DUKE GEOLOGICAL LABORATORY

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TRIPS ON THE ROCKS

Guide 16: Cameron's Line and the Bronx Parks, New York

Trip 21: 24 November 1991; Trip 26: 08 May 1993

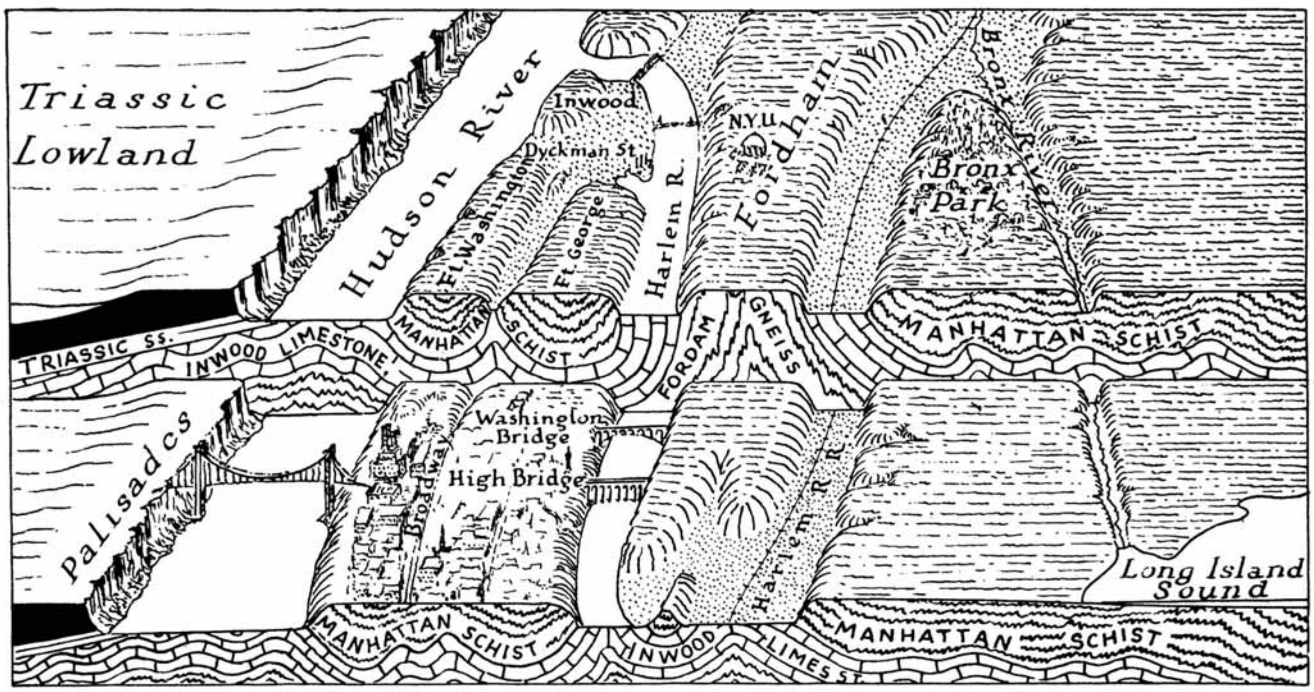

Figure 1 – Physiographic block diagram of the Bronx, northern Manhattan, the Harlem and Hudson Rivers and New Jersey showing the generalized structural geology and drainage controls of the region. (Drawing by A. K. Lobeck, Columbia University.)

Field Trip Notes by:

Charles Merguerian and John E. Sanders

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Trip 21: 24 November 1991
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Logistics:
Departure from NYAS: 0830
Return to NYAS: 1800
Bring lunch, including drinking water or other beverages.

INTRODUCTION

In several of the the public parks in the Bronx are displayed some relationships that are critical to our revised interpretations of the geologic history of New York City (Figure 1, cover). These relationships include not only the bedrock (notably the configuration and position of Cameron's Line in the Bronx), but also the morphologic history of the region (particularly the number- and directions of Quaternary glaciations and age of the Bronx River Gorge in the New York Botanical Garden). These new aspects of the geology to be seen today are based on both our individual- and joint research efforts.

Today's trip will be to four readily accessible localities ("stops") in the Bronx (Figure 2). All of them are easily reached by car, by bus, or by subway. We have chosen them as being the most-critical exposures on which we have based our new interpretations of the bedrock- and glacial geology of the New York City region. For the past ten years, CM has concentrated his efforts on the stratigraphy and structural geology of the Paleozoic metamorphic rocks of New York City with special emphasis on identifying ductile- and brittle faults in the region. Thus, one purpose of today's trip is to outline the methods used in unraveling the geology of complexly deformed metamorphic rocks and to examine the field evidence to support CM's new, more-complicated view of the stratigraphy and structure of the Bronx. The second, allied purpose of today's trip, based on nearly twenty years of field investigation by JES, is to present evidence for new hypotheses concerning the glacial- and drainage history of New York City. Thus, our trip will concentrate on the features of Layers I, II and VII as outlined in Tables 1 and 2.

Utilizing geologic maps and -cross sections, the following paragraphs describe the geologic background of our trip route and present, in historical perspective, the origins of geological concepts concerning the bedrock of the Bronx and New York City. The history of glacial investigations is outlined under the heading Layer VII and is also summarized in our Manhattan and Long Island guidebooks. Our combined research efforts enable us: (1) to present modern plate-tectonic interpretations on the Paleozoic bedrock of New York City; (2) to identify the southernmost traces of the Taconic allochthon; (3) to present evidence in support of the validity of the much-maligned Fuller (1914) stratigraphic interpretation of the Pleistocene glacial deposits of the region; and (4) to present new arguments in support of Kemp's view of the postglacial age of the Bronx River gorge in contrast to the pre-glacial age stated by Schuberth.

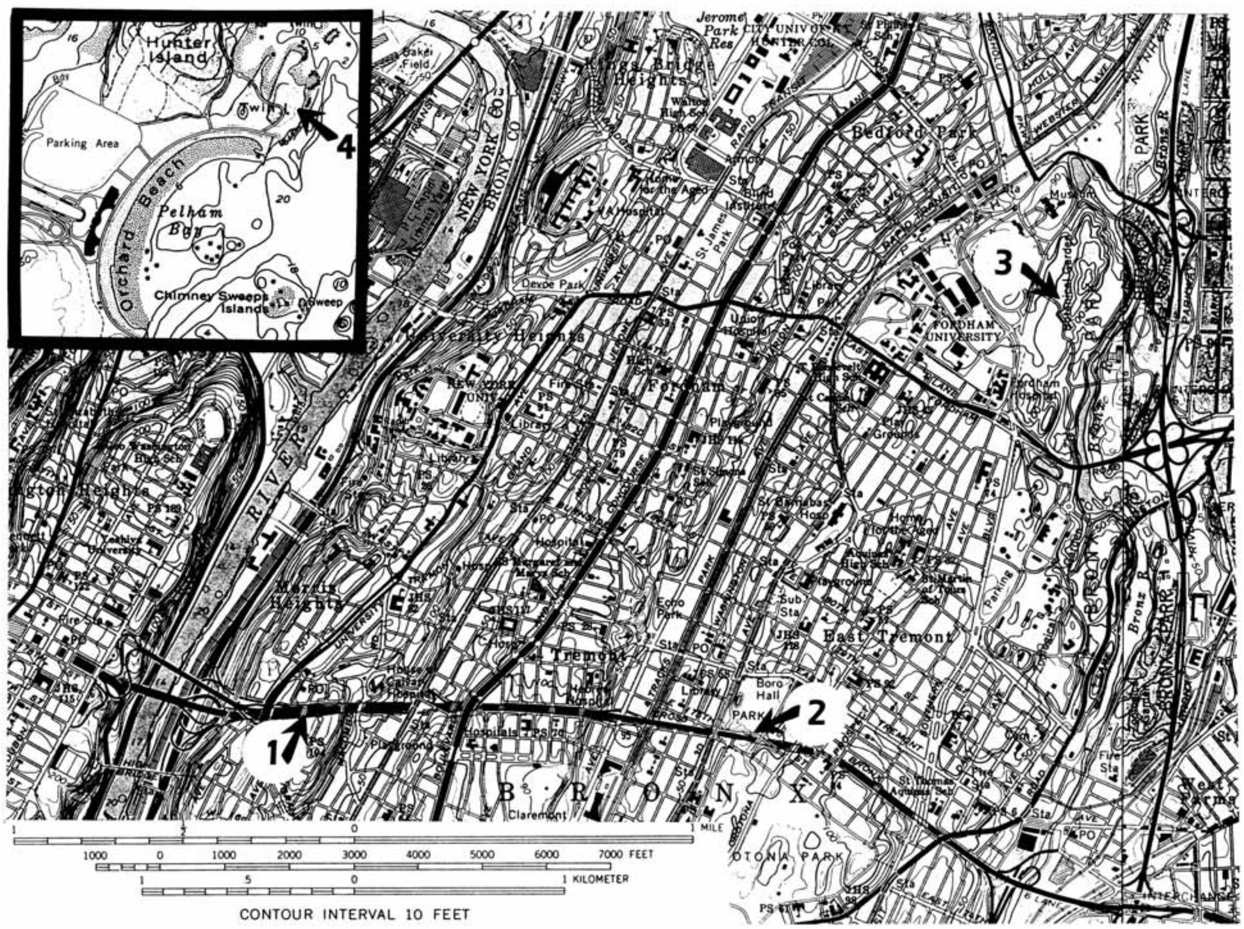


Figure 2 - Outcrop locations for trip stops (1 through 4) as shown on segments of the Central Park and Flushing 7.5-minute topogographic quadrangle maps of U. S. Geological Survey. Inset shows location of Stop 4 which is roughly 8 km ENE of Stop 3.

GEOLOGIC BACKGROUND

New York City and the Bronx are situated at the southerly terminus of the Manhattan Prong (Figure 3), a region of low, rolling ridges and valleys that is underlain by a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic- to Lower Paleozoic rocks. The Manhattan Prong ends on the southwest at Jersey City, but widens northeastward into the New England Upland, which is underlain by crystalline terranes of various Paleozoic- and older ages. Southward from New York City, the crystalline rocks of the Manhattan Prong plunges southwestward and disappears beneath a covering blanket of Cretaceous coastal-plain sedimentary strata and overlying Pleistocene (glacial) sediments. A continuation of this same belt of metamorphic rocks reappears at the Earth's surface in the vicinity of Philadelphia, Pennsylvania.

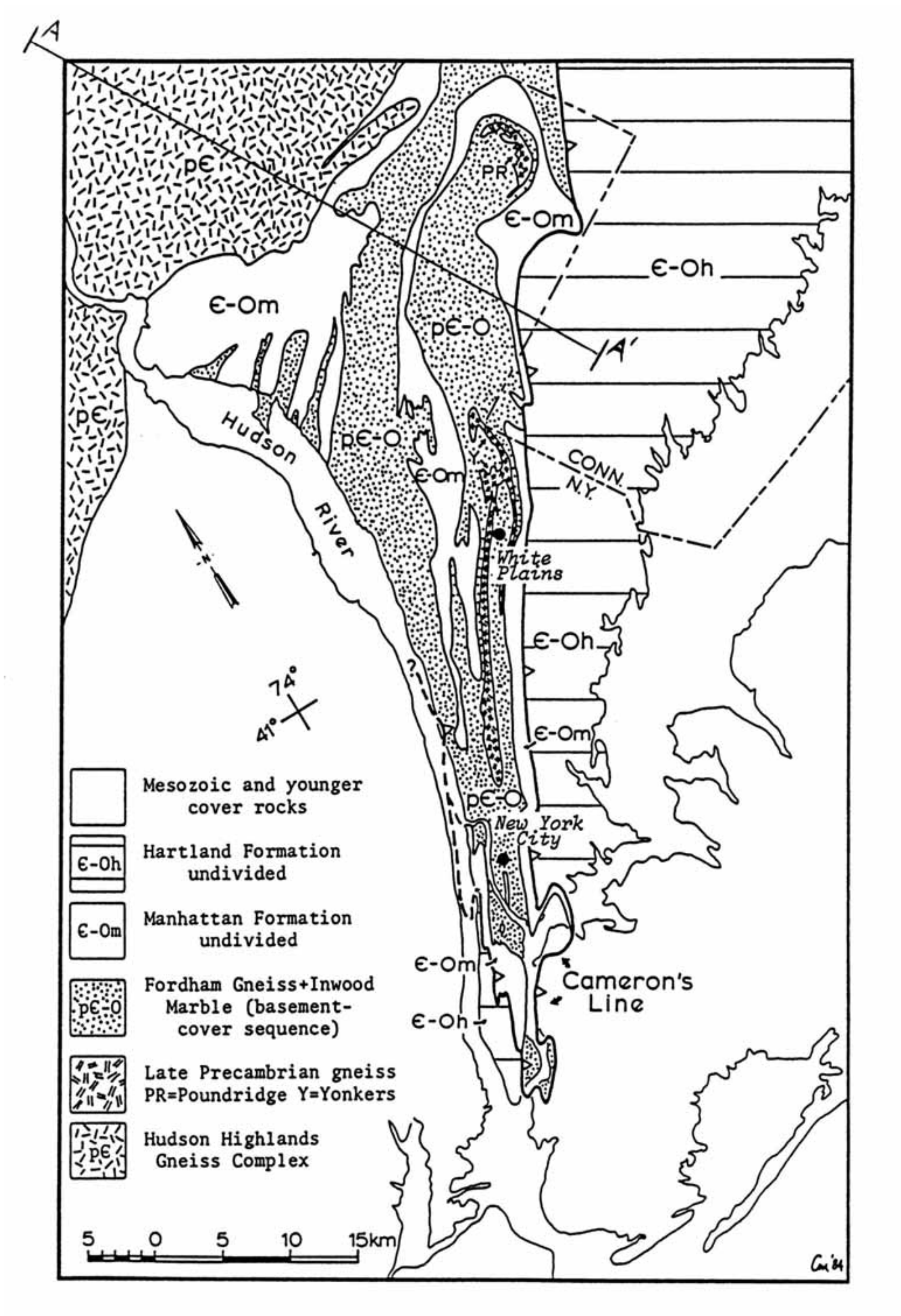


Figure 3 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted (Mose and Merguerian, 1985).

West of the Bronx and Manhattan Island, in New Jersey, the deeply eroded bedrock of Manhattan, a series of gently west-dipping sedimentary rocks of Late Triassic to Early Jurassic age overlaps and buries the deeply eroded bedrock of Manhattan. As indicated in the west-east cross section from New Jersey to the Bronx (Figure 4), the W-dipping Mesozoic sedimentary rocks of the Newark Basin have been intruded by the Palisades Sheet whose tilted- and eroded edge forms prominent cliffs along the western margin of the Hudson channel. Together, the Mesozoic sequence lies on a pre-Triassic surface of unconformity that projects out of the Hudson River valley and skirts over the crystalline rocks of Manhattan and the Bronx. Note the asymmetric folds in the bedrock units of Manhattan and the Bronx beneath the pre-Triassic planation surface and the apparently simple, folded "layer-cake" arrangement of the bedrock units (Figures 4, 5).

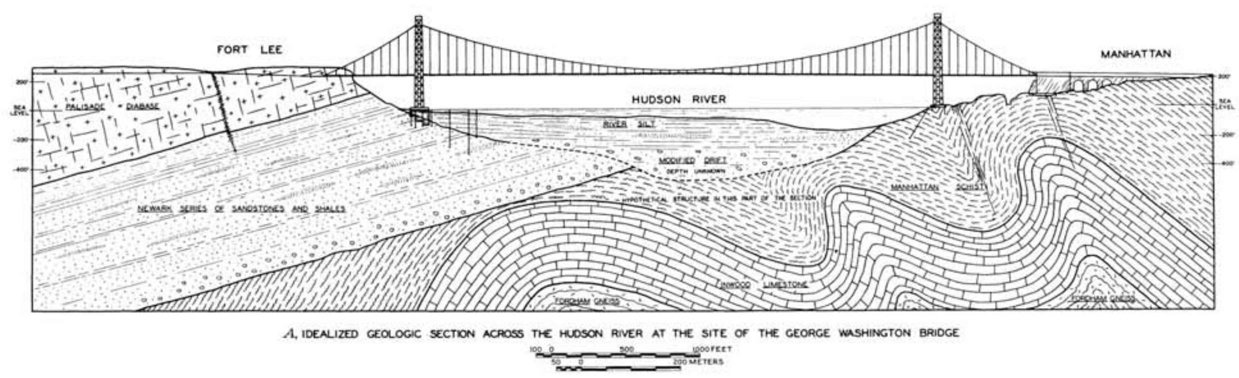


Figure 4 - West-east profile-section across Hudson River at George Washington bridge, showing geologic relationships determined from study of exposed rocks and of borings made for the footing of the western tower of the bridge. (Berkey, 1933, pl. 8, fig. A.)

Although the rocks underlying the Bronx were first studied by naturalists in the 1700's, and by geologists in the 1800's and 1900's, systematic detailed geologic mapping began in the mid- to late 1800's by W. W. Mather and F. J. H. Merrill, respectively. Details of these early works are given below under the heading "History of Bedrock Geologic Investigations."

BEDROCK UNITS

Under this section we describe the history of bedrock investigations, details of the geology of Layers I, IIA, and IIB, and the specifics of the stratigraphy-, geologic structure-, and metamorphic geology of New York City.

History of Bedrock Geologic Investigations

The earliest written record on the geology of New York City is a report written by Johann David Schopf, published in 1787, entitled "Beytrage zur Mineralogichen Kenntniss des Ostlichen Theils von Nord-Amerika und seiner Geburge". Schopf's thorough report was translated and annotated by Edmund M. Spieker and published by the Hafner Publishing Company, New York in 1972 (now out of print).   Schopf's comments, limited to the mineralogy-, lithology-, and topography of Manhattan and the New York City area (including Long Island), did not include a geologic map. S. L. Mitchill (1798) wrote "A sketch of the mineralogical (sic) and geological history of the State of New York" but we were not able to obtain a copy at press time for this guidebook so we do not know about its contents. According to Speiker (1972), Schopf's observations did not serve as a foundation for Mitchill's apparently independent contribution.

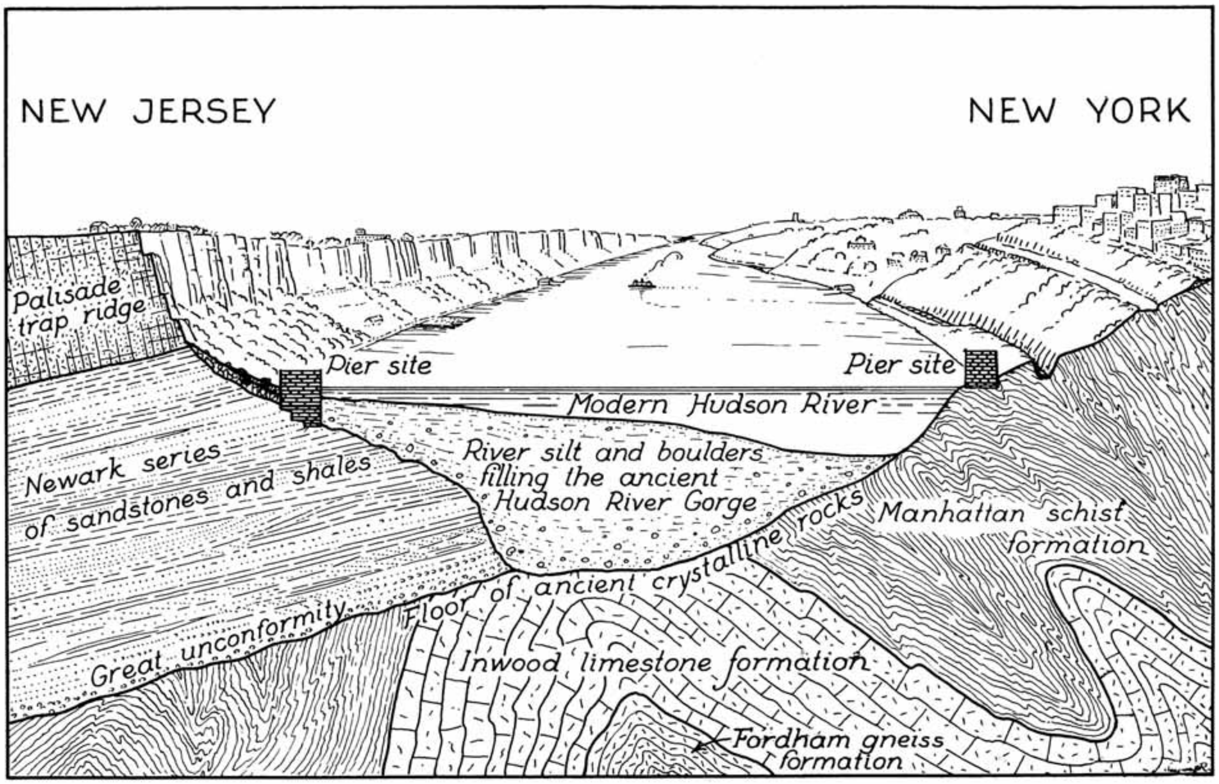


Figure 5 - Schematic block diagram of the lower Hudson River, viewed upstream from the site where the George Washington Bridge would later be built (cover, Berkey, 1948).

Maclure's (1817) water-colored regional map of the eastern United States (Figure 6) adopted the rock-stratigraphic nomenclature of Werner and the Neptunists (not a punk-rock band but an early "school of geology" that envisioned that all rocks had formed as deposits from a "universal ocean."). Maclure, in fact, considered all of the metamorphic rocks of New England (and the entire Appalachian belt, for that matter) a part of Werner's "Primitive Series" of rocks. In the accompanying 127-page text, Maclure located the primitive rocks of the Hudson Highlands and those east of the Hudson River. He astutely discussed and correlated the metamorphosed dolostone and -limestone sequences cropping out as far distant as Stockbridge and Kent, Connecticut, Dover and in the Bronx, New York, with those found roughly three hundred miles away near Philadelphia, Pennsylvania. In the areas examined by Maclure, the extensive belt of carbonates (now assigned as part of the Sauk Sequence, our Layer IIA(W), in Table 2) is mapped as the Cambrian to Ordovician Inwood Marble and correlatives.

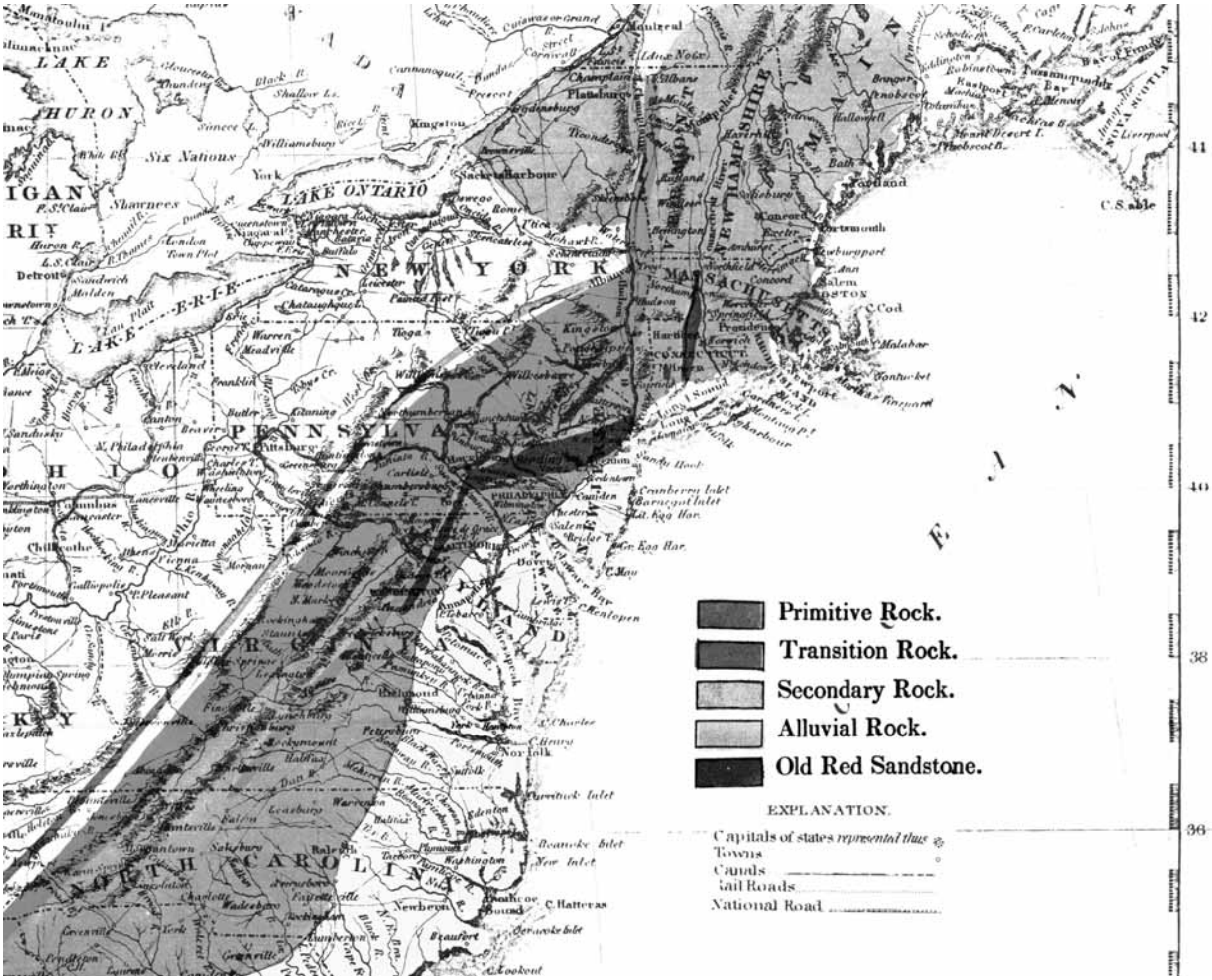


Figure 6 - Northeastern part of William Maclure's geologic map of the United States (1817).

James Pierce (1820) described the regional geology- and mineralogy of New York and New Jersey but concentrated on the scenery and mineral deposits of the trap-rock areas of New Jersey. He mentioned the rocks of the Hudson Highlands and described New York harbor but did not discuss the geology of New York City. L. D. Gale's contributions (1839, and in an addenda in Mather, 1843, p. 581-604), together provide a thorough account of the glacial- and bedrock geology of Manhattan Island in the format of a street-by-street diary before many buildings had been constructed. Thus, Gale's diary, provided the first detailed report on the structure- and lithology of Manhattan Island (without a map, unfortunately), discussed the glacial boulders found in situ, and included drill-core data and construction costs. Gale's (1839) observations (with field work conducted in 1828-1829) on glacial features were outlined in our Manhattan guidebook (Merguerian and Sanders 1991b).

In his study of the First Geological District under the auspices of the Geological Survey of New York, Mather (1843) produced the first geologic map of the New York City area. Drawing heavily from Gale's investigations, Mather's map of New York included the five boroughs (Figure 7) and showed the distribution of "Primitive" crystalline rock including granite, gneiss (uncolored in Figure 7), "limestone of New York County" (black lenticular areas in Figure

7), serpentine (on Staten Island), and overlying alluvial sand and marshland, and drainages. In these halcyon days of geologic mapping, all crystalline rocks were lumped together as the Primitive Series (Proterozoic and Archean of the modern usage). Note the marble quarry in the area of the Bronx extending up from West Farms on Figure 7 and the stream flowing southward to the west of and parallel to the Bronx River (in the Webster Avenue valley). This former stream valley has now been totally filled in; the New York Central railway (now Metro-North) occupies most of its strike length. An excellent review of American geology from the late eighteenth to late nineteenth centuries is contained in George P. Merrill's book on the history of geology (1924). Interested readers are urged to consult this book.

