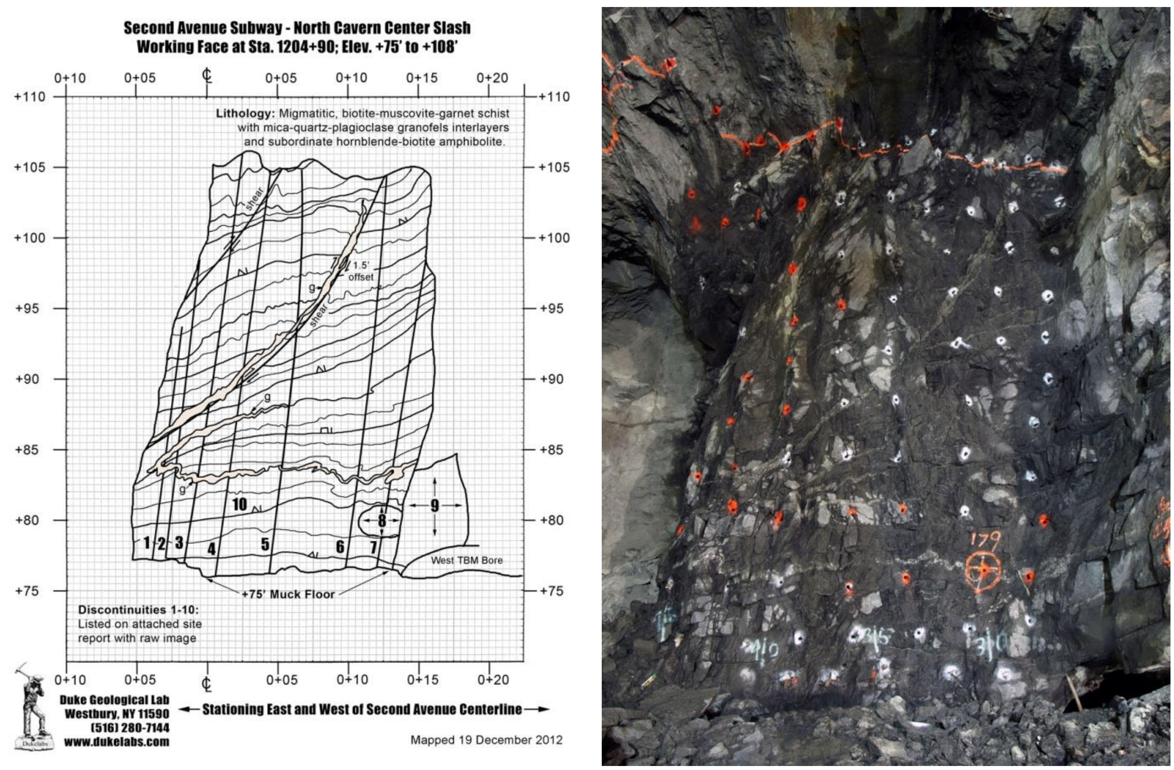

Figure 13 - Isoclinal recumbent folds of early SE-dipping foliation in Hartland formation (O€h) outlined by grantoid sills (g) with gently inclined penetrative foliation. Recrystallization during folding and shearing produces penetrative mica foliation (Feature 10.) that has formed parallel to compositional layering. Gently inclined foliation joints are prominent discontinuities (J_1) and have formed parallel to the foliation and parallel compositional layering. These are intersected by steep NE-trending (J_2) and NW-trending (J_3) joints and faults producing overbreak seen at top of image. (Digital image taken 19 December 2012.)

<u>Discontinuities of Center Slash</u>

NNE-trending Set (J_2) – Associated with NNE-trending fault system
1 – N32°E, 76°SE, planar, rough joint (one of 11 joints measured in easternmost 5' of rock face)
2 – N34°E, 82°SE, planar, rough joint (one of 11 joints measured in easternmost 5' of rock face)
3 – N30°E, 81°SE, planar, rough joint (one of 11 joints measured in easternmost 5' of rock face)

4 – N30°E, 78°SE, planar, rough joint (one of 15 joints measured in easternmost 10' of rock face)
5 – N19°E, 84°SE to N23°E, 86°NW planar, smooth joints
6 – N31°E, 90° planar, smooth joint
7 – N37°E, 77°SE planar, rough joint

