TRIP A-5 - FIELD GUIDE TO ISHAM, INWOOD, and CENTRAL PARKS, NYC, NY

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The following field guide and road log is intended to provide participants with keys to understanding our subdivisions of the venerable Manhattan Schist into three separable units by utilizing exposures in New York City including Isham, Inwood Hill and Central parks and to show in the bedrock structural evidence for our tectonic interpretations. The field guide is split into two major field localities, each with individual stops. Locality 1 is Isham and Inwood Hill parks in northern Manhattan and Locality 2 is the south part of Central Park in midtown Manhattan.

Meeting Points: NE corner of Isham Street and Seaman Avenue, NYC, NY. Parking is available in the streets to the north, south and east of meeting point. Parking is typically good on weekends but be sure to read posted parking signs to avoid ticketing. We plan to use public transportation (A-Train at 207th Street and Broadway downtown to Columbus Circle) to travel between Locality 1 and Locality 2. Those planning to drive to Locality 2 should leave ample time for parking on midtown Manhattan.

*****Maximum of 20 participants - Bring lunch and drinking water!*****

Locality 1 - Isham Park and Inwood Hill Park entrances (Isham Street and Seaman Avenue).
Locality 2 - Central Park at the SW entrance (59th Street and Eighth Avenue).

Meeting Point Coordinates: Locality 1 - 40.869°N; 73.921°W; Locality 2 - 40.768°N; 73.981°W

Meeting Times: Locality 1 - 9:00 AM sharp; Locality 2 - about 1:30 PM (01 October 2016).

Distance in miles

Cumu-lative	Point to Point	Route Description
0.0	0.00	Start out at Hilton Hotel in Nanuet (425 State Route 59, Nanuet, NY).
0.06	0.06	Drive east on NY-59/Route 59 then stay straight to ramp for Palisades Interstate Parkway.
0.33	0.27	Merge onto Palisades Interstate Pkwy S (Crossing into NJ).
18.63	18.30	Drive S on PIP, then take I-95 N/US-1 N/US-9 N (Crossing into NY).
19.67	1.04	Take the NY-9A/Henry Hudson Pkwy exit (EXIT 1).
20.08	0.41	Keep right to take the ramp toward NY-9A N.
20.28	0.20	Merge onto NY-9A N/Henry Hudson Pkwy N via the ramp on left toward Pkwy N/Upstate.
21.79	1.51	Take EXIT 17 toward Dyckman Street.
21.91	0.12	Turn slight right onto Riverside Drive.
22.10	0.19	Turn slight left onto Broadway/US-9 N.
22.53	0.43	Destination = Isham Street and Broadway, just beyond W. 207th Street. Isham Park is upslope, west of Broadway on Isham Street just before Seaman Avenue.

Locality 1 – Isham and Inwood Hill Parks

Today's field trip will start where bedrock is exposed in northernmost Manhattan in Isham and Inwood Hill parks (Figure 1). Northern Manhattan boasts the highest natural point of elevation at +265.5' achieved atop rocky ridges in Bennett Park. The rocky ridges rise abruptly above the lowland plain to the east underlain by Inwood Marble. The adjacent prominent ridges are underlain by the venerable Manhattan Schist (OZm). Our analysis of the area departs a bit from published work in that we recognize schistose rocks in Manhattan aside from the Manhattan Schist. Indeed, in Inwood Hill Park representatives of all three ductile fault bounded schistose units can be found (Walloomsac [Ow], Manhattan [OZm] and Hartland [OꞒh] formations).

A cut-away cross-sectional view of northern Manhattan appears on a Google Earth basemap in Figure 2. Note the interpretation of the structure suggesting that the rocky ridges of northern Manhattan are controlled by overturned synforms of Manhattan Schist rooted by a major shear zone known as the St. Nicholas thrust which cuts both the Inwood Marble (OꞒi) and locally, the Walloomsac Schist (Ow). Below the flat plains of northeastern Manhattan, the Inwood is folded upward to the earth's surface and beveled above two eroded F_3 antiforms cored by Fordham Gneiss and an intervening F_3 synform with all folds and most associated fabrics overturned toward the NW.

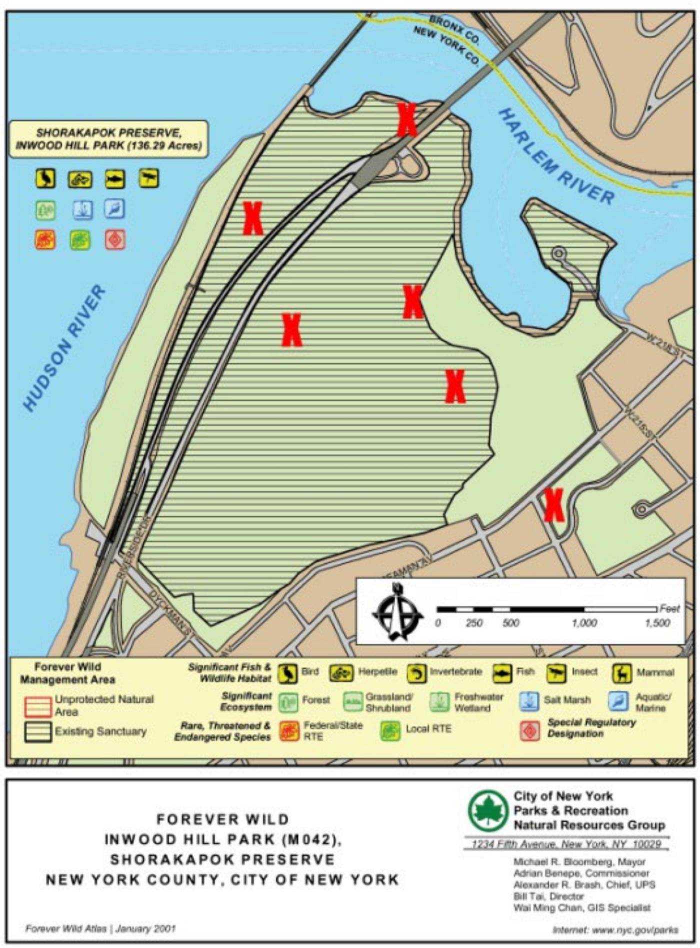

Figure 1 - Index map of Isham and Inwood Hill Parks showing the location of our intended sub-stops.

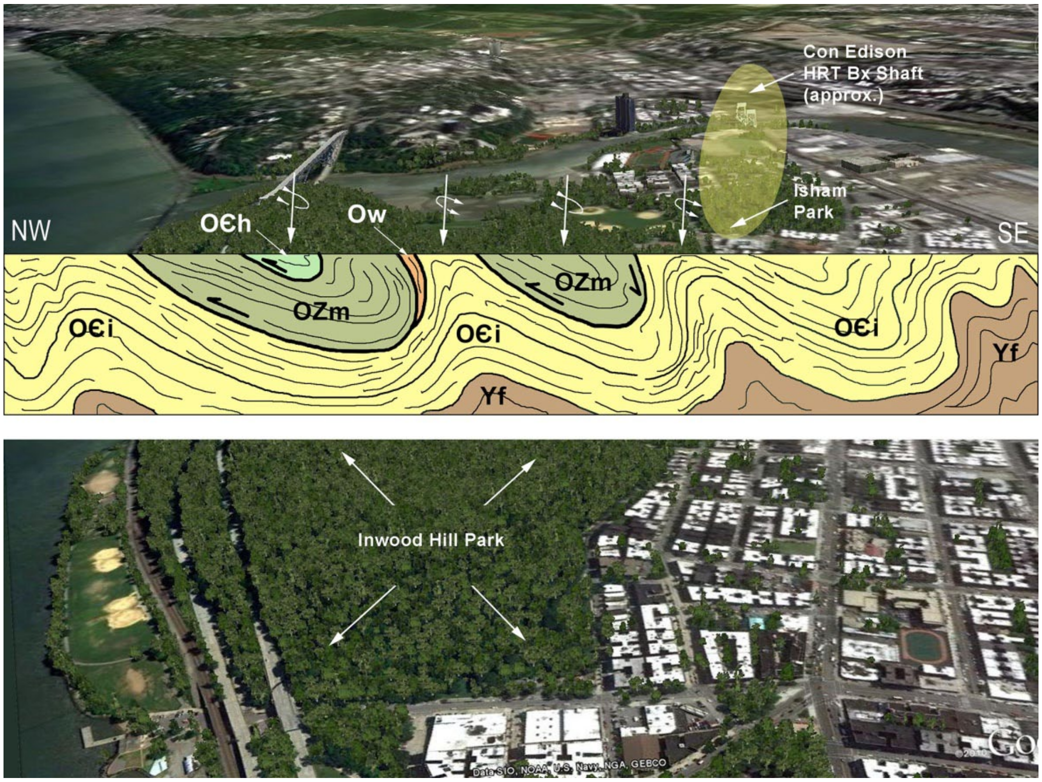

Figure 2 - Oblique northeastward Google Earth terrain view of northern Manhattan and the Bronx with Dyckman Street near the edge of the lower section. Interpretive geological section in cut-away slice roughly across Isham Street in Manhattan. Proposed along-strike correlation between Isham Park and the Bronx Shaft of a utility tunnel (approximately located for security reasons) shown in yellow shading marks the along strike extension of the SE-dipping limb of an overturned SW-plunging F_3 antiform. Note the positions of major overturned F_3 antiforms and synforms (shown in white), the folding of sheared lithologic contacts, and the position of a thin slice of Waloomsac Schist (Ow) exposed beneath the south footing of the Henry Hudson Bridge in Inwood Hill Park.

Isham Park contains near continuous exposure of white to blue-white Inwood Marble cut by high-angle conjugate joints which have facilitated the weathering process by allowing aqueous solutions to permeate the rocks (Figure 3). Several lithologies occur such as dolomitic marble, calcite marble, amd foliated calc-schist, units that contain siliceous layers and calc-silicate aggregates that stand in relief on the weathered surface (Figure 4).