Before the turn of the century, many geologists were examining the geology of New York City as building construction and industrial development began in ernest. Reports based on work by Frederick J. H. Merrill (1886a, b; 1890, 1891a, b; 1898a, b, and c) on the glacial- and metamorphic geology of New York City, examination of metamorphic rocks in Dutchess County by James D. Dana (1880, 1881, 1884) and the Harrison granodiorite gneiss in adjacent Westchester County by Heinrich Ries (1895), and J. F. Kemp's studies (1887, 1895, 1897), provided important contributions to our knowledge of both the glacial- and bedrock geology of southeastern New York. The first detailed geologic map and structure sections across Manhattan Island and sections across the East River at Seventieth Street were published before the close of the nineteenth century (Kemp 1887, 1895).

In 1890 (p. 390), Merrill named the Manhattan Schist for the micaceous metamorphic rocks found on Manhattan Island and suggested, following the views of Professors W. W. Mather (1843) and J. D. Dana (1880), that they represent metamorphosed equivalents of the Paleozoic strata of southern Dutchess County, New York. A reference in Merrill (1890) states that "the name Manhattan Group was proposed by R. P. Stevens, Esq., to include the rocks of New York Island". Merrill extended "Group" status to include the Manhattan Schist, the Inwood limestone, Fordham Gneiss, and the Yonkers Gneiss. Later, in 1902, Merrill and coworkers correctly correlated the Fordham gneiss with Proterozoic sequences of the Hudson Highlands. Formal removal of the significantly older Fordham and Yonkers gneisses from the "Manhattan Group" had to await the refinement and application of radiogenic dating techniques and detailed mapping of lithologies in the 1960's. Formal "de-Grouping" of the "Manhattan Group" took place after spirited debate at a Symposium on the New York City Group of Formations at the 1968 meeting of the New York State Geological Association at Queens College, Queens, New York (Alexandrov, ed., 1969).

Merrill, in concert with other geologists, published the first comprehensive geologic map of New York City in the United States Geological Survey New York City Folio (Merrill, Darton, Hollick, Salisbury, Dodge, Willis, and Pressey, 1902). In this compilation, based on previous studies, Merrill outlined, in map form (Figure 8) the basic stratigraphic- and structural framework that modern geologists would test, promote, and amplify. Merrill's major contribution was subdivision of Mather's Primitive Series into mappable units. He first defined the correct relative chronology of the basal Proterozoic Fordham Gneiss ([fgn] = white stippled pattern in Figure 8), the overlying Cambrian to Silurian? Stockbridge dolomite ([ꞒSs] = light-colored areas with horizontal ruling in Figure 8), and the Silurian Hudson Schist ([Sh] = dark shaded areas in Figure 8 now known as the Manhattan Schist and correlatives).

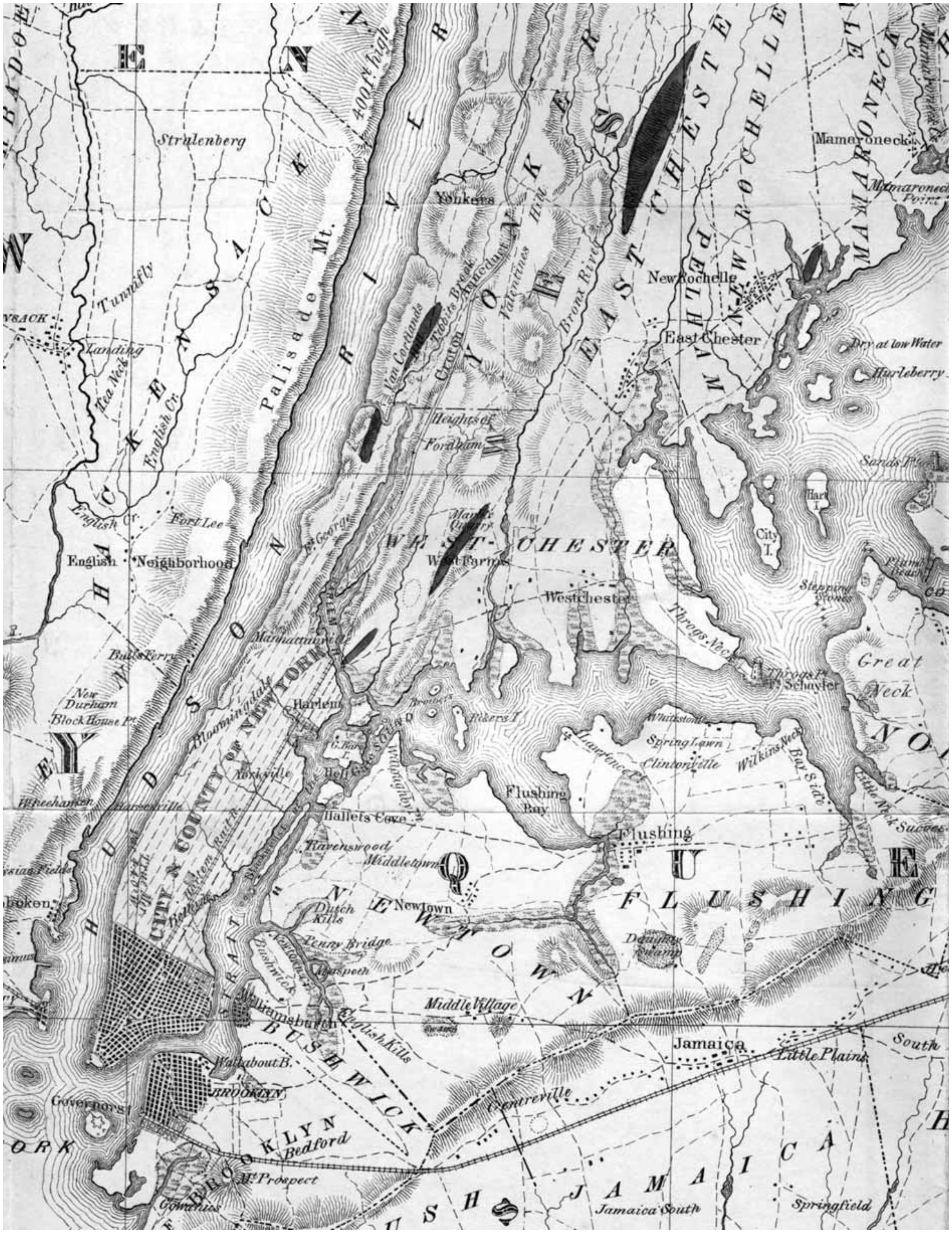


Figure 7 - Portion of Mather's (1843) map of New York City and vicinity that accompanied his report on the First Geological District of the State of New York. Notice that the built-up area of Manhattan is confined to the southern part of the island.

In keeping with the stratigraphy proposed by Dana for Dutchess County, Merrill and coworkers chose to use the name Hudson Schist for the schistose rocks of New York City and considered them to be of Silurian age. Thus, they served up a layer-cake model (un-iced and without coffee), gave the general age assignments (the modern reader should substitute Ordovician for Silurian above), and made the regional lithostratigraphic correlation between the metamorphic rocks of New York City and those of southeastern New York. The pioneering work by Merrill and coworkers set the stage for a series of detailed investigations in the early 1900's by many geologists that helped define the lithology- and structure of New York City bedrock units. On the basis of this knowledge, massive engineering construction projects including power generation, water supply, transportation, and sewage disposal were able to proceed, literally on a firm footing.

Figure 8 - Portion of Merrill et al's (1902) map showing the geology of the Bronx, parts of Manhattan, New Jersey, and Queens.

Before 1945, workers such as Hobbs (1905a, b), Kemp (1907, 1909, and 1910), Gratacap (1909), Ziegler (1911), Berkey (1907, 1910, 1911, 1930, 1933), Berkey and Healy (1911), Flinn

(1913), Fettke (1914), and Reeds (1925a, b, 1926, 1927, 1930, 1933), helped form our modern views on the bedrock geology of New York City and vicinity. In 1933, Berkey edited the guidebook for field trips in New York City held in connection with the 16th International Geological Congress meeting in Washington, D. C. Guidebook 9, a classic document, includes summary sections by A. K. Lobeck on the Geography of New York City, the Geology of New York City by G. I. Finlay, the Pleistocene geology of New York City by C. A. Reeds, and a detailed section on the engineering geology of New York City by C. P. Berkey. (Berkey's contribution is basically a recap of his 1911 New York State Museum Bulletin publication on the geology of the New York City aqueduct.)

Berkey 91933 fieldtrip guidebook) published a geologic map (Figure 9) showing a departure from Merrill's time-stratigraphic interpretation of bedrock units in the New York City area. Note that Berkey's map, (See Legend, Figure 9.) has "pushed back the temporal frontier" of Merrill's metamorphosed Paleozoic strata into the abyss of Proterozoic time. Although Berkey adhered to Mather's "Primitive" stratigraphy, strangely enough, his map is based largely on the formational contacts published by Merrill et al (1902; New York City Folio). (Compare Figures 7 and 9.)

In the period after the International Geological Congress, Charles P. Berkey, in his position as Chief Geological Consultant for the Board of Water Supply for the City of New York and his assistant Thomas W. Fluhr, were responsible for compiling engineering-drill-core data and tunnel maps which enabled them to enjoy a long-lasting tenure as the "experts" on New York City geology. This tenure resulted in a great number of scientific publications and a great number of internal engineering reports by C. P. Berkey, T. W. Fluhr, W. O. Crosby, and H. R. Blank which are listed and described in an important geotechnical summary by Fluhr and Terenzio (1984).

The multitude of engineering reports, maps, and boring logs by private-, state-, and municipal agencies provides a wealth of information on the geology of New York City. These documents can be divided into two groups: (1) those that were made in connection with projects carried out prior to the 1933 International Geological Congress (and also pre-Robert Moses) and (2) those related to projects that came after the 1993 Congress. In the first group are most of the tunnels for water suppy, for the subways, and for the railroads; the older bridges across the East River; and the George Washington Bridge over the Hudson River. In the second group are mostly the parkways and interstate highways and the newer bridges (exception, Brooklyn-Battery Tunnel), including the Triborough Bridge, Bronx-Whitestone Bridge, Throngs Neck Bridge, and Verrazano-Narrows Bridge. J. J. Murphy, the engineer who was appointed to design the West Side Highway, started the vast project known as the "rock data map" of Manhattan. Murphy began by assembling all the data from the thousands of borings available to him in the mid-1930's. The project eventually involved a staff of geologists supported by the Works Progress Administration (WPA) using office space made available at Columbia University via Professor Berkey. Each boring log was drawn in ink on tracing linen; these are still preserved in the subsurface branch of the New York City topographic division. The data were compiled on a large-scale map of Manhattan showing the altitude of the bedrock surface (Murphy, 1940; Murphy and Fluhr, 1944). We have benefited from and therefore list the efforts of Singstad (1944), Berkey (1948), Berkey and Fluhr (1948), deLaguna (1948), deLaguna and Brashears

(1948), Suter, deLaguna and Perlmuter (1949), Perlmuter and Arnow (1953), Blank (1934, 1972, 1973), Fluhr (1957), and Binder (1975, 1978). At present, all the boring logs and engineering data on municipal contruction projects in New York City are archived at the New York City Subsurface Exploration Section, 1 Centre Street, New York, New York. Many of the cores from city construction projects are at Hofstra University.

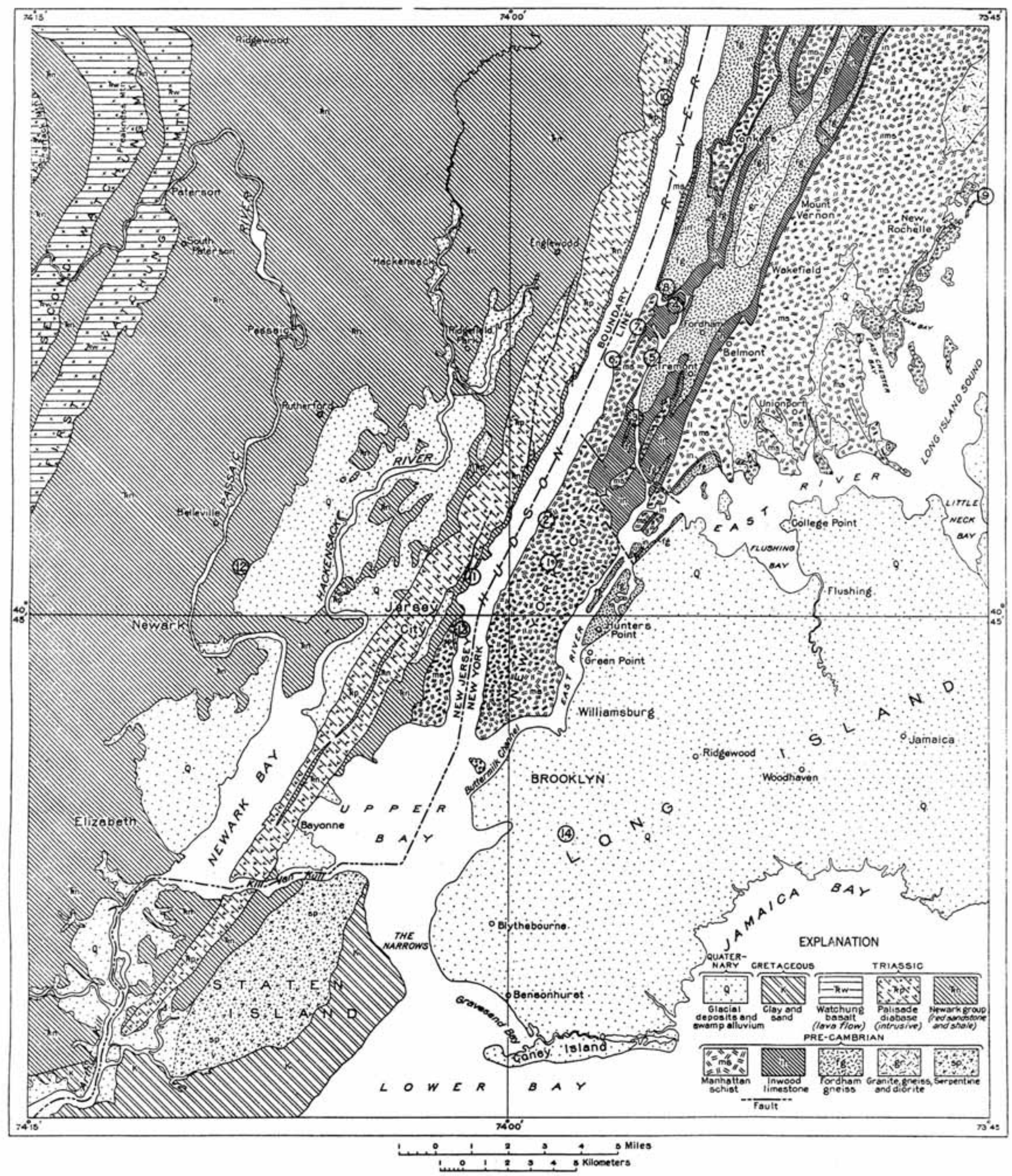


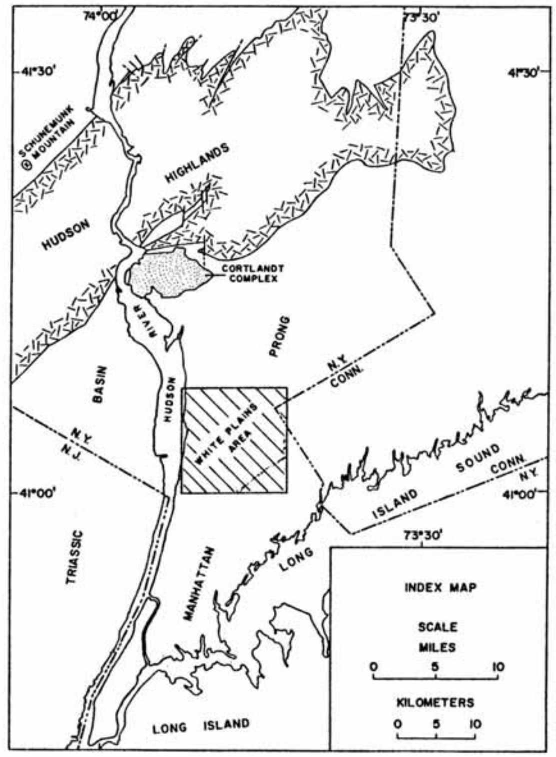
Figure 9 - Geologic map of New York City and adjacent part of New Jersey, generalized from U. S. Geological Survey Folio No. 83 (New York City, 1902). Circled numbers refer to trip stops on excursions offered by the 16th International Geological Congress, which met in the USA in 1933. (Berkey, 1933.)

The geologic work of the 1950's and 1960's included detailed mapping in the vicinity of New York City by Norton and Geise (1957) and Norton (1959) on the Lowerre Quartzite and work by Langer (1966), Langer and Bowes (1969), and Bowes and Langer (1969) on the products of metamorphism and polyphase deformation of the Manhattan Schist in Manhattan and the Bronx. Broader-scale investigations in Westchester County and adjacent areas included attempts at regional correlation of the New York City "Group" by Balk and Barth (1948), Lowe (1949, 1950, 1958), Paige (1956), Prucha (1956, 1959), Scotford (1956), Prucha, Scotford, and Sneider (1968), Lowe and Schaffel (1958), Schaffel (1958), Hall (1968a, b, c, 1969), Seyfert and Leveson (1968, 1969), Leveson and Seyfert (1969), and by Ratcliffe and Knowles (1969). Early, typically inaccurate, attempts at radiometric dating of metamorphic rocks and cross-cutting igneous rocks by Long and Kulp (1958, 1962), Long, Cobb, and Kulp (1959), Clark and Kulp (1968), and Long (1961, 1969a, b) helped provide important "ballpark" estimates on the ages of metamorphism of the New York City strata and of intrusion of the crosscutting igneous rocks.

Most of the post-1945 work was summarized in four collegiate symposia on the geology of New York City held in 1958, 1968, 1985, and in 1986. The first of these, chaired by our dear friend, Professor Kurt E. Lowe (Professor Emeritus, City College of New York, Ret.), was held at the New York Academy of Sciences in Manhattan. Lowe (1959) edited a series of papers (including one himself on the Palisades Sill) presented at the conference into an annals volume published by the Academy which included papers on the geology of New York City by (Long, Cobb, and Kulp, 1959; Norton, 1959; and Prucha, 1959).

As mentioned earlier, a 1968 Symposium on the New York City Group of Formations, was held at a meeting of the New York State Geological Association at Queens College, Queens, New York (Alexandrov, ed., 1969). Based largely on the work of Paige (1956), Hall (1968a, b, c), Ratcliffe (1968), and Ratcliffe and Knowles (1968), the formations in the New York City Group of were "de-Grouped." Leo M. Hall's identification of truncation of subunits of the Fordham Gneiss beneath various members of the Inwood Marble in Westchester County, provided the first, concrete evidence that a surface of unconformity separates the Proterozoic rocks of the Fordham and overlying Paleozoic rocks of the Lowerre-Inwood-Manhattan sequence in the Manhattan Prong (Figure 10). Isotopic-age determination (Grauert and Hall, 1973) yielded a 1.1 Ga (Proterozoic Y) age based on U-Pb analyses of zircons from the Fordham Gneiss. The combination of isotopic data and paleontologic evidence (Ratcliffe and Knowles, 1968; Ratcliffe, 1968) proved the Early Paleozoic age of the Inwood Marble. Based on the principle of superposition (Manhattan above Inwood) and regional relationships (late mid-Ordovician age of the Taconic unconformity), the Manhattan Schist was considered to be younger than the Inwood but older than Silurian. Thus, by the late 1960's, a refined, layer-cake model (this time with icing but still, no coffee!) for the lower Paleozoic strata was proposed which was basically in keeping with Merrill's original ideas.

Based on his work in the Glenville area of Westchester County, Hall (1968a, b, c, 1976, 1980), found that he could subdivide the Manhattan Schist into lithically variable members (designated by letters A, B, and C). He correlated parts of the Manhattan Schist with Cambrian rocks of the Taconic allochthon of eastern New York State (Figures 10, 11). Recent studies by Baskerville (1982a, b, 1987, 1989), Merguerian (1983a, 1986a, b), Mose and Merguerian (1985), Merguerian and Baskerville (1987), Taterka (1987), and Baskerville and Mose (1989), have demonstrated the extreme stratigraphic- and structural complexity of the Manhattan Prong in the vicinity of New York City. Not surprisingly, rather significant variations in stratigraphic- and structural interpretation can be found in these studies.



Index map for the White Plains area.

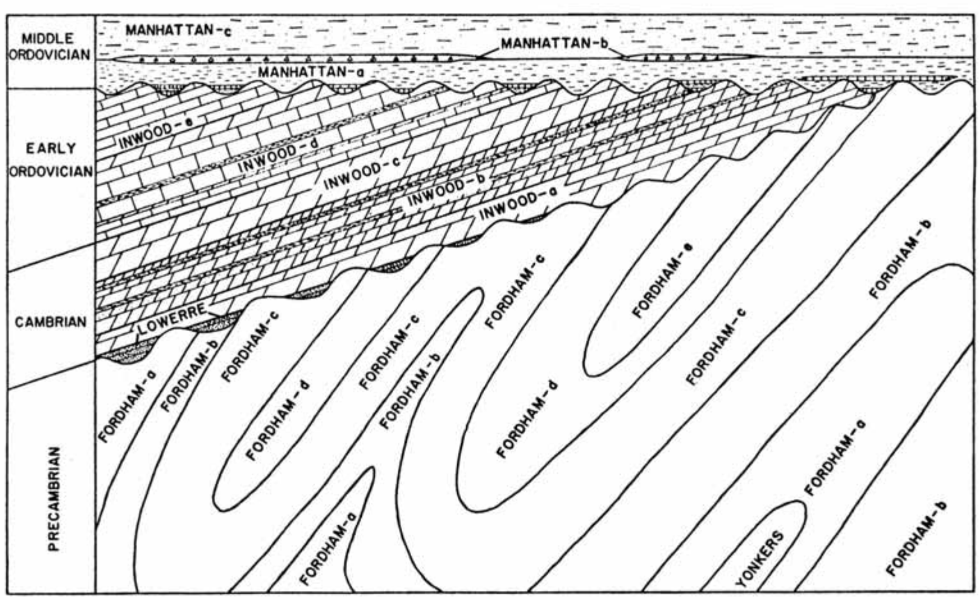


Figure 10 - Index map showing location of White Plains area (diagonal lines) and schematic profile-section showing inferred relationships among members of the Fordham Gneiss, Inwood Marble, and Manhattan Formation. (Hall, 1968a.)

STRATIGRAPHY OF THE GLENVILLE AREA

AGE	FORMATION	MEMBER	BRIEF DESCRIPTION	REGIONAL CORRELATION
UNCERTAIN	HARRISON GNEISS		DARK GRAY BIOTITE AND/OR HORNBLENDE-QUARTZ-FELDSPAR GNEISS WITH SUBORDINATE QUARTZ.	UNCERTAIN. HAWLEY FORMATION (CHIDESTER AND OTHERS, 1967)
UNCERTAIN	HARTLAND FORMATION	S	BROWN OR BROWNISH-TAN WEATHERING GARNET-MUSCOVITE-BIOTITE-QUARTZ-FELDSPAR SCHIST AND MUSCOVITE-BIOTITE-QUARTZ-FELDSPAR GNEISS AND GRANULITE. THE SCHIST COMMONLY CONTAINS SILLIMANITE AND/OR KYANITE.	UNCERTAIN. MORETOWN FORMATION (CHIDESTER AND OTHERS, 1967)
		W	LIGHT GRAY OR WHITE BIOTITE-MUSCOVITE GNEISS WITH LOCAL GARNET	UNCERTAIN — ROWE SCHIST (CHIDESTER AND OTHERS, 1967).
		CP	INTERBEDDED GRAY OR WHITE BIOTITE-MUSCOVITE-GNEISS, BROWN OR RUSTY WEATHERING GARNET-MUSCOVITE-BIOTITE SCHIST WITH LOCAL SILLIMANITE AND/OR KYANITE AND AMPHIBOLITE.	UNCERTAIN
		A	AMPHIBOLITE	UNCERTAIN
UNCERTAIN	MANHATTAN SCHIST	C	PREDOMINANTLY BROWN-WEATHERING FELDSPATHIC SILLIMANITE-GARNET-MUSCOVITE-BIOTITE SCHIST OR SCHISTOSE GNEISS; SILLIMANITE NODULES COMMON. ALTHOUGH SILICEOUS BEDS ARE PROMINENT IN SOME PLACES, BEDDING IS NOT COMMONLY CLEARLY DEFINED.	CORRELATION OF MEMBERS B AND C IS UNCERTAIN BUT THEY MAY BE EQUIVALENT TO THE WARAMAUG FORMATION (GATES AND BRADLEY, 1952), THE HOOSAC FORMATION (CHIDESTER AND OTHERS, 1967), AND LOWER CAMBRIAN AND CAMBRIAN (?) ROCKS OF THE TACONIC SEQUENCE (ZEN, 1967, FIG. 4).
		B	A DISCONTINUOUS UNIT OF AMPHIBOLITE AND MINOR SCHIST; ALTHOUGH THIS UNIT IS COMMONLY AT THE BASE OF MEMBER C, THERE ARE MANY PLACES WHERE IT IS WITHIN MEMBER C.	
MIDDLE ORDOVICIAN		A	GRAY OR DARK GRAY FISSILE SILLIMANITE-GARNET-MUSCOVITE BIOTITE SCHIST WITH INTERBEDDED CALCITE MARBLE LOCALLY AT THE BASE. UNCONFORMITY	BALMVILLE (FISHER, 1962) AND WALLOOMSAC (ZEN AND HARTSHORN, 1966).
LOWER ORDOVICIAN	INWOOD MARBLE	E	GRAY OR WHITE CALCITE MARBLE, COMMONLY TAN WEATHERING	COPAKE LIMESTONE AND ROCHDALE LIMESTONE (KNOPF, 1962).
		D	INTERBEDDED DOLOMITE MARBLE, CALCITE MARBLE AND SOME CALC-SCHIST.	ROCHDALE LIMESTONE AND HALCYON LAKE FORMATION (KNOPF, 1962).
CAMBRIAN		C	WHITE OR BLUE-GRAY CLEAN DOLOMITE MARBLE.	BRIARCLIFF DOLOMITE (KNOPF, 1962).
		B	INTERBEDDED WHITE, GRAY, BUFF, OR PINKISH DOLOMITE MARBLE, TAN AND REDDISH BROWN CALC-SCHIST, PURPLISH-BROWN OR TAN SILICEOUS CALC-SCHIST AND GRANULITES, TAN QUARTZITE, AND CALCITE-DOLOMITE MARBLE; BEDDING ONE HALF INCH TO FOUR FEET THICK IS PRONOUNCED.	PINE PLAINS FORMATION (KNOPF, 1962).
		A	WELL BEDDED WHITE, GRAY, OR BLUE-GRAY DOLOMITE MARBLE.	STISSING DOLOMITE (KNOPF, 1962).
	LOWERRE QUARTZITE		TAN OR BUFF-WEATHERING FELDSPATHIC QUARTZITE AND GRANULITE, MICAEOUS QUARTZITE AND GLASSY QUARTZITE; DARK GRAY, BROWNISH AND LOCALLY RUSTY-WEATHERING GRANULITE AND SCHIST THAT COMMONLY CONTAIN SILLIMANITE ARE LOCALLY PRESENT AT THE BASE. UNCONFORMITY	POUGHQUAG QUARTZITE (KNOPF, 1962).
PRECAMBRIAN	FORDHAM GNEISS	G	INTERBEDDED GRAY GARNET-BIOTITE GNEISS, GRAY BIOTITE-HORNBLENDE GNEISS AND AMPHIBOLITE.	UNKNOWN.
		AMP	PREDOMINANTLY AMPHIBOLITE WITH SOME GRAY BIOTITE-QUARTZ-FELDSPAR GNEISS.	UNKNOWN.
		CS	LIGHT-GRAY, BROWN, WHITE, OR GREENISH CALC-SILICATE ROCK.	UNKNOWN.
		AM	AMPHIBOLITE.	UNKNOWN.
		P	PINKISH BIOTITE-QUARTZ-FELDSPAR GNEISS.	UNKNOWN.

