

Geology of Central Park – From Rocks to Ice

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Introduction

Geologically, Central Park exposes metamorphosed Paleozoic and possibly older allochthonous bedrock of the **Taconic Sequence** (Hartland and Manhattan formations) and minor exposures of the **Tippicanoe Sequence** (Walloomsac formation). Carbonate rocks of the **Sauk Sequence** lurk just outside the northern confines of the park as the Inwood Marble. The three sequences constitute parts of an evolving passive margin that changed over to a convergent margin during the Taconic orogeny (Merguerian and Sanders, 1996a). The rocks of Central Park show evidence for polydeformation under ductile conditions with Taconian shearing and recrystallization followed by younger folding, retrograde metamorphism, and subsequent brittle faulting. In addition, the bedrock knolls of the park have been modified by multiple episodes of Pleistocene glacial erosion. The park is simply a marvelous outdoor teaching laboratory for inquiring students of all aspects of geology.

Starting in 1972, the senior author (CM) began field and laboratory investigations in New York City area that persist to the present day. Drawing upon comparisons made with New England rocks in Connecticut and Massachusetts, by 1981 he concluded that the rocks assigned to the Manhattan Schist in Manhattan and The Bronx could be subdivided into three roughly coeval schistose tectonostratigraphic units separated by two regionally important ductile shear zones known as Cameron's Line and the structurally lower St. Nicholas thrust. These interpretations agreed in part with designations proposed by Hall (1976, 1980), but indicated the presence of a hitherto unrecognized, structurally higher schistose sequence that was a direct lithostratigraphic correlative of the Hartland formation of western Connecticut (Merguerian 1981, 1983a, b). The three ductile-fault-bounded schist units of Manhattan Island were presumably juxtaposed during a Medial Ordovician collision between the eastern continental margin of North America and an offshore volcanic archipelago (the Taconic arc).

Over the past two decades, while conducting fieldtrips for Hofstra University geology majors and for the On-The-Rocks field trip program hosted by the New York Academy of Sciences, continual field checking and remapping throughout NYC has resulted in a new map of Central Park, which draws heavily from mapping performed in 1980-83 and all new work conducted since. The junior author (MM) became involved in this project by attending field trips over the past few years and by directly assisting in remapping most of the park in late 2003.

In connection with the bedrock mapping, information on the glacial history of the region was collected that fully supports the multi-glacier hypothesis for New York City promoted by Sanders (1974a, b) and Sanders and Merguerian (1991a, b; 1994, 1995, 1996, 1998). Some of our field observations from Central Park are collected into field trip descriptions at the end of

this fully-extended abstract. What is more, these and almost two hundred other local field trip locality descriptions can be downloaded at either of the following web addresses:

http://people.hofstra.edu/faculty/charles_merguerian/On%20The%20Rocks/LocalityListBlurb.htm, or,

<http://www.dukelabs.com/On%20the%20Rocks/LocalityListBlurb.htm>

Bedrock Stratigraphy of New York City

The schistose rocks of Manhattan Island are divided into three, lithologically distinct, structurally imbricated, lithostratigraphic units of upper amphibolite facies metamorphic grade. Two of these schistose sequences, the Hartland (€-Oh in Figure 1) and Manhattan (€-Om) are allochthonous and either structurally overly or are faulted against the Fordham Gneiss (Yf), Lowerre Quartzite (€l), and the Inwood Marble (€-Oi). A third schistose unit is found in some cases near the Inwood Marble. Near the Walloomsac-Inwood contact the schistose rocks contains layers of calcite marble (probably metamorphosed Balmville, the basal limestone of the Tippecanoe Sequence). This distinctive rusty-weathering schist is considered a metamorphosed lithostratigraphic equivalent of the Walloomsac formation (Ow) according to Merguerian and Sanders (1991, 1993a, 1993b), who also correlate this autochthonous unit with parts of the middle Ordovician Annsville and Normanskill formations of SE New York and the Martinsburg formation of eastern Pennsylvania. In NYC, the Fordham and overlying Inwood-Walloomsac strata constitute the autochthonous miogeosynclinal basement-cover sequence and foreland basin fill of the New England Appalachians and are the products of metamorphism of Paleozoic and possibly older sediment formerly deposited on the Proterozoic Y craton. Work in Westchester County (Brock, 1989, 1993) and in The Bronx (Brock and Brock, 2001) has identified a Proterozoic Z rift facies (Ned Mountain formation) originally deposited between the Inwood and Fordham. Trace element geochemical studies on amphibolites establish a correlation of parts of the Ned Mountain with the Manhattan (Brock and Brock, 2001).

In Manhattan and in the west Bronx, the basement-cover sequence is disconformably overlain by the autochthonous Walloomsac Schist (Ow). This unit is composed of brown-to rusty-weathering, fine- to medium-textured, typically massive, biotite-muscovite-quartz-plagioclase-kyanite-sillimanite-garnet-graphite-pyrite schist and migmatitic schist containing interlayers centimeters to meters thick of mica granofels and layers of calcite±diopside±tremolite marble and calc-silicate rock. Strongly pleochroic reddish biotite and rutilated garnet are diagnostic petrographic features of the formation. The Walloomsac is found interlayered with the underlying Inwood at three localities in Manhattan - (1) at the north end 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 northwestern corner of Central Park (this abstract). 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, Short, and Merguerian, 1999), (3) below the St. Nicholas thrust in the north part of the New York Botanical Garden (Merguerian and Sanders, 1998), and (4) in the northeastern part of Crotona Park (jointly discovered with Pamela and Patrick Brock during a superb field trip in 2002).