Depending on the amount of impurities the Inwood Marble weathers gray or tan and produces a sugary-textured surface on outcrops that ultimately develops into residual calcareous sand. Overall, the outcrops illustrate profound differential weathering with dolomite-silicate units standing in higher relief and calcite marble forming local depressions. With a bit of imagination, an overview of the entire outcrop at Isham Park allows a vision of mini-karst-like topography. Perched on this eroded surface are a number of Palisades diabase erratics and red-colored till, products of glacial advance from the NW.

A preliminary geological map of Isham Park is shown as Figure 5. Four major lithotypes are shown – white, coarse-textured calcite marble, white to gray dolomitic and calcite marble, marble, schist and calc-silicate rock and well-layered white to gray dolomitic marble. Although variable, the Inwood trends roughly N55°E, 73° SE in Isham Park and forms the eastern overturned limb of a large F_3 synform which is cored to the west in Inwood Hill Park by the Manhattan Schist.

Figure 3 - Northward view of highly jointed east-dipping Inwood Marble exposed in Isham Park in Manhattan. Although well-foliated, the obvious compositional layering preserves ancient bedding in the rock mass. (Digital image taken 19 August 2007.)

Figure 4 - View of a cluster of aligned 6-12 cm tremolite porphyroblasts found to overgrow the S_1 x S_2 composite foliation in dark gray marble with interlayered calc-schist. We are convinced that these are pseudomorphs after diopside. Exposed portion of knife is 6 cm long. (From Merguerian, Merguerian, and Cherukupalli 2001.)

The marble, schist, and calc-silicate unit is intensely sheared and internally deformed by F_2 tight- to isoclinal and F_3 asymmetric folds producing complex interference patterns, boudinage and internal shearing of schistose boudins over a meter in dimension (Figure 6). Clearly, the marble + schist + calc-silicate sub-unit shows overthickening and repetition of layers however most of the remaining carbonate sequence exposed in Isham Park appears to be homoclinal. Perhaps the overthickening of the calc-schist unit is the result of the buttressing effect of the massive, well-layered marble that surrounds it. Asymmetric south-plunging F_3 folds are locally developed in the Inwood of Isham Park (Figure 7). Abundant examples of boudinage of the quartzite and calc-silicate layers into lenses occur presumably the result of ductility contrast between the more competent siliceous rocks and the surrounding marble (Figure 8).

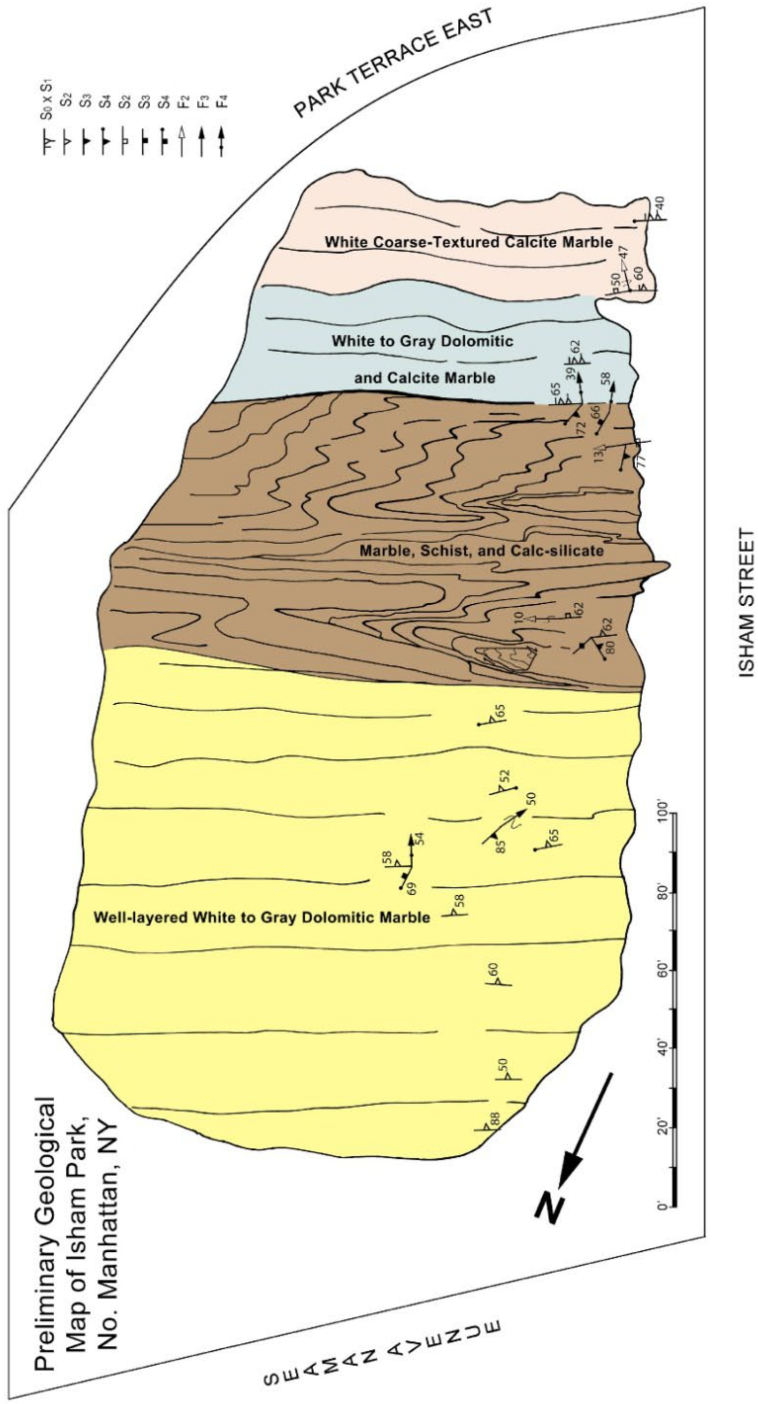

Figure 5 - Preliminary geological map of Isham Park showing the four major lithologic varieties and the form lines of the composite S_1 x S_2 foliation and parallel compositional layering. (From Merguerian, Merguerian, and Cherukupalli 2011.)

The broad outcrop-scale folding and warping of the S_1 x S_2 fabric is controlled not only by regional F_3 folds but also are affected by open 2 m-wavelength SE-plunging F_4 crenulate folds and open warps (~ 55° plunge) with axial planar slip cleavage (S_4), solution cleavage and joints trending ~ N-S bearing moderate to steep dips.

Figure 6 - View on internal deformation in the Inwood Marble of Isham Park in Manhattan showing shearing and disarticulation of resistant quartzite and calc-silicate interlayers and meter-scale blocks of calc-marble and the overall complex patterns produced by gently plunging upright F_2 isoclinal folds. (Digital image taken 08 Sept 2007.)

Figure 7 - View of a south-plunging asymmetric F_3 z-fold of layering and foliation in the Inwood Marble of Isham Park in northern Manhattan. Pen points in plunge direction. (Digital image taken 08 Sept 2007.)

Figure 8 - View of disarticulated boudin of quartzite (former chert?) in differentially weathered Inwood Marble exposed in Isham Park in northern Manhattan. Such features result from the mechanical differences between the competent quartzite and the less competent marble which undoubtedly flowed around the resilient quartzite layers and lenses. Note 9-cm long black pocket knife to left of boudin for scale. (Digital image taken 19 August 2007.)

Inwood Hill Park

The area of Manhattan north of Dyckman Street is known as the Inwood section. Except for Inwood Hill Park most of the region is underlain by the Inwood Marble marking the type-locality for that particular unit of NYC bedrock. This unit was originally called the Inwood Limestone by Merrill (1890). The geology of Inwood Hill Park is published elsewhere (Merguerian and Sanders 1991; Merguerian, Merguerian, and Cherukupalli 2011) but a brief summary is in order. Inwood Hill Park is located in the extreme northwest corner of Manhattan Island (Figure 22). The park is bordered by Dyckman Street on the south, the Hudson River on the west, Spuyten Duyvil (Harlem Ship Canal) on the north, and Payson and Seaman Avenues on the east. Isham Park occupies the flat area northeast of Inwood Hill Park extending eastward to Broadway between Isham and West 214th Streets.

We enter Inwood Park by following the path past the playground. The first prominent ridge to your left is composed of Manhattan Schist (OZm) which also dips steeply toward the SE, essentially parallel to the orientation of the Inwood Marble exposed in Isham Park. The S_3 foliation in the schist is related to F_3 folds with axial surfaces oriented N4l°E, 75°SE and south-plunging hingelines. The F_3 structures are superimposed on an older gently inclined S_2 metamorphic layering which trends across Manhattan at roughly N50°W, 25°SW (Merguerian, 1983, 1996a). Both units are in contact but the contact is covered with soil. They form part of a huge south-plunging syncline with the Manhattan Schist preserved in the central core of the structure (Figure 10).

Strangely, the downfolds (synclines) hold up ridges and the upfolds (anticlines) underlie the flat valleys in northern Manhattan. Such inverted topography results from the marked contrast in weathering susceptibility afforded by the marble and schist. In the overall wet temperate climates such as we experience in this region, carbonate rocks (such as the Inwood Marble) weather and dissolve much more readily than do silica-rich rocks of the Manhattan Schist. As a result, structural synclines tend to be preserved to form topographically high ridges and structural anticlines are breached by weathering and erosion and commonly underlie the low valleys. (See Figure 2.) Such topographic inversions are well known in the folded central and northern Appalachians.