NW-trending Set (J_3) – Associated with NW-trending fault system
8 – N41°W, 51°NE undulating, rough joint
9 – N29°W, 82°NE planar, smooth joint face with trace of K-feldspar and microcrystalline epidote

Foliation and Layering Joints (J_1)
10 – Foliation, layering and parallel J_1 joints are ~ N70°E, 20°SE

West Slash. Also exposed in late 2012, the west slash of the 86th street north main station cavern exposed highly fractured and jointed Harland schist, granofels, and amphibolite. The map and image of the west slash (Figure 14) shows SE-plunging F_2 isoclinal reclined recumbent folds of early SE-dipping gently inclined penetrative foliation. Recrystallization during folding and shearing produces penetrative mica foliation (Feature 13.) that has formed parallel to compositional layering and the S_2 axial surface.

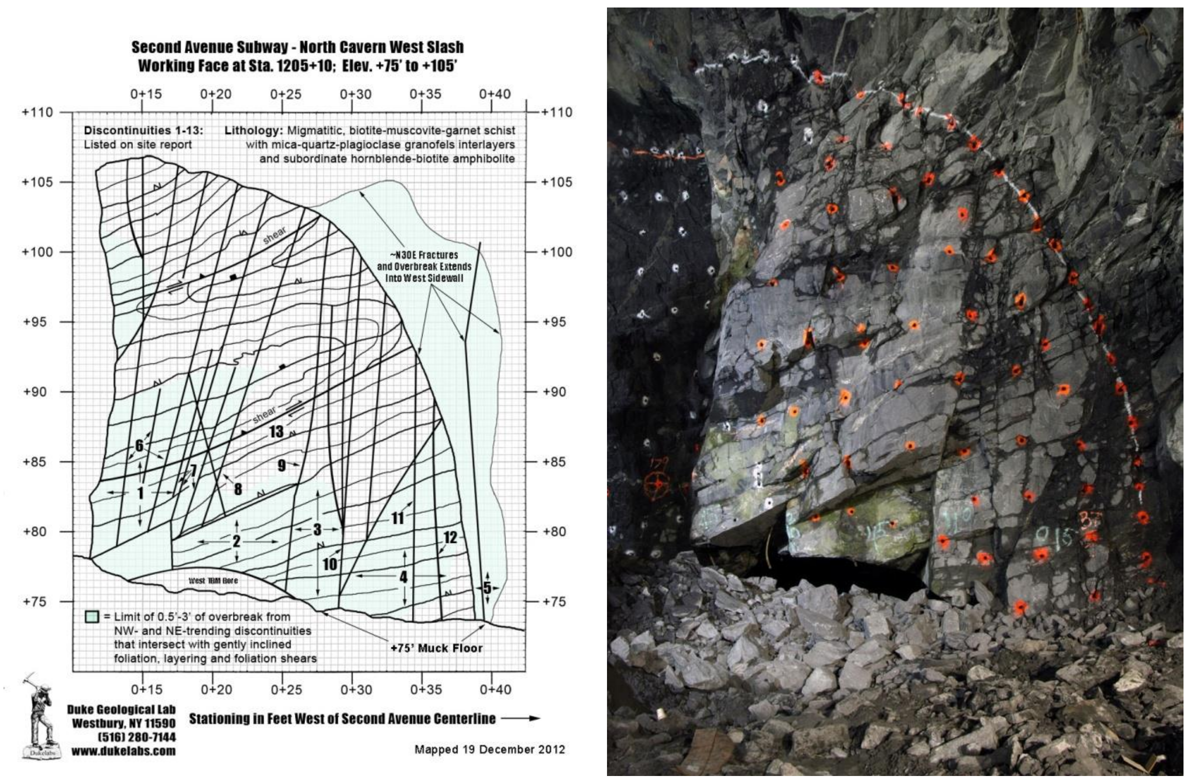

Figure 14 - Geological map and southward view digital image of west slash of North Cavern below 85th street in NYC. Note the internal structure dominated by internally sheared gentle SE-plunging isoclinal recumbent folds of early SE-dipping gently inclined foliation in Hartland formation (O€h). Recrystallization during folding and shearing produced penetrative mica foliation (Feature 13.) that formed parallel to transposed compositional layering. Gently inclined foliation joints are prominent discontinuities (J_1) and have formed parallel to the foliation and parallel compositional layering. These are intersected by steep NNE-trending (J_2) and NW-trending (J_3) joints and faults producing overbreak (light green shading). (Digital image taken 19 December 2012.)