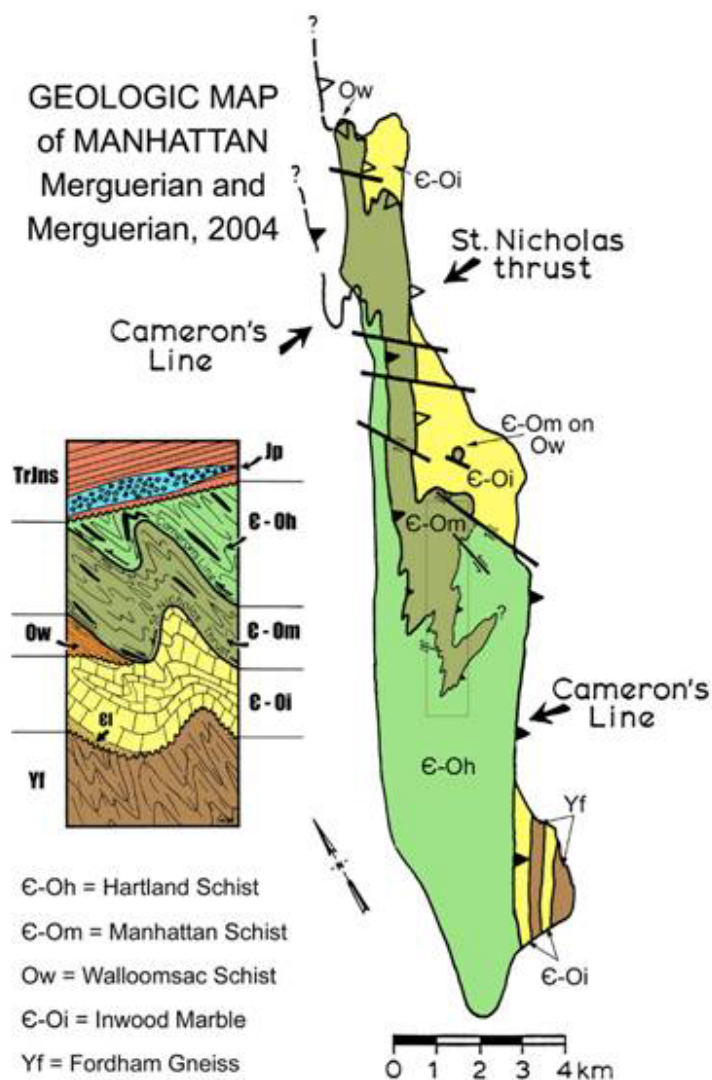


Figure 1 – Bedrock map of Manhattan showing the three schist units found in Manhattan and how our new mapping has altered the map pattern. The closure of the Manhattan Schist to the east of the park is pure conjectural owing to a lack of geological information.

The Walloomsac Schist and the Inwood Marble are structurally overlain by the Manhattan Schist (E-Om) which forms the bulk of the “exposed” schist on the Island of Manhattan. (See Figure 1.) The Manhattan consists of massive rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist. The unit is characterized by the presence of kyanite+sillimanite+quartz+magnetite layers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite, and scarce quartzose granofels. The unit is lithologically identical to Hall's Manhattan B and C and to the Waramaug and Hoosac formations of Cambrian(?) to Ordovician age in New England (Hall, 1976; Merguerian, 1977, 1981, 1983a). These rocks are

inferred to represent metamorphosed Cambrian to Ordovician sedimentary- and minor mafic volcanic rocks formed in the transitional slope- and rise environment of the ancestral passive continental margin of eastern North America.

The structurally high Hartland formation (€-Oh) is dominantly gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss, and granofels with cm- and m-scale layers of greenish amphibolite±garnet. Although typically not exposed at the surface, the Hartland underlies most of the western part and southern half 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 southeastern New York, CM has correlated them with the Hartland and has extended the name Hartland into New York City. The Hartland represents metamorphosed deep-oceanic shale, interstratified graywacke, and volcanic rocks formed offshore adjacent to North America during Early Paleozoic time. Based on minor- and trace-element geochemical differences, Brock and Brock (2001) offer a further subdivision of the Hartland into Bronx Zoo type and Pelham type, a suggestion initially proposed by field analysis by Schaffel (1958) and Baskerville (1982).

In summary, the three distinctive mappable units of the "Manhattan Schist" represent essentially coeval foreland-basin-fill- (Ow), transitional slope/rise- (€-Om), and deep-water (€-Oh) lithotopes that were juxtaposed when the ancestral North American shelf edge was telescoped in response to closure of the proto-Atlantic (Iapetus) ocean during the Taconic orogeny. The units formerly within the old Manhattan Schist are separated by two ductile faults. The "basal Taconic thrust," which to the north in the areas of the classic Taconic orogen brings continental-rise Taconic rocks above the black Tippecanoe rocks of the foreland-basin fill, is represented locally by the **St. Nicholas thrust** (See Figure 1). In NYC, the allochthonous Manhattan formation (€-Om) is thrust above autochthonous rocks of the Walloomsac (Ow). Higher up, **Cameron's Line**, marks the regional ductile contact between allochthonous continental-rise-type Taconic strata (€-Om) and the deep oceanic-type Taconic strata (€-Oh).

The Geology of Central Park

The impressive natural 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 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 30 km. Uplift and erosion have elevated these former deep-seated rocks allowing analysis and interpretation by many geologists.

J. F. Kemp (1887) produced the first detailed map of Manhattan, here colorized and reproduced as Figure 2. 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 construction. Sections G-H and E-F especially show the dominant tightly-folded structure of Central Park.