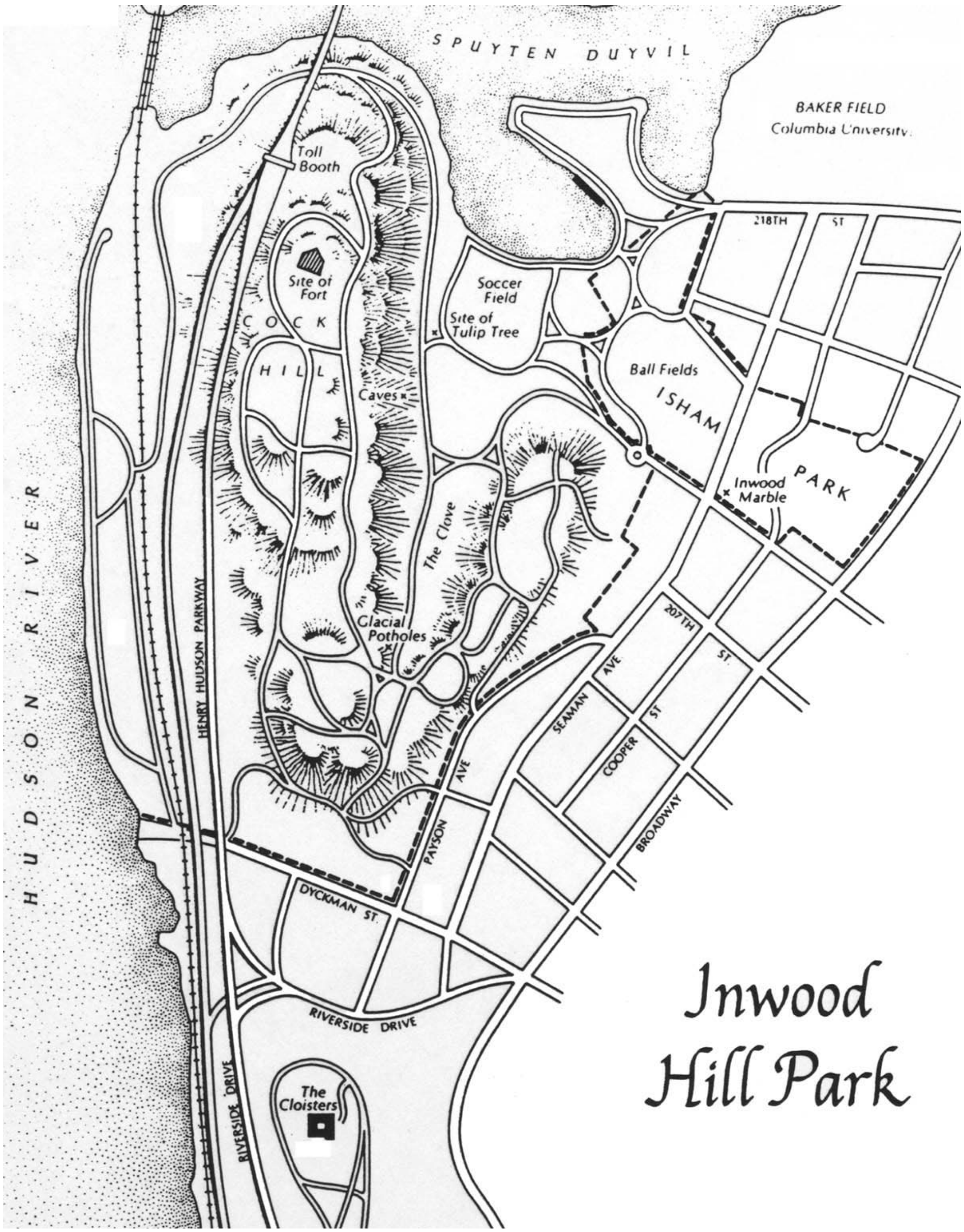

Figure 9 - Index map showing the location of our field trip area in Isham and Inwood Hill parks in northern Manhattan. You can use this map to put in the ad-hoc field stops for today's trip to Locality 1.

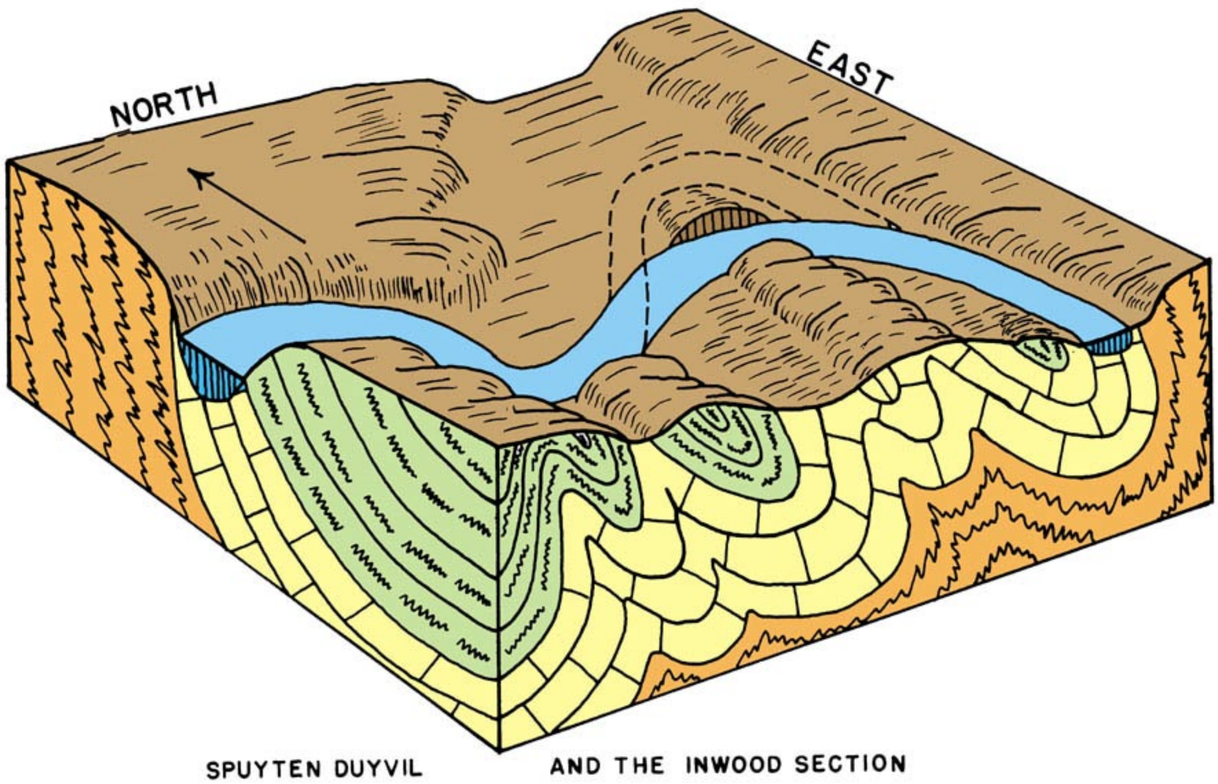

Figure 10 - Block diagram illustrating the structural geology of Inwood and Isham parks. Note that the topographically higher portions of Inwood Park are underlain by the Manhattan Schist (green) and that the topographically lower portions are underlain by the Inwood Marble (yellow). This is the result of the difference in weathering susceptibility of the Inwood and Manhattan. In overall humid, wet climates such as we experience in this region, carbonate rocks (such as the Inwood) weather much more readily than do silica-rich rocks of the Manhattan Schist. Note how the topographically higher ridges are structural synforms (downfolds) yet the valleys are underlain by structural upfolds (antiforms). Such "inverted" topographic relationships are common in the folded Appalachians. (Legacy diagram from CCNY Geology Department.)

Take the “high-road” path going southward to examine the dual potholes drilled into the east-facing slope of the westernmost synclinal ridge. The structure of the westernmost ridge is another south-plunging syncline overturned toward the northwest. (See Figure 10.) The S_3 foliation in the Manhattan schist has transposed earlier fabrics and is associated with tight isoclinal F_3 folds south-plunging hingelines and axial surfaces oriented N41°E, 75°SE. At the north end of this ridge, we'll see the S_2 foliation change trend from NE to NW to wrap around the synformal trough.

At the top of the trail, a bonus for glacial enthusiasts, two circular potholes produced by torrents of meltwater during the Pleistocene deglaciation are found (Figure 11). Clearly the potholes are cut into an already glacially polished rock outcrop. Here, we assume that resistant glacial drift boulders settled into a small depression (perhaps in ridge hugging drift) and then began to drill downward in response to vortices produced during turbulent flow from liberated glacial melt waters. A self-fulfilling prophesy, once the drilling begins the resistant boulders are trapped and constantly replenished by new boulders moved by water. In this case (Figure 11) the upper pothole merged to drill a second adjacent pothole. Since the potholes are developed on a sloping glaciated surface (pre-Woodfordian?), it may be tempting to envision that the potholes formed during a younger glaciation (Woodfordian?).

Figure 11 - View of dual potholes “drilled” by resistant boulders driven by glacial meltwater torrents. (Digital image taken 13 Nov 2004.)

Farther up at the top of the trail past the potholes but before the trail bends into a hairpin turn to the right, note the highly polished outcrop of Manhattan Schist (Figure 12). The glacial striae and grooves are oriented N35°W to S35°E indicating the same glaciation that brought Palisades boulders from New Jersey. Sanders and Merguerian (1998) suggest this glaciation (from the NW to SE) was responsible for most of the deep glacial erosion in the NYC area and produced the prominent Harbor Hill moraine that extends across Staten Island, Brooklyn, Queens, and Long Island.

Figure 12 - View from the NNW of a glacially polished outcrop of Manhattan Schist in Inwood Hill Park showing a smooth up-glacier side (foreground) and steep, rough down-glacier side (behind White Fang). The glacial striae and grooves are oriented N35°W to S35°E, a product of the pre-Woodfordian glaciation. (Digital image taken November 2007.)

<u>To Scenic Overlook of Hudson River and Palisades Intrusive Sheet</u>

Continue up the trail on top of the westernmost ridge and jog left after awhile to get to the fine overlook across the Hudson to the Palisades ridge of New Jersey (Figure 13). Here, the columnar joints of the Palisades ridge are quite visible forming a steep wall of mafic rock that was intruded at shallow depth during the late Triassic-Early Jurassic split up of Pangea. Thus, we view across the Hudson, the products of a totally different type of tectonic activity than we have been viewing today. The metamorphic rocks of New York City were produced during deep-seated compressive deformation while the sedimentary and igneous rocks of New Jersey were produced by extensional tectonics associated with initial formation of the Altantic Ocean basin. A cross sectional view from Manhattan to central New Jersey (Figure 14) shows that the entire Newark Basin is a rotated block of the earth's crust with downward motion and westward tilting accommodated along the Ramapo fault. In this way the ancient Newark Basin is analogous to the modern rift basins of East Africa.