Figure 11 - Correlation chart of the metamorphic rocks of southeastern New York (Hall, 1968b, c).

Field- and laboratory investigations of the bedrock geology in the New York City area by Merguerian since 1979 have drawn heavily from earlier- and contemporary studies and suggest that the Manhattan Schist exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three, structurally complex, roughly coeval, tectonostratigraphic units. Merguerian's investigations agree, in part, with designations proposed by Hall (1976, 1980), but indicate the presence of a hitherto-not-recognized, structurally higher schistose unit that is a direct lithostratigraphic correlative of the Hartland Formation of western Connecticut (Merguerian, 1981a, 1983b, 1984). CM's interpretations on the stratigraphy of the Manhattan Schist were presented during a lecture at the New York Academy of Sciences on December 17, 1984 entitled "Will the real Manhattan Schist please stand up!"

In 1985, a symposium in honor of Kurt E. Lowe, was held in conjunction with a meeting of the Northeast Section of the Geological Society of America, in Kiamesha Lake, New York and CM presented a paper on the structural geology of the East River entitled "Tunnel vision--a deep view of the bedrock geology of New York City". In 1986, Merguerian organized a conference on the Geology of Southern New York at Hofstra University, in Hempstead, New York, wherein both JES and CM spoke on glacial- and bedrock geology, respectively. Details on the metamorphic stratigraphy are outlined in a later section entitled "The bedrock stratigraphy of New York City."

With the development of plate-tectonic concepts to explain mountain building as the result of ancient interactions of lithospheric plate boundaries, new interpretations and -models have been spawned by remapping orogenic belts such as the New England Appalachians (Merguerian, 1979; Hall, 1980; Robinson and Hall, 1980). In CM's view, the three ductile-fault-bounded Lower Paleozoic rocks (the three schist units of Manhattan), were juxtaposed during mid-Ordovician suturing of the eastern continental margin of North America and an offshore volcanic archipeligo (herein called the Taconic arc).

Layer I: "Basement Complex" (Proterozoic Z and Y)

Proterozoic rocks are now subdivided, by decree of the United States Geological Survey, into the older Archean (4.5 - 2.5 Ga [Ga = giga-, or billion years ago]) and younger Proterozoic (2.5 Ga - 575 Ma [Ma = million years ago]). Both Archean greenstone-gneiss terranes and crosscutting rocks of the Proterozoic mobile belts crop out to form the surface mosaic of the deeply eroded, 2.8 to 1.0 Ga, Canadian Shield of North America. The shield areas (or cratons) contain the oldest rocks on Earth and form the essential "continental seed crystals", which eventually, through the effects of plate tectonics, collected fringing Phanerozoic mobile belts. In this way, the continents have grown radially outward through time, enabling them to push back the oceans and eventually, to cover 29% of the Earth's surface. Thus, the eroded remnants of past mountain-building episodes are preserved as the cratonic nucleii of our modern continents. North America is no exception.

The Canadian Shield consists of deformed metamorphic-, metaigneous-, and igneous rocks. The surface eroded across these formations dips southward. Thus, the basement rocks of the shield become buried beneath the Paleozoic- and younger strata of the central United States.

These basement rocks do crop out on the surface in local areas associated with upwarps, fault blocks, and in elongate tracts along the core zones of both the Cordilleran- and Appalachian mountain belts. The extent of crystalline basement rock in the vicinity of New York State is shown in a depth-to-basement map (Figure 12). This is essentially a negative contour map, produced by geophysical studies, that shows contours on the plunging surface at the top of crystalline "basement". Isachsen's (1964) map shows that crystalline rocks trend east-west through most of New York State. The surface eroded on these rocks and dips south- to southeastward from the Canadian Shield beneath the Appalachian Basin (marked as the Allegheny Synclinorium). The ancient North American craton is phenomenally exposed in the Adirondack Mountains and along fault-bounded basement massifs to the east and southeast (Green Mountains of Vermont, Berkshire Mountains of Massachusetts and northern Connecticut, and the Housatonic Mountains in Connecticut and New York). Grenvillian Proterozoic rocks are also exposed along the Hudson Highland-Reading Prong and in the adjacent Manhattan Prong. The Grenville rocks are also present in isolated areas such as Snake Hill (Berkey, 1933), Stissing Mountain (Knopf, 1962), and the Ghent block (Ratcliffe, Bird, and Bahrami, 1975). JES and CM suppport Isachsen's (1964) interpretation and suspect that many of these are remnants of ancient overthrust sheets. Some are of Taconian age; others, of the terminal-stage, latest Paleozoic Appalachian overthrusting. possibly all have been subjected to mid-Jurassic deformation that included strike-slip couples (Sanders, 1962; Merguerian and Sanders, 1991).

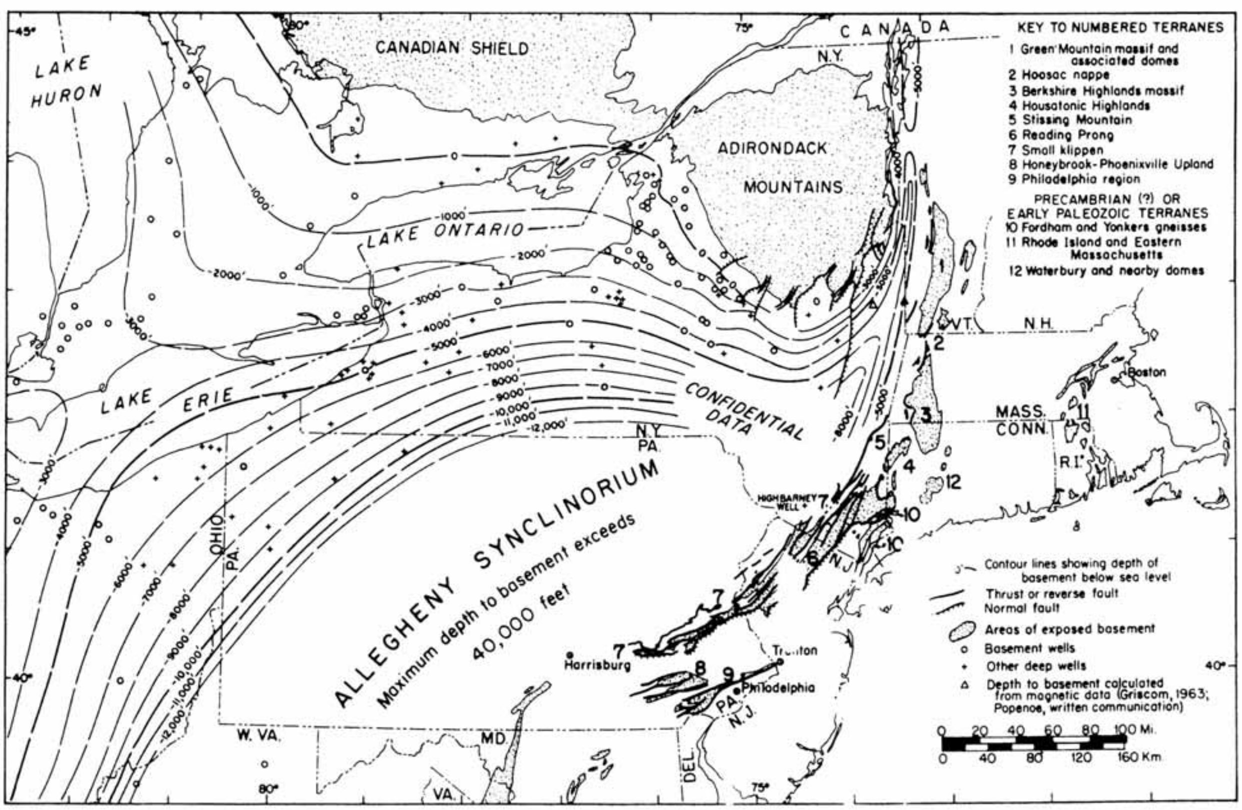


Figure 12 - Configuration of Precambrian surface and areas of exposed basement (Isachsen, 1964).

The oldest recognized strata in southeastern New York include the Fordham Gneiss in the Manhattan Prong of Westchester County and the New York City area and the Hudson Highlands gneisses. (See Figures 1, 3, and 5.) The Highlands gneisses are composed of complexly deformed layered feldspathic gneiss, schist, amphibolite, calc-silicate rocks, and massive granitoid gneiss of not-certain stratigraphic relationships which together form an impressive, glacially-sculpted cratonic sequence. Southeast of the Hudson Highlands, the Fordham has been intricately folded with Paleozoic rocks of the Manhattan Prong. We will examine the Fordham Gneiss today on the first stop of our field-trip route (Stop 1).

In the Pound Ridge area (PR in Figure 3), the Proterozoic Y gneisses of the Fordham have yielded 1.1 Ga Pb207/Pb206 zircon ages (Grauert and Hall, 1973) that fall well within the range of the Grenville orogeny. Rb/Sr data of Mose (1982) suggests that metasedimentary- and metavolcanic protoliths of the Fordham are 1.35 Ga old. Farther south in Westchester County, subunits in the Fordham are cut by Proterozoic Z granitic gneiss (the Pound Ridge Gneiss and correlative Yonkers Gneiss (Y in Figure 3). All Proterozoic units are unconformably overlain by the Lower Cambrian Lowerre quartzite (Hall, 1976; Brock, 1989). Using Rb-Sr, Mose and Hayes (1975), have dated the Pound Ridge Gneiss as latest Proterozoic (579+21 Ma). This gneiss body shows an intrusive-, or possibly an nonconformable relationship (Patrick Brock, personal communication) with the Grenvillian basement sequence. The Yonkers Granitic Gneiss has yielded ages of 563+30 Ma (Long, 1969b) and 530+43 Ma (Mose, 1981). The Pound Ridge along with the Yonkers Gneiss, are thought to be the products of latest Proterozoic alkali-calcic plutonism (Yonkers) and/or -volcanism (Pound Ridge?) in response to rifting of the ancient Gondwanan supercontinent.

Recent work by Pamela Chase Brock (1989, and personal communication) in the vicinity of the Peach Lake quadrangle, New York and Connecticut, shows the presence of a vast rift sequence (now metamorphosed) of potash feldspar-rich felsic gneiss, calc-silicate rock, volcaniclastic rock, amphibolite gneiss, and minor quartzite (Ned Mountain Formation) that rest unconformably on the Fordham basement rocks. As such, Brock may have identified a metamorphosed, easterly volcaniclastic facies of Proterozoic Z intrusive igneous activity whose probable feeder area is now marked by the Yonkers and Pound Ridge gneisses. Together, the Proterozoic Y and Z terranes represent the ancient continental crust of proto-North America that was involved in both the Grenville orogeny and post-Grenville, pre-Iapetus extensional tectonic activity. Keep in mind that during subsequent Paleozoic orogenesis, these ancient rocks were involved in intense compressional deformation and metamorphism.

The rifting of the Proterozoic Y craton in latest Proterozoic time thus sets the stage for the first of the Paleozoic trailing-edge continental margins of eastern North America. This trailing edge of the Iapetus Ocean, (or passive margin I) was to receive clastic, then carbonate sediments of Layer IIA. (See Tables 1 and 2.) Thus, early into the Paleozoic Era, this part of the Appalachian mountain belt region became the trailing edge of a continental plate, a passive continental margin (Figure 13) adjacent to the ancestral Atlantic Ocean (Iapetus). This tectonic setting persisted until the Taconic orogeny, late in the middle Ordovician Period. Interestingly, the contemporary passive-continental-margin setting of eastern North America, [deformed Paleozoic and older basement covered by essentially nondeformed Mesozoic and younger sediments that were (and continue to be) deposited as the margin subsides toward an ocean basin to the east] more or less duplicates that of Early Paleozoic time!

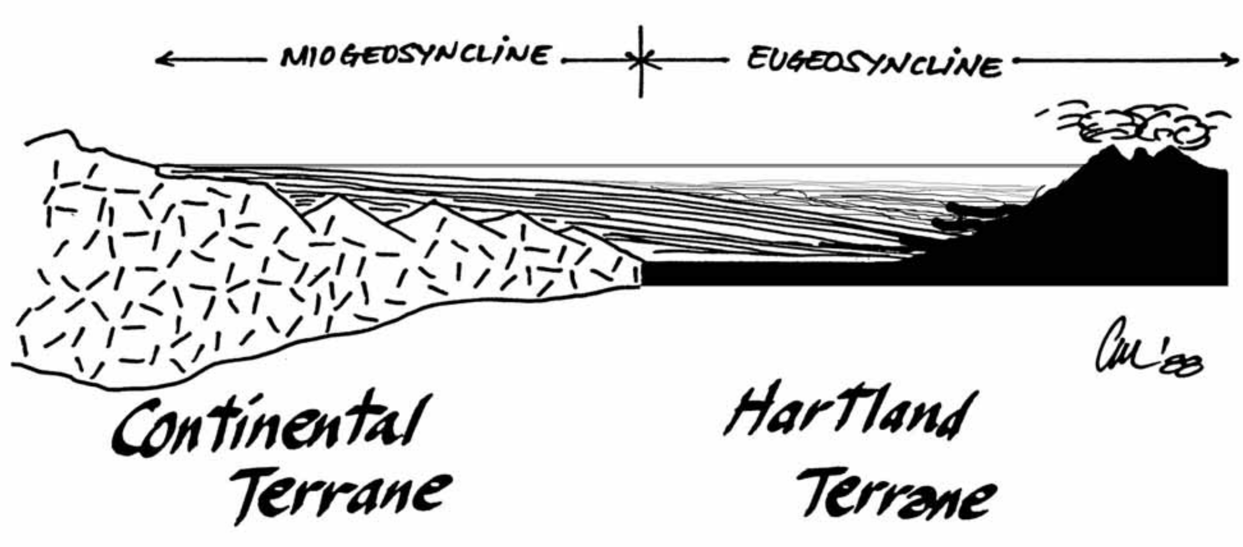


Figure 13 - Diagrammatic sketch of the passive margin of eastern North America in Early Paleozoic time showing the contrast in miogeosynclinal and eugeosynclinal depositional areas.

Layers IIA and IIB: Cambro-Ordovician Strata

As we examine rocks in the Bronx today, we will walk upon the metamorphosed products of two contrasting paleogeographic-paleotectonic regimes: (1) sediments deposited on an ancient passive continental margin, which lasted from early in the Cambrian Period until the medial Ordovician Period (Figure 14) and which featured a carbonate-platform interior (now designated as the Sauk Sequence) that was bordered on the east by a continental-rise prism of fine-textured terrigenous sediment (Taconic Sequence) and an oceanward volcanic source [Layers IIA(W) and (E)]; and (2) the filling of a foreland basin, part of an actively converging continental margin [Layer IIB; now designated as the Tippecanoe Sequence], which commenced later in the Ordovician Period and extended through at least the end of the Ordovician period. The Tippecanoe Sequence holds the eroded products of important convergent mountain-building event (the Taconic orogeny), which featured mountains that were elevated where formerly the sea stood and that eventually, during the Silurian and Devonian periods, shed coarse sediments [Layer III] westward toward the interior of the continent. (See Tables 1, 2.)

The important change from a passive continental margin to a convergent margin involved overthrusts toward the continent, slope reversal, and geographic rearrangements. The first of the overthrusts toward the continent broke inboard of the former shelf edge and brought felsic continental basement rocks above the muds on the floor of the foreland basin where the Tipppecanoe Sequence was accumulating. Later,the Taconic allochthon was emplaced, whereby the the fine-textured terrigenous sediments of Layer IIA(E), deposited in the vicinity of the ancient continental rise and oceanward (Taconic Sequence), were displaced physically above carbonates and clastics of the Sauk Sequence [Layers IIA(W) and IIB]. Synorogenic flysch [Layer IIB] above Layer IIA actively filled the rapidly subsiding foreland basin. The evidence for this change consists of karst landscape and karst-depression-filling breccias at the top of the basal limestone of the Tippecanoe Sequence and the eventual covering of this karst surface with graptolite-bearing Tippecanoe-Sequence shales [Layer IIB] (Figure 14). A complicating factor is that the overthrust sheets (including the Taconic allochthon) were emplaced along the sea floor where the foreland-basin fill was accumulating. Modern hypotheses contend that the loading of the continental margin by the advancing Taconic allochthon may have caused the foreland basin to subside. According to CM, a small part of the Manhattan Schist formation represents the metamorphosed clastics that were part of this foreland-basin- filling material.

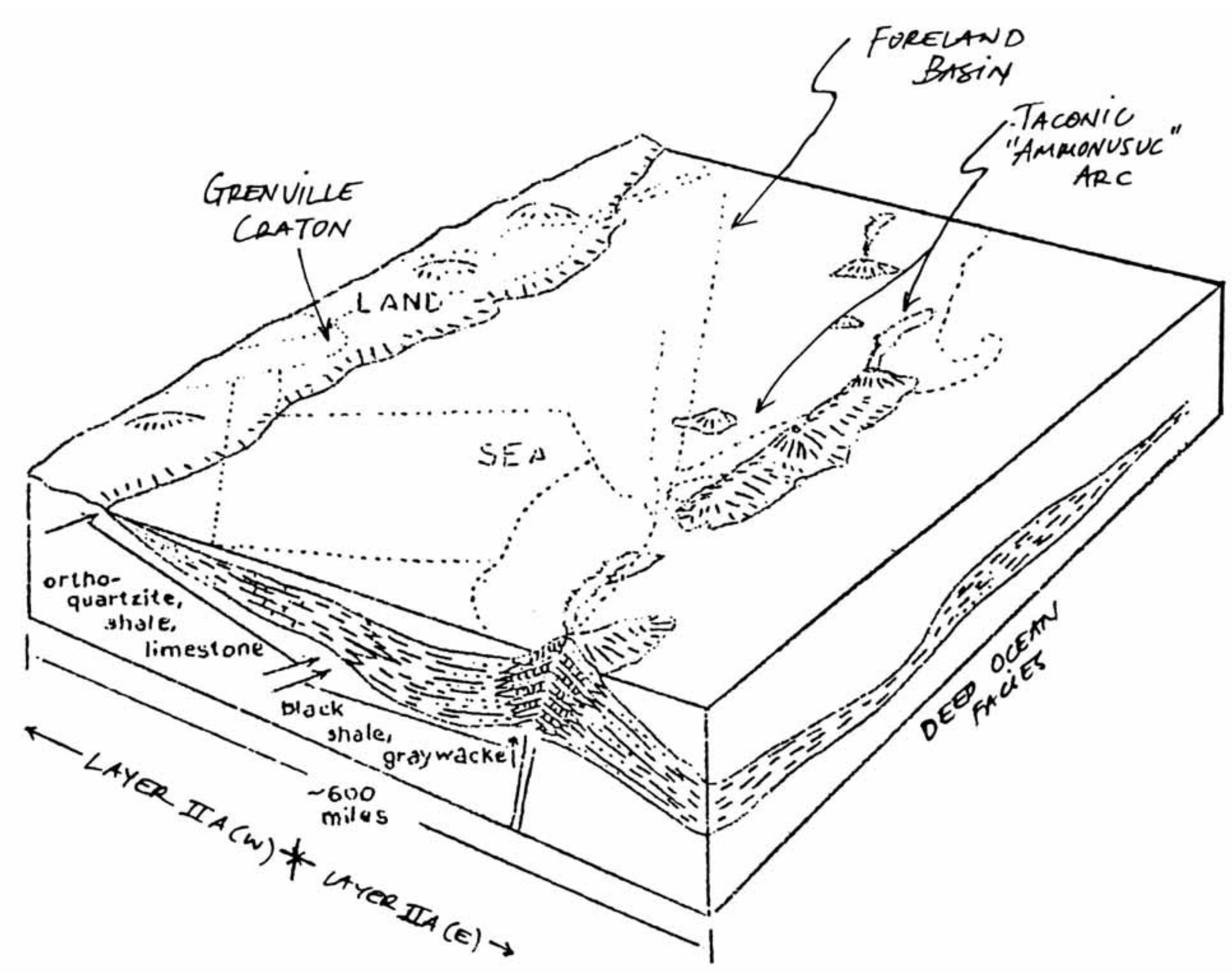


Figure 14 - Block diagram showing the Early Paleozoic continental shelf edge of embryonic North America immediately before the deposition of Layer IIB. Current state outlines are dotted. The depositional areas for Layers IIA(W) and IIA(E), and the position of the Taconic arc and foreland basin are shown.

In terms of large stratigraphic units, the Cambro-Ordovician carbonate succession (Layer IIA(W)), deposited on the former continental platform, is collectively designated as the Sauk

Sequence (local representatives of which are the Wappinger Group (local name taken from Wappinger Creek, E and S of Poughkeepsie) or Kittatinny Group (New Jersey name), and their metamorphosed equivalents. (From Connecticut northward the Woodville, Vermont, Stockbridge, and Woodbridge marbles; in the New York City region, the Inwood Marble.) This vast sheet (Figure 15) of carbonates is known elsewhere by other names. It is the famous oil-bearing Arbuckle Group of Oklahoma and Kansas; the Ellenburger Group of Texas; and the Knox Group of the southern Appalachians. In general, the carbonates consist of quartzose dolomite, and dolomitic rocks of Cambrian and Early Ordovician ages. In the marginal troughs, they are underlain by Lower Cambrian quartzose clastic rocks. Outside the marginal troughs, the basal clastics are of Late Cambrian age. The Cambrian clastic strata are known as the Cheshire Quartzite in Massachusetts, the Poughquag Quartzite in New York, and as the Lowerre Quartzite in the vicinity of New York City. Farther south, correlatives include the Hardyston Quartzite in New Jersey and the Setters Quartzite, still farther south in Pennsylvania.

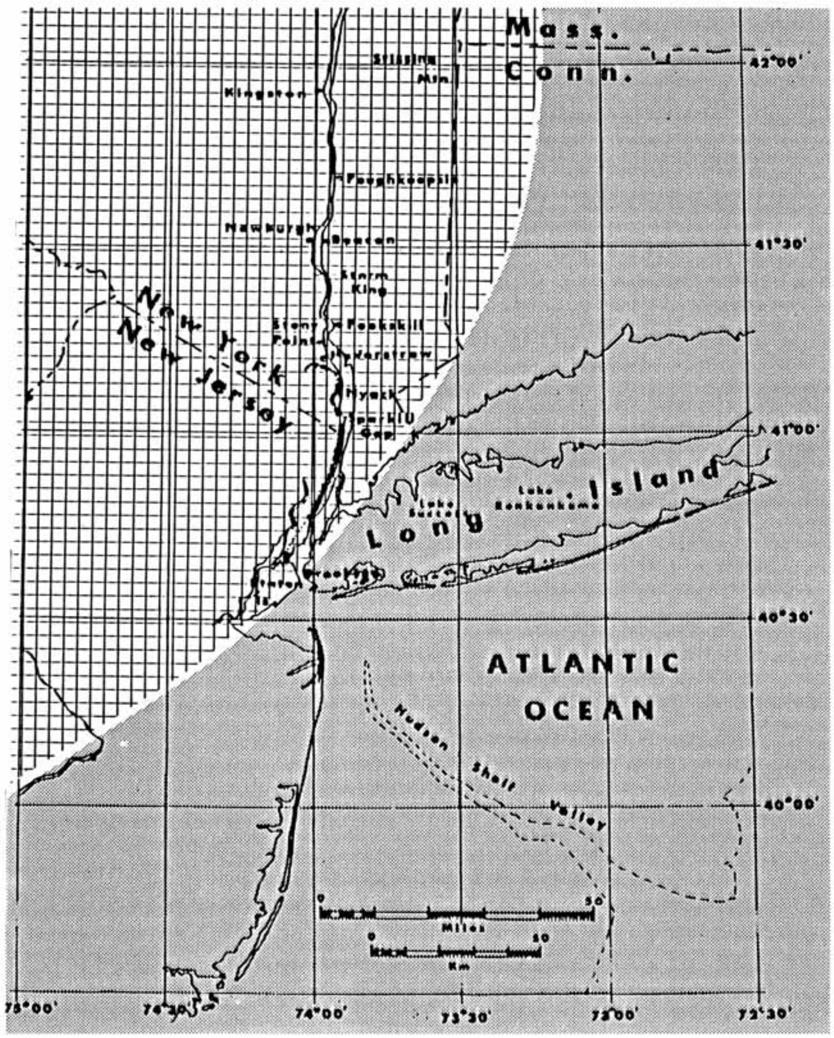


Figure 15 - Boundary between carbonate platform (pattern of squares) and deeper-water area to the east where terrigenous sediments were deposited (shaded), during the Cambrian and early part of the Ordovician periods. JES diagram.

Exposures of the Lowerre Quartzite have never been found in the Bronx. As a result of sediment covering, construction, as well as its very local development, the Lowerre is no longer exposed on the surface. In fact, in comparison to areas immediately to the north and south in the Appalachian range, Cambrian clastic rocks are rare in the vicinity of New York City. Perhaps during early Cambrian time, the New York City area was emergent and shed coarse clastic sediment rather than collecting it. CM has encountered a thin basal quartzite in drill core from the subsurface of the Bronx and Manhattan.

Bedrock Stratigraphy of New York City and the Bronx

The bedrock underlying Manhattan includes the Fordham Gneiss, Lowerre Quartzite, Inwood Marble, and various schistose rocks formally included in the Manhattan Schist. These metamorphosed, Lower Paleozoic bedrock units are found west of Cameron's Line, a major tectonic boundary in New England. Together, they constitute the autochthonous miogeosynclinal basement-cover sequence of the New England Appalachians (pꞒ-O in Figure 3) and are the products of metamorphism of sediments formerly deposited on Proterozoic crust. Rocks found east of Cameron's Line in western Connecticut and southeastern New York belong to the Hartland Formation (Cameron 1951, Gates 1951, Rodgers and others 1959, Merguerian 1977, 1983b) or Hutchinson River Group (Seyfert and Leveson 1968, 1969; Levesen and Seyfert 1969), or Pelham Bay Member of the Hartland Formation (Baskerville 1982a).

In contrast to the basement-cover sequence, the Hartland Formation consists of a sequence of metamorphosed eugeosynclinal rocks formerly deposited on oceanic crust (Ꞓ-Oh in Figure 3) which became accreted to North America during the Medial Ordovician Taconic orogeny (Hall, 1979; Merguerian 1979, 1983b; Merguerian and others, 1984; Robinson and Hall, 1980). To the west of Cameron's Line, in Manhattan, rocks with lithologic affinities transitional to these extremes crop out.

Merrill (1890) established the name Manhattan Schist for the well-exposed schists of Manhattan Island. Hall's (1968a, b, c) mapping in White Plains established subdivisions of the Manhattan Schist into two basic units. The autochthonous Manhattan A, which was originally deposited as part of the Tippecanoe Sequence overlying the basal Tippecanoe limestone that forms the topmost unit of the Inwood Marble and the allochthonous (transported rocks not found where deposited) Manhattan B and C members (Figure 11). Hall (1976) suggested that the Manhattan C (schist) and B (interlayered amphibolite unit) were Early Cambrian (or possibly older) in age, and thus are parts of the Taconic Sequence (Layer IIA(E) in our scheme) and were deposited below aluminous schist and granofels of the Hartland Formation. In Figure 3, Manhattan A is included in the basement-cover sequence (pꞒ-O) and Manhattan B and C are designated Ꞓ-Om. Merguerian (1983a, 1985a) interprets the Manhattan B an C as a slope-rise-facies that was formerly deposited continentward of the Hartland Formation and now separated from them by Cameron's Line. Thus, in contrast to Hall's (1976, 1980) views, CM views the Manhattan B and C and the Hartland as essentially coeval tectonostratigraphic units.