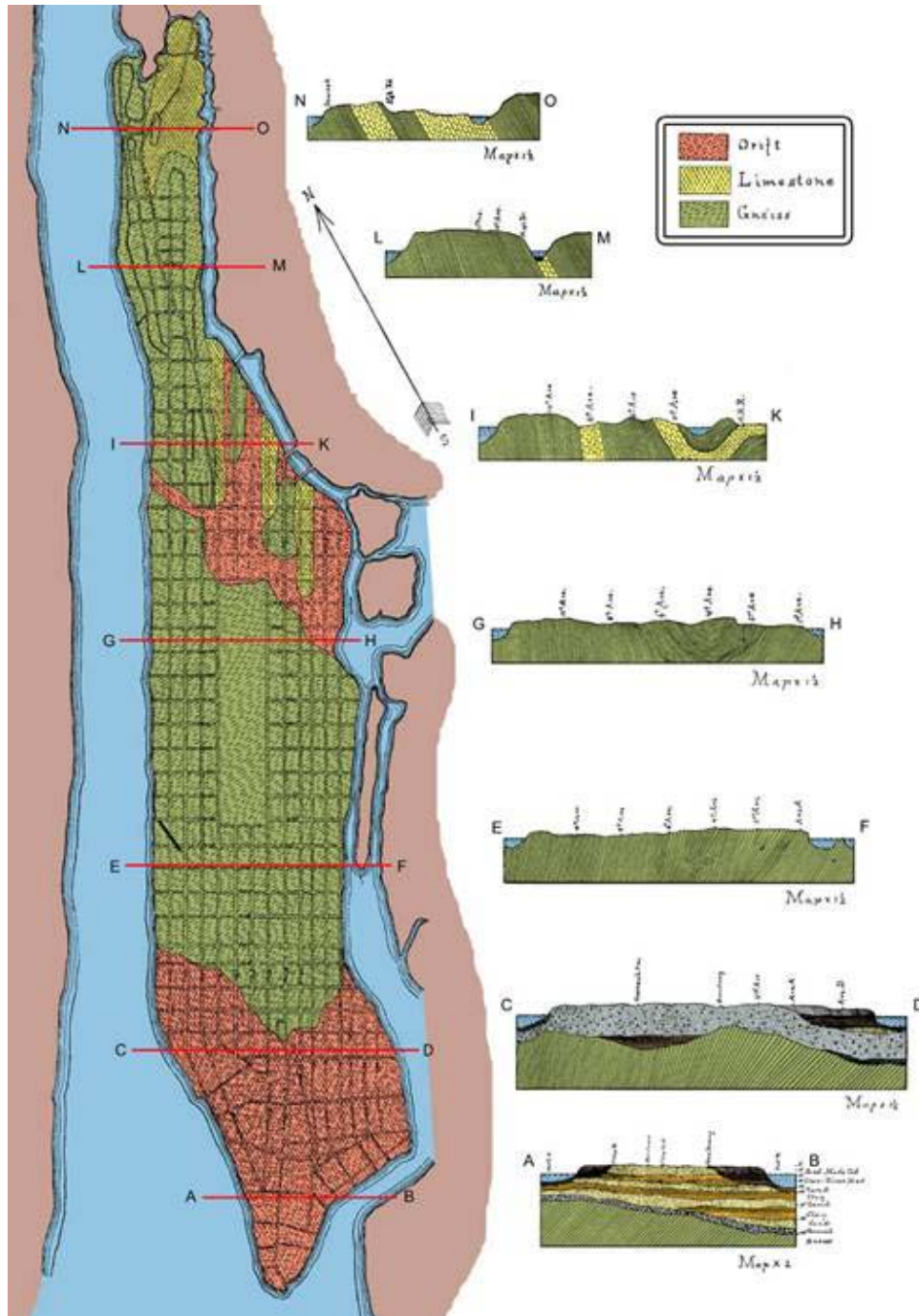


Figure 2 – Colorized version of the first geological map of Manhattan based on the work of J. F. Kemp (1887). The geological profile-sections were drawn parallel to streets in Manhattan with subsurface relationships in the southwestern part based on borings. Produced in an era when rocks were exposed 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.

CM's interest in the rocks of Central Park was spawned at an early age during visits as a child. His mineral- and rock collection still includes a garnet specimen found in the park. In those days, all of the schistose metamorphic rocks of Central Park (and all of New York City, for that matter) were lumped together as the Manhattan formation; geologists would focus on deciphering the complex fold structures. The work of Langer and Bowes (1969) and Bowes and Langer (1969) first described superposed folds in Central Park and elsewhere on Manhattan Island. Hanley and Graff's charming book (1976) about the rocks in Central Park was not strongly focused on geologic problems but did provide include useful illustrations and descriptions of the glacial features, the orientation of cracks (joints), faults, and some details on structure in a series of outcrop sketches arranged as a walking tour through the park.

While studying in the graduate programs at The City College and Columbia University, CM's interest in the rocks of Central Park and NYC continued to develop. Thus was laid the groundwork for an enormous number of field trips run by CM for his students from these fine institutions as well as for students from the New School, Hunter College, and Hofstra University. In the decade from 1988 to 1998, forty field trips were conducted by John E. Sanders and CM with the On-The-Rocks field trip program under the auspices of the New York Academy of Sciences. CM freely admits that he would show just about anyone the rocks in Central Park at anytime. He estimates that more than five hundred individuals have shared this similar fate.

Detailed work throughout Manhattan by CM in the 1980s and 1990s 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 Walloomsac-Inwood sequence. With few exceptions, the southern part of Central Park consists of rocks of the Hartland formation (€-Oh). North of roughly 80th Street, the metamorphic rocks are predominantly Manhattan Schist (€-Om). Rocks within the contact zone possess mylonitic fabrics related to the formation of Cameron's Line, a former deep-seated shear zone. By 1983 a geological map of the south part of Central Park (Figure 3) showed the distribution of Hartland and Manhattan rocks and the position of Cameron's Line between them.

Taterka's (1987) work in Central Park agrees 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 4, 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 4, 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 but have found Walloomsac in the NW corner of Central Park during recent reconnaissance mapping. We will be examining those exposures in more detail later this year.