Figure 13 - View from the overlook atop the westernmost ridge of Inwood Hill Park westward across the Hudson River towards New Jersey. Note the glacially polished exposure of schist and the NW-SE trending grooves and striae pointing to the Palisades sheet of New Jersey. (Digital image taken November 2007.)

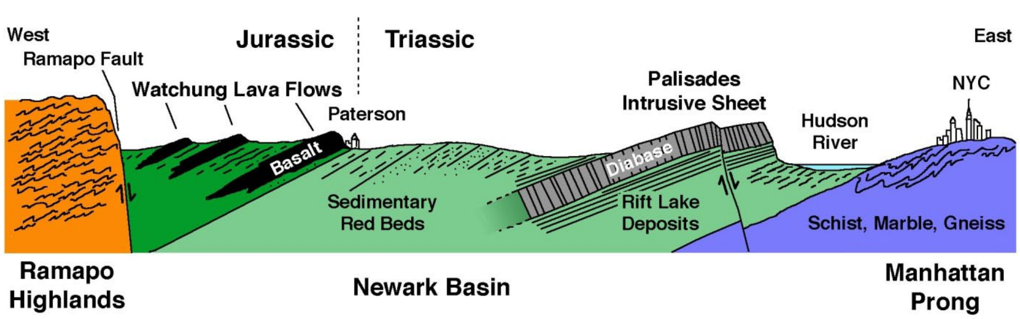

Figure 14 - Cross section showing the geology of the Newark Basin and its relationship to the basin marginal Ramapo fault. Note also the nonconformable contact with the deformed rocks of New York City. The nonconformity spans roughly 300 million years of missing time and thus project with regional tilt of about 12° NW above Manhattan Island. (From Bennington and Merguerian 2007.)

From the scenic overlook walk northward along trail toward the Henry Hudson Bridge and note that the foliation in the schistose rocks is oriented northwesterly and dips southward at the end of the trail before it heads downward. As mentioned earlier, this is the result of the wrapping of the early S_1 x S_2 foliation in the schist about the southward-plunging keel of the overturned F_3 synform that holds up the westernmost ridge.

The contact between the middle and lower schist units (the St. Nicholas thrust) is exposed in a 20 m zone from beneath the Henry Hudson Bridge abutment to river level. Structurally beneath the Manhattan Schist, a 0.5 m layer of sheared (mylonitic) amphibolite is deformed by folds. Unlike the amphibolite in the schist unit above, which contains subidioblastic hornblende, this exposure of Manhattan amphibolite has been intensely sheared. Green hornblende porphyroclasts are set in a wavy, anastomosing foliation consisting of colorless amphibole, biotite, and quartz ribbons. The thrust zone is structurally complex consisting of intercalated lithologies of Walloomsac (Ow) and Manhattan Schist (OZm) together with mylonitic amphibolite. The Wallomsac is highly flattened and mylonitic at this location with a strong down-dip lineation, the result of localized shearing associated with the St. Nicholas thrust zone.

Directly beneath the bridge, where a dirt trail leads down to the river, a coarse-textured gray-white calcite marble with differentially eroded calc-silicate nodules is exposed at low tide. It is unknown whether the marble exposed at the low-tide mark is an interlayer in the Walloomsac schist (Ow) or the Inwood Marble (OꞒi). Unquestionably, the Inwood Marble lurks nearby as it wraps around the westernmost ridge of Manhattan Schist and underlies the Spuyten Duyvil, Marble Hill in the Bronx, and the Hudson River and was penetrated by a utility tunnel found east of and parallel to the Broadway Bridge. As a geometric result of the southward plunge of the major folds, the oldest unit of the NYC bedrock (Fordham Gneiss) projects up to the surface in the Bronx in a huge vertical exposure immediately across the Harlem Ship Canal. Here, in the Bronx, the Fordham is painted blue with the Columbia University “C”.

Locality 2 - Central Park

The impressive natural rock exposures left in Central Park by implementation of Olmstead and Vaux's Greensward Plan stand as geologic sentinels that offer the geologist a glimpse into the past. Sculpted by glacial ice from at least two contrasting ice-flow directions during Pleistocene times, the rocky knolls expose at the earth’s present surface evidence of sedimentary- and volcanic protoliths that were folded and metamorphosed at depths originally exceeding 20 km. Uplift and erosion have elevated these former deep-seated rocks allowing analysis and interpretation by geologists.

J. F. Kemp (1887) produced the first detailed map of Manhattan, here colorized and reproduced as Figure 15. The map and closely spaced sections were made at a time when bedrock was well exposed in the city both naturally and as a result of active construction. Sections G-H and E-F especially show the dominant tightly-folded structure of Central Park. Detailed work throughout Manhattan by CM started in the early 1970s which ultimately indicated that all three of the units formerly lumped as the Manhattan Schist were present in Central Park. The bulk of the rocks are in tectonic contact with the underlying autochthonous Walloomsac-Inwood sequence. With few exceptions, the southern part of Central Park consists of rocks of the Hartland formation (OꞒh). North of roughly 80th Street, the rocks are predominantly Manhattan Schist (OZm) and Wallomsac (Ow) and Inwood (OꞒi) dominate from

105th Street northward. They crop out along the edges of Mt. Morris Park (near 123rd Street), a klippe that places Manhattan Schist structurally above Walloomsac and Inwood. Rocks found within Cameron's Line bear mylonitic fabrics recording a former deep-seated ductile shear zone. By 1983 a geological map of the south part of Central Park (Figure 16) showed the distribution of Hartland and Manhattan rocks and the position of Cameron's Line between them.

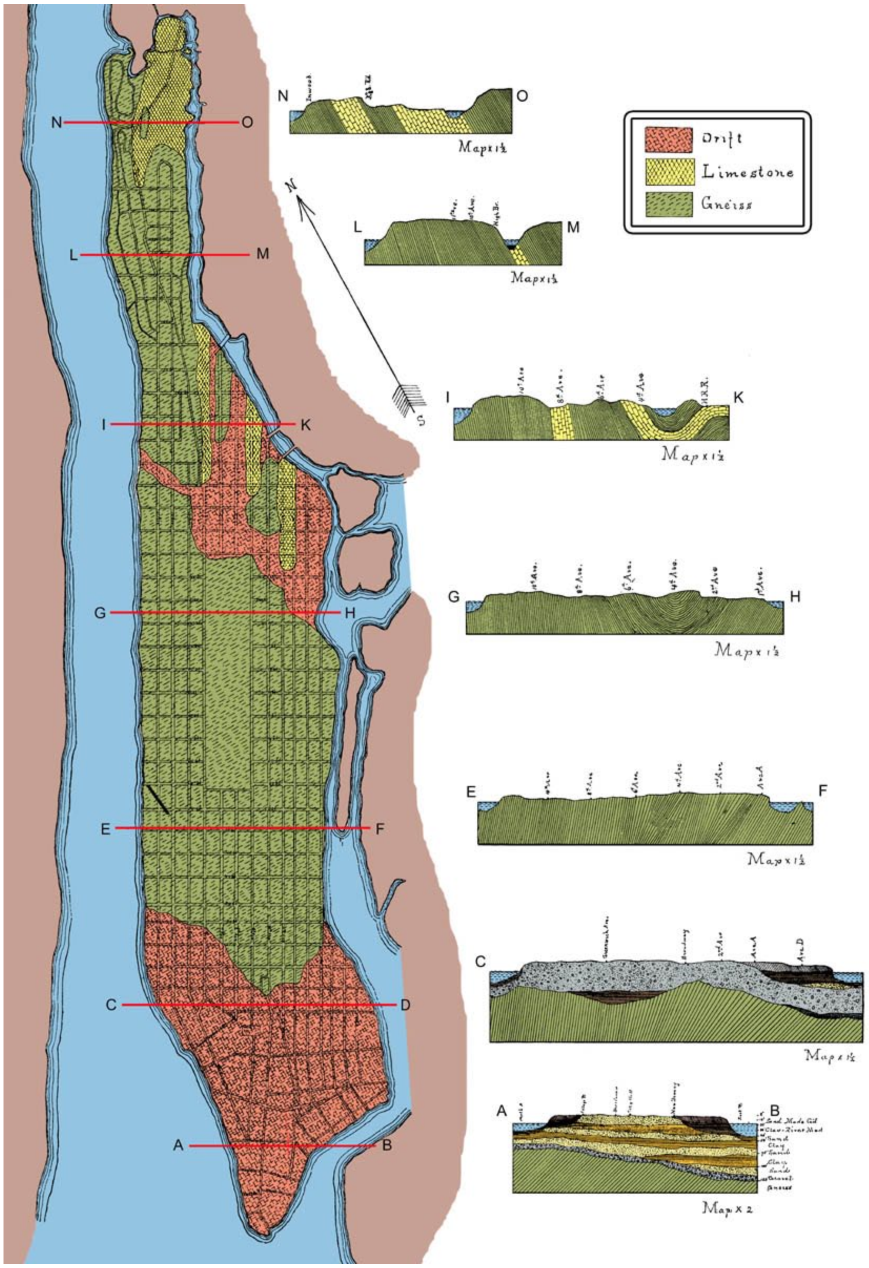

Figure 15 – Colorized version of the first geological map of Manhattan based on the work of J. F. Kemp (1887). The geological profile-sections were drawn parallel to streets in Manhattan with subsurface relationships in the southwestern part based on borings. Produced in an era when rocks were exposed in a rural setting in the north half of the island and when they were also being uncovered in excavations, Kemp's sections are detailed. For the purposes of illustration, we have colored the Manhattan "Gneiss" as a single unit as Kemp originally intended. Notice that the scale of the profile-sections does not match that of the map.