To answer a question posed by Dr. Patrick Brock of Queens College, we are not sure how basaltic volcanics become interstratified with Cambro-Ordovician slope/rise sediments but offer two possible models. Basalts may represent offscraped oceanic crust tectonically imbricated within the subduction complex during the Taconic orogeny. This model would suggest no stratigraphic significance to the mafic horizon near the base of Manhattan C and careful mapping may indicate that Hall's (1968) call on the stratigraphic position of the mafic unit may be oversimplified. A second model would place the basalt into the slope/rise sediments as a sill-like intrusive sheet. In this case, the basalts would be the result of Cambrian- or Eocambrian rifting and antedate the Taconic orogeny. (These may be comparable with the basalts in the Rensselaer Graywacke of the high Taconics.)

Strong evidence for three subdivisions and possibly allochthony within the Lower Paleozoic schists exists in New York City (Merguerian, 1981a, 1983a; Mose and Merguerian, 1985). On the basis of lithostratigraphic- and structural evidence, most of the exposed schist on Manhattan Island is interpreted as part of a transitional slope-rise Taconic Sequence (Ꞓ-Om) and as the deep-water oceanic Hartland Formation (Ꞓ-Oh), not as the stratigraphically youngest unit as suggested in all "pre-plate tectonics" bedrock interpretations!

Based on his detailed mapping, CM divides the schist on Manhattan Island into three, lithologically distinct, structually imbricated, lithostratigraphic units of kyanite- to sillimanite metamorphic grade that plunge toward the south (Figure 16). The structurally lowest unit (Om), crops out in northern Manhattan and the west Bronx. This unit is composed of brown-to rusty-weathering, fine- to medium-textured, typically massive, muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet schist containing interlayers centimeters- to meters thick of calcite+diopside marble. The minerals are listed in order of decreasing relative abundance. This lower unit is lithically correlative with the Middle Ordovician Manhattan member A of Hall (1968a) because it "looks like it" and is found interlayered with the underlying Inwood at two localities (Stops 3 and 6 from our Manhattan On-The-Rocks trip; Merguerian and Sanders, 1991b), and contains layers of calcite ("Balmville") marble near the Inwood contact. Because it is interpreted as being autochthonous (depositionally above the Inwood Marble), CM informally refers to it as "the Good-Old Manhattan Schist" and assigns it a middle Ordovician age as part of the Tippecanoe Sequence. (JES notes that this is in contrast to the older, "Bad-New Manhattan Schist" mentioned below.)

The lower schist unit and the Inwood Marble are structurally overlain by the middle schist unit (Ꞓ-Om) which forms the bulk of the "schist" exposed on the Island of Manhattan (Figure 16). The middle schist unit consists of rusty- to sometimes maroon-weathering, medium- to coarse-textured, massive biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist. The middle schist unit is characterized by the presence of kyanite+sillimanite+quartz+magnetite layers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite (metamorphosed basaltic rock), and quartzose granofels. The middle unit is lithologically identical to Hall's Manhattan B and C and the Waramaug and Hoosac formations of Cambrian to Ordovician ages in New England (Hatch and Stanley, 1973; Hall, 1976; Merguerian, 1981a, 1983b). These rocks are inferred to represent metamorphosed Cambrian to Ordovician sedimentary- and minor volcanic rocks formed in the transitional slope- and rise environment of the Early Paleozoic continental margin of ancestral North America.

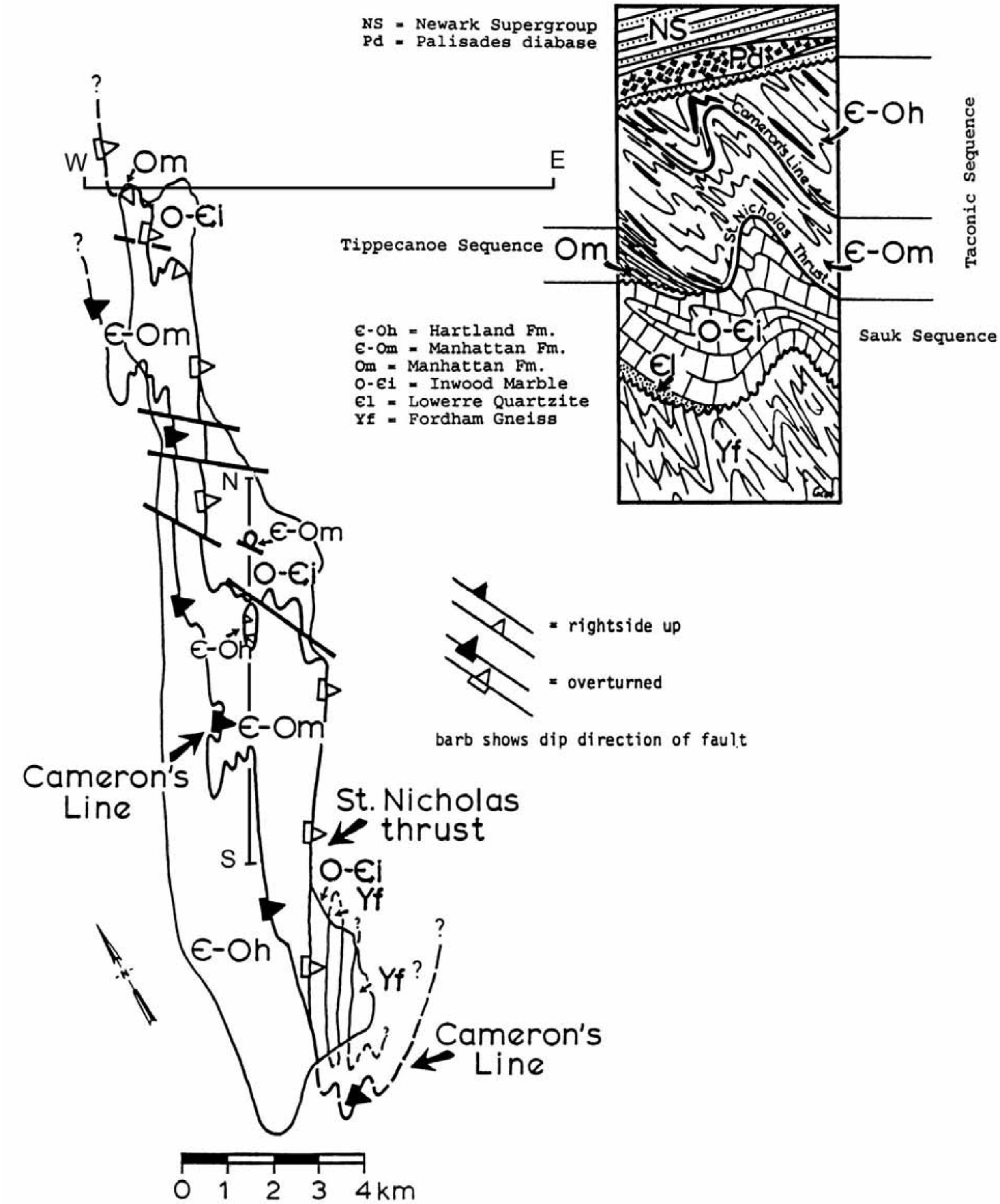


Figure 16 - Geologic map of Manhattan Island showing a new interpretation of the stratigraphy and structure of the Manhattan Schist. Drawn and mapped by C. Merguerian.

The structurally highest, upper schist unit (Ꞓ-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. The upper schist unit, which based on CM's study of more than 500 outcrops in Manhattan and the Bronx, and a multitude of drill cores and construction excavations, underlies most of the western- and southern third of Manhattan, and the eastern half of the Bronx and is lithologically identical to the Cambrian and Ordovican Hartland Formation of western Connecticut and southeastern New York. On this basis, CM correlates them with the Hartland. Therefore, CM has extended the name Hartland into New York City. Accordingly, CM infers that together they represent metamorphosed deep-oceanic shales, interstratified graywackes, and volcanic rocks formed adjacent to North America during Early Paleozoic time.

In summary, the three distinctive mappable units of the "Manhattan Schist" represent essentially coeval shelf- (Om), transitional slope/rise- (Ꞓ-Om), and deep-water (Ꞓ-Oh) lithotopes that were juxtaposed during telescoping of the ancestral North American shelf edge in response to closure of the proto-Atlantic (Iapetus) ocean during the Taconic orogeny (Figure 17). Regional correlation suggests, then, that the higher structural slices of the Manhattan Schist are older, or possibly the same age as, the lower unit (Om). The structural evidence that CM uses to define the contacts among the three Manhattan "schists" is described below. The discussion of that structural evidence is located after the following general introduction to geologic structure that we have included as a matter of convenience to readers whose knowledge of structural geology may be in need of a bit of refreshing.

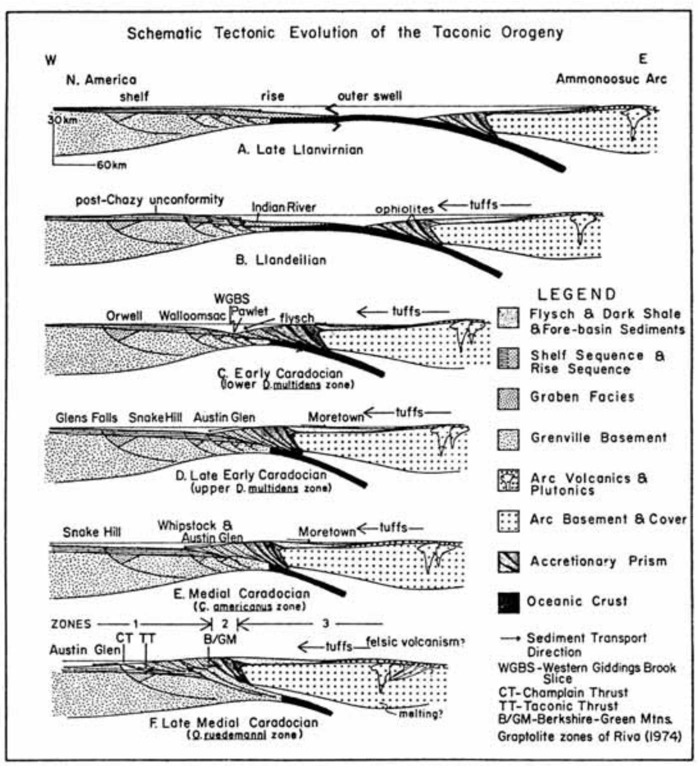


Figure 17 - Sequential tectonic cross sections for the Taconic orogeny in New England. From Rowley and Kidd (1981).

Geologic Structure - a Primer

Geologists use terminology to confuse the layman and to enable them to amass a huge library of terms that are undeniably useless in most social situations. Our structure classes are an exception, luckily, and we can now bury you in a mountain (how about a deeply eroded mountain range?) of terms to help you understand the major types of structures and geologic features that you will hear about today. In the following section, we describe folds, faults, surfaces of unconformity, sedimentary structures, structures in sedimentary- vs. metamorphic rocks, and tectonostratigraphic units.

Folds

When subjected to differential forces, under high confining pressures and elevated temperatures, rocks (like humans) begin to behave foolishly, squirming in many directions and upsetting the original orientation of primary- or secondary planar- and linear features within them. Geologists try to sort out the effects of deformation by working out the order in which these surfaces or linear features formed. In dealing with the structural geology of sedimentary rocks, the first surface one tries to identify positively is bedding or stratification. The boundaries of strata mark original sub-horizontal surfaces imparted to sediments in the earliest stage of the formation of sedimentary rock. Imagine how such strata, buried by the weight of overlying strata and laterally compressed by the advance of lithospheric plates, are subjected to the differential force necessary for folds to form. Contrary to older ideas, we now realize that vertical burial cannot cause regional folds (although small-scale slumping and stratal disharmony are possible). Rather, tangential force must be applied to provide the driving force behind the creation of folds and faults. At crustal levels below 10 km, the behavior rocks is described as ductile. Folds and faults are accompanied by recrystallization and reorientation of newly formed metamorphic minerals. More on metamorphic textures later. For now let's discuss some geometric aspects of structural geology.

If layers are folded into convex-upward forms we call them anticlines. Convex-downward fold forms are called synclines. In Figure 18, note the geometric relationship of anticlines and synclines. In eroded anticlines, strata forming the limbs of the fold dip away from the central hinge area or core (axis) of the structure. In synclines, the layers forming the limbs dip toward the hinge area. Given these arrangements, we expect that older stratigraphic layers will peek through in the arches of eroded anticlines whereas younger strata will be preserved in the eroded troughs of synclines. In metamorphic terranes, field geologists are not always sure of the correct age relationships of the metamorphosed strata. Therefore, it is helpful to make use of the terms "antiform" and "synform," which describe the shapes of folds but do not imply anything about the ages of the strata within them.

Axial surfaces of folds physically divide the fold in half. Note that in Figure 18 the fold is deformed about a vertical axial surface and is cylindrical about a linear fold axis which lies within the axial surface. The locus of points connected through the domain of maximum curvature of the bedding (or any other folded surface of the fold) is known as the hinge line (which is parallel to the fold axis). This is geometry folks; we have to keep it simple so geologists can understand it.

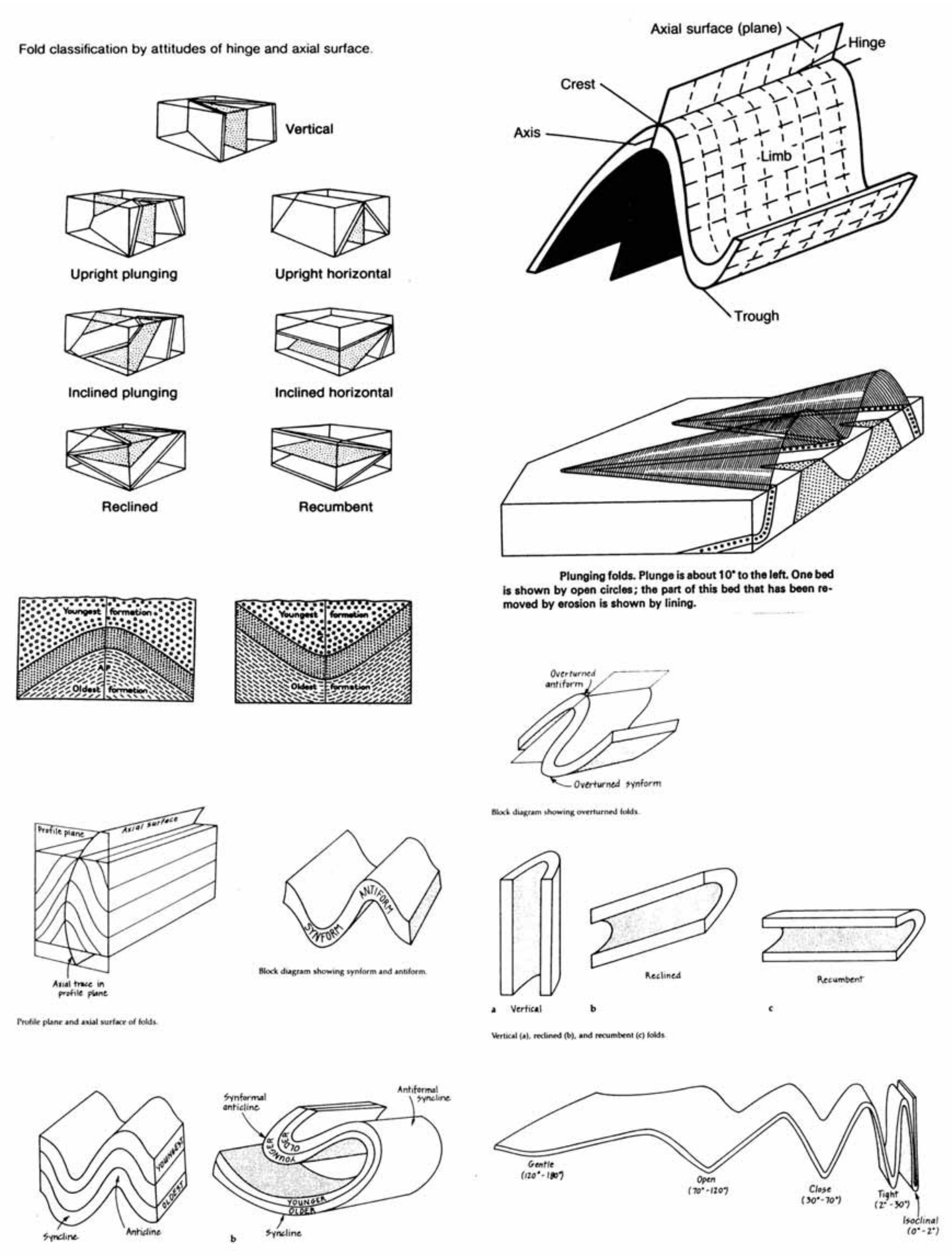


Figure 18 - Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the text.

Realize that in upright folds, axial surfaces are vertical and fold axes, horizontal. Keep in mind that folding under metamorphic conditions commonly produces a penetrative mineral fabric with neocrystallized minerals (typically micas and amphiboles) aligned parallel to the axial surfaces of folds. Such metamorphic fabrics are called foliation, if primary, and schistosity, if secondary. The long axes of elongate minerals can also become aligned to produce a metamorphic lineation. Such features can be useful in interpreting a unique direction of tectonic transport or flow direction. Because folds in metamorphic rocks are commonly isoclinal (high amplitude to wavelength aspect ratio) with limbs generally parallel to axial surfaces, a penetrative foliation produced during regional dynamothermal metamorphism will generally parallel the reoriented remnants of stratification (except of course in the hinge area of folds). Thus, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they mark regional-fold hinge areas.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine that the axial surface of a fold can be tilted, to form inclined- or overturned folds, or be sub-horizontal, to form recumbent folds, all accomplished by keeping the fold axis horizontal (Figure 18). In addition, we can keep the axial surface vertical and within it, change the orientation of the axis from horizontal to some angle other than 0° to produce a plunging fold. Such folds can be plunging anticlines (antiforms) or plunging synclines (synforms). Vertical folds (plunging 90°) also occur, in which case the terms anticline and syncline are not meaningful. Most folds in complexly deformed mountain ranges show the effects of more than one episode of deformation and as such their ultimate configuration can be quite complex (i. e., plunging folds with inclined axial surfaces and overturned limbs).

Structural geologists use a relative nomenclature to discuss superimposed products of several episodes of deformation (Dn), folding (Fn), foliation (Sn), and metamorphism (Mn), where n is a whole number starting with 1. Bedding is commonly designated as S_0 (or surface number zero) as it is commonly overprinted by S_1 (the first foliation). To use this relative nomenclature to describe the structural geology of an area, for example... "during the second deformation (D_2), F_2 folds formed with the development of an axial planar S_2 foliation under progressive M_1 metamorphic conditions."

Another point about the alphabet soup of structural geology. Seen in cross section, folds fall into one of three groups, the S's, the M's (or W's), and the Z's. Usually only one variety of small folds will be found on a given limb of a larger fold. Therefore, if one notices a change in the pattern from S folds to Z folds (or vice versa), one should be on the lookout for a fold hinge where the M folds or W folds are present.

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the main forces that produced the fold. Therefore, the orientation of the folds give some hint as to the direction of application of the active forces (often a regional indicator of relative plate convergence). In complex regions, the final regional orientation of the structures is a composite result of many protracted pulses of deformation, each with its unique geometric attributes. In these instances, simple analysis is often not possible. Rather, a range of possible explanations for a given structural event is commonly presented.

Faults

Imagine taking a cylinder of rock out of the Earth and torturing it in a tri-axial compression machine to see what happens. Some geologists get a big charge out of this and tell us (the field geologists) that they really understand how rocks behave under loads. CM thinks they need to perform these experiments over a longer time frame than a few generations of siblings will allow and thus relies more on field observation and inferences than from rock-squeezing data to gain a feel for the complex nature of ductile vs. brittle folding and -faulting. In any case, a few simple relationships are generally agreed upon regarding brittle- and ductile faulting and these are discussed below.

Start with a block of rock and assume that the elastic limit to intracrystalline glide and lattice deformation have been exceeded to the point where the rock begins to behave as a brittle (as in peanut brittle) solid rather than in a plastic (as in toothpaste) manner. Once a failure begins (fracture) it will propagate, produce offset and form a fault surface that will show elongate gouges (called slickensides) that may possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides. The fault block situated below the fault plane is called the footwall block and that situated above the fault plane, the hanging-wall block (Figure 19). With extensional force acting on the sides of the block, the hanging wall will slide down the fault plane producing a normal fault. If the forces are compressive, the hanging wall slides up the fault plane and this results in a reverse fault. A reverse fault with a low angle (<30°) is called a thrust fault. In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane. These, therefore, illustrate dip-slip motion.

Rather than apply extension or compression, suppose one were to shear the block along its sides (i.e., attempt to rotate the block about a vertical axis but do not allow the block to rotate). This type of force will generate a strike-slip fault (Figure 19) with the fault plane showing slickensides oriented subhorizontally. Two, and only two directions of motions are possible: left lateral and right lateral. To determins the sense of motion, imagine that you are standing on one block facing toward the fault so that you can see the oppposite block. If the oppposite block has moved relatively to your left, the motion is left lateral. If the opposite block has moved to your right, then the motion is right lateral. Convince yourself that it matters not which block you choose to observe from! Naturally, complex faults show movements having components of both dip-slip and of strike-slip motion, rotation about axes perpendicular to the fault plane, or reactivation in a number of contrasting directions or variety. This, however, is no fault of ours.

Tensional- or compressional faulting resulting from brittle deformation, at crustal levels shallower than 10 km, is accompanied by seismicity and the development of highly crushed and granulated rocks called breccias and cataclasites (including fault gouge, fault breccia, and others). Starting at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallizing during flow. These unique metamorphic conditions prompt the development of highly strained (ribboned) quartz, feldspar porphyroclasts (augen), and frayed micas, among other changes, and results in highly laminated rocks called mylonites. In complexly deformed terranes, such ductile fault rocks can be identified only by detailed mapping of metamorphic lithologies and establishing their geometric relationship to suspected mylonite zones. Unfortunately, continued deformation under load often causes early formed mylonites to recrystallize and thus to produce annealed mylonitic textures (Merguerian, 1988) that can easily be "missed" in the field without careful microscopic analysis. Cameron's Line, a recrystallized ductile shear zone showing post-tectonic brittle reactivation, is an original ductile-fault zone (mylonite) having a complex geologic history.

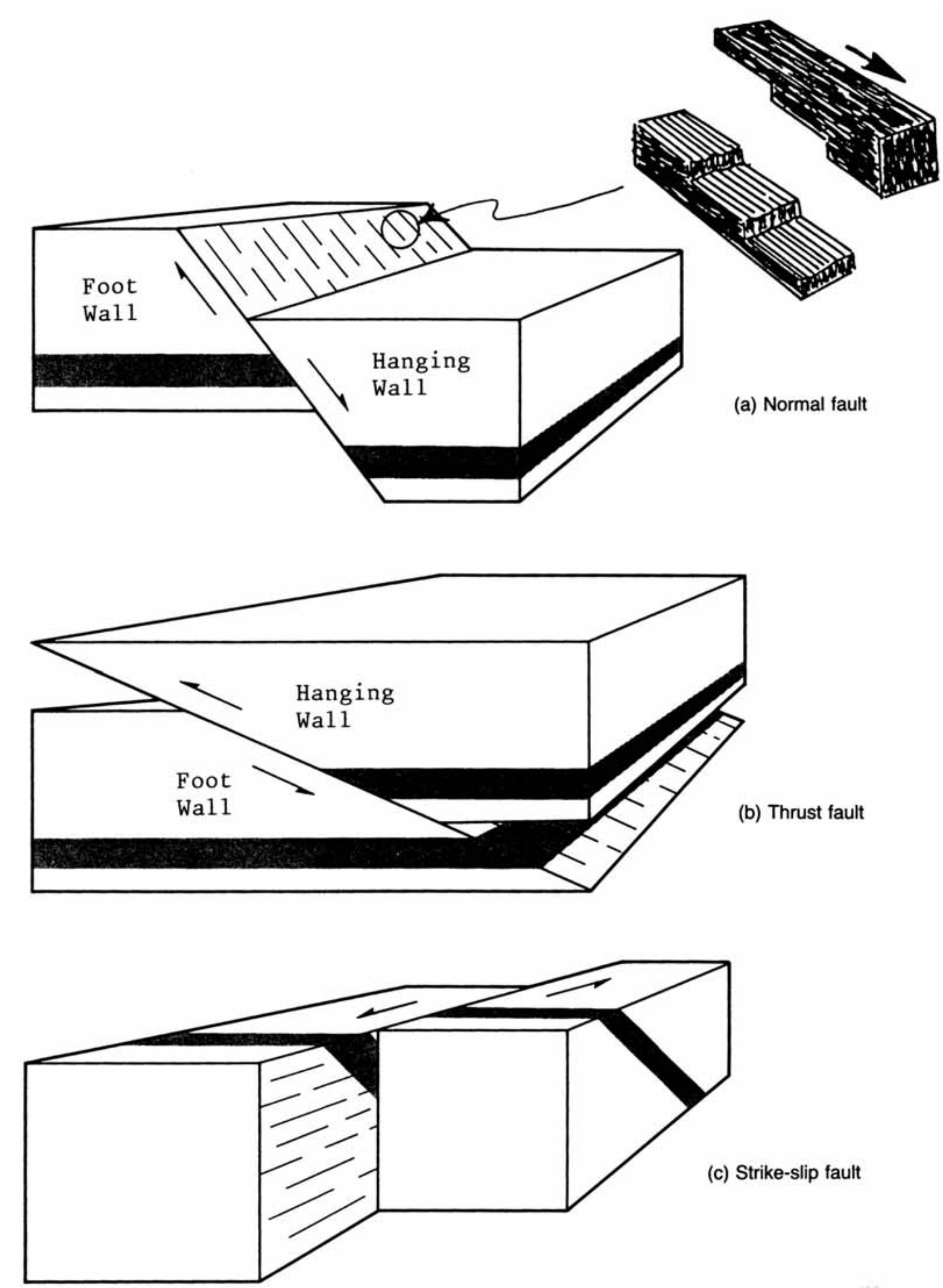


Figure 19 - Composite diagram from introductory texts showing the three main types of faults.

Tectonostratigraphic units

In metamorphic terranes, tectonostratigraphic units can best be described as large-scale tracts of land underlain by bedrock with similar age range, protolith paleoenvironment, and structure. Such terranes are generally bounded by ductile fault zones (mylonites), surfaces of unconformity, or brittle faults. Unravelling the collisional plate-tectonic history of mountain belts is greatly facilitated by identifying former cratonic (ancient crustal), continental-margin, continental-slope-, and rise, deep-oceanic, and volcanic-island tectonostratigraphic units. The major distinction in unravelling complexly deformed mountain belts is to identify former shallow-water shelf deposits (originally deposited on continental crust) and to separate them from deep-water oceanic deposits (originally deposited on oceanic crust). We use the terms miogeosynclinal and eugeosynclinal, respectively, to designated the products of these contrasting depositional realms.

Structural Geology of New York City

The three schist units and the underlying rocks have shared a complex structural history which involved three superposed phases of deep-seated deformation (D1, D2, and D3) followed by three or more episodes of open- to crenulate-fold phases (D4, D5, D6+). Based upon relationships developed in Manhattan and tested in the Bronx, CM infers that the synmetamorphic juxtaposition of the various schist units occurred very early in their structural histories.

A ductile shear zone, informally named the St. Nicholas thrust (open symbol in Figure 16) truncates the base of the middle schist (Є-Om). The upper schist unit (Є-Oh) is in probable ductile-fault contact with the middle schist unit along Cameron's Line in the Bronx (Stops 2 and 3) and in Manhattan. Both in the Bronx and in Manhattan, good exposures of Cameron's Line are rare.