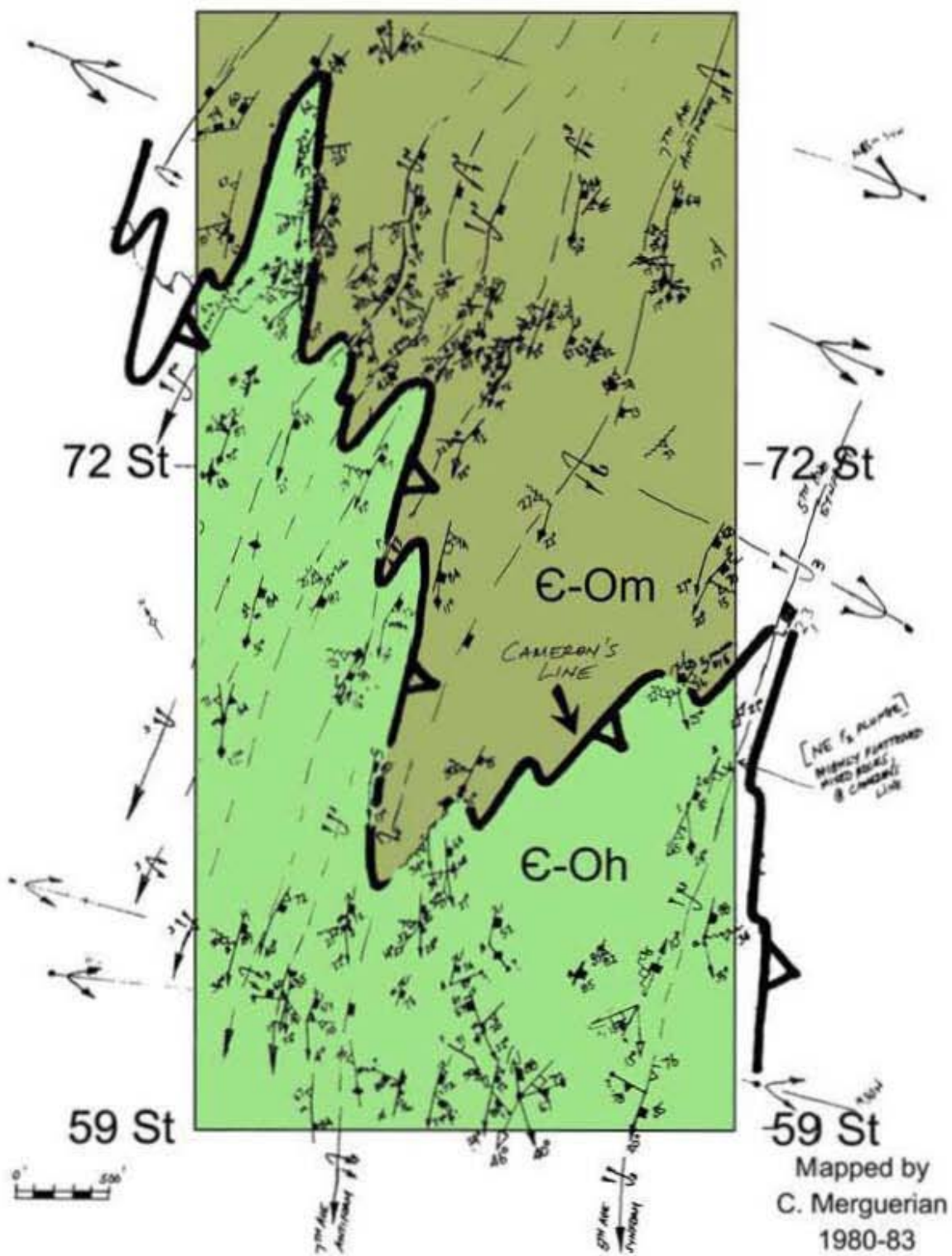


Figure 3 – Geological map of the southern part of Central Park showing the trace of Cameron’s Line, axial surface traces of major folds, and structural details.