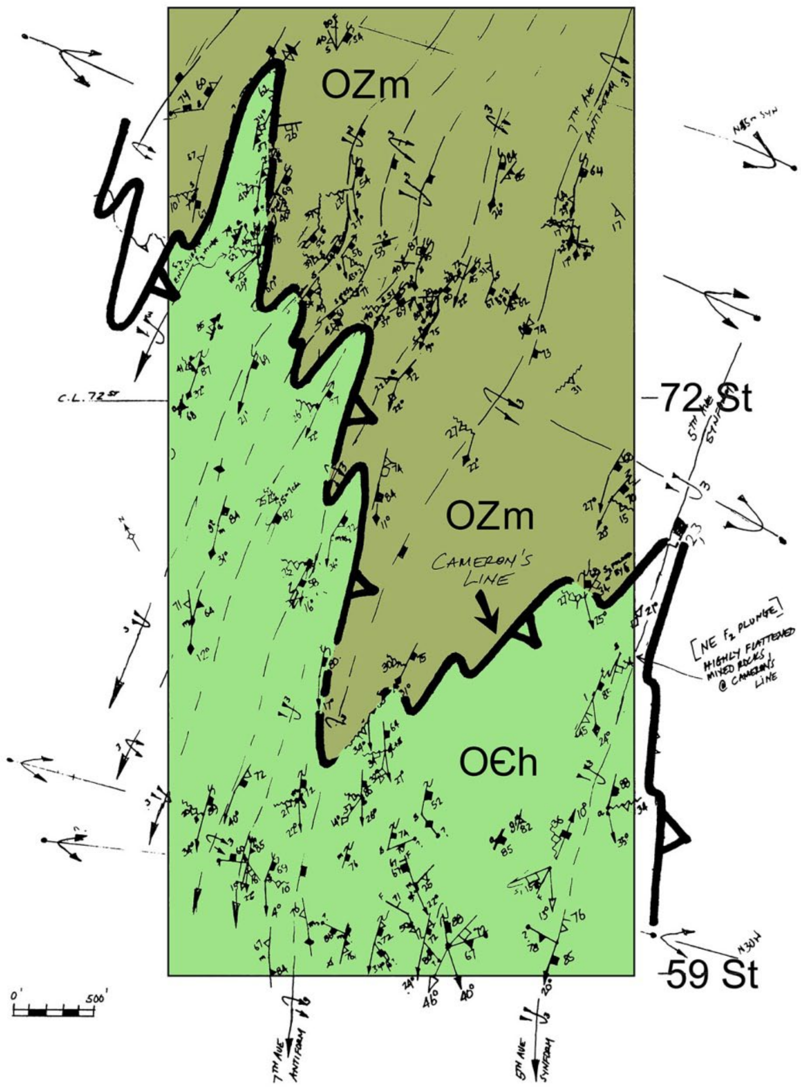

Figure 16 – Geological map of the southern part of Central Park showing the trace of Cameron's Line, axial surface traces of major folds, and structural details.

Taterka's (1987) work in Central Park agreed with CM's earlier interpretation of the overall geologic relationships. Taterka placed the trace of Cameron's Line across an outcrop-free area of Central Park in the vicinity of the Great Lawn between 80th and 86th streets (Figure 17, left panel) and showed a relatively simplistic folded structure unlike the patterns actually found in the bedrock. He subdivided the Manhattan and was able to trace early structures across the park and provided important basic cartographic and petrographic information. Based on our new investigations and considering the degree of superposed F_1 and F_2 isoclinal folding and shearing observed in the field, we suggest that Taterka's interpretation and CM's previous interpretation of the geometry of Cameron's Line are too simple. Baskerville's (1994) placement of Cameron's Line across the extreme northern part of Central Park (Figure 17, right panel) simply does not agree with our mapping. Yet, he has identified the Walloomsac in the northern part of the park in an area mapped as the 110th Street member of the Manhattan by Taterka. We agree with the Manhattan call on the bulk of these rocks and have found Walloomsac in the northern part of Central Park during recent mapping.

New Geological Map of Central Park

Our new bedrock map of Central Park (Figure 18) is similar to earlier efforts (compare with Figures 16 and 17) but we have modified the position of Cameron's Line and have adjusted the position of bounding lithotypes. The major revision that we have made is that well-layered Hartland rocks occupy a broader area on the east-central side of the park and a refinement of the structural interpretation. Owing to a lack of exposure to the east of the park we are not sure whether the northern Hartland exposures constitute a separate allochthonous sheet that terminates against the 125th Street fault (along the NE corner of the park), whether the two strands of Cameron's Line are sheared against each other, or whether they merge into an F_2 fold hinge. In the third case, the development of the dislocation known as Cameron's Line would be very early in the structural sequence (D_1). If the exposed areas are indeed separate, Cameron's Line may be the product of the D_2 event. Clearly, Cameron's Line shows strong deformation by S-plunging F_3 major and minor folds.

The complex sequence of structural events established from other parts of New York City (Merguerian 1996a, 2015) is identical to the structural sequence mapped in Central Park. The obvious map scale folds in Central Park (F_3) are those with steep N- to NE-trending axial surfaces (S_3) and variable but typically shallow plunges toward the S and SW. The folds are typically overturned to the NW with a steep SE-dipping schistosity. 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 during both the D_2 and 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). As explained in our accompanying 2016 NYSGA paper, we suspect that all of these structures (D_1, D_2, and D_3) are products of the Taconic orogeny (Figure 19).

During D_2, the rocks acquired a penetrative S_2 foliation consisting of intergrown and oriented kyanite with flattened quartz together with staurolite and garnet porphyroblasts. The 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, 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 event, a period of L-tectonism, smeared the previously flattened kyanite+quartz layers and lenses into elongate shapes parallel to F_3 axes.

The D_1 to D_3 folds and crosscutting fabrics 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 fabric elements. We suspect that the younger fold phases record the effects of the Acadian- and terminal-stage Appalachian orogenies. On the geological map (Figure 18) we show 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. Their brittle 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. Their abundance suggests a major post-Taconian retrograde metamorphism, presumably coincident with the intrusion of post-Taconian wet granitoids throughout the Manhattan Prong discussed by Brock and Brock (2001).

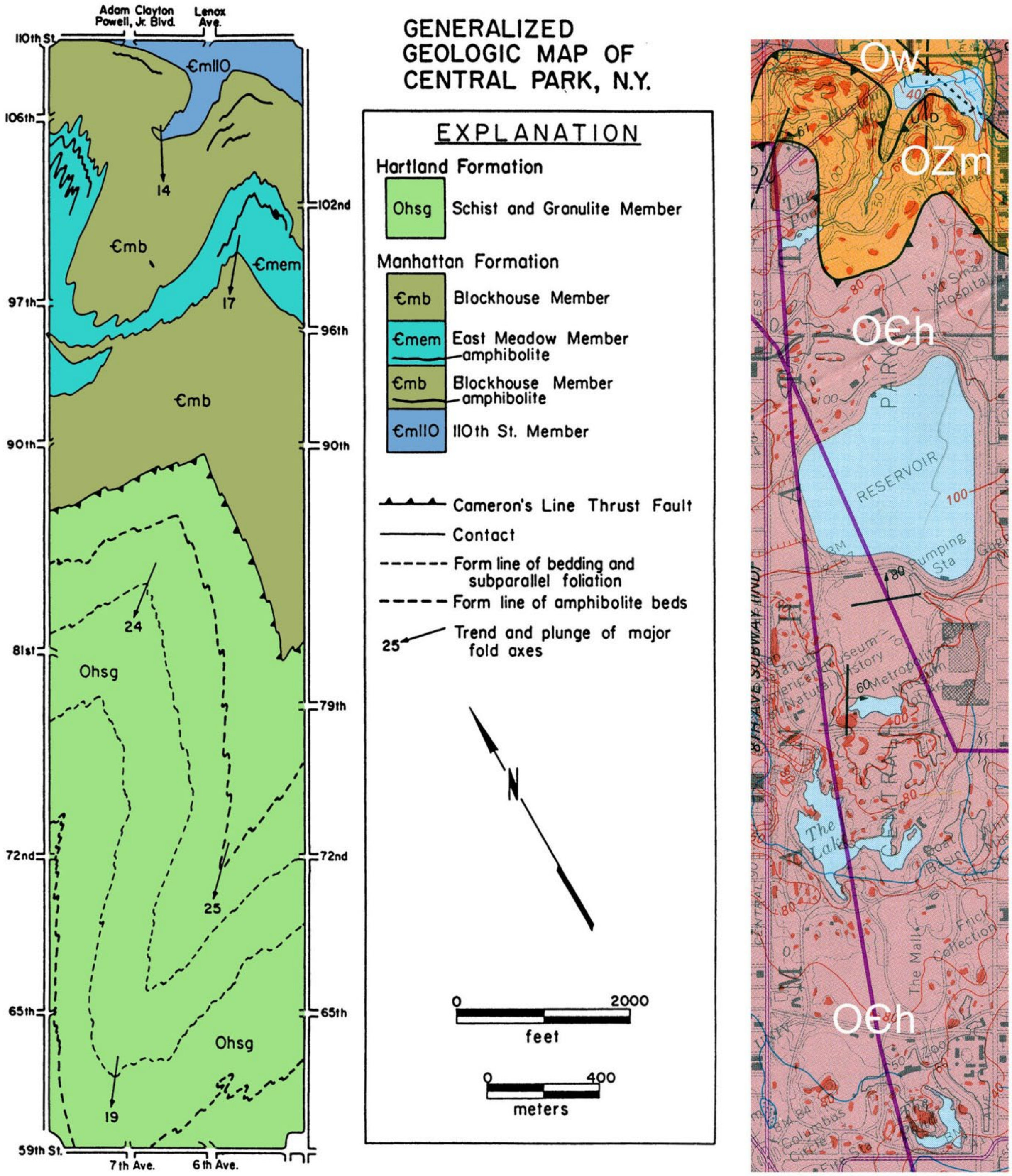

Figure 17 – Colorized and annotated bedrock maps of Central Park by Taterka (1987, left panel) and Baskerville (1994, right panel). See discussion in text.