Cameron's Line and the St. Nicholas thrust developed during two progressive stages of ductile deformation accompanied by isoclinal folding (F1 + F2). The F1 folds are inferred from a locally preserved S1 foliation. An annealed highly laminated mylonitic texture occurs at the thrust zone. Recrystallized mylonitic layering formed; ribboned- and locally polygonized quartz, lit-par-lit granitization, and quartz veins developed parallel to the axial surfaces of F_2 folds. During D_2, a penetrative foliation (S2) and metamorphic growth of lenses and layers of quartz and kyanite + quartz + magnetite up to 10 cm thick formed axial planar to F_2 folds which deformed the bedrock into a large-scale recumbent structure that strikes N50°W and dips 25° SW.

Although the regional metamorphic grain of the New York City bedrock trends N50°W, the appearances of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25° (Figure 16). S_3 is oriented N30°E and dips 75°SE and varies from a spaced schistosity to a transposition foliation often with shearing near F_3 hinges. The F_3 folds and related L_3 lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz- and kyanite lenses and layers into elongate shapes.

At least three phases of crenulate- to open folds and numerous brittle faults and joints are superimposed on the older ductile fabrics. The effects on map contacts of these late features is negligible but the scatter of poles to S_3 are deemed the result of post-D_3 deformation.

Structure Sections

Our previous guidebooks describe critical evidence for new structural interpretations of the Paleozoic schists exposed in New York City. Figure 20 presents a simplified W-E structure section across northern Manhattan into the Bronx roughly parallel to the Cross Bronx Expressway (I-95). Keyed to Figure 23, the sections illustrate the general structure of New York City and how the St. Nicholas thrust and Cameron's Line place the middle unit of the Manhattan Schist, and the Hartland Formation respectively, above the Fordham-Inwood (Sauk)-lower schist unit (Tippecanoe) strata. The major F3 folds produce digitations of the structural- and lithostratigraphic contacts that dip gently south, downward out of the page toward the viewer.

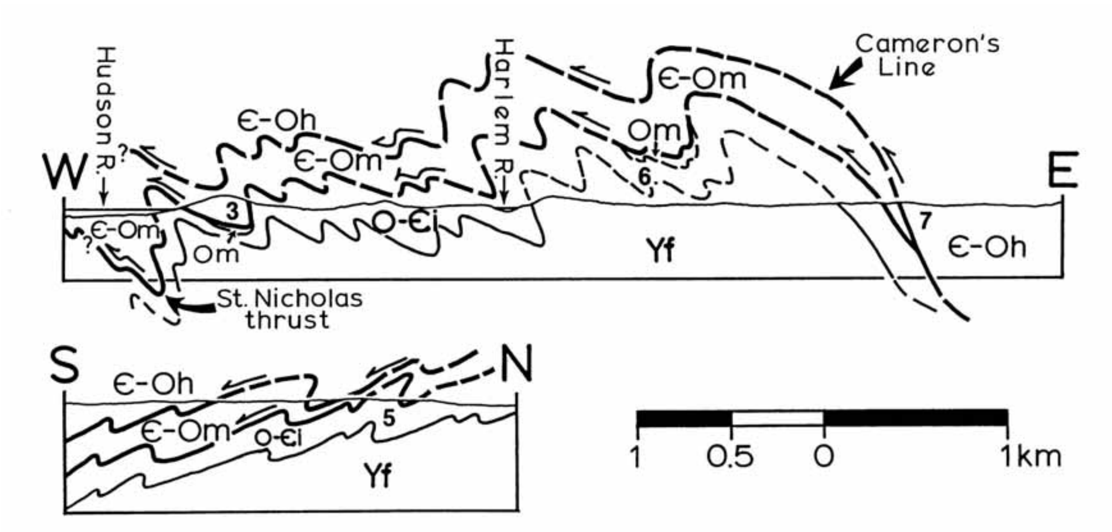


Figure 20 - Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). Symbols defined on Figure 16. (Merguerian, unpublished data).

Figure 21 is a map and geologic section of the geology of the 8 m-wide New York City water tunnel trending N60°W and running roughly 240 m beneath the East River channel (Merguerian, 1986b; and unpublished data). This section is keyed to Figure 23. CM's detailed mapping, which was accomplished between May and August of 1985, before the tunnel was lined with cement, identifies the intrusive contact of the Ravenswood Granodiorite with rocks of the Hartland, identifies the ductile fault known as Cameron's Line in two places with repetition resulting from brittle faulting, shows complex folds within the Inwood Marble (Members A and B), and shows how in the vicinity of New York City, Cameron's Line places Hartland rocks structurally against the Fordham Gneiss. Thus, along the length of Cameron's Line from western Connecticut to New York City, the Hartland is in structural contact with stratigraphically deeper bedrock units.

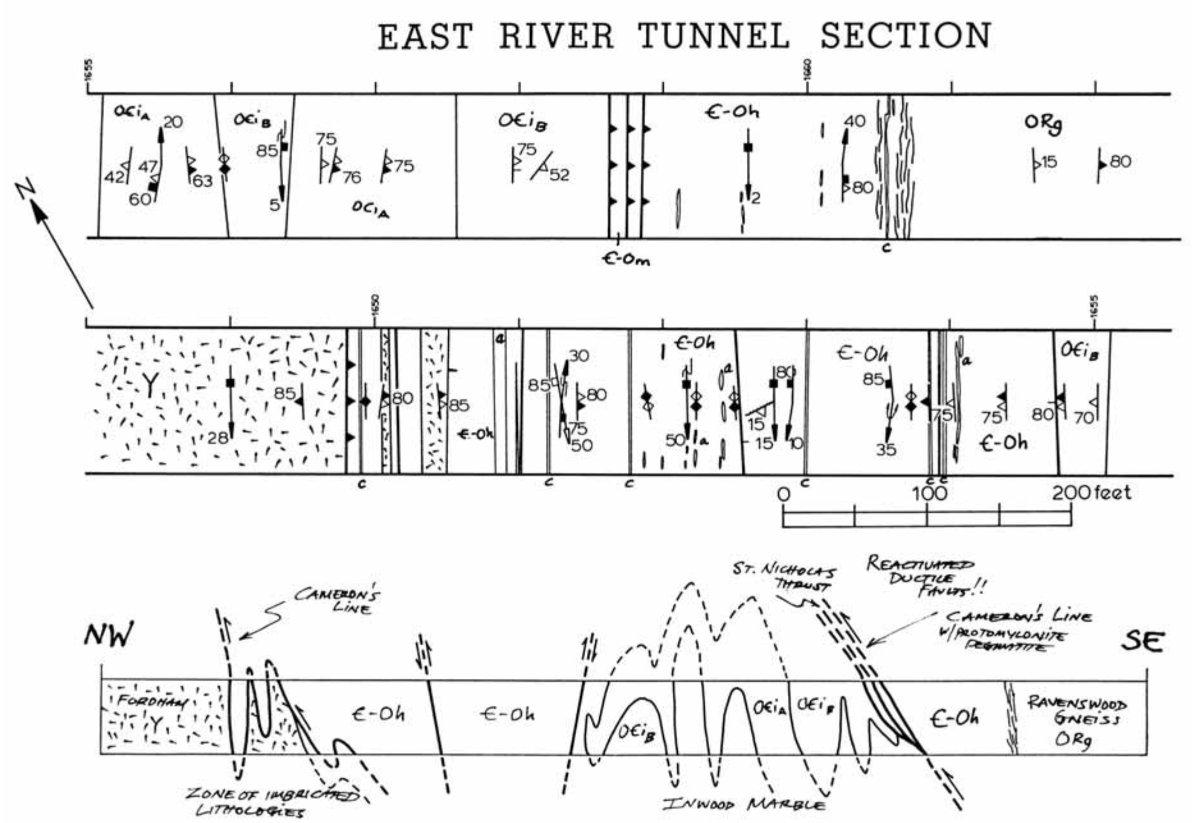


Figure 21 - Geologic map and section of the bedrock exposed in the New York City water tunnel beneath the east channel of the East River between Roosevelt Island and western Queens. (Merguerian, unpublished data).

Not shown on this map and section are a multitude of brittle faults with complex movement histories that cut the section both parallel to, and at high angles to lithologic contacts.

Faults and Seismicity

It is generally agreed by all geologists and seismologists that abrupt movement on dislocations known as faults produces earthquakes; thus preexisting faults tend to localize new earthquakes. The bedrock of New York City, always considered to be solid and impervious to seismic activity, is cut by a great number of ductile- and brittle faults. In addition to the ductile Cameron's Line and the St. Nicholas thrust, CM's geologic map of Manhattan north of 125th Street (Figure 16) shows five northwest-trending brittle faults. Lobeck (1939) showed two of the major faults of Manhattan south of the 125th Street fault (Figure 22). One of these, the famous 14th Street fault, controls the lower-than-average height of buildings of the New York skyline in the area of Manhattan south of 23rd Street and north of Canal Street.

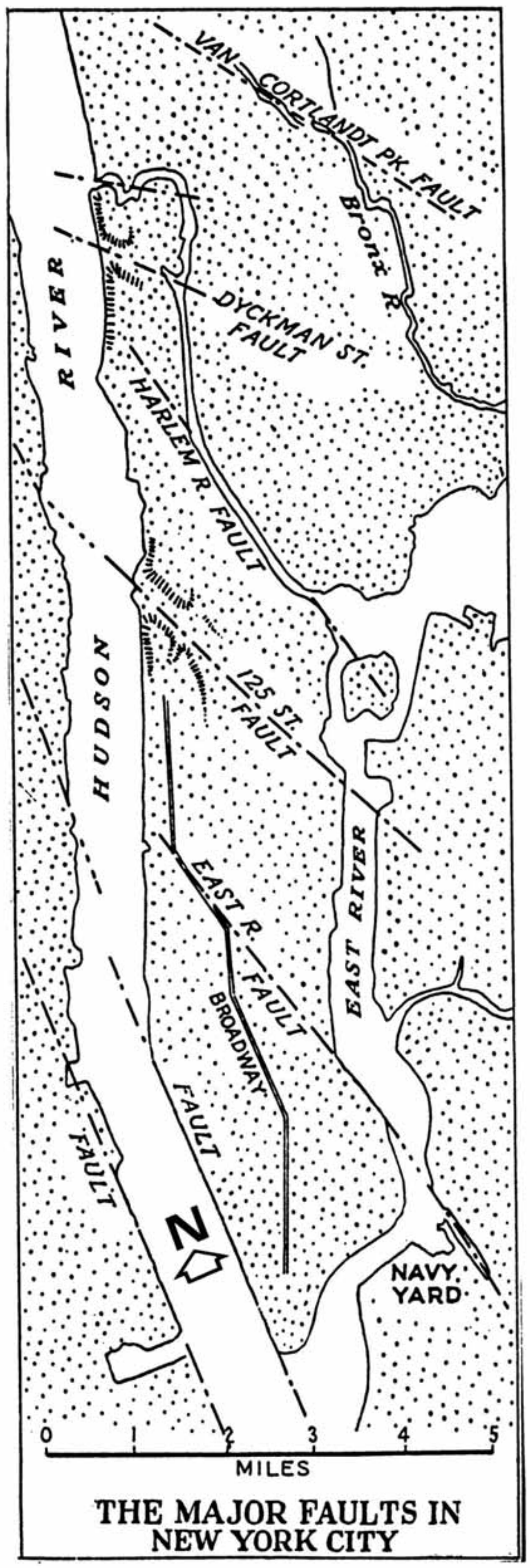


Figure 22 - Map of Manhattan showing major faults inferred on the basis of subsurface data in water tunnels and physiographic relationships. (A. K. Lobeck, 1939.)

During CM's detailed mapping in the water tunnels beneath Manhattan and the East River in the period from 1983 to 1985, he identified a multitude of brittle faults that fall into two broad categories: (a) those that trend northeasterly (parallel to the length of Manhattan), and (b) those that trend NW and transect the island of Manhattan at a high angle. Invariably, where the ductile faults are oriented northeasterly, they have been reactivated by brittle faults marked by fresh clay-rich gouge up to 5 cm thick. In addition, NW-trending, steep NE-dipping faults and joints are lined with calcite, pyrite, and zeolite minerals. Thus, the intersections of these two important fault sets has cut New York City into discrete blocks. CM is preparing a new map showing the surface distribution of all ductile- and brittle faults but a finalized version was not available at press time. Copies should be available at all subway token booths and in Mayor Dinkins' office until midnight on 04 July 1993.

According to CM's unpublished field data, ductile faults (especially Cameron's Line) have been reactivated by brittle faults in New York City. What is more, based on geometric relationships and superimposed slickensides, the movement histories of the northwest-trending faults are more complex than those that trend NE. A case in point was mapped in the east channel of the East River (Merguerian, 1986b), where a NW-trending, steep NE-dipping left-lateral strike-slip fault bearing sub-horizontal slickensides, shows overprint by N- to NE-plunging slickensides. This composite movement has resulted in roughly 7 cm of offset of a quartzose segregation in gneisses of the Hartland Formation. CM interprets that this overprinting indicates a change from strike-slip to oblique-normal slip movement.

A second case in point was observed where the water tunnel cuts the 125th Street fault beneath Amsterdam Avenue in Manhattan. Here, in an abrupt zone of highly fractured Manhattan Schist, 40 m wide, cuts orthogonally across the tunnel line and the foliation in the schist and thus beautifully displays the 125th Street fault. (See Figure 33 in our Manhattan guidebook, Merguerian and Sanders, 1991b.) CM was amazed to observe in the roof of the tunnel that enormous blocks of the Manhattan, which remained internally coherent within the zone of sheared rock, had been rotated up to 90° about a vertical axis. Clearly, this observation indicates that along the 125th Street fault, some of the motion has indeed been strike slip.

A third observation made by CM and students of his Cartography class (11/91) near 101 Street on the east side of Central Park also demonstrates the significance of NW-trending faults in New York City. Here a vertical fault striking N12°W cuts through a synform of amphibolite in the Hartland Formation. The limbs of the synform are vertical and offset is marked by a sharp lithologic contrast between the schist and amphibolite contact. Left-lateral offset along this fault has been more than 30 cm. Along a second, parallel fault 3 m to the NE, left-lateral offset has been 7 cm. Thus, in this composite zone, 37 cm of left-lateral offset have been recognized. The fault zone is marked by gouge 0.5 cm thick, but because the surface of the outcrop has been eroded to a flat "pavement," no slickensides were found. Given that the fault and layering are vertical, however, strike-slip offset is mandated.

In the Bronx, the bedrock units have been cut by numerous faults and joints that are products of deformation under conditions in which the rocks were brittle. Of these faults, Schuberth (1968, p. 88) wrote:

"In Van Cortlandt and Bronx parks, both in Bronx County, there are also several faults. Of particular significance is the fault trending through the northern part of Bronx Park. It appears to control, to a large degree, the present lower course of the Bronx River. (See Figure 22.) Instead of continuing in the valley underlain by Inwood marble, the river eroded a strikingly scenic gorge through the tougher Manhattan formation.

[JES note: the part of the "Manhattan Schist" that CM now reinterprets as belonging to the Cambro-Ordovician Hartland Formation].

This chasm is seen in the New York Botanical Garden near the Snuff Mill Restaurant. The lower portion of the river apparently was diverted into this fault zone of decayed mica schist from its earlier course. Originally the ancestral Bronx River, in its journey to the sea, flowed along the entire length of the marble-floored valley. Since (sic) the fault zone intersects the valley a few hundred feet upstream from the mill, the Bronx River changed its course and eroded a new, narrow gorge along this fault through the mica schist, thereby abandoning the lower part of its original valley. This diversion of the Bronx River into its present course may have happened within the past twenty or thirty million years. At that time, the zone of decayed rock may have represented a more direct (sic) route to the sea than the former course."

According to Baskerville's recently published geologic map (1987), the Mosholu Parkway fault (= Van Cortlandt fault of Figure 22, as originally mapped by Merrill and others in 1902) trends northwest-southeast parallel to the Mosholu Parkway. Baskerville has mapped this fault as being roughly 5.5 km long; his map shows it cutting across the Fordham ridge toward Van Cortlandt Park. The map symbols indicate Baskerville regards the Mosholu Parkway fault as being a right-lateral strike-slip fault. (Along a right-lateral strike-slip fault trending NW-SE, the SW side moved toward the NW.) A key factor associated with strike-slip faults is that they displace vertical surfaces. Indeed, as argued above, the identification of a displaced vertical feature constitutes one of the most geologically satisfying proofs that movement on a given fault has been strike slip. Baskerville's map displays what has to be regarded as an unusual state of affairs: along its extent, the lithologic- and structural contacts that it intersects are not shown as having been offset. Considering the fact that both the fault and the rock-unit contacts it intersects dip steeply, then something about his mapping is peculiar.

At the south end of the Mosholu/Van Cortlandt fault, where it crosses the Bronx River, midway between Allerton Avenue and the Pelham Parkway, Baskerville's map (1987) shows another fault. 0.5 km long, trending west-northwest and dipping 28° toward the north.

On 19 October 1985 a Richter-magnitude 4.0 earthquake in Ardsley, Westchester County, woke light sleepers early on a Saturday morning and shook up the scientific community and the engineering community as well. The initial shaking was followed by roughly a dozen, smaller aftershocks. The quake rekindled seismic memories of a magnitude-5.0 earthquake that shook New York City, offshore to the south of Brooklyn in 1884. According to "felt" reports, that quake caused damage to structures and was felt as far south as Philadelphia and as far north as Hartford, Connecticut.

Analysis by Leonardo Seeber and coworkers at Lamont-Doherty Geological Observatory indicated that the Ardsley quake was related to a few centimeters of slip along a NW-trending fault. This NW trend is identical to those mapped in Manhattan by CM! Imagine the result if 37 cm of offset occurred all at once! The news media, of course, ate the earthquake story up and both CM and JES were awarded with their "15 minutes of fame" [per Andy Warhol] in interviews for printed- and televised transmission. Invariably, the main question put forth was, can it happen here? CM and JES agree that it can and signed a contract with ABC to produce a new geologically oriented TV quiz show entitled "Name That Quake" and have attempted to corner the market for earthquake insurance.

CM and students at Hofstra have embarked on an interesting project involving compilation and statistical analysis of brittle-fault-related earthquakes in the New York City area. Preliminary results of data from the last 300 years indicate that the average depth of a New York City earthquake is roughly 5 km below the surface and that average Richter intensity readings are less than 2.0.

Cameron's Line and the Taconic Orogeny

According to Eugene Cameron (of Cameron's Line fame) in a confidential personal communication to CM, the geologic relationship of Cameron's Line was first noted by William Agar who shared them with E. Cameron. According to EC - "I don't know why they called it Cameron's Line, it should have been called Agar's Line!". In any case, Cameron's Line delimits the easternmost exposures of Proterozoic Y and Z gneiss [Layer I] and overlying lower Paleozoic quartzite and marble (shallow-water sedimentary strata [Layer IIA(W)]) originally formed on continental crust of proto-North America. Together, Layers I and IIA(W) represent deformed North American craton and overlying shelf deposits.

In western Connecticut, the Hartland Formation [or Complex of Merguerian (1983b)] is interpreted as an internally sheared imbricate thrust package that marks the former site of a deep-seated accretionary complex or subduction zone. The complex consists of a thick sequence of interlayered muscovite schist, micaceous gneiss and granofels, amphibolite, and minor amounts of calc-silicate rock, serpentinite, and manganiferous- to ferruginous garnet-quartz granofels (coticule) (Merguerian, 1980, 1981b). Hartland rocks (Unit Є-Oh in New York City) are correlative with metamorphosed eugeosynclinal (deep-water deposits) Cambrian to Ordovician rocks found along strike northward into New England (Figures 23, 24). The allochthonous portion of the Manhattan Schist (Unit Є-Om) is directly correlative with rocks of western

Connecticut and Massachusetts along the east flank of the Berkshire and Green Mountains massifs.

Numerous lower Paleozoic calc-alkaline plutons are present in southeastern New York and in western Connecticut. Near West Torrington, Connecticut, the Hodges mafic-ultramafic complex and the Tyler Lake Granite were sequentially intruded across Cameron's Line (Merguerian, 1977). Because of their formerly elongate shapes and because the regional metamorphic fabrics related to the development of Cameron's Line in both the bounding Waramaug and Hartland formations display contact metamorphism, these plutons are interpreted as syn-orogenic. The recognition of significant medial Ordovician plutonism across Cameron's Line (Mose, 1982; Mose and Nagel, 1982; Merguerian and others, 1984; Amenta and Mose, 1985) establishes a Taconian- or possibly older age for the formation of Cameron's Line and the syntectonic development of regional metamorphic fabrics in western Connecticut (Merguerian, 1985a).

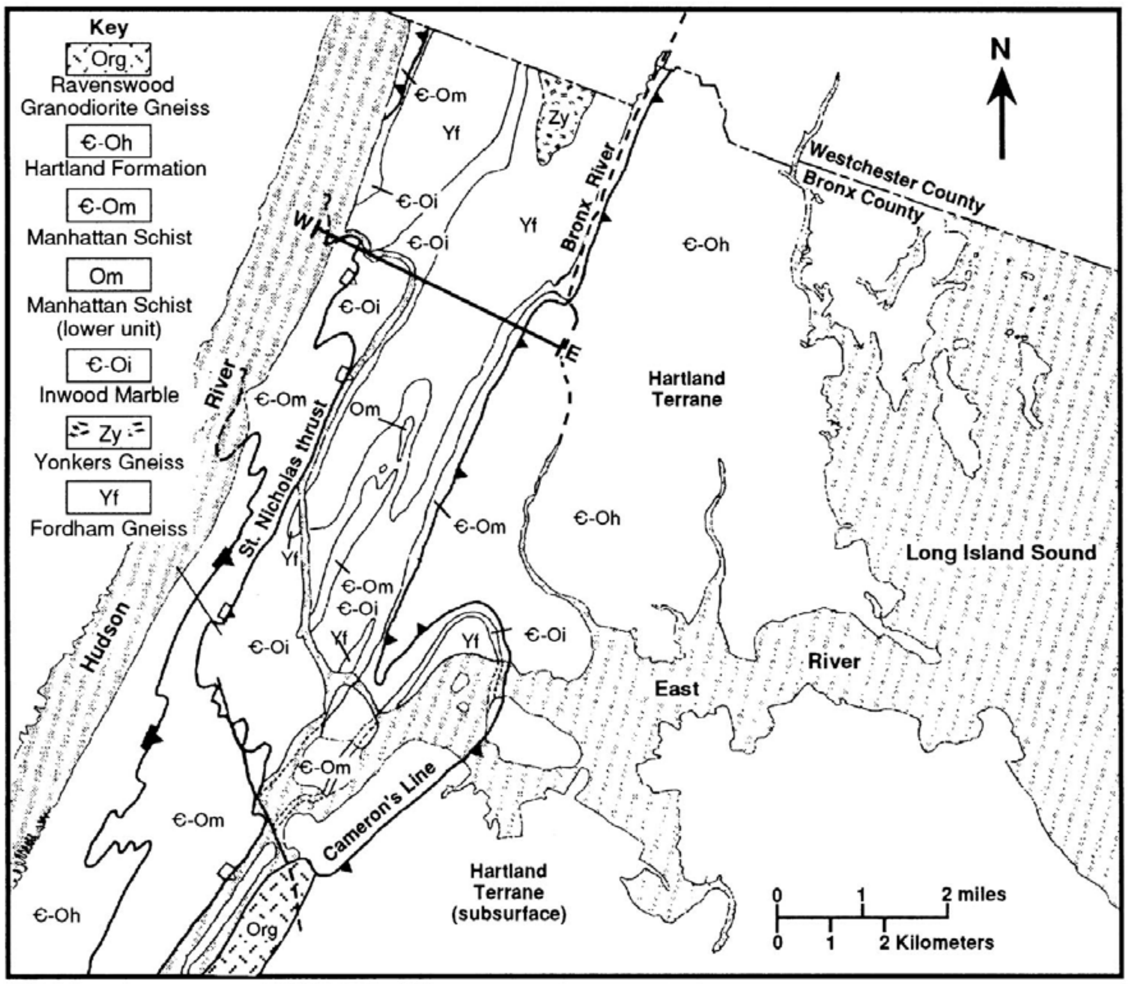


Figure 23 - Geologic map of Manhattan and the Bronx showing the geometry and distribution of Cameron's Line, the Hartland Terrane, and the Ravenswood Granodiorite (Merguerian and Baskerville, 1987).

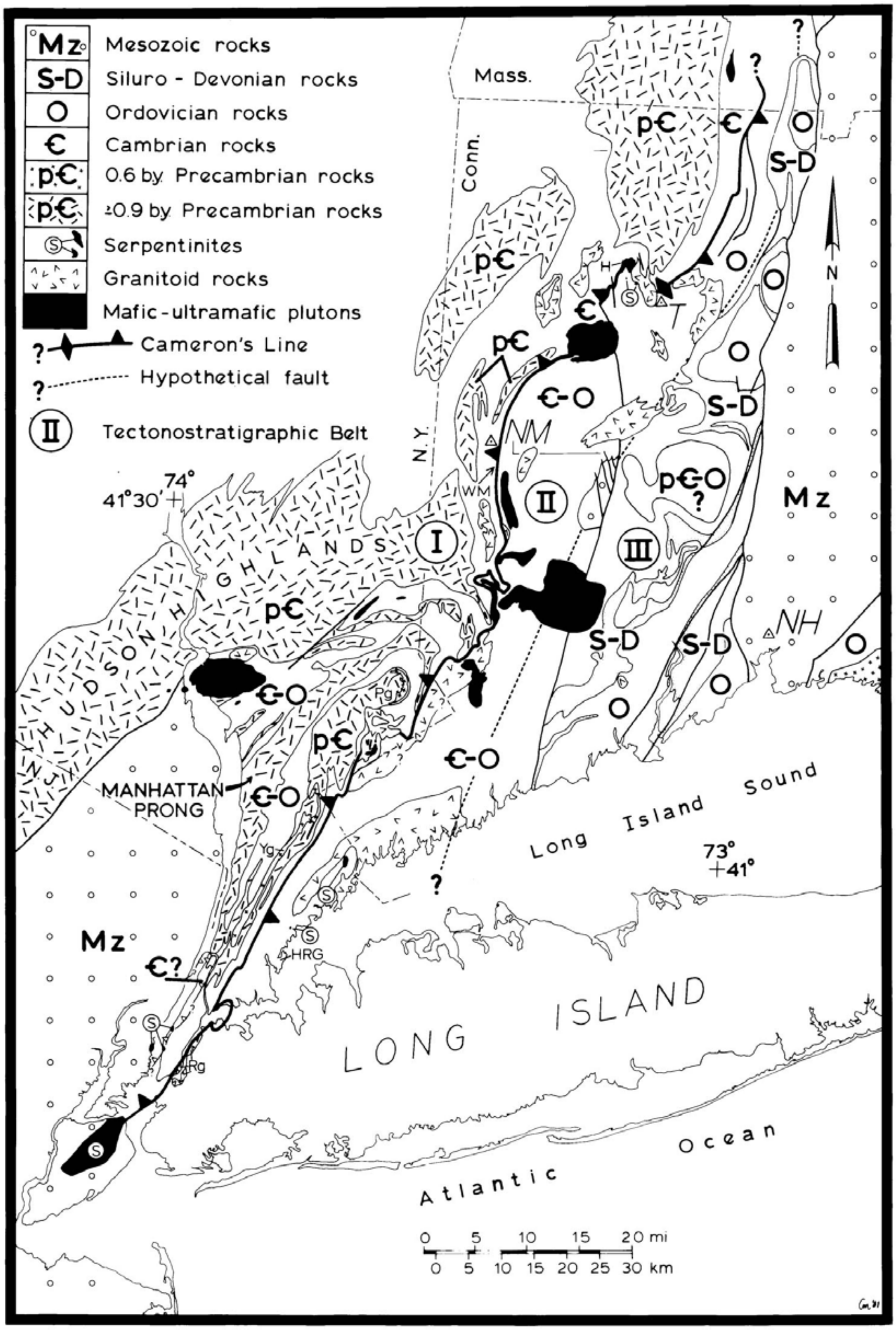


Figure 24 - Geotectonic map of New England showing Cameron's Line and the distribution of northeast-trending tectonostratigraphic units (Merguerian, 1983).