Gently inclined foliation joints are prominent discontinuities (J_1) that formed parallel to the foliation and parallel compositional layering. Listed below Figure 14, these are intersected by steep NNE-trending (J_2) and NW-trending (J_3) joints and faults producing overbreak (green shading in Figure 14). Figure 15 shows the mineralized coatings on the prominent NW-trending J_3 joints.

Discontinuities of West Slash

NW-trending Set (J_3) – Associated with NW fault system
1 – N37°W, 81°SW, planar, smooth joint filled with K-feldspar and microcrystalline epidote
2 – N50°W, 77°SW, planar, smooth fault filled with K-feldspar and microcrystalline epidote
3 – N40°W, 88°NE, undulating, smooth joint filled with K-feldspar and microcrystalline epidote
4 – N27°W, 88°NE, planar, smooth joint filled with K-feldspar and microcrystalline epidote
5 – N20°W, 87°NE planar, smooth joint filled with K-feldspar and microcrystalline epidote

NNE-trending Set (J_2) – Associated with NNE fault system
6 – N35°E, 86°SE, planar, rough joints (3)
7 – Same as 6 (3 joints)
8 – N41°E, 77°SE, undulating, rough joint
9 – N25°E, 87°SE, slickensides of clay, steep down-dip slicks, planar, rough dip-slip fault
10 – N41°E, 62°SE to 90° at base of wall, undulating, rough reverse fault, seamy with 1.5" stilbite infilling and associated splays/joints (3)
11 – N37°E, 87°SE, undulating, stepped joint
12 – Same as 11

Foliation and Layering Joints (J_1)
13 – Foliation, layering and parallel J_1 joints vary from N66°E, 17°SE to N71°E, 20°SE

Figure 15 - View of microcrystalline epidote (green) and overgrown K-feldspar mineral coating on NW-trending joints cutting Hartland rocks above southbound TBM tunnel. (Digital image taken 19 December 2012.)

To summarize, field studies prior to 1983 (See Figure 11.) and the new views provided by the Second Avenue Subway excavation prove that the internal structure of NYC is dominated by gentle SSW- to SE-plunging recumbent isoclinal long-limbed reclined F_2 folds of an earlier S_1 foliation. This has resulted in a gently inclined (<30°) southward dipping composite penetrative regional foliation (S_1 x S_2) striking NW to ENE that formed mostly parallel to compositional layering (S_0) and includes sill-like masses and thin veins of foliated granitoid. Steeper dips are found in F_2 hinge areas and along the transposed limbs of upright southward plunging F_3 folds where the earlier S_1 x S_2 regional foliation and compositional layering are locally oversteepened. In NYC, the superposed ductile structures are cut by foliation joints (J_1) produced parallel to the regional foliation and by steep NNE- to NE-trending (J_2) joints and dip-slip faults infilled by stilbite+calcite, by younger steep NW-trending (J_3) joints and strike-slip faults infilled by K-feldspar, microcrystalline epidote, quartz and pyrite, and by moderately dipping J_4 joints.

<u>Younger Folds</u>

A geological map of Central Park (Merguerian and Merguerian, 2004 and Figure 18 in our allied 2016 NYSGA field guide) shows the F_4 folds as a series of warps and open folds with axial traces that strike roughly N30°W and exhibit dominantly steep dips to the SW. The effects on map contacts of these late features is negligible but the scatter of poles to S_3 and localized northward plunges of F_3 fold axes and L_3 lineations are the result of post-D_3 deformation. (See Figure 11.) Brittle S_4 cleavages in the bedrock may have helped localize the late stage brittle NW-trending faults that cut the region. Idioblastic muscovite pseudomorphs after D_3 kyanite are common throughout Central Park and many other places throughout NYC. Their abundance suggests a major post-Taconian retrograde metamorphism, presumably coincident with the intrusion of wet granitoids throughout the Manhattan Prong (Brock and Brock, 2001).