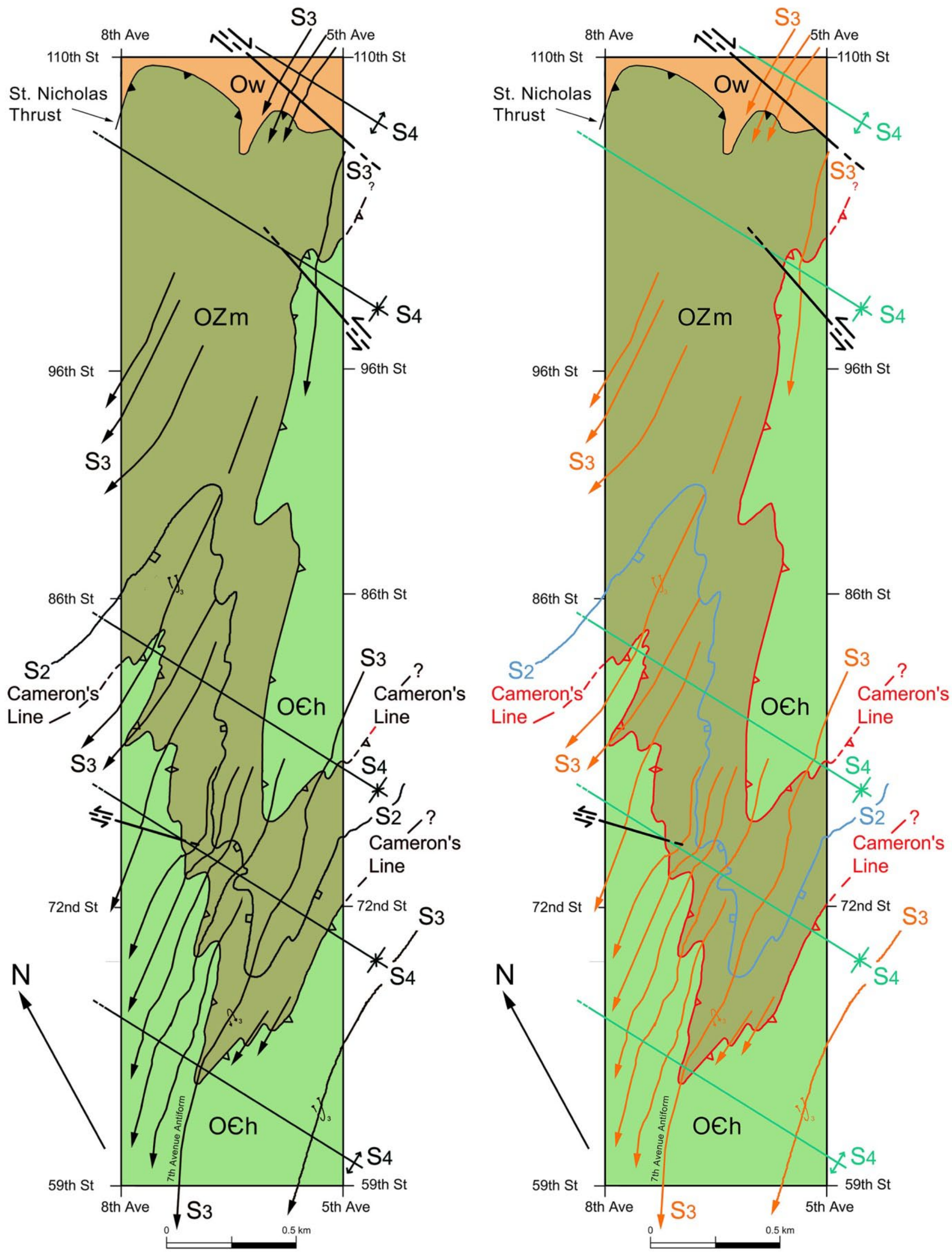

Figure 18 – Preliminary bedrock geological map of Central Park showing ductile and brittle faults and the axial traces of the major structural features, based on our current mapping program.

Figure 19 – Downplunge view of south-plunging F_3 fold in Hartland formation with green pencil aligned with the steep SE-dipping S_3 axial trace. Note how the F_3 synform folds an older F_2 long-limbed isocline in thin quartzose granofels. The similarity in metamorphic grade and style of the three superposed structures suggests they are genetically related; we suspect the Taconic Orogeny as the culprit (CM Stop N361.)

Brittle Faults

Two generations of brittle faults cut Central Park. They conform to the Group D and Group E faults found in the Queens Tunnel and elsewhere in NYC (Merguerian 1996b, 2002a). Group D faults form a major system of NNE-trending dip-slip normal faults and related joints with an average N21°E trend and steep dips. Fault-associated mineralization takes the form of zeolite minerals (especially orange stilbite) and calcite. In the fault surface, dip-slip slickenlines show oblique-slip reactivation, the result of younger (Group E) faults. Both Group D and Group E faults cut Permian (295 Ma) rhyodacite dikes in the Queens Tunnel (Merguerian, 2001, 2002b, 2004). Regional joints mimic the brittle fault orientations and are characterized by their unique infilling mineralization.

The youngest group of brittle faults trend N20°W to N50°W, exhibit steep dips and show predominately strike-slip offset. These typically healed faults are steeply inclined with subhorizontal slickensides, flower structure, and mineralization that includes quartz, K-feldspar, and microcrystalline epidote veining. In the Queens Tunnel, areas cut by the Group E faults are typically highly fractured and show evidence of high internal strain in the form of overstress phenomenon including invert heave, spalled rock slabs, rock popping, and other forms of overstress phenomenon within the excavated tunnel perimeter (Merguerian and Ozdemir 2003).

Both left-lateral and right-lateral Group E faults cut the park in three places. Across the NE tip of the park right-lateral offset is indicated for the 125th Street or Manhattanville fault, based on regional map pattern. (See Figures 18 and 20) Two areas in Central Park show evidence for left-lateral strike slip faulting. The northern fault (N12°W) cuts vertical isoclinally folded gneiss and amphibolite of the Manhattan formation near 101st Street and the East Drive. Three main slip surfaces and many healed microfaults cut the glaciated exposure and show well over a meter of composite offset (Figure 20). The southern fault (N45°W, 90°) shows very minor left-lateral offset in highly jointed Hartland granofels near the Ladies Pavilion on the west side of The Lake.

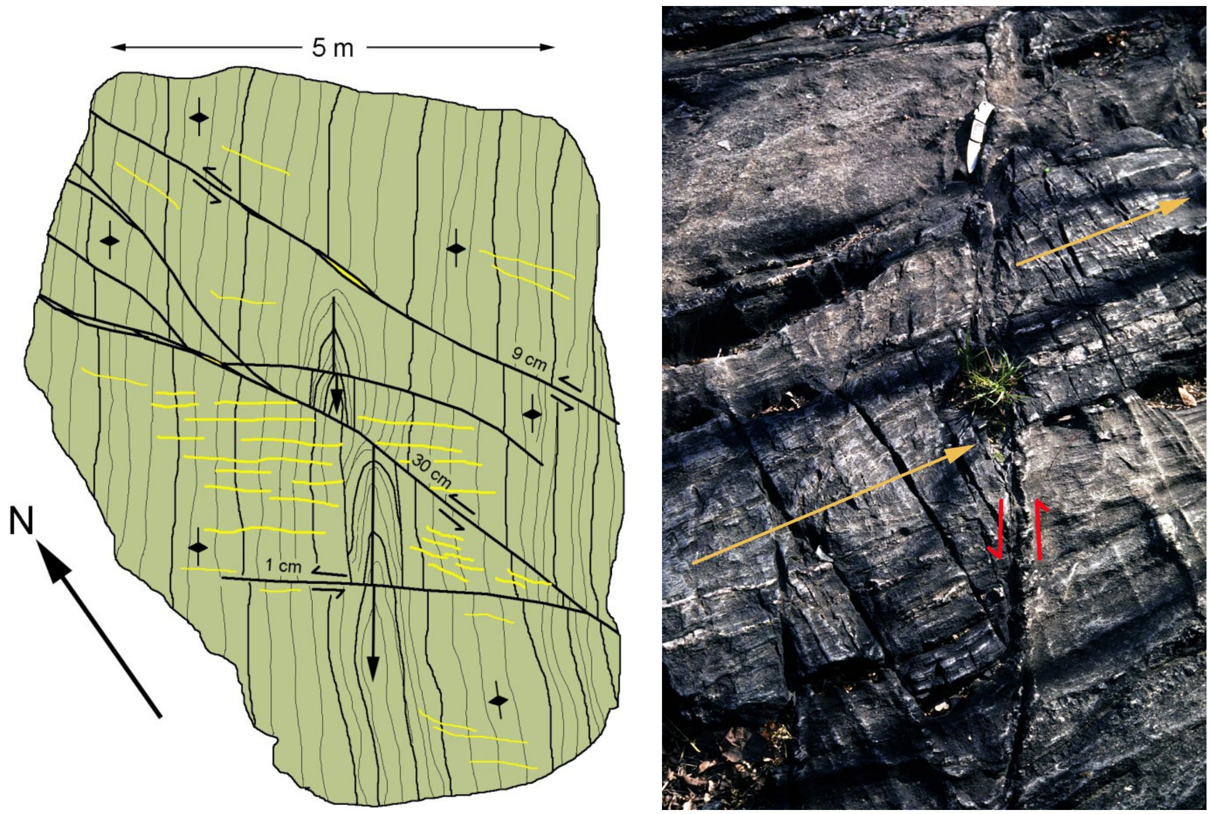

Figure 20 - Field sketchmap showing Group E fault in northern Central Park near intersection of 101st Street and the East Drive. Field image (R) shows 30 cm left-lateral offset of isoclinal folds and vertical fabrics in Manhattan Schist (OZm). (CM Stop N537.)

The famous McCoun map of 1609 shows the drainage systems before urbanization took hold in Manhattan. In Figure 21, we have shown the NW-trending Group E fault traces mapped in the park and suggest that other drainages outline faults not found in the field owing to poor exposure. The epicenter of a small earthquake (~2.4 Richter) localized in NYC on 17 January 2001 plots adjacent to the trace of the 125th Street fault near 102nd Street and Park Avenue in Manhattan. Later that year, on 27 October 2001, another similar earthquake (~2.6 Richter) struck NYC with an epicenter near 55th Street and Eighth Avenue. I have plotted these epicenters on Figure 7 to show that they are spatially coincident with NW-trending faults. North of NYC, seismicity along the NW-trending Dobbs Ferry fault in late October 1985 included two small (~4.0) tremors and many aftershocks. More robust earthquakes in and around the vicinity of NYC were recorded in 1884 (~5.0-5.5), 1783 (~4.9), and 1737 (~5.2). In The Bronx, field and geomorphic evidence suggests that right-lateral offset along the NNW-trending Mosholu fault was a post-glacial phenomenon with demonstrable offset of surface drainage (Merguerian 1996b; Merguerian and Sanders 1996, 1997). Because the contemporary stress regime in the lithosphere is oriented NE-SW, left-lateral offset should be expected in W- to NW-trending faults but NNW-trending faults might exhibit contemporary right-lateral offset. Given the modern stress regime, the presence of Group E NNW- and NW-trending faults in the NYC area portend seismic risk.