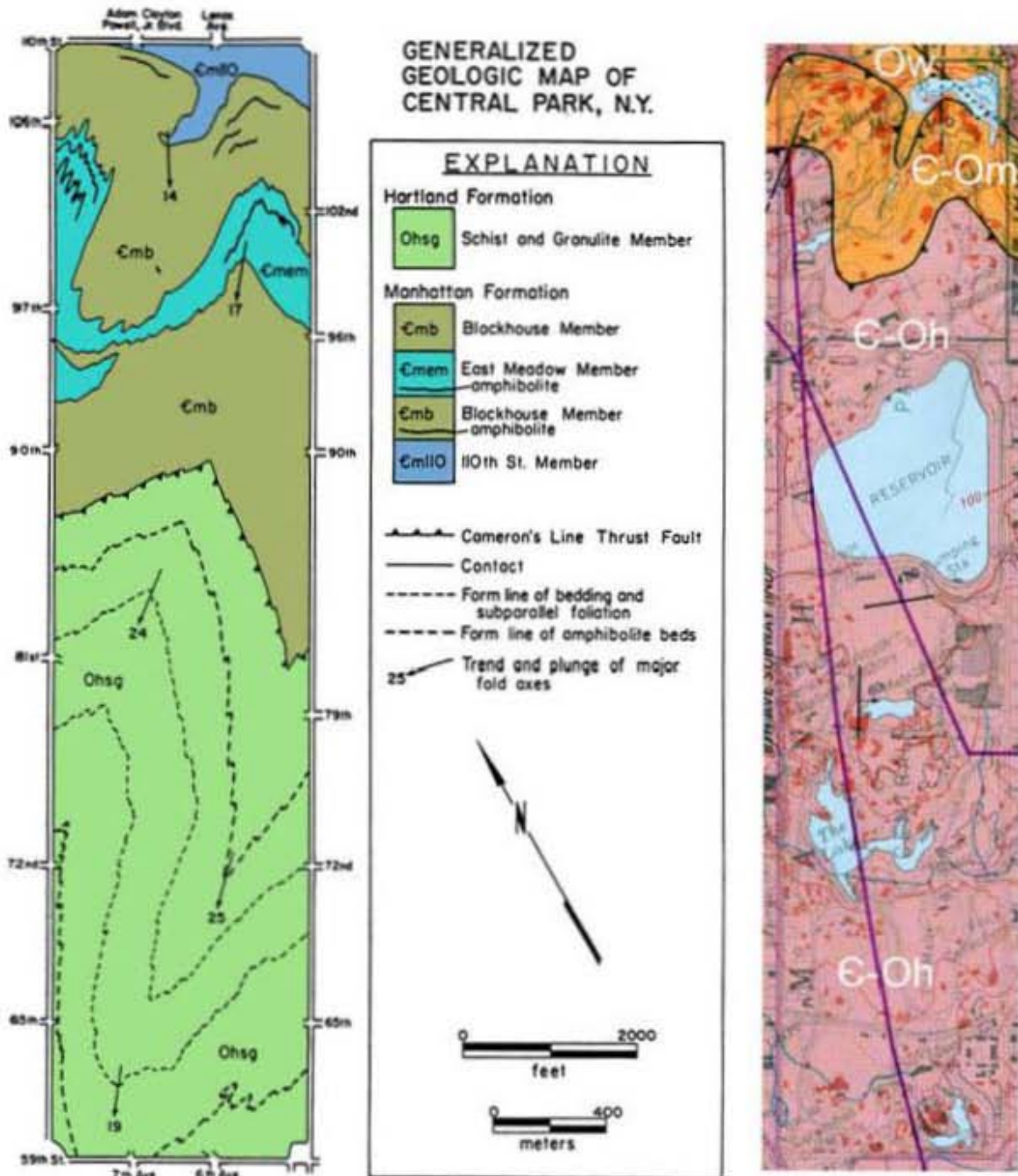


Figure 4 – Colorized and annotated bedrock maps of Central Park by Taterka (1987, left panel) and Baskerville (1994, right panel). See discussion in text.

New Preliminary Geological Map of Central Park

Our new bedrock map of Central Park (Figure 5) is similar to earlier efforts (compare with Figures 3 and 4) 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 (Figure 5) 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 F₂ fold hinge, as suggested without prejudice in Figure 1. In the third case, the development of the dislocation known as Cameron's Line would be very early in the structural sequence (D₁). If the exposed areas are indeed separate, Cameron's Line may be the product of the D₂ event. Clearly, Cameron's Line shows strong deformation by S-plunging F₃ major and minor folds.

The complex sequence of structural events established from other parts of New York City (Merguerian, 1996a) is identical to the structural sequence mapped in Central Park. The obvious map scale folds in Central Park (F₃) are those with steep N- to NE-trending axial surfaces (S₃) 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 (Figure 6). Shearing along S₃ axial surfaces typically creates a transposition foliation of S₁, S₂, and S₃ that is commonly invaded by granitoids to produce migmatite during both the D₂ and D₃ events. (See Figure 5.) The third-generation structures deform two earlier structural fabrics (S₁ and S₂). The older fabrics trend roughly N50°W and dip gently toward the SW (except along the limbs of overturned F₃ folds). We suspect that all of these structures (D₁, D₂, and D₃) are products of the Taconic orogeny.

During D₂, the rocks acquired a penetrative S₂ 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 D₂. Near ductile fault contacts the S₂ 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 F₂ folds. The D₃ event, a period of L-tectonism, smeared the previously flattened kyanite+quartz layers and lenses into elongate shapes parallel to F₃ axes.

The D₁ to D₃ 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 5) we show the F₄ 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 D₃ kyanite are common throughout Central Park. Their abundance suggests

a major post-Taconian retrograde metamorphism, presumably coincident with the intrusion of wet Devonian granitoids throughout the Manhattan Prong discussed by Brock and Brock (2001).