In western Queens, the Ravenswood Granodiorite of Zeigler (1911) crops out. (Unit ORg in Figure 23.) Field relationships in the water tunnel beneath western Queens and in surface exposures in Long Island City (Merguerian, unpublished data), indicate that the Ravenswood is a foliated metaplutonic rock (hornblende gneiss) which encloses foliated screens and xenoliths of coticule-bearing Hartland rocks. A poorly constrained, Early Paleozoic Rb/Sr date on the Ravenswood by Doug Mose seems to fit the pattern observed along Cameron's Line in western Connecticut. No one has established structural relationships of the Harrison Gneiss in Westchester but it is probably similar to the other syntectonic plutons described above. Judging by metamorphic minerals in the D2 regional fabric and the aligned S2 kyanite along Cameron's Line and the St. Nicholas thrust, Layers IIA(W) and IIA(E) were juxtaposed at depths of roughly 25 km during early Paleozoic time. The force behind such deep-seated deformation presumably resulted from a collision between a volcanic-arc terrane and the passive continental margin of North America. (See Figure 17.) The plutons intruded across Camerons Line are the probable results of intrusion of calc-alkaline magmas into the accretionary prism of an oversteepened subduction zone. At present, the arc terrane is exposed in the Bronson Hill Anticlinorium and its extension southward into central Connecticut and probably in the subsurface of Long Island. (See Figure 24.)

In summary, during a series of Paleozoic mountain-building episodes (the Taconic, Acadian, and Appalachian orogenies), the sedimentary protoliths [Layers IIA(W and E) and IIB] of the New England Appalachians were sheared, folded, and metamorphosed during a collision between an exotic volcanic-island chain and the passive continental margin of proto North America. Much of the bedrock in New York City and western Connecticut is therefore interpreted to be allochthonous (a fancy term intended to confuse the layman which simply means transported from somewhere else or not deposited where currently found!). In this model, Cameron's Line, and the subsidiary St. Nicholas thrust, mark a fundamental plate-tectonic boundary (suture) between continental [Layer IIA(W)] and oceanic realms [Layer IIA(E)] and marks the root zone for much of the Taconic sequence in eastern New York state. The Hartland Formation (Complex) marks the deeply eroded roots of an uplifted accretionary complex marking the former trench into which the raw edge of North America was subducted.

For an overview of the historical details relating to the Taconic controversy kindly refer to our discussions in our Taconic or Manhattan guidebooks (Merguerian and Sanders, 1989 and 1992; 1991b). The late Medial Ordovician orogenic events are collectively designated as the Taconic Orogeny. Formed during this orogenic episode were the Taconic overthrusts (as already mentioned). At the same time, and somewhat earlier, an extensive fold belt, a zone of regional metamorphism, and various plutons dated at roughly 460 to 400 Ma were intruded. (See Table 1.) As mentioned, while the deep-water turbidites and related sediments of the Tippecanoe Sequence were accumulating in a foreland basin, overthrusts were active. Both the slices including continental basement and overlying Sauk Sequence carbonates and those including the Taconic allochthon was emplaced as the thrusts moved along the sea floor. To many geologists, subscribing to the older thinking (Zen, 1967; Bird and Dewey, 1975; Ratcliffe and others, 1975) the Taconic orogeny was envisioned as a series of gravity-induced slides (the Low Taconics) and eventually overthrusts (the High Taconics) of the oceanic sequence [Layer IIA(E)] above the Appalachian carbonate platform [Layer IIA(W)] and overlying flysch [Layer IIB]. This episode of continentward displacement was driven by the encroachment of a volcanic arc (the

Ammonoosuc-Oliverian Complex in Figure 17) against the passive continental margin of Ordovician North America.

Many modern workers [including CM, JES, Rowley and Kidd (1981), Stanley and Ratcliffe (1985)] do not believe in gravity sliding as a model for the emplacement of the structurally lowest Taconic allochthons. Rather, based on stratigraphic- and structural evidence, these workers envision all Taconic displacements as being the result of continentward hard-rock overthrusting, first of slices (including basement gneisses) that broke loose from inboard of the former shelf edge and later, slices composed of the deeper-water oceanward-facing continental-margin strata (Taconic Sequence) and the encroaching Taconic arc (Figure 17). The main argument for gravity-induced sliding of the Taconic allochthons was their composition of pelitic strata coupled with a general ignorance of the overthrusts composed of continental-type basement rocks overlain by the Sauk Sequence. A subsidiary argument was based on the presence of olistostromes and wildflysch conglomerates containing pieces of the Sauk Sequence along the western edge of the outcrop of the Taconic rocks. These rudites containing pieces of the Sauk Sequence are new considered to be debris that accumulated on the floor of the foreland basin after having been shed down the front of an overthrust that later overrode its droppings. As far as is now known, the Taconic allochthon itself includes only sedimentary strata; no pre-Taconic continental basement has been found. However, such massive overthrusts of strata over strata may be accompanied by thrust slices in which the basement overrides sedimentary strata. In eastern New York State, Zen and Ratcliffe (1966) and Ratcliffe and others (1975) have mapped thrust masses of Sauk Sequence carbonates that they have interpreted as being mere slivers within the base of Taconic sole thrusts. These geologists have always considered all Sauk carbonates to be "autochthonous" (or perhaps under duress, "parautochthonous") and not parts of real he-man, allochthonous overthrusts.

Similar to the relationships noted in the Antler orogenic belt of California and Nevada, the deep-seated Taconian folding, metamorphism, and igneous activity occurred shortly before the Taconic allochthon had been emplaced (Merguerian, 1985b). Available age data indicate that the compressive ductile deformation in the igneous- and metamorphic root zone of the Taconic orogen led the supracrustal emplacement of overthrust sheets by a minimum of 20 Ma. The polydeformed internal massifs presumably mark the deep levels of continentward-facing accretionary complexes within which deep subduction and deformation of oceanic deposits preceded the collision of the encroaching volcanic arc terranes. Final docking of the arc resulted in cratonward thrusting of the shallow levels of the subduction complex to form the Taconic allochthon. As such, we see a time gap in deep-seated versus supracrustal deformation, wherein a geometrically predictable vertical pattern of diachroneity within subduction complexes in collisional orogens takes place.

Plate-Tectonic Interpretation

During Early Paleozoic time, the present eastern seaboard of North America formed a broad continental margin with a broad oceanward-facing shelf similar to today. The early Paleozoic shelf received clastic products of the weathering- and erosion of the exposed Proterozoic continental crust and carbonate sediments that accumulated on a shallow sea floor in a near-equatorial warm- water environment (Figure 25). Thus, a continental terrane was formed with a basal layer of Proterozoic granitoid rocks (Fordham protolith) unconformably overlain by discontinuous sand, lime, and clay (Lowerre, Inwood, "Good Old" Manhattan Schist protoliths). Outboard of the former shelf edge, on quasi-continental "transitional" crust a succession of poorly bedded silt and turbidites formed (middle unit of the Manhattan Schist - Ꞓ-Om) and in the deeper oceanic environment, deep-water shales, turbidites, and intercalated volcanic rocks accumulated on oceanic crust in the vicinity of a volcanic archipeligo (Hartland Terrane - Ꞓ-Oh). (See Figure 14.)

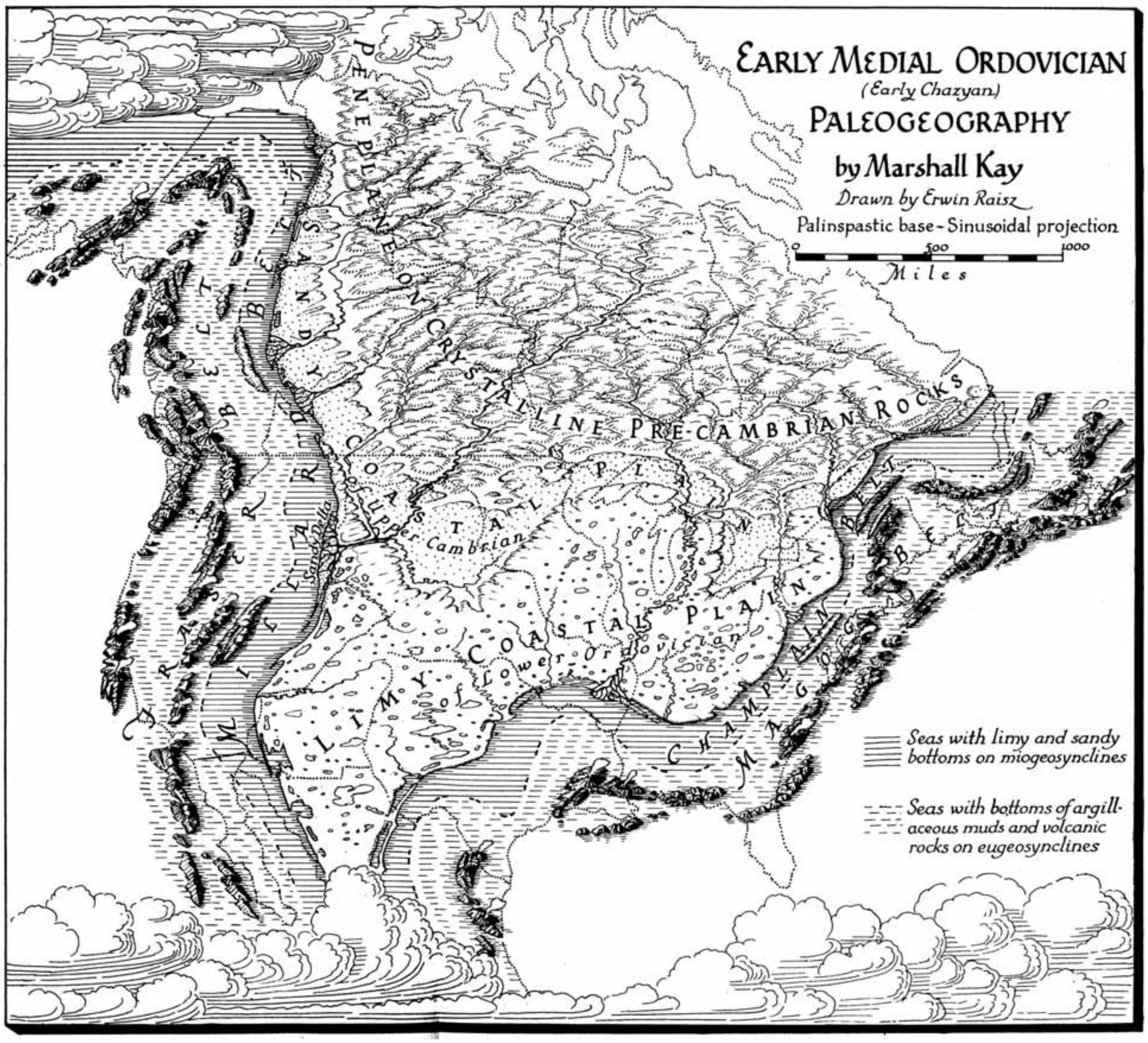


Figure 25 - Paleogeographic map of North America in Early Paleozoic time (Kay, 1951).

During the Medial Ordovician Taconic orogeny, as a result of arc-ward subduction, the Taconic volcanic arc collided with, and was accreted to the North American shelf edge, which was a part of the former passive continental margin of ancestral North America. Deformation and metamorphism of the bedrock units of New York City took place deep within a trench beneath the Taconic arc with internal telescoping of the continental shelf, slope/rise, and oceanic realms along arcward-dipping shear zones within a deep-seated subduction complex. Development of the St. Nicholas and Cameron's Line thrust faults accompanied closure of the marginal ocean basin separating the Taconic arc from the mainland. The bedrock geology of southeastern New York and western Connecticut preserves this collisional boundary (Figure 24) in a series of subvertical, northeasterly trending, fault-bounded lithotectonic belts. Belt I is bounded on the east by Cameron's Line and marks the Continental Terrane. Locally, within Belt I are allochthonous rocks of the slope/rise sequence. Belt II is the Hartland Terrane of deep-water oceanic deposits and Belt III consists of the roots of the Taconic volcanic arc which also crops out to the east of the Connecticut River valley basin and extend through central Massachusetts into New Hampshire.

In the CM view of things, the "good old Manhattan Schist" is the metamorphosed equivalent of the Tippecanoe Sequence strata that were deposited in a foreland basin unconformably above the basal Tippecanoe limestones). By contrast, the "bad new Manhattan Schist" is the metamorphosed equivalent of the Taconic Sequence (= Hartland Formation), whose protoliths are basically the same age as the Inwood Marble and owe their structural positions above the marble (and also above the "good old Manhattan Schist") to displacement along a great overthrust.

How to sort all this out depends on how one feels about the term "Manhattan Schist." If one adopts the view that the only appropriate basis for continuing to use "Manhattan Schist" is as implied in the original definition, i. e., schists younger than the Inwood Marble, then only CM's "good old Manhattan Schist" merits the designation of "Manhattan Schist." By contrast, if one adheres to the view that all the schists on Manhattan Island are what belong under the term "Manhattan Schist," then continued use of the term "Manhattan" merely serves to perpetuate confusion about the correct ages and structural relationships of the schists. Accordingly, the term "Manhattan Schist" should be discontinued and replaced by two new names: one for the in-situ Tippecanoe-age schists and another, for the overthrust marble-age schists. You pays your money, and you takes your choice.

LAYER VII: QUATERNARY SEDIMENTS AND ASSOCIATED FEATURES ERODED BY GLACIERS ON BEDROCK SURFACES

Under this heading we include: (1) features of Pleistocene age (related to former continental glaciers) and (2) features (mostly sediments) of Holocene age that resulted from the Flandrian submergence, which took place as the continental glaciers disappeared.

Features of Pleistocene Age

Features of Pleistocene age are distinguished by their associations with the several continental glaciers that formerly flowed across the region. These glaciers eroded the bedrock, transported various erratics to new locations, and deposited blankets of sediment. These sediments consist of sheets of till and various bodies of outwash that were deposited when the glaciers melted. As veteran On-The-Rockers are well aware, JES and CM (the two chief "Off-Their-Rockers") have entered the debates about the glacial history of the New York region, initially by finding hitherto ignored- or not-noticed features of glacial erosion and/or indicator erratics. Such features have provided them with new insights into the stratigraphic relationships displayed by the Pleistocene sediments. Moreover, their studies of the Pleistocene sediments are now providing feedback into their continuing investigations into glacial sculpting of the bedrock. All their new information totally destroys the prevailing "one-glacier-did-it-all" concept that seems to have hypnotized most modern stratigraphers of the Pleistocene deposits. The "one-glacier" interpretation further 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) and furthermore that this Woodfordian glacier flowed down to New York City from the Labrador highlands following an azimuth that is about N15°E to S15°W (a direction that is down the Hudson-Hackensack lowlands). JES and CM find that only a few local glacial features can be ascribed to the effects of the Woodfordian ice. Instead, they find numerous features that can be ascribed only to several older glaciers. Some of these older glaciers must have flowed from NNE to SSW (as did the Woodfordian ice), but many flowed from various azimuths in the NW quadrant toward the SE, across the Hudson Valley. We review briefly the features made by glacial erosion, summarize some data from indicator stones, and then discuss the Pleistocene sediments.

Features Made by Glacial Erosion of Bedrock

Features eroded by glaciers in bedrock include striae and grooves, crescentic marks, roche moutonnées, and rock drumlins. All are useful in determining one of the most-fundamental points about a former glacial, namely which way did the glacier flow?

Striae and grooves

In flowing over certain kinds of solid bedrock, a glacier may create a generally smooth, possibly rounded surface on which may be linear scratches (striae, erroneously referred to as "striations" by many geologists whose use of the English language is in such a state of disarray that they do not bother to distinguish between words for attributes and words for substantive things) and even large grooves. The linear scratches and -grooves provide a straightforward basis for inferring ice-flow direction: it is parallel the trend of the linear grooves, -striae, and other elongate features.

Such delicate marks as striae do not survive exposure to the atmosphere for more than a few decades or so. Examples that can be used for showing the rate of destruction of the marks come from Finland, where postglacial crustal elevation has caused many islands to emerge from beneath the water of the Baltic Sea. The water has removed the fines from the till, leaving behind a glaciated rock pavement on which rest various large erratics. Not many striae have survived for longer than a century.

In a study of glacial striae cut into the bedrock by the Saskatchewan Glacier, Alberta, Iverson (1991) illustrated examples of three categories: (a) groove widening in a down-flow direction and ending abruptly in a deepened part against a slope that dips steeply in an up-flow direction; (b) groove symmetrical and ending at sharp points at both ends with deepest excavation at midpoint; and (c) groove widest at up-flow end [a near-mirror image of those of group (a)]; long profile asymmetric, beginning at a steep slope, dipping in a down-flow direction, and dying out at the pointed down-flow end. He also carried out experiments in which blocks of carbonate rock were forced against a fixed striator point having various shapes.

Crescentic marks

In some places, glacial ice created various crescentic marks. Such marks have been subdivided and named according to the relationship between their curvature and the direction of flow (Flint, 1971, p. 95; Gilbert, 1906; Harris, 1943; MacClintock, 1953). Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the direction of flow (Figure 26).

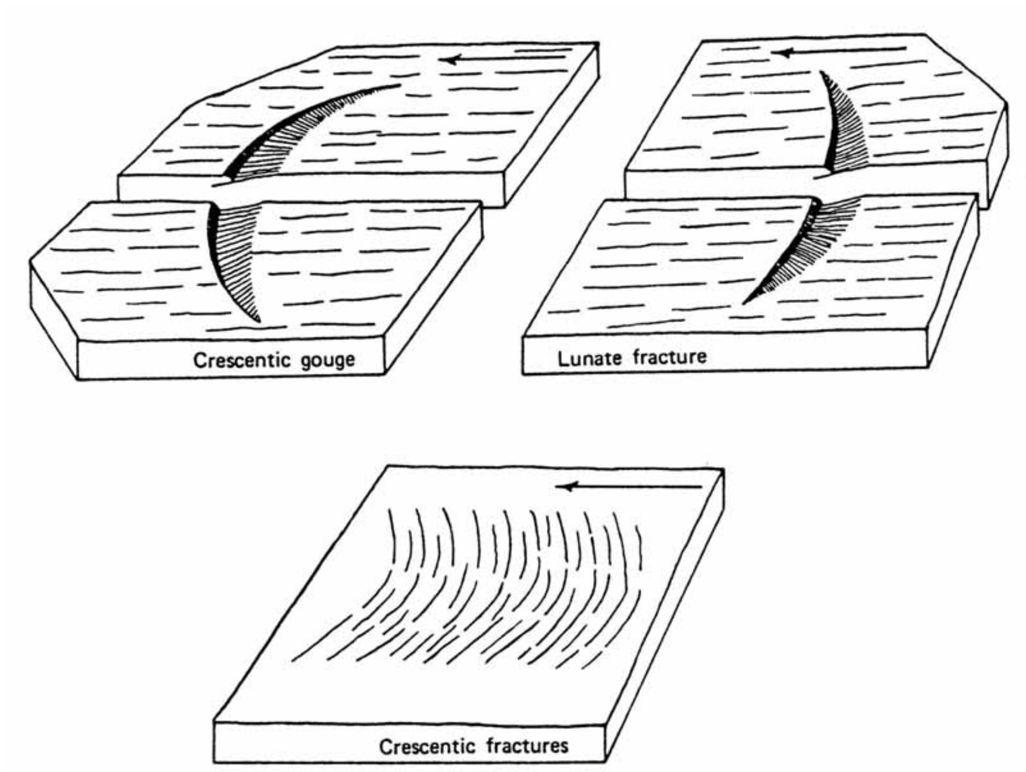


Figure 26 - Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

Crescentic marks can be used to infer the direction of ice flow by means of the asymmetric longitudinal profiles through the centers of the crescents. The ice came from the gently dipping side. The direction of concavity is not reliable.

Roche Moutonnée

The distinctly asymmetric relief features sculpted by a glacier in the bedrock are known as roche moutonnée (Figure 27). These are smooth, broadly rounded and gently dipping on the side from which the ice flowed (a result of the glacier's grinding on an obstruction to flow); but jagged, irregular, and steep on the side toward which the ice flowed [a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction (Figure 27)].

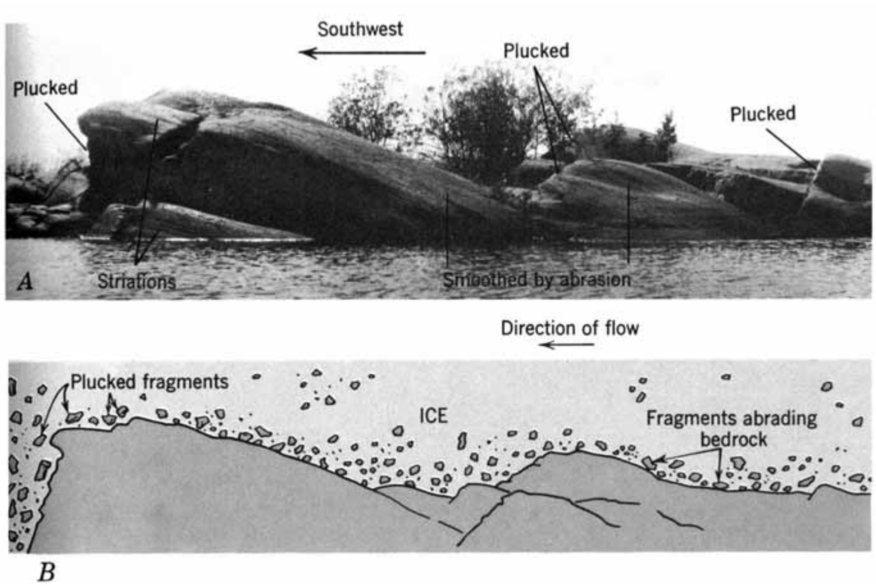


Figure 27 - Roche moutonnée in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roche moutonnées sculpted in Precambrian granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnées beneath a glacier.

The asymmetry described above is based on the effects of a single direction of ice flow. In the New York City region, JES and CM have found many features displaying only part of the morphologic expression of a classic roche moutonnée. The rounded, gently dipping part is present, but the jagged, steep side is not present. Evidently a "classical" roche moutonnée made by one glacier has been modified by flow across and over it of a glacier flowing from a direction that differs by about 45° from the direction of the first glacier.

Drumlins (especially Rock Drumlins)

Another kind of asymmetric feature fashioned by a glacier is an elongate streamlined hill known as a drumlin. The long axis of a drumlin is parallel to the flow direction of the ice; the steeper side is toward the direction from which the ice came (Figure 28). Drumlins consist of till, of bedrock, or of some combination of till and bedrock. The term used by itself implies a feature composed of till. A rock-cored drumlin is one that consists of both till and of bedrock. A rock drumlin consists only of bedrock. (We do not know why a glacier forms a rock drumlin instead of a roche moutonnée or vice versa.)

The point of emphasizing rock drumlins is that their elongation and asymmetry clearly indicate an ice-flow direction. Their shapes can be modified by a later glacier.

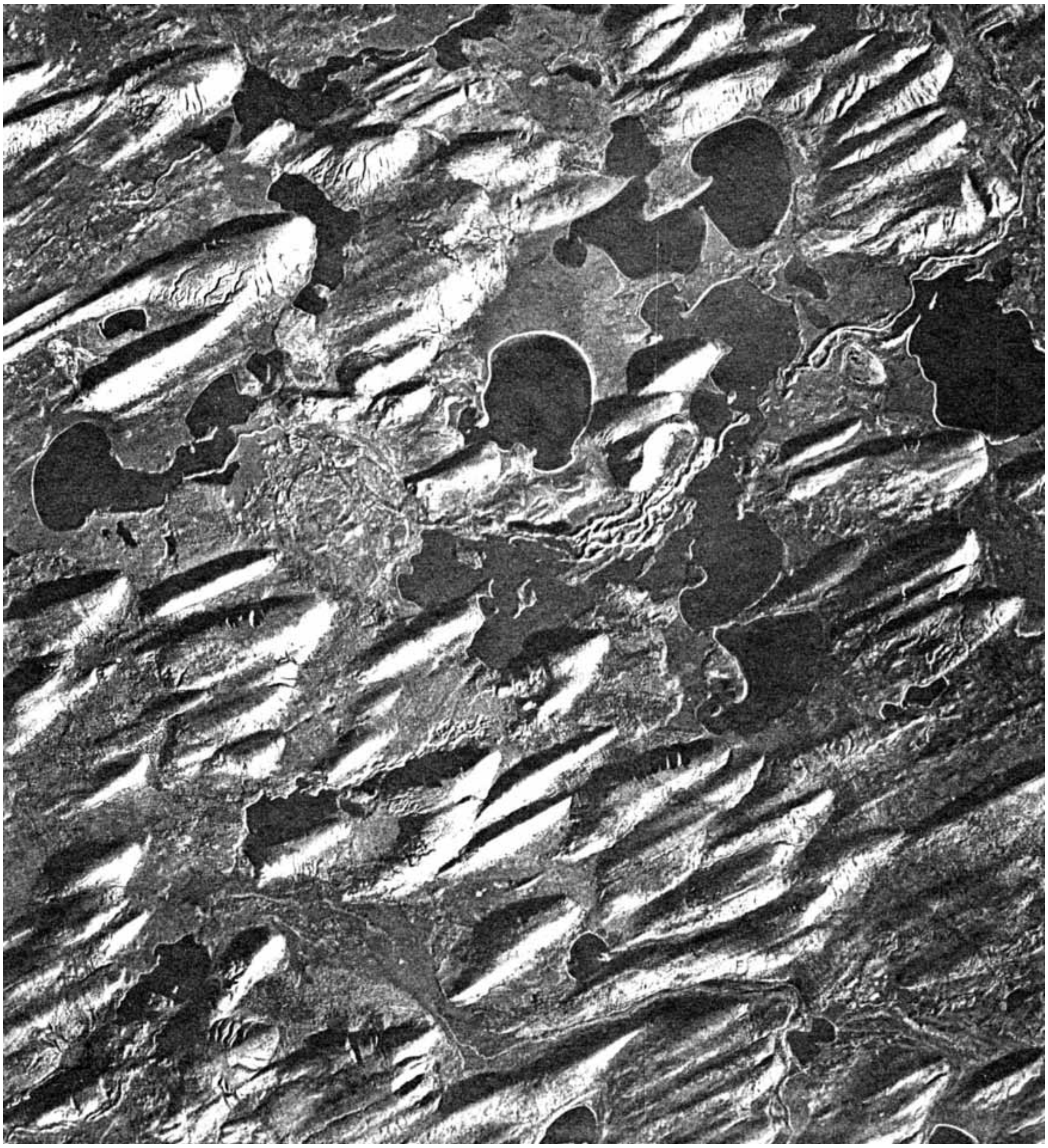


Figure 28 - Swarm of drumlins viewed from vertically above in aerial photograph, northern Saskatchewan, Canada, created by a glacier that flowed from NE (upper right) to SW. The small circular lakes give the scale; their diameters are about 1 kilometer. The thin, curviliner light-toned features extending from the center of the view to the upper right margin are parts of an esker complex. (Geological Survey of Canada, Canadian Government Copyright; published in J. E. Sanders, 1981, fig. 13.24, p. 323.)

Data from Indicator Stones

The general name for the study between sedimentary particles and their parent (or "source") deposits in the bedrock is provenance. Because glaciers can transport stones long distances, one commonly finds a collection of glacial particles unlike the bedrock on which the glacial deposits rest. Such stones are known as erratics. If an erratic can be traced to a distinctive source, it becomes an indicator stone.