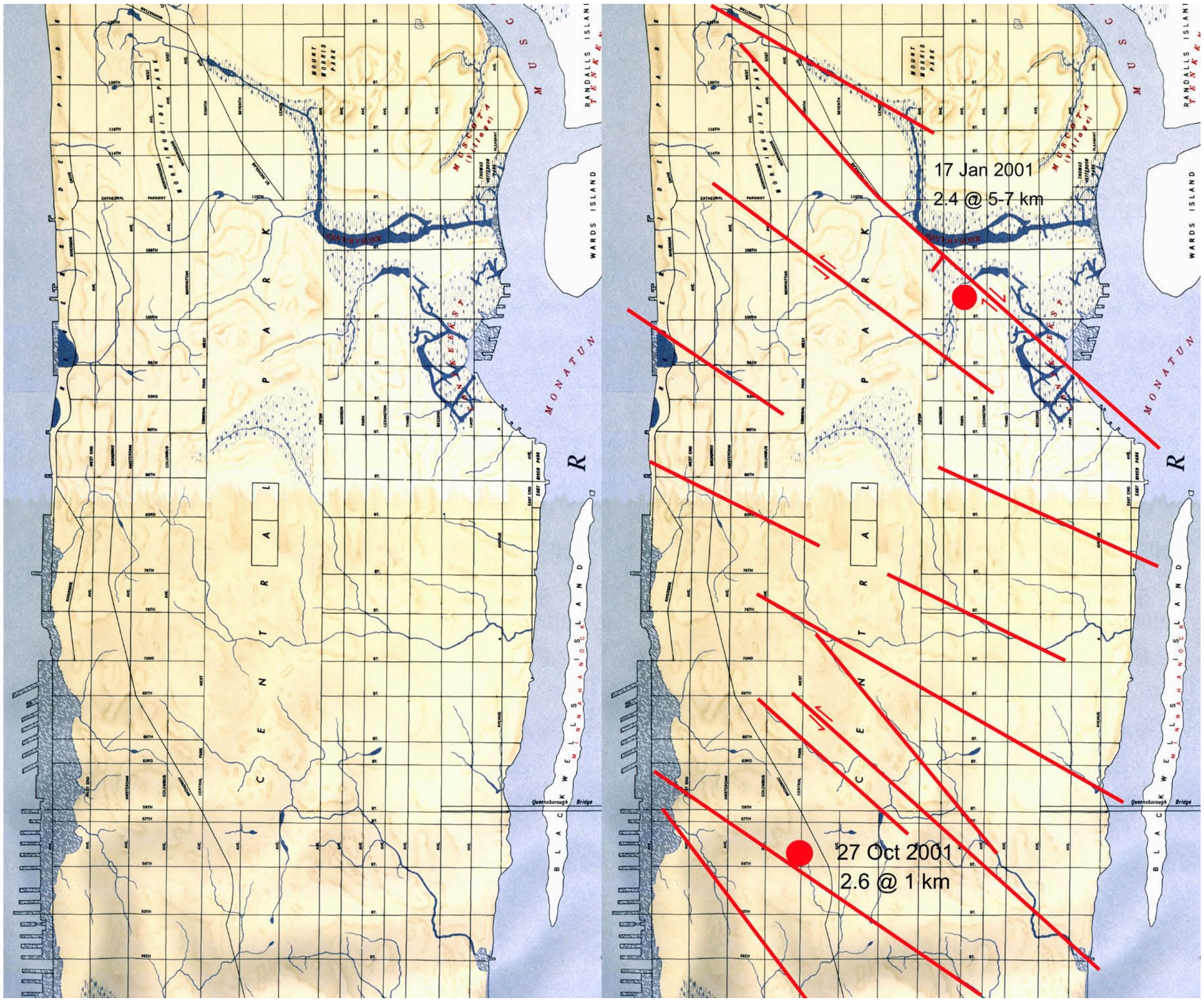

Figure 21 – Topographic map of Manhattan by McCoun (1609) showing the pre-industrial era drainage patterns. Drainages follow zones of structural weakness in crystalline rocks, typically faults. The pronounced NNW-SSE alignment of creek and stream valleys is striking. The right panel shows the traces of three mapped faults in Central Park (faults showing offset symbols), other inferred faults based on stream patterns and topography, and epicenters of two small tremors that struck Manhattan Island in 2001. Note that the vertical edge of the figure is oriented ~N30°E.

CENTRAL PARK FIELD STOPS

Field trip stops for the southern part of Central Park (Figure 22) illustrate the geology of critical exposures in the park. We will undoubtedly go visit other exposures as well.

Figure 22 – Index map showing locations of Central Park field trip stops described below.

STOP 1 - SE of Zoo work shed, Hartland formation. *[UTM Coordinates: 586.75E / 4513.10N, Central Park quadrangle.]*

The exposure consists of gray- and locally brown-weathering muscovite-biotite schist and thin interlayers of biotite granofels, rocks typical of the Hartland formation (OЄh) in New York City. The S_2 foliation, which predominates at this exposure, consists of parallel thin laminae and local syntectonic granitoid veins oriented N80°W, 34°SW. F_3 z-folds are also obvious with traces of axial surfaces oriented N42°E, 88°SE and F_3 axes plunging 35° into S17°W. Abundant pegmatite veins (some with large books of muscovite) and veinlets create a nubby weathering appearance, but should not be confused with the aluminosilicate-induced nubby weathering of the OZm unit of the Manhattan Schist. Some of the pegmatite veins have been folded by the F_3 folds. Local 10-cm thick quartzose segregations are present. An amphibolite, 15 cm thick, can be found at the south end of the exposure near 63rd Street.

Evidence for SE-directed glacial flow is obvious in the glacially sculpted exposure in the form of large- and small grooves oriented N30°W to N35°W wrapping around the south end of the exposure and at an azimuth of N40°W on top of the exposure.

STOP 2 - E of walkway just N of 65th Street Transverse Road; mylonitic Hartland formation cut by glacial grooves. *[UTM Coordinates: 586.85E / 4513.32N, Central Park quadrangle.]*

The exposures of Hartland here consist of slabby, gray-weathering vitreous quartzite layers (thicknesses usually 4 to 5 cm, but locally up to 30 cm), granofels, minor schist and amphibolite with a laminated fabric developed parallel to a composite S_2 foliation. S_2, subparallel S_1 and bedding (S_0), are strongly transposed (oriented N56°E, 45°SE) because of the effects of F_3 z-folds with axial surfaces trending N50°E, 85°SE. The F_3 folds and associated lineations plunge 24° into S21°W. Away from the limbs of minor F_3 folds, at the NE corner of the first exposure, the S_2 fabric returns to its typical orientation, roughly N53°W, 28°SW. Pegmatites, up to 2 m thick, containing K-feldspar megacrysts up to 30 cm in size, have been intruded parallel to S_3. Vertical healed joints cut the exposures at a high angle (N42°W) and show positive relief producing a reticulate pattern with the dominant lithologic layering and parallel metamorphic fabrics.

All of the scattered outcrops show the effects of glacial rounding and -polish. Glacial grooves are oriented N47°W to S47°E; they resulted from ice flowing toward the SE.

STOP 3 - E of walkway near "X" crossing of paths S of "The Dene;" mylonitic Hartland formation and glacial grooves. *[UTM Coordinates: 586.90E / 4513.40N, Central Park quadrangle.]*

Similar to the last exposure (still in view toward the S), here the Hartland possesses a pronounced mylonitic fabric because we are approaching Cameron's Line. The composite $S_2 + S_3$ foliation is oriented N70°E, 49°SE (the combined effect of transposition by F_3 fold and late warps) and has been intruded by numerous foliated lit-par-lit granitoids. In fact, two generations of granitoids cut the bedrock: 1) an older foliated generation, as mentioned above, and 2) a younger sinuous granitoid that cuts across the metamorphic layers.

Glacial grooves are here oriented N25°W to N32°W; they are products of a glacier that flowed SE.

STOP 4 - Outcrop W of "The Dene"; two sets of cross-cutting glacial features on polydeformed Hartland formation. *[UTM Coordinates: 586.83E / 4513.40N, Central Park quadrangle.]*

This large polished exposure contains rocks similar to the last three stops and shows the effects of superposed F_2 and F_3 folds. The composite $S_2 + S_3$ foliation is oriented N53°E, and is vertical (90°) or dips steeply SE. The bedrock has been cut by two generations of healed fractures, an older one trending N40°W and a younger one, N-S.

Obscured by post-glacial weathering on the E end of the exposure a partial pothole greets the observant student of geology. Nearby, glacial grooves are oriented N35°W again, supporting our earlier observations, indicating a SE-directed glacial ice-flow direction. At the NE end of the exposure a glacial treat awaits our eyes. Here, a subdued roche-moutonnée structure oriented N37°E is cut by N36°W-trending glacial grooves. Thus, one of our older glacial advances has left its indelible mark on the bedrock. (See Table 1.)