PRELIMINARY GEOLOGICAL MAP OF CENTRAL PARK, NYC

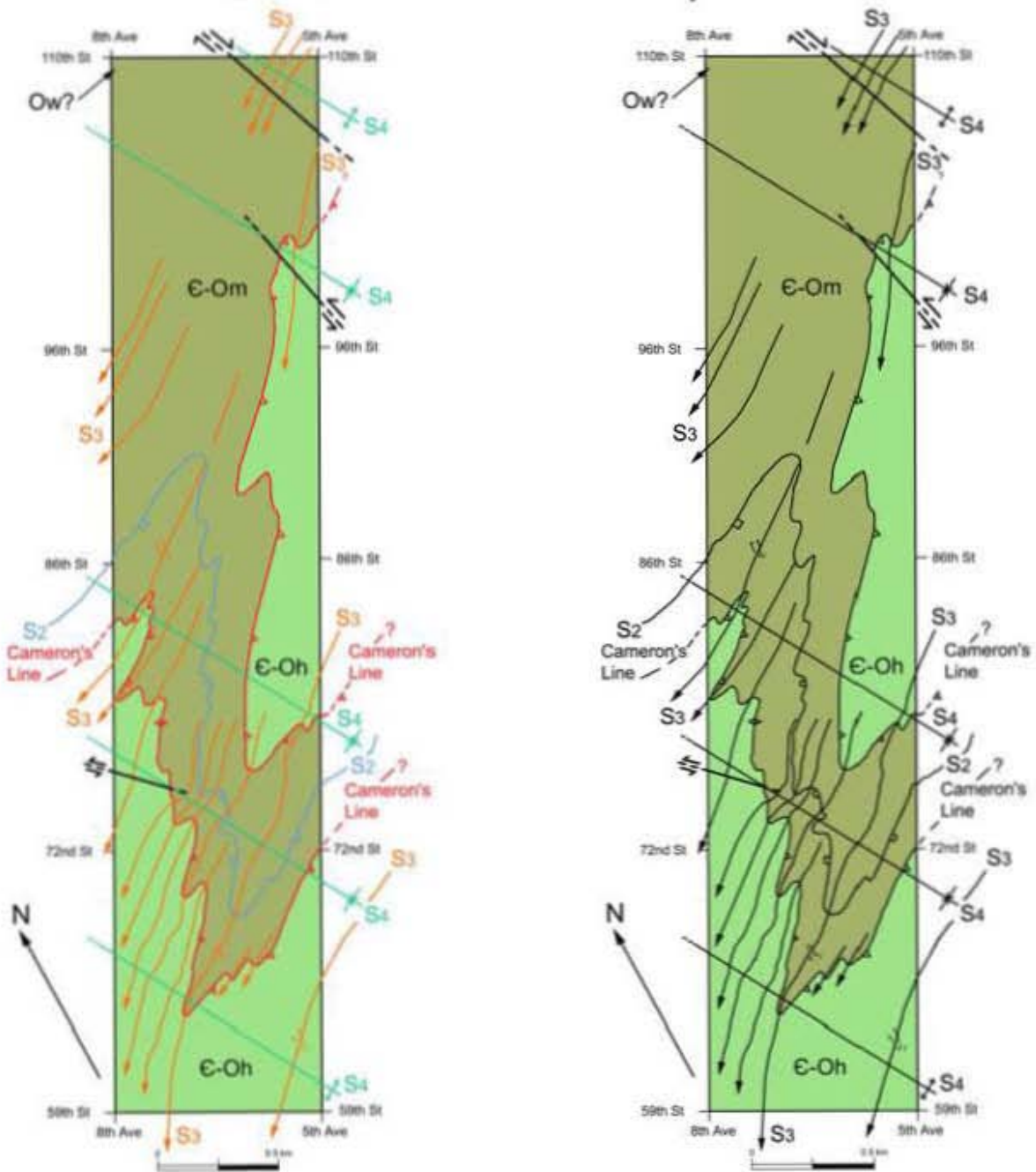


Figure 5 – Preliminary bedrock geological map of Central Park showing ductile and brittle faults and the axial traces of the major structural features, based on our current mapping program.



Figure 6 – 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 (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 the city (Merguerian, 1996, 2002a). Group D faults form a major system of NNE-trending dip-slip normal faults and related joints with an average $N21^\circ E$ trend and steep dips. In the fault surface, dip-slip slickensides

show oblique-slip reactivation, the result of younger (Group E) faults. Both Group D and Group E faults cut Permian rhyodacite dikes in the Queens Tunnel (Merguerian, 2001, 2002b, 2004).

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 little mineralization with the local exception of quartz 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 4 and 5.) Two areas show evidence for left-lateral strike slip faulting. (See Figure 5.) 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. 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.

The famous McCoun map of 1609 shows the drainage systems before urbanization took hold in Manhattan. In Figure 7, 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 1996b, 1997). Because the contemporary stress regime in the lithosphere is oriented NE-SW (Dr. Klaus Jacob, personal communication), 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.

Features of Pleistocene Age

Central Park offers additional interest to students of glacial geology because of the sculpted rock exposures. Features of Pleistocene age are distinguished by their associations with the several continental glaciers that formerly flowed across the region. We list these in Table 1. The glaciers have eroded the bedrock, transported various erratics to new locations, and

deposited blankets of sediment. All their new information destroys a prevailing "one-glacier-did-it-all" concept that seems to have hypnotized most modern stratigraphers of the Pleistocene deposits. The "one-glacier" interpretation specifies that the glacial features made in the New York metropolitan region are not only the work of a single glacier but that this glacier should be correlated with the Woodfordian episode (interval from about 20 ka to 13 ka, namely the most-recent general ice advance). According to this school of thought, Woodfordian glacier flowed down to New York City from the Labrador highlands following an azimuth that is about N15°E to S15°W. We find numerous features that can be ascribed only to several older glaciers. Many flowed from various azimuths in the NW quadrant toward the SE, across the Hudson Valley (Sanders and Merguerian, 1998).