A few examples of indicator stones found by JES and CM include pyroxenites from the Cortlandt Complex (near Peekskill), the red-brown sandstones/conglomerates from the Newark Supergroup (indicator stones only locally, as in Westchester County and in NW Long Island, where they clearly demonstrate flow from NW to SE, across the Hudson River), the mafic igneous rock (texture ranging from basalt to gabbro) from the Palisades sheet (indicator stones only locally, as in the red-brown sedimentary rocks), the Green Pond Formation (Silurian of northwestern New Jersey and adjacent southeastern New York State), and anthracite (from the Scranton region of northeastern Pennsylvania). The finding by JES of natural erratics of anthracite in the red-brown till along the east side of the Hudson River suggests that the fossiliferous pieces of Carboniferous material found in the Country Club road excavations in the Bronx are glacial erratics and not indicators of a buried Carboniferous basin, as suggested by Zen and Mamay (1968).

Pleistocene Sediments

The Pleistocene sediments consist of several contrasting varieties deposited either directly by now-vanished continental glaciers or as a consequence of the melting of these glaciers. We will be especially interested in the characteristics of till (deposited directly from a glacier) and outwash (deposits made as the glacier melted).

Till

Till is a general name for any sediment deposited directly by the flowing ice of a glacier. Typically, till is not stratified and contains a wide range of particle sizes, from boulders to clay.

Outwash

Outwash is a general term for any sediment deposited by water melted from a glacier. Outwash includes such contrasting sediments as stream sands and lake clays. The key point about recognizing outwash is the stratification that resulted from the action of water.

Previous Interpretations of Glacial-flow-direction Indicators

The first systematic attempt to record directions of striae and grooves on the bedrock in New York City, was carried out in 1828-29 by L. D. Gale (Mather, 1843). Gale's initial investigation of the "diluvial scratches and furrows" on the surface of the bedrock was made on the rocks exposed in the then-undeveloped central- and northern parts of Manhattan. We interpret Gale's results as constituting direct evidence of ice flow from the NW to the SE but with displacement of erratic indicator stones (anthophyllitic rock and white marble) showing a contrasting direction of NNE to SSW. (For a full presentation of Gale's results, kindly refer to our Manhattan and Long Island guidebooks, Merguerian and Sanders, 1991b; 1990; 1991b)

Subsequently, other investigators confirmed and extended Gale's results and proposed various interpretations of these indicators of two directions of ice flow. The two ideas analyzed here are: (I) that various changing conditions caused the direction of flow of a single ice sheet to shift with time, and (II) each set of flow directions was made by a single glacier having only one dominant flow direction.

(I) Almost without exception, geologists who have studied the Pleistocene deposits in the New York metropolitan area concur that a single ice sheet of Late Wisconsinan age created all the flow indicators observed. The following review includes what we consider to be critical papers dealing with this topic. We make no claim that this review is comprehensive or complete.

The idea that only one Late Pleistocene ice sheet invaded the New York City region was proposed by T. C. Chamberlin (1895), reinforced by R. D. Salisbury and assistants (1902), and is implicit in all recent papers where the term "lobe" is used with respect to the margin of the ice sheet (for example, Connally and Sirkin, 1970, 1973).

Salisbury and assistants (1902) found that the predominance of ice-flow indicators showed glacial flow from the NNW to the SSE over the Palisades whereas by contrast, such indicators demonstrated that glacial flow over the Watchung ridges had been predominantly from the NNE to the SSW. In his interpretation of these indicators of contrasting directions of ice flow, Salisbury argued that within the margins of an ice sheet are localized zones within which the ice-flow paths are faster than elsewhere. Accordingly, the ice-flow "streamlines" are thought to be crowded close together, as in the sketch map of the region surrounding Lake Michigan (Figure 29). On either side of such supposed zones of concentrated flow, the ice tends to spread out toward each side. In applying this concept to the New York metropolitan area, Salisbury inferred that during the latest glaciation of the New York City region, the axis of fastest-flowing ice had not been down the Hudson Valley, as one might expect on the basis of valley size, but rather followed the Hackensack Valley to the west (Salisbury and assistants, 1902). From this inferred zone of concentrated flow down the Hackensack Valley, they thought that the ice had flowed toward the south-southeast over the Palisades ridge and Manhattan, and toward the south-southwest over the crests of the Watchung Ridges in New Jersey (Figure 30). Salisbury admitted that the regional distribution of erratics of the distinctive Silurian Green Pond Conglomerate from northwestern New Jersey constituted an anomaly to this explanation of marginal-flow divergence within a single glacier as the cause of the divergent orientations of the glacial grooves and -scratches. Salisbury acknowledged that another succession of events which could explain the distribution of erratics of Green Pond Conglomerate involved two glaciations, but he merely mentioned the possibility of two contrasting glaciers.

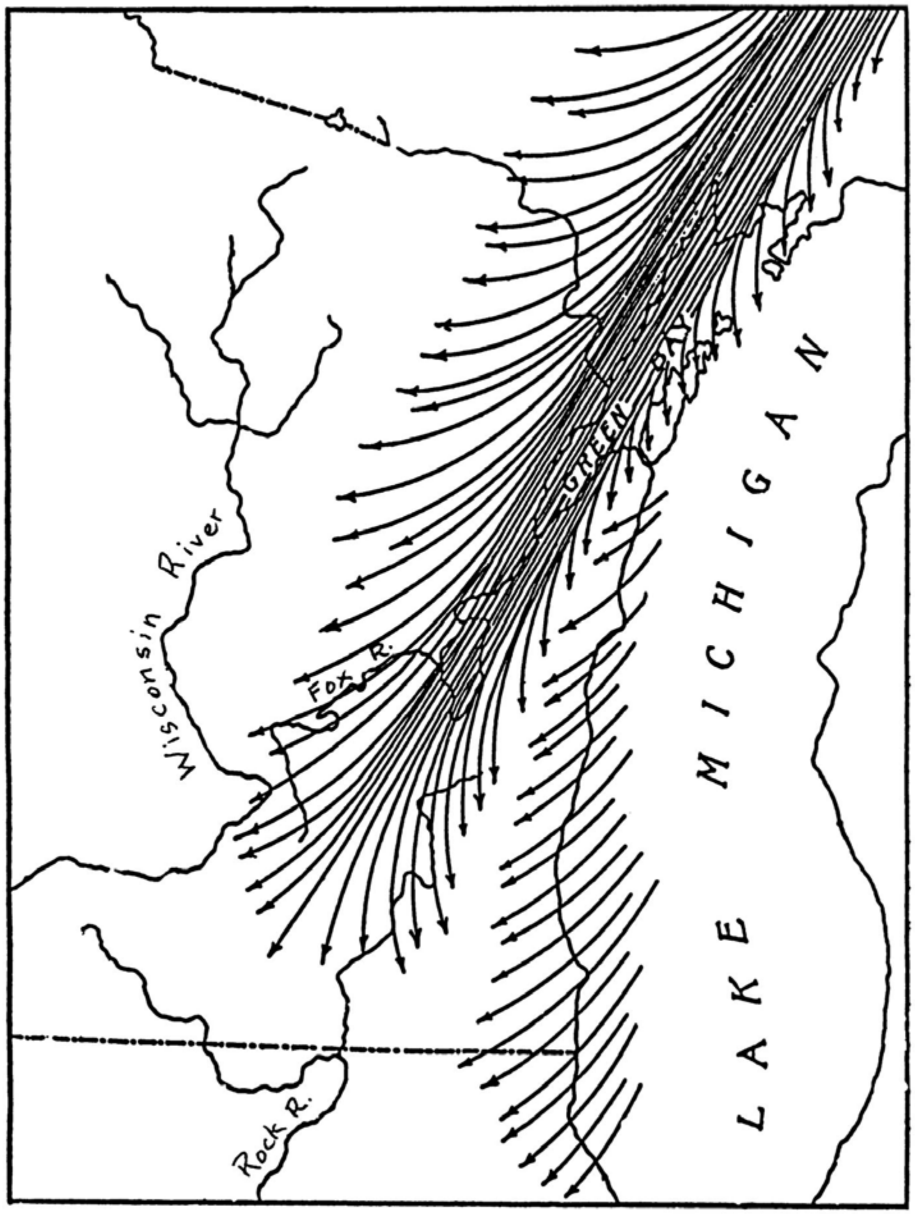


Figure 29 - Sketch map of area west of Lake Michigan (mostly in Wisconsin, but including parts of Michigan and Illinois), showing concept of divergent flow from a narrow zone (centered above Green Bay, Wisconsin) of rapid flow within an ice sheet. (R. D. Salisbury, 1902, fig. 31.)

Another version of how a single glacier could create flow indicators having several directions is based on the behavior of ice lobes. Such lobes characterize the terminus of a valley glacier that has spread beyond the confining bedrock valley walls. Although the main flow direction of ice in a valley glacier is parallel to the trend of the valley, within the terminal lobe, the spreading ice creates divergent flow paths.

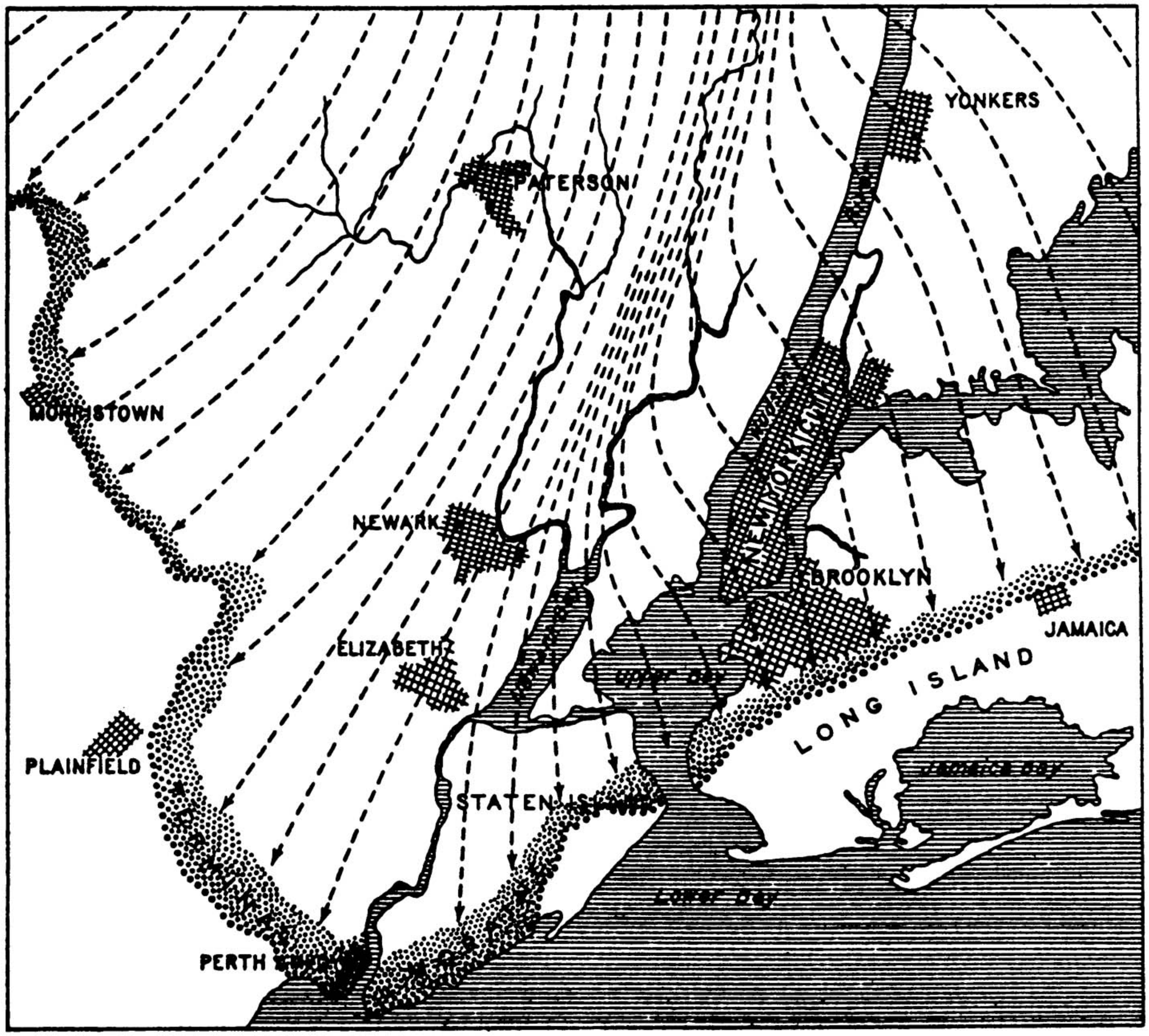


Figure 30 - Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (U. S. Geological Survey, Passaic Folio, No. 157, Figure 11, 1908, rendering of R. D. Salisbury).

The theoretical background in support of the concept that one and the same continental ice sheet could display multiple flow directions was proposed at the time when the modern version of the Laurentide Ice Sheet was advocated (Flint, 1943). According to Flint, the Laurentide Ice Sheet began as one or more snowfields in the highlands of northeastern Canada. With continued additions of snow, an ice cap appeared and it began to spread southward and westward. The azimuth from the northeastern Canadian highlands to New York City is 195° or along a line from N15°E to S15°W. After this ice cap had become a full-fledged ice sheet and had attained something close to its full thickness, it is presumed to have itself become a factor in localizing where further snow would fall. Flint inferred that the ice sheet could divert the flow of moisture-bearing winds from the Gulf of Mexico and thus would have acted as an orographic source of precipitation. In other words, the ice sheet forced the air to rise and to be cooled and thus to drop its moisture. Enough snow is therefore thought to have been heaped up at various localities near the outer margin of the ice sheet and thus to have formed ice domes whose relief altered the direction of flow. Thus, the initial direction of regional rectilinear flow toward the SSW as a result of snow supply from northeastern Canada, could change locally to centers of quasi-radial flow under of the influence of the ice domes each of which could display divergent flow patterns, including zones of flow from NNW to SSE. During retreat, the above-described situation would be reversed. The factors responsible for radial ice-dome flow, including sectors from NNW toward the SSE, would cease to operate and those causing rectilinear flow toward the SSW to resume their former pre-eminence. The predicted pattern of flow for each advance of such an ice sheet, therefore, would involve three phases in the following order: (1) rectilinear flow from the NNE toward the SSW; (2) quasi-radial flow from the glacier-marginal ice domes, but locally from the NNW toward the SSE; and (3) rectilinear from the NNE toward the SSW.

Flint opposed the multiple-glacier hypothesis because he was convinced that if two glaciers had flowed over an area and both had extended their influence deep enough to polish and scratch the bedrock, then the younger glacier would obliterate all traces of the older one. Accordingly, he argued that all the striae must have been made by only one glacier, the youngest one.

Figure 31 shows a map of North America with what was for a long time the standard view of how the Pleistocene ice covered Canada and northern United States. Notice that New York is within the flow pattern shown for the Labrador Ice Sheet.

Given the concept that ice from the Labrador center should have been present in New York City, then the expected direction of such glacier flow is from the NNE to the SSW, a direction that is parallel to the Hudson River. However, in Manhattan and on the top of the Palisades Ridge, striae are oriented from about N20°W to S20°E, or even more toward the NW-SE direction. A previous generation of glacial geologists adopted the view of deviated flow from a central lobate glacier (Figure 30).

According to this concept, the main flow of the latest (and, according to many, the only Wisconsinan) glacier was concentrated down the Hackensack lowland, but the ice deviated to its left and crossed the Palisades ridge and New York City on a NW-to-SE course. This concept of a single glacier flowing in a direction that is parallel to the Hudson Valley was reinforced by the results of thousands of engineering borings through the thick bodies of sediment underlying the Hudson, Hackensack, and other valleys that trend NE-SW. These borings show bedrock overlain by a fresh till that is in turn overlain by outwash (sands/gravels and/or lake clays and -silts) that is overlain by estuarine deposits.

Interpretations of the Pleistocene glacial history of New York City and vicinity have been powerfully influenced by two factors: (1) the two prominent terminal-moraine ridges on Long Island (the older Ronkonkama and younger Harbor Hill moraines); and (2) the subsurface stratigraphic relationships in major valleys that trend NNE-SSW, most notably the Hudson Valley. Both the terminal-moraine ridges and the subsurface stratigraphic units have been ascribed to the latest glaciation, of latest Wisconsinan age, an interval known as the Woodfordian.

Figure 31 - Reconstruction of North American Pleistocene Ice Sheets with Keewatin center and Labrador center shown as attaining simultaneous maxima. Further explanation in text. (U. S. Geological Survey).

The interpretation formulated on the basis of these relationships in New York has left its mark on a far wider area than that of metropolitan greater New York City. Indeed, Long Island's terminal moraines have been cited as proof that the latest Pleistocene glacier was areally more extensive than its predecessors. The proposition is widely presumed to be valid that the intensity of climatic cooling determined the extent of the ice sheets, that is the colder the climate, the bigger the ice sheets, and vice versa. Given the areal relationships of the Long Island moraines, and applying the widely presumed climate-glacier area proposition, the conclusion followed logically that the climate of latest Wisconsinan time must have been colder than that during earlier glacial episodes.

Study of the hundreds of engineering borings made in connection with bridges and tunnels crossing the Hudson Valley and for highways and other structures in the Hackensack Valley to the west supported the conclusion that the Pleistocene history included only one glacial advance. A fresh-looking till was found to be resting on bedrock and to be overlain by pro-glacial lake sediments, typically varved. These lake sediments in turn are overlain by gray organic silts and/or peats related to the encroachment of the modern sea.

Proponents of multiple glaciers with contrasting flow directions are not numerous and for the most part, their interpretation has been ignored. They have been crushed in the "one-glacier-did-it-all" stampede. One of the earliest advocates of the multiple-glaciers possibility was Woodworth (1901), who found in Long Island City that red-brown till, resting on a striated pavement displaying striae oriented NNW to SSE, composes the Harbor Hill Moraine. Fuller (1914) demonstrated the stratigraphic relationships involved in pre-Wisconsinan glaciations. Our only significant difference from Fuller's work is that he assigned Long Island's two major moraine ridges (older and southern Ronkonkama and younger and northern Harbor Hill) to the Wisconsinan. Based on Woodworth's work in Long Island City and out own results on relative ages of the various glacial features, we assign the Harbor Hill Moraine a pre-Wisconsinan (possibly Illinoian, an age likewise advocated by C. A. Kaye, 1964b) age and the Ronkonkama Moraine to a still-older glaciation.

C. A. Kaye (1982) has interpreted the Pleistocene deposits in the Boston area in terms of multiple glaciations by ice flowing from two contrasting direction: NNW to SSE and NNE to SSW. Kaye based his conclusions on study of striae, crescentic marks, directions of asymmetry of roche moutonnées, long axes of drumlins, and indicator stones. Kaye numbered these tills from I (oldest) to IV (youngest). Tills I, II, and III flowed from the NW to the SE, with means as follows:

Till	Mean flow direction
III	S31°E, +/- 02°
II	S64°E, +/- 18°
I	S23°E, +/- 01°

Using these same features, as mentioned above, we conclude that more than one glacier flowed across the New York region; flow indicators prove that the ice came from not one but rather from several directions. JES has prepared Figures 32 and 33 to show how he interprets the flow patterns of glaciers in the same area of Figure 30. In Figure 32, the ice flowed rectilinearly from NW to SE, across the highest ridges and across the Hudson Valley without deflection. This suggests a thick ice sheet whose flow pattern was governed by the gradient on the top of the glacier. Figure 33 shows the flow from NNE to SSE as resulting from a later glacier. According to JES, the two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 32. The latest glacier, shown in Figure 33, 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.

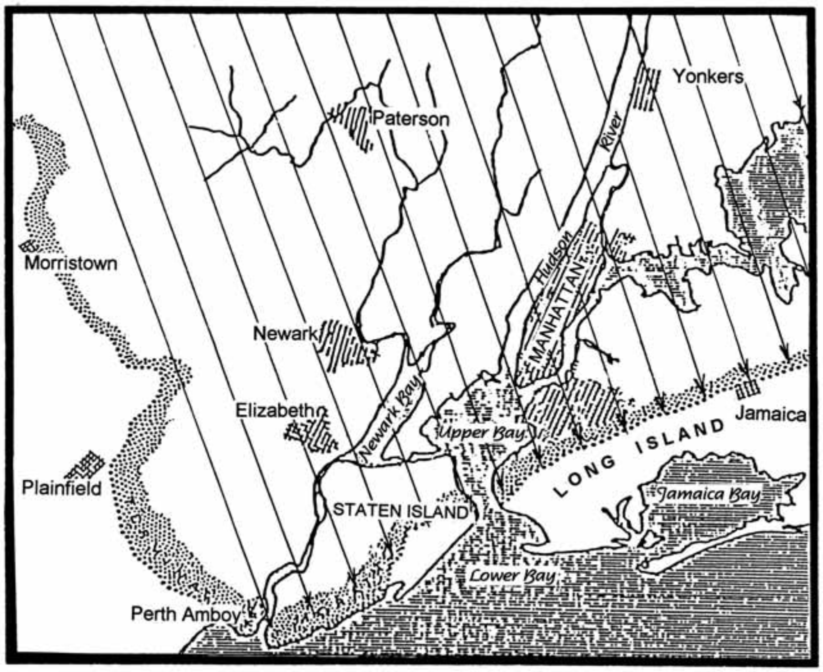


Figure 32 - Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders).

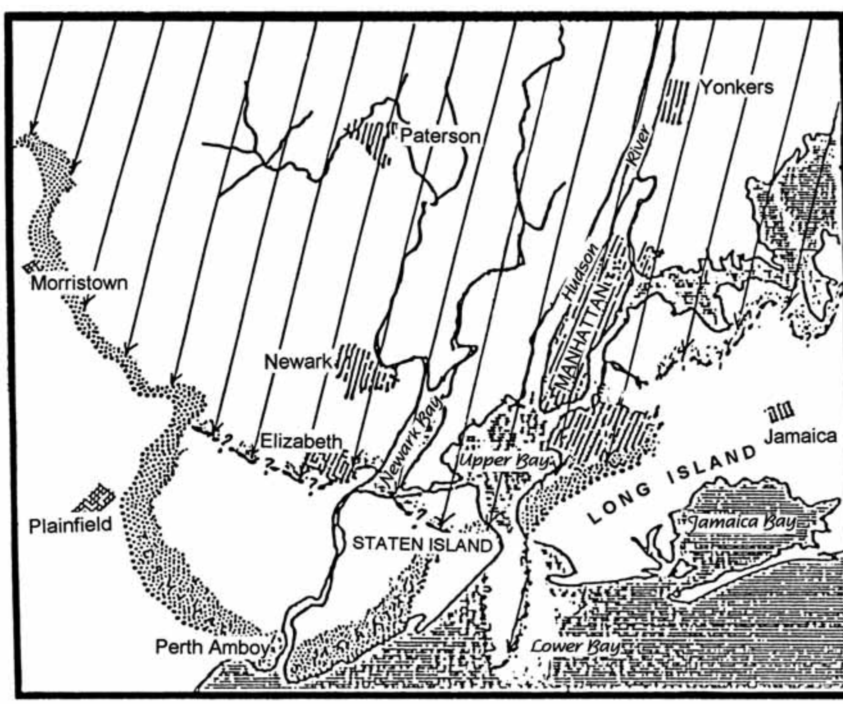


Figure 33 - Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

Evidence for glacial flow from the NW to the SE is not confined to the territory near New York City. Figure 34 shows examples based on swarms of drumlins near Charlevoix, Michigan (northwestern part of southern peninsula) and on indicator stones in New England.

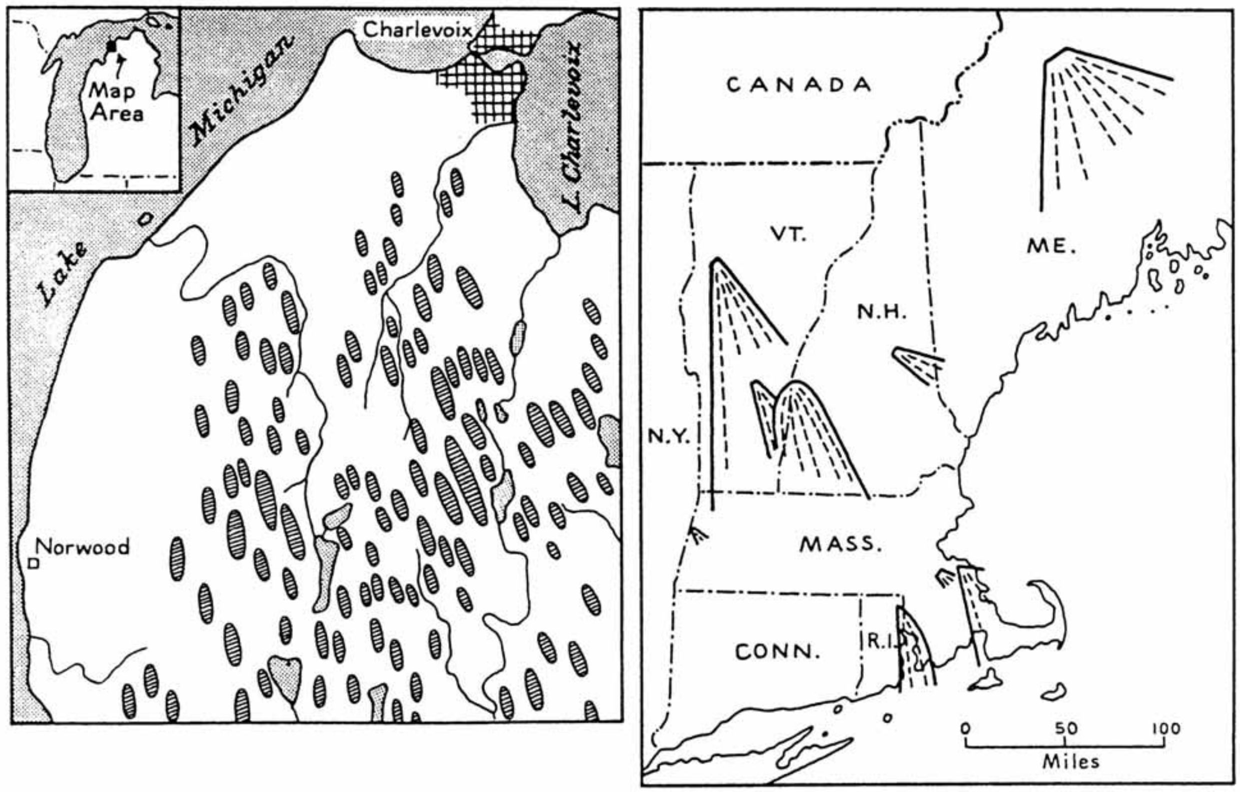


Figure 34 - Sketch maps showing other regions in the United States where glacier flow was from NW to SE.
A. Swarm of drumlins south of Charlevoix, Michigan. (Frank Leverett, and F. B. Taylor, 1915, p. 311; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-20, p. 188.)
B. Boulder trains in New England, all products of regional glacier flow from NW to SE. (J. W. Goldthwait, in R. F. Flint, 1945; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-22, p.

Holocene Sediments Deposited by the Flandrian Submergence

The rapid melting of the Late Wisconsinan ice sheet returned vast quantities of water from the ice back to the oceans. As a result, the sea rose rapidly. This rapid rise of sea level has been named the Flandrian submergence. In the New York City region, the oldest deposit of the rising sea is the so-called gray "organic silt" found in the major river valleys, such as the Hudson. The thickness of the Holocene organic silt ranges up to 150 feet or so, as indicated in borings made for engineering structures.