STOP 5 - By "Platform" (outcrop E of "The Dene" and N of playground); beginning of the Cameron's Line shear zone, and glacial features. *[UTM Coordinates: 586.92E / 4513.43N, Central Park quadrangle.]*

At this exposure, we will try to convince you that deep-seated mylonitic faults such as Cameron's Line are not unique single surfaces of dislocation but rather zones of imbricated lithologies (termed mélange) bearing mylonitic fabrics. Here, we see comingled gray-weathering quartzite- and granofels-bearing schist of the Hartland (OЄh) and rusty-weathering schist and gneiss of the Manhattan (OZm) formations in fault rocks bearing a highly penetrative $S_1 + S_2$ mylonitic foliation. Lithologies typical of unit OZm are mostly found near the north end of the exposure. Although variable because of F_3 folding, at the south end of the exposure, the $S_1 + S_2$ mylonitic foliation strikes N68°E and dips 22°SE and can be traced parallel to the axial surfaces of F_2 folds of the S_1 foliation in quartzites. The F_2 folds are reclined and plunge 25° into S10°W. Elsewhere, the enveloping S_2 mylonitic foliation is oriented N46°W, 27°SW.

At the north end of the large exposure, where rusty-weathering OZm predominates, OЄh granofels layers, 30 to 50 cm thick, can be seen "floating" in a schistose matrix (Figure 23). Such intermixing is perhaps the product of shearing and imbrication related to the formation of mélange within the Cameron's Line thrust zone. Here the S_2 foliation swings to N75°W, 35°SW. The folds and fabrics related to the F_2 and older folds are strongly reoriented by F_3 folds. Tight- to isoclinal F_3 folds plunge 25° into S15°W with axial surfaces oriented N28°E, 68°SE. Beautiful examples of F_2 x F_3 interference patterns are found in this exposure.

Glacial plucking has here been facilitated by joints oriented N85°E, 70°NW. A broad roche-moutonnée structure oriented N10°E occurs at the north end of the exposure and glacial grooves and troughs are found elsewhere oriented N32°W but crosscutting relationships were not observed. Based on what we saw at Stop 4, we suspect that the NW-trending grooves are younger than the roche-moutonnée structure.

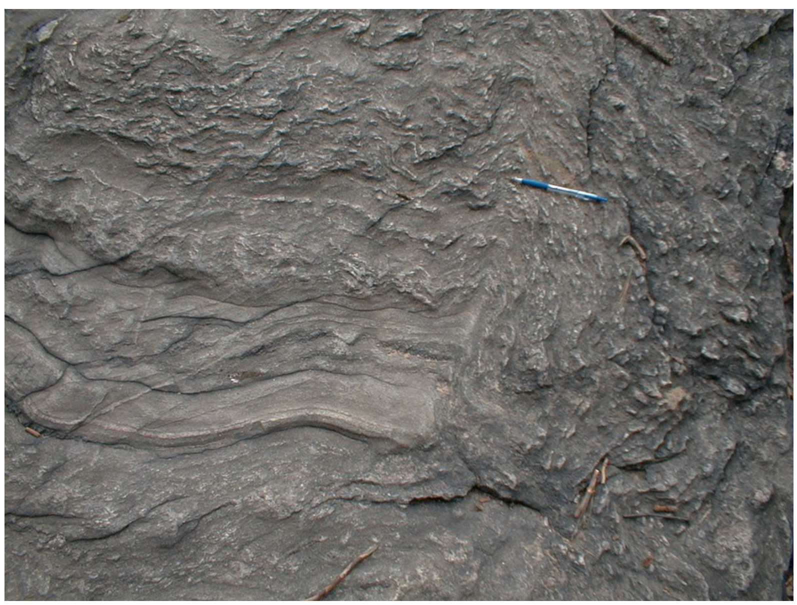

Figure 23 – Image of outcrop showing disarticulated Hartland granofels block in a tectonic mélange near Cameron's Line. (Digital image taken March 1998.)

STOP 6 - At USGS bench mark S of The Pond; typical Hartland Formation away from the Cameron's Line thrust zone. *[UTM Coordinates: 586.58E / 4512.93N, Central Park quadrangle.]*

Rocks of the Hartland formation here consist of typical gray-weathering, highly muscovitic schist and massive, structureless granofels in an exposure at the SE corner of "The Pond", across from the Plaza Hotel. The granofels layers are quite numerous; their thickness varies from 3 cm to 50 cm and they are separated by schistose layers, 3 cm to 4 cm thick, exceedingly rich in muscovite (only about 5% biotite).

Bedding is thus preserved and our interpretation is that the protoliths of the granofels layers were turbidites. With a little imagination, relict grading indicates that bedding tops toward the NW with S_0 and parallel S_2 and S_3 oriented N48°E, 70° to 80°NW.

Upright F_3 synformal folds of S_0 and S_2 plunge 20° into S45°W with axial surfaces oriented N45°E, 85°SE. A marked difference in mechanical behavior is indicated as the granofels layers show only large-scale warping at the hands of F_3 folds yet the schistose interlayers are strongly folded and crenulated. Glacial grooves are oriented N32°W indicating SE-directed glacial-ice flow.

STOP 7 - W of the Pond, opposite the Avenue of the Americas access to Park; folded and glacially polished Hartland formation. *[UTM Coordinates: 586.39E / 4513.05N, Central Park quadrangle.]*

Muscovite schist and interlayered granofels of the Hartland are cut by open warps of the composite S_2 + S_3 foliation. These folds, which must postdate the F_3 folds, plunge southward at 51° with NE-trending axial surfaces. A minor shear zone in the center of the exposure cuts through a 10-cm-thick layer of amphibolite and an F_2 reclined fold refolded by F_3 occurs on the south end of the exposure.

STOP 8 - On S side of West Drive, near SW boundary of Park; Hartland rocks sheared along F_3 limbs and glacial features. *[UTM Coordinates: 586.32E / 4513.04N, Central Park quadrangle.]*

The effects of shearing along the limbs of F_3 folds here produce a penetrative foliation oriented N32°E, 90° in highly muscovitic rocks of the Hartland formation. The effects of rounding and smoothing of the bedrock surface here are quite obvious as are glacial grooves oriented N38°W.

STOP 9 - On N side of West Drive near bridge over walkway from 7th Avenue; Hartland rocks exhibiting bedding. *[UTM Coordinates: 586.27E / 4513.20N, Central Park quadrangle.]*

Pronounced interlayering of granofels and muscovite schist here typify the Hartland formation. Bedding (S_0) and the S_2 foliation are oriented N43°W, 30°SW near the vicinity of an F_3 antiformal hinge area (7th Avenue Antiform of Figures 16 and 18). The F_2 folds here show z-fold symmetry indicating we are on the eastern side of the south-plunging antiform.

STOP 10 - Umpire Rock; Hartland rocks "safe at home". *[UTM Coordinates: 586.27E / 4513.37N, Central Park quadrangle.]*

Umpire Rock is the most-spectacular natural exposure in the southern part of Central Park. Here, rocks of the Hartland formation show the superposed effects of F_2 and F_3 folds, abundant syn- and post-tectonic pegmatite intrusives, brittle faults, and numerous glacial features. The rocks consist of interlayered muscovite schist and granofels that have been cut by numerous granitoids. F_2 fold hinges are locally preserved but the glacial smoothing of the outcrop surface inhibits direct measurement of plunge orientation. The S_2 axial-planar foliation is strongly folded here but displays an average enveloping surface of N77°W, 21°SW.

F_3 z-folds vary from open- to tight- to isoclinal in profile and plunge 22° into S25°W with axial surfaces oriented N35°E, 72°SE. Beautiful interference patterns result from the superposition of F_2 and F_3 folds. Late-stage open warps with southward plunges are locally developed. Some pegmatites are syntectonic (foliated) and were intruded parallel to S_2. Other granitoids are thin aplites oriented N50°E and crosscut all structural fabrics. Yet younger micaceous pegmatites cut the aplites. At least two brittle faults oriented N32°E cut the exposure; the one on the eastern edge of the outcrop shows a crumbly gouge zone roughly 3 m thick.

Perhaps the most-obvious geologic features here are of glacial origin. At the NW edge of the exposure, glacial meltwaters have modified spectacular glacial troughs oriented N28°W. These troughs are related to the overall SE-directed roche-moutonnée shape of the exposure with its steep drop off toward the playground area. A potpourri of glacial erratics can be found on this outcrop. We identified erratics of Palisades diabase and hornfelsic Lockatong Formation from the Newark basin W of the Hudson River, granite, and diorite.

Around the steep, north-facing wall of the exposure, note the glacial grooves oriented N46°W and the grooves oriented N35°W on the eroded outcrops immediately north of the north-facing wall. Of additional structural interest, the north-facing wall offers a rare glimpse at the shallow dip of the S_2 foliation and a sub-parallel granitoid sill, all folded by F_3? or younger open warps.

STOP 11 - E side of walk E of Heckshcer Playground; pegmatite erratic on glacially polished Hartland rocks. *[UTM Coordinates: 586.39E / 4513.38N, Central Park quadrangle.]*

The most-obvious feature of this stop is the 2m-high K-feldspar megacrystic pegmatite erratic but we can not be sure whether the erratic has been placed there during park construction or renovation. The "erratic" rests on rocks of the Hartland that have been scored by N38°W glacial grooves. F_3 s-folds are locally found in the exposure.

STOP 12 - E of junction of walks N of Stop 11; mylonitic Hartland rocks. *[UTM Coordinates: 586.39E / 4513.39N, Central Park quadrangle.]*

The Hartland formation here shows some evidence for lithologic mixing; rocks of the Manhattan formation are present in the form of tectonic inclusions consisting of wisps- and shreds of aluminosilicate-bearing, rusty- to maroon-weathering schist. The outlines of the wisps and shreds are masked by shearing along S_2 and S_3. S_2 is well developed here and is oriented N68°W, 42°SW. F_3 folds are not hard to spot with their typical southward plunges and steep NE-trending axial surfaces.

STOP 13 - By the Carousel; the Manhattan formation. *[UTM Coordinates: 586.45E / 4513.43N, Central Park quadrangle.]*

The exposure of rocks immediately west of The Carousel show the rusty- to maroon-weathering typical of the Manhattan Formation (OZm). Layers and lenses of kyanite+quartz+magnetite weather in positive relief and outline the S_2 foliation which is largely mylonitic. Here, S_2 is variable but oriented N70°E, 25°SE because of pervasive F_3 folds plunging 34° into S25°W. The F_3 axial surfaces trend N42°E, 68°SE. We map this area as the beginning of the Cameron's Line thrust zone and links these exposures to those found at our earlier Stop 5.

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