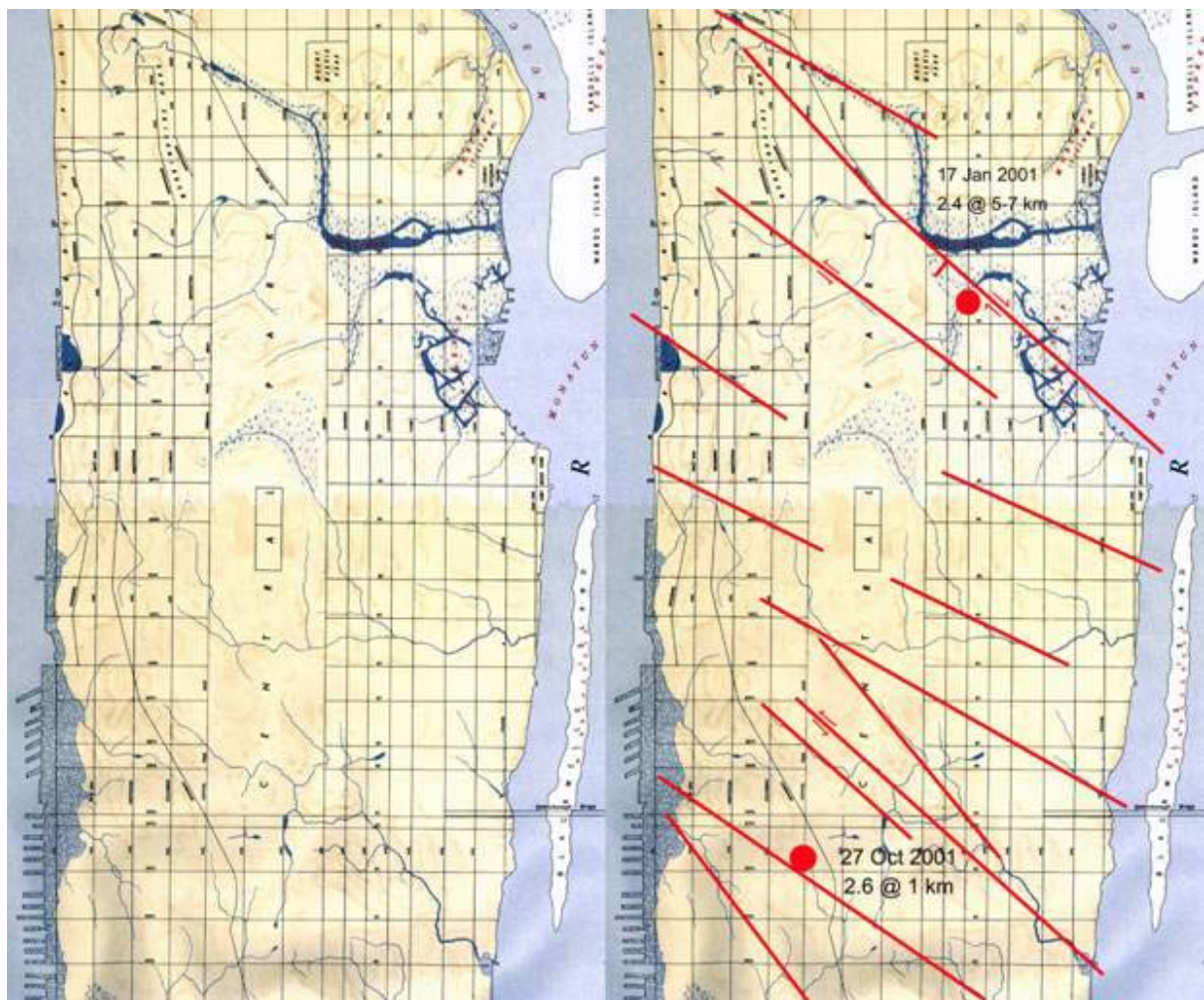


Figure 7 – Topographic map of Manhattan by McCoun (1609) showing the pre-industrial era drainage patterns. Drainages follow zones of structural weakness in crystalline rocks, typically faults. The pronounced NNW-SSE alignment of creek and stream valleys is striking. The right panel shows the traces of 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 N29°E.

The multitude of glaciations from the NNW and NNE flow directions (Table 1) and some degree of ice-front deformation, overthrusting, and imbrication of units (including the underlying Cretaceous) has created a Pleistocene sequence with complex internal stratigraphy and structure. Glacial ice-flow indicators in Central Park prove that the ice came from not one but rather from several directions. Ice flowed rectilinearly from NW to SE, across the highest ridges and across the Hudson Valley without deflection (Figure 8). This suggests a thick ice sheet whose flow pattern was governed by the gradient on the top of the glacier. Figure 9 shows the flow from NNE to SSE as resulting from a later glacier. The two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 8. The latest glacier, shown in Figure 9, did not reach much of Long Island. It covered parts of Queens and Brooklyn, Manhattan, and Staten Island. What its terminal moraine was like is not yet known but the youngest glacier from the NNE was unable to erode or disrupt the Harbor Hill moraine ridge (Till II in Table 1), a terminal moraine of Early Wisconsinan age that was eventually breached by a post-Wisconsinan flood through the Narrows channel (Merguerian, 2003).

Table 1 – Proposed classification of the Pleistocene deposits of New York City and vicinity (From Sanders and Merguerian, 1998, Table 2.)

Age	Till No.	Ice-flow Direction	Description; remarks
Late Wisconsinan ("Woodfordian"?)	I	NNE to SSW	Gray-brown till in Westchester Co., Staten Is., Brooklyn, & Queens (but not present on rest of Long Island); Hamden Till in CT with terminal moraine lying along the S coast of CT; gray lake sediments at Croton Point Park, Westchester Co.
Mid-Wisconsinan (?)			Paleosol on Till II, SW Staten Island.
Early Wisconsinan(?)	II	NW to SE	Harbor Hill Terminal Moraine and associated outwash (Bellmore Fm. in Jones Beach subsurface); Lake Chamberlain Till in southern CT.
Sangamonian(?)			Wantagh Fm. (in Jones Beach subsurface).
Illinoian(?)	IIIA	NW to SE	Ronkonkoma Terminal Moraine and associated outwash (Merrick Fm. in Jones Beach subsurface).
	IIIB		Manhasset Fm. of Fuller (with middle Montauk Till Member; in lower member, coarse delta foresets (including debris flows) deposited in Proglacial Lake Long Island dammed in on S by pre-Ronkonkoma terminal moraine.
	IIIC		
Yarmouthian			Jacob Sand, Gardiners Clay.
Kansan(?)	IV	NNE to SSW	Gray till with decayed stones at Teller's Point (Croton Point Park, Westchester Co.); gray till with green metavolcanic stones, Target Rock, LI.
Aftonian(?)			No deposits; deep chemical decay of Till V.
Nebraskan (?)	V	NW to SE	Reddish-brown decayed-stone till and -outwash at AKR Co., Staten Island, and at Garvies Point, Long Island; Jameco Gravel fills subsurface valley in SW Queens.
			Pre-glacial (?) Mannelto Gravel fills subsurface valleys.

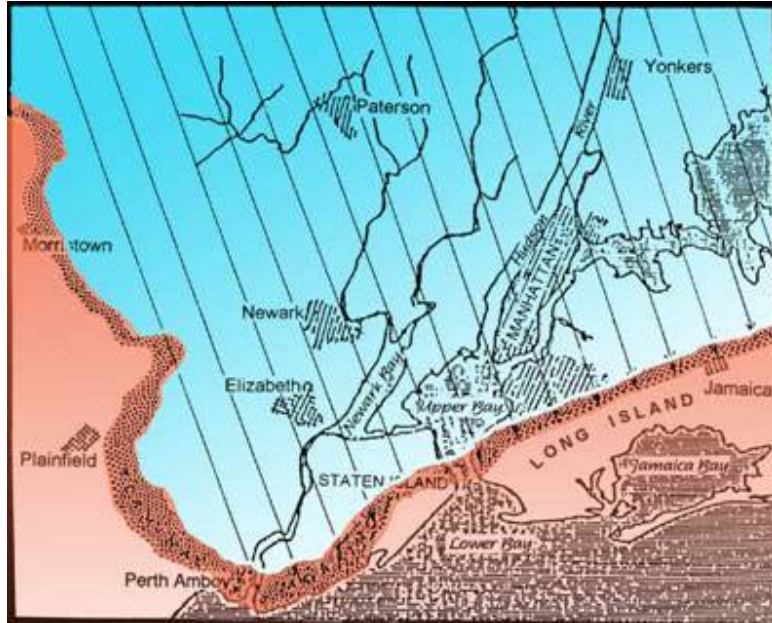


Figure 8 - Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (Adapted from Salisbury and others, 1902.)