Once this silt began to be deposited in an area, the pattern has not changed. We note a few points about this Holocene silt. First of all, it is full of gas bubbles. As a result, it is very reflective to sound waves. This means that the silt serves as a blanket which effective precludes the use of ordinary small-boat continuous seismic-reflection profiling, as with sparkers, boomers, and air guns. Many a hopeful investigator has supposed that it would be possible to obtain seismic profiles of the sediments in the Hudson Estuary. An equal number has been defeated; all they ever got was multiples (remember the chorus in the song about Mary Ann McCarthy who went out to dig some clams? "All she ever got was mussels, etc.")

Attempts have been made to date the basal silt from samples obtained at Iona Island and at the Newburgh-Beacon bridge on I-84. Based on samples dated by the radiocarbon method, Newman, Thurber, Zeiss, Rokach, and Musich (1969) concluded that the age of the oldest estuarine silt is 12,000 radiocarbon years. D. Weiss (1974) placed the date at 11,000 years B. P. (before present). Owens, Stefansson, and Sirkin (1974) compared the clay minerals from the lake sediments with those of the estuarine silt and also performed chemical analyses on the silt. Other papers devoted to the Holocene sediments are by Agron (1980) in the Hackensack meadowlands, New Jersey; and by Averill, Pardi, Newman, and Dineen (1980) for both the Hackensack and Hudson valleys.

New insights into the behavior of the fine sediments in the Hudson Estuary have come from the use of geochemical tracers, from the atmosphere, from discharges of radionuclides from the Indian Point reactors, and from the General Electric capacitor-manufacturing plants at Hudson Falls and Fort Edward (results from the geochemical laboratory at Lamont-Doherty Geological Observatory of Columbia University, by the team headed by H. J. Simpson, and including Richard Bopp, Curt Olsen, and others). Using the vertical distribution in sediment cores of the radioactive isotope of cesium (137; derived from nuclear-weapons tests carried out in the late 1950's and distributed worldwide via the atmosphere), these investigators have found two contrasting depositional settings: (1) marginal flats, where the post-fallout sediment is only a few millimeters thick (equals the modern rate of submergence); and (2) dredged channels, where the thickness of post-fallout sediment ranges up to several tens of centimeters. In the marginal flats, sediment has evidently built up to the profile of equilibrium and new sediment can be added only as this profile is lowered (as it is during submergence). In newly dredged channels, sediment fills in very rapidly, at rates in the tens of centimeters per year (C. R. Olsen, Simpson, Bopp, S. C. Williams, Peng, and Deck, 1978; Simpson, C. R. Olsen, S. C. Williams, and R. M. Trier, 1976).

In the spring of 1974, and again in 1976, two mighty surges of sediments highly contaminated with PCBs from the General Electric plants at Hudson Falls and Fort Edward spread throughout the Hudson Estuary and beyond. Prior to 1973, these sediments were kept upriver behind the ancient Fort Edward Dam. For reasons of safety, and to prevent a disastrous downriver surge of sediments that would accompany a damburst flood, the Niagara-Mohawk Power Company, owner of the dam, obtained permission from the Federal Power Commission and New York State Department of Environmental Conservation to remove the Fort Edward Dam. Granted this permission, Niagara-Mohawk dismantled the dam, starting in July 1973 and ending in October 1973. Two subsequent floods and a general time of high flows brought about the very result that removal of the dam was supposed to forestall!

The effects of industrial pollution have obliterated the once-fluorishing oysters of the Hudson estuary. In 1966, JES participated in a small experiment of lowering a TV camera and light to the bottom of the Tappan Zee off Irvington. The bottom is paved with dead oyster shells.

In many places, intertidal salt marshes are encroaching on the land as the sea rises. In order to become established, such marshes require a base of tidal sediments, usually silt/mud. But, an established marsh can keep up with a rising sea; and, the marsh spreads out landward as it grows vertically as the water-level rises. We shall see examples of intertidal salt marshes encroaching on the glaciated pavement at Pelham Bay Park.

DRAINAGE HISTORY

In attempting to work out the drainage history of an area, one can make use of one or more of the following "tools of the drainage-history trade:" (a) "prospect" the geologic record for times when the lands stood high and were being eroded; (b) actually find valleys that have become "fossilized" (i. e., filled with sediment) and then use geologic evidence to infer their ages; (c) use provenance data and relate such data to regional geologic history (with reference to times when particular rock types may or may not have been available to circulate as sediment at the Earth's surface); (d) use cross strata and other features within sediments to infer which way the currents flowed when these sediments were being deposited; and (e) search for drainage anomalies, such as "cross-axial" drainage where a stream flows across a belt of resistant rock that it normally would flow around or away from rather than across. The following paragraphs elaborate on these "tools."

Times of Erosion

Reference to the geologic time chart (Table 1), shows that after the Newark basin-filling strata ceased to accumulate and before the Pleistocene glacial ages, two times of significant erosion are: (i) post-Newark and pre-coastal-plain strata (from about 180 million years ago to about 100 million years ago); and (ii) after the spreading of fans away from the Appalachians late in the Miocene Epoch until the first Pleistocene glacier arrived (from about 6 million years ago to about 1.5 million years ago). The Pleistocene Epoch included several times of erosion and the start of new drainage networks. Each arriving glacier covered and possibly obliterated previous river systems. As each glacier melted, a possibility existed for establishing new drainage networks. Although these Pleistocene times of erosion were short (possibly not longer than a hundred thousand years), they included powerful agents of erosion: glacial ice and torrents of melt water.

Buried Valleys

Buried valleys are "fossil" evidence for ancient drainage. The significance of a buried valley in drainage history depends on how closely one is able to determine its age. The age of a buried valley can be bracketed by finding the youngest strata the valley cuts and the oldest sediments in the valley fill. Complications exist because an old valley may have been filled and later uncovered in part or in whole and re-occupied by a river that was not responsible for the original erosion of the valley.

Provenance Data

Provenance data can become parts of drainage history by suggesting directions of travel of distinctive debris and by their implications for what areas may have been eroded to contribute sediment and, by contrast, what areas may have been covered and thus could not have contributed sediment. Both of these aspects of provenance data affect reconstructions of ancient drainage networks.

Features in Sediments Made by Currents

Many kinds of features are made in sediments by currents and some are particularly useful for inferring the directions of flow of the ancient currents. Cross strata furnish a useful example. Cross strata, defined as layers that are oblique to their enclosing strata, result from the migration of bed forms (Figure 35a, d) or from the building of "embankments" (Figure 35c, e). The direction of dip of the cross strata formed by downcurrent migration of a bed form or from the forward growth of an "embankment" is downcurrent. Trough cross strata form by the migration of cuspate megaripples (Figure 36).

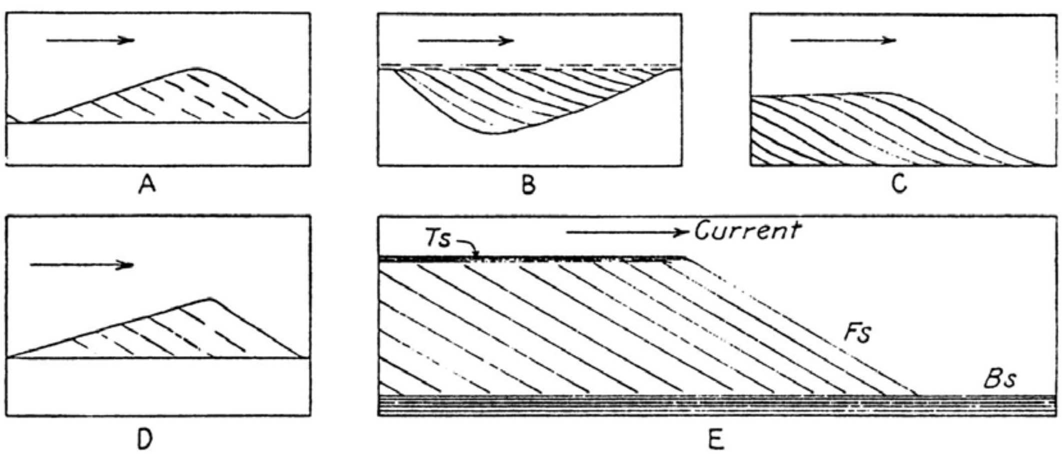


Figure 35 - Sketches of cross strata dipping to the right and formed by current flowing from left to right.
A and D, Longitudinal profiles through individual bed forms that have migrated to the right (downcurrent) by at least one
wavelength, thus preserving as internal cross strata many former downcurrent faces.
B, Longitudinal profiles through cross strata that have filled in an asymmetric depression.
C and E, Longitudinal profiles through cross strata deposited by downcurrent growth of an embankment (such as a delta lobe), built where the flow enters slightly deeper water. (R. R. Shrock, 1948, fig. 207, p. 245.)

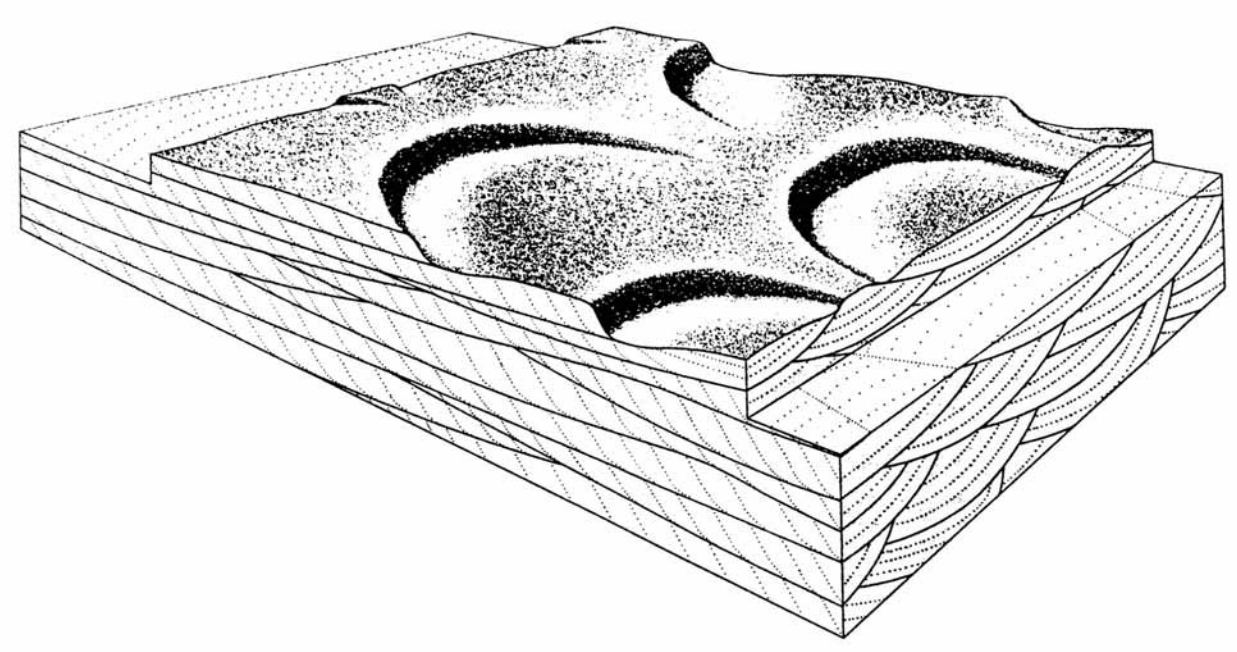


Figure 36 - Block diagram showing trough-type cross strata formed by downcurrent migration of lunate megaripples. Current from upper left to lower right. (H.-E. Reineck and I. B. Singh, 1980, fig. 52, p. 43.)

Drainage Anomalies

Anomalous drainage is a term applied to any drainage network in which the predominant flow is not down the regional slope. Obviously, water does not flow uphill, but it can flow along the contours of the slope rather than straight down the slope. Another category of drainage anomalies includes rivers that cut across high-standing areas of resistant rocks, collectively designated as cross-axial drainage. A water gap is the name given to a river valley that cuts across a resistant layer (Figure 37a). Cross-axial drainage can result from several combinations of geologic circumstances. For example, after a stream has become well established in a valley, an anticline or fault may grow along a line trending across the stream. If upward growth is slow and stream power sufficient, the stream may maintain its course and eventually, can cut a water gap (Figure 37b). Such a stream is known as an antecedent stream; it is older than the axis it has cut across. Another possiblity is superposition (Figure 37c). Superposition results from a multi-stage geologic history. First, the belt of resistant rock is established. Then, it is buried. The stream becomes established on the covering strata and commences downcutting. After the stream has cut through the cover, it "discovers" the buried transverse axis. But, because its course has been locked in, so to speak, on the covering strata, it is able to cut a water gap through the resistant transverse axis and may do so in more than one place as has been inferred for the ancestral Hudson across the Watchung mountains, New Jersey.

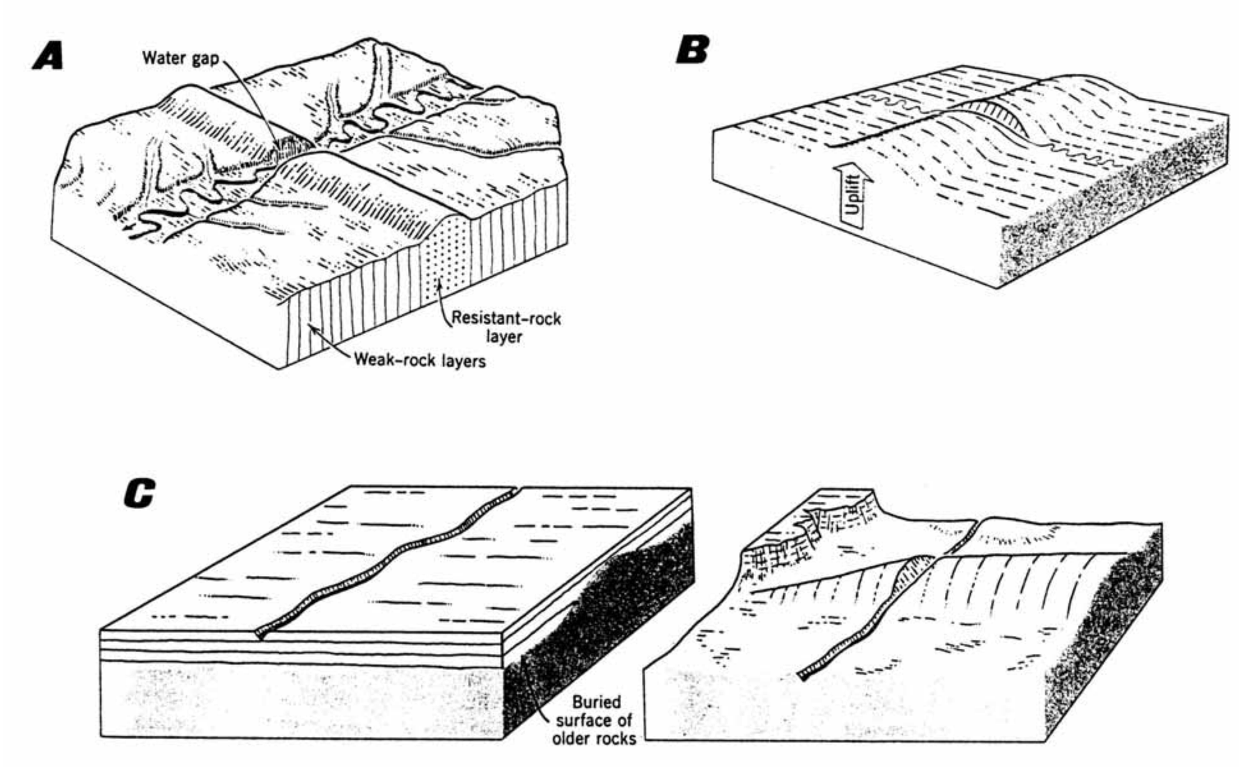


Figure 37 - Drainage anomalies associated with cross-axial stream flow, schematic block diagrams. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969: A, fig. 10-12, p. 225; B, fig. 10-15, p. 227; C, fig. 10-16, p. 227.)
A. Stream cuts a water gap through a ridge formed by resistant rock.
B. Stream continues to flow as anticline is uplifted across its path; downcutting equals or exceeds rate of uplift, thus enabling the stream to maintain its course. The stream, which is older than the uplift of the anticline, is named an antecedent stream.
C. Two stages in the history of a superposed stream. In block at left, a prominent ridge has been buried by horizontal strata, on which the stream establishes its course. In block at right, all covering strata except for a small remnant at upper left have been removed and the stream has cut a cross-axial path through the ridge of resistant rock.

A final category of drainage anomaly is what is known as a barbed tributary, defined as a tributary that enters the master stream in such a way as to make an acute angle in what is the downstream direction of the master stream. The usual arrangment is that the tributary joins the main stream and makes an acute angle in the upstream direction. This follows from the fact that the slope of the master valley is downstream. Therefore, any tributary from the side tends to flow down the master valley before it joins the master stream. In so doing, it makes an acute angle on the upstream side.

Local Examples

We have discussed the drainage history of the New York City region in our Manhattan guidebook. We will not repeat the local examples mentioned there but will concentrate on a local drainage anomaly related to the Bronx River.

Modern rivers are flowing in lowlands some of which have been in existence for hundreds of millions of years, and others of which are only a few tens of thousands of years old. Locally, the rivers flow in lowlands occupied by the Inwood Marble, the least-resistant rock unit in the New York City area (under today's humid-temperate climate).

In the northern part of the Botanical Garden, the Bronx River flows out of a lowland underlain by the Inwood Marble, which trends NNE-SSW, and crosses the more-resistant Hartland Formation (the "Manhattan Schist" of Schuberth). This is a first-order drainage anomaly. Why does not the Bronx River continue to flow southwestward into the Webster Avenue valley which is underlain by the Inwood Marble?

Notice that on the north side of the block diagram of the Botanical Gardens (Figure 38), the Bronx River occupies a mature, U-shaped valley underlain by the Inwood Marble. This represents the typical situation. We think that a slight modification of the relationships between the Bronx River and the Mosholu Parkway fault as summarized by Schuberth (in the paragraph quoted above in the section on "Faults and seismicity") may be in order.

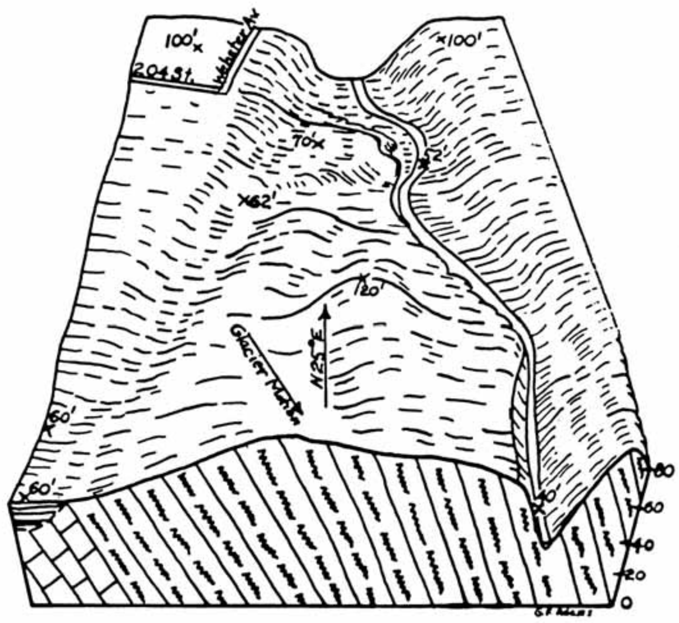


Figure 38 - Block diagram of the New York Botanical Gardens (drawn by G. F. Adams [formerly from the City College of New York]) showing the generalized structure of the Inwood Marble and the Hartland Formation and transverse profiles of the Bronx River valley. Note that the valley is broad where the Bronx River flows on the Inwood and narrow where it flows on the Hartland.

About at the Mosholu Parkway, the outcrop belt of the marble, and with it, the usual lowland, may have been displaced to the northwest (an effect of Baskerville's Mosholu Parkway right-lateral strike-slip fault? None of the previously published geologic maps shows such an inferred fault offset in the outcrop of the Inwood Marble. Rather, they all show a shift resulting from a fold.) Where the Bronx River turns to its left, it has eroded a V-shaped valley that is underlain by metasedimentary- and metavolcanic rocks of the Hartland Formation. Notice the narrow, V-shaped profile of this valley in the lower right corner of the block diagram (Figure 38). Whether or not a previous Bronx River was able to follow the offset lowland (Webster Avenue Valley) to the SSW as Schuberth so positively asserts that it did), we do not know. As for the geologic timing of this change, we do not follow Schuberth's suggestion that it took place as long ago as 20 million years to 30 million years. Rather, we agree with Kemp (1897), and think that in postglacial time, the river found a cul-de-sac at the Mosholu Parkway. Further flow to the SSW was not possible, perhaps because sediments related to the glacier filled in part of the former valley. Had this NS-trending segment of the Bronx River valley been eroded before the latest glacier arrived in the New York City region, then the ice would surely have changed the valley's transverse profile from a narrow V shape to a broader U shape. Therefore, we think that the narrow V profile of the Bronx River is a powerful argument in favor of a postglacial age for the river's shift into its present course. In years, this would mean no older than about 12,000. At the south end of the grounds of the Bronx Zoo Park, the Bronx River once again occupies a broad lowland.

So much for our long-winded geologic background. We now turn to the specifics of the trip, starting with our field trip objectives.

OBJECTIVES

1) To study the effects of extreme folding, faulting and metamorphism of the Lower Paleozoic strata of the Bronx.

2) To examine lithologic variations in the three schist units of the Bronx formerly "lumped" together into the Manhattan Formation.

3) To examine the evidence for Cameron's Line.

4) To get up close and personal with mylonitic rocks.

5) To examine the effects of multiple glaciations.

6) To get in the groove, glacial-, that is!

7) To find sufficient restrooms to keep field trip participants happy, and,

8) To try to visit all of our planned stops.

LIST OF LOCALITIES ("STOPS") TO BE VISITED

Stop 1: Fordham Gneiss on I-95, Bronx
Stop 2: Cameron's Line, I-95, Bronx
Stop 3: New York Botanical Gardens
Stop 4: North and South Twin Islands, Pelham Bay Park

DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

The following four stops (Figure 2) illustrate the evidence for changes in the interpretation of the stratigraphy, structure, and presence of ductile shear zones between the schistose rocks in New York City. It is not known at present whether significant displacement has occurred along the ductile contacts. However, based on regional stratigraphic relationships, the three schist units of the "Manhattan Schist" are interpreted as coeval miogeosynclinal, transitional, and eugeosynclinal depositional sequences that were juxtaposed at depth during Middle Ordovician deformation of the North American passive continental margin and adjacent oceanic strata.

STOP 1 - Fordham Gneiss on the Cross Bronx Expressway, The Bronx. [UTM Coordinates: 590.9E / 4521.9N, Central Park quadrangle.]

We would like to begin today's field trip with a short stop to view the "Grand-daddy" bedrock unit of the Bronx. Here in spectacular vertical exposures that Robert Moses' busy work crews blasted away to make room for the Cross Bronx Expressway (CM laments - What a waste of rock!), the Proterozoic Y Fordham Gneiss Member B is exposed. The Fordham consists of a steep, west-dipping, highly folded- and faulted sequence of garnetiferous quartzofeldspathic gneiss and migmatite, biotite schist, and amphibolite. Elsewhere, greenish calc-silicate layers are present. Of interest here are the obvious asymmetric Z-folds of the older foliation with steep- to subvertical axial surfaces and with a gentle horizontal plunge. The obvious folds are probably correlative with the F_3 folds found elsewhere in the Bronx and Manhattan.

We will walk along the length of the outcrop until carbon monoxide poisoning begins to set in. You will know this has happened when CM begins waving his arms, talking about superposed deformation, migmatites, and ductile shear zones. We have not examined these exposures in great detail but in passing them at 55 MPH, we have noticed brittle- and ductile faults as well as a multitude of faults. Keep you eyes peeled for spare car parts and "previously owned, partly used" major appliances.

STOP 2 - Cameron's Line or the St. Nicholas Thrust - Boro Hall and Crotona Parks, Cross Bronx Expressway, The Bronx. [UTM Coordinates: 592.94E / 4521.75N, Central Park quadrangle.]

Boro Hall Park in the Bronx is surrounded by East Tremont Avenue on the north, Third Avenue on the west, Arthur Avenue on the east, and East 175 St. on the south. The latter also serves as the westbound service road for the Cross Bronx Expressway (I-95). South of the expressway, Crotona Park exposes a continuation of the rocks exposed in Boro Hall Park.

Along East 175 Street (SW corner of Boro Hall Park the outcrops nearest Third Avenue are sheared a brown-weathering, medium-grained, gray, biotite-muscovite schist and granofels of the lower schist unit (Om in Figure 11) containing several pegmatite dikes. Test borings for the I-95 overpass near this locality indicate that marble occupies the Third Avenue valley to the west. Indeed, interlayered marble, calc-schist, mica schist, and granofels (Om) are exposed along the W edge and and NW corner of Boro Hall Park. Preliminary mapping of Boro Hall Park (Fuller, Short and Merguerian, 1999) indicates that Hartland rocks do not occur there, despite our earlier contrary views published in previous OTR guides. The Manhattan middle schist unit (Ꞓ-Om) occupies the bulk of the exposures in the eastern half of Boro Hall Park and the western half of Crotona Park including the exposure at the NW edge of the park, south of I-95. Thus, the St. Nicholas thrust, which can be traced through Boro Hall Park southward to immediately west of Crotona Park, separates Om from Ꞓ-Om.

East of the lower- and middle schist units, based on reconnaissance fieldwork conducted in 1998 and 1999 by Merguerian and Hofstra students in Boro Hall and Crotona Parks, well layered Hartland rocks (Ꞓ-Oh) crop out well to the east of Boro Hall Park and can be mapped in the central and eastern parts of Crotona Park to the south of the expressway. These rocks are well-layered tan-weathering, gray muscovite-biotite-quartz-plagioclase-garnet schist and granofels with granitoid sills and layers of greenish amphibolite. They are correlative with the upper schist unit exposed at STOP 1 in Manhattan within Riverside Park.

The contact between the middle schist unit (Ꞓ-Om) on the west and the Hartland Formation (Ꞓ-Oh) is never exposed. Rocks on either side of the contact are highly flattened; the microscope shows little evidence for mylonitization due to recrystallization during D_3. Microscopically, brittle fractures are well-developed in the minerals, suggesting the contact may be a brittle fault reactivating an older ductile contact. Regionally, the contact between these units is known as Cameron's Line (Figure 20), a ductile fault separating eugeosynclinal rocks of the Hartland Formation on the east from dominantly miogeoclinal basement-cover rocks of the Manhattan Prong (Ꞓ-Oi and Om) and allochthonous Manhattan (Ꞓ-Om).

Dr. Patrick W. G. Brock of Queens College, who took a class to this stop, collected specimens, and examined the rocks petrographically, detected a corroded grain of corundum that had been highly retrograded by younger, higher-crustal-level metamorphic overprinting. Although it was not in contact with quartz and clearly had undergone retrograde reactions, the corundum discovery suggests that the rocks in this region had progressed up the metamorphic scale at least up to K-feldspar-sillimanite grade (we will examine K-feldspar-sillimanite-grade rocks later at Stop 4) and perhaps the metamorphic conditions at the Boro Hall stop had been even higher.

Brock also notes that along the NW edge of Boro Hall Park, marble and calc-silicate rocks are found interlayered with the Manhattan. CM agrees with PB in his suggestion that these rocks are the "Good Old Manhattan Schist with interlayered "Balmville-type" marble (= Middle Ordovician Walloomsac/Balmville sequence farther north).

STOP 3 - New York Botanical Garden. [UTM Coordinates centered on: 594.7E / 4523.6N, Central Park quadrangle. Detailed trail maps in guidebook.]

The structural geology of the New York Botanical Garden was the subject of investigations by Langer (1966) and Bowes and Langer (1969). The rocks exposed in this area of the Bronx