<u>Brittle Faults and Joints</u>

Five generations of brittle faults and joints cut polydeformed bedrock units of the NYC area (Merguerian, 2002; 2015). The brittle faults include NW-trending gently SW-dipping faults **(Group A)**, younger ENE-trending faults with moderate to steep dips **(Group B)**, subhorizontal faults and fractures **(Group C)**, and a steep dip-slip NNE-trending fault set **(Group D)** with thick clay- and zeolite-rich gouge zones. These are cut by NW- to NNW-trending strike-slip faults of the "Manhattanville" fault set **(Group E)**. Reactivation of older faults is quite common. The two youngest brittle fault sets (Groups D and E) cross cut all metamorphic structures in NYC and cut the Permian (295 Ma) glassy rhyodacite dikes.

The NYC Water Tunnel #3 cuts through the 125th Street "Manhattanville" fault beneath Amsterdam Avenue in Manhattan. Here, in an abrupt zone of highly fractured Manhattan Schist 40 m wide, the Manhattanville fault dips 55˚ to 75˚ SW and cuts orthogonally across the tunnel line and the steeply dipping foliation in the schist. In the crown of the tunnel, 2 to 3 m blocks of the Manhattan schist, which remained internally coherent within the broad zone of cataclastic rock, showed a minimum of 90˚ rotation about a vertical axis. Clearly, this observation indicates that along the Manhattanville fault, much of the motion has been strike-slip. Indeed, slickensides indicate that right-lateral, normal, oblique slip was the most recent offset sense. Cross-fault offset of the prominent Manhattan ridge indicates over 200 m of composite right-lateral slip.

Joint Orientations. Protracted brittle faulting in the NYC area has developed three mutually intersecting fracture orientations (NW, NNW, and NNE) that together produce a pattern of crustal weakness. Five joint sets, which are parallel to the brittle faults, are found in the NYC area. These include:

1) NW-trending, NE-dipping joints and their conjugates. The NW-trending joints are A-C joints related to southward-plunging F_3 folds.

2) NNE-trending joints with steep dips related to Group D faults. Also includes foliation parting joints and conjugate joint surfaces. Typically with a NE trend these are found more commonly in areas of regional F_3 fold limbs where parallelism of axial surfaces of folds, compositional layering, and foliation occur.

3) Gentle SW-dipping foliation joints developed parallel to SW-dipping foliation and original compositional layering at F_3 fold hinges.

4) Subhorizontal unloading joints and joints related to subhorizontal shear zones, and,

5) Steep ENE joints related to the oldest brittle fault set.

TECTONICS

Modern studies of the Appalachian orogen indicate that an arc-continent collision during the Taconic orogeny produced the imbrication of the oceanward facing passive continental margin of proto North America, development of primary penetrative metamorphic fabrics, F_1 though F_3 folding and the D_2 development of the St. Nicholas and Cameron's Line thrusts. Thus, the deformed Paleozoic bedrock of NYC may have originated within the deep-seated convergent walls of a subduction zone formerly situated off shore from proto-North America. The D_1 to D_3 folds and crosscutting fabrics that presumably formed during the Taconic orogeny are overprinted by two- and possibly three fold phases that, based on their style and general lack of attendant foliation, undoubtedly took place at much-higher crustal levels than did the three Taconian fabrics and are responsible for retrograde fabrics and mica growth. As such, the younger fold phases record the effects of the Acadian- and terminal-stage Appalachian (Alleghenian) orogenesis.

FIELD TRIP GUIDE

In the associated field guide, participants will find more specific details on the trip to Isham, Inwood, and Central parks with individual stop descriptions for each stop. We will try to visit all of the intended stops and will endeavor to fit in additional stops. So pay attention, get your digital cameras ready and for heaven's sake leave the iPods, iPhones, and other distractions in your bags as they are strictly forbidden during the day on our trip! Public humiliation and post-trip drive-by insults at your homes will be a deterrent. Remember that hammering and rock collecting in NYC parks is strictly forbidden.

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