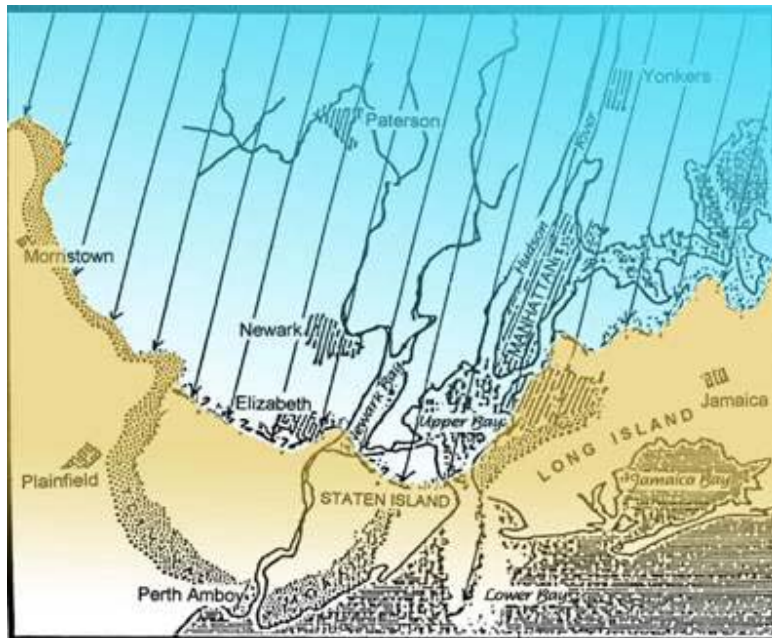


Figure 9 - Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (Adapted from Salisbury and others, 1902.)

Central Park Field Trip

Field trip stops for the southern part of Central Park (modified from Merguerian and Sanders, 1993a and keyed to Figure 10) describe the geology of critical exposures in the park. They are reproduced below for the interested reader or for those that would like to examine the evidence for our bedrock- and glacial interpretations.



Figure 10 – 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 (€-Oh) in New York City. The S_2 foliation, which predominates at this exposure, consists of parallel thin laminae and local syntectonic granitoid veins oriented $N80^\circ W, 34^\circ SW$. F_3 z-folds are also obvious with traces of axial surfaces oriented $N42^\circ E, 88^\circ SE$ and F_3 axes plunging 35° into $S17^\circ W$. 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 €-Om 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 S₂ foliation. S₂, subparallel S₁ and bedding (S₀), are strongly transposed (oriented N56°E, 45°SE) because of the effects of F₃ z-folds with axial surfaces trending N50°E, 85°SE. The F₃ folds and associated lineations plunge 24° into S21°W. Away from the limbs of minor F₃ folds, at the NE corner of the first exposure, the S₂ 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 S₃. 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 subparallel 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 S₂ + S₃ foliation is oriented N70°E, 49°SE (the combined effect of transposition by F₃ 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 F₂ and F₃ folds. The composite S₂ + S₃ 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 (€-Oh) and rusty-weathering schist and gneiss of the Manhattan (€-Om) formations in fault rocks bearing a highly penetrative $S_1 + S_2$ mylonitic foliation. Lithologies typical of unit €-Om 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 (plunge down the dip of their axial surfaces) 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 €-Om predominates, €-Oh granofels layers, 30 to 50 cm thick, can be seen "floating" in a schistose matrix (Figure 11). 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 $F_2 \times F_3$ 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.

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 $N48^\circ E$, 70° to $80^\circ NW$.

Upright F_3 synformal folds of S_0 and S_2 plunge 20° into $S45^\circ W$ with axial surfaces oriented $N45^\circ E$, $85^\circ SE$. 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 $N32^\circ W$ indicating SE-directed glacial-ice flow.



Figure 11 – Image of outcrop showing disarticulated Hartland granofels block in a tectonic mélange near Cameron's Line.

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.

Glacial grooves are here oriented $N28^\circ W$ and a subdued roche moutonnée structure is oriented $N40^\circ E$. We observed SSW-oriented chattermarks (Glacier IV?) on the northward-sloping surface of the roche moutonnée.

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 $N32^\circ E$, 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 $N38^\circ W$.

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 interbedding of granofels and muscovite schist here typify the Hartland formation. Bedding (S_0) and the S_2 foliation are oriented $N43^\circ W$, $30^\circ SW$ near the vicinity of an F_3 antiformal hinge area (7th Avenue Antiform of Figure 5). 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 $N77^\circ W$, $21^\circ SW$.

F_3 z-folds vary from open- to tight- to isoclinal in profile and plunge 22° into $S25^\circ W$ with axial surfaces oriented $N35^\circ E$, $72^\circ SE$. 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 S₂ foliation and a sub-parallel granitoid sill, all folded by F₃? 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. F₃ 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 S₂ and S₃. S₂ is well developed here and is oriented N68°W, 42°SW. F₃ 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 (€-Om). Layers- and lenses of kyanite+quartz+magnetite weather in positive relief and outline the S₂ foliation which is largely

mylonitic. Here, S_2 is variable but oriented $N70^\circ E, 25^\circ SE$ because of pervasive F_3 folds plunging 34° into $S25^\circ W$. The F_3 axial surfaces trend $N42^\circ E, 68^\circ SE$.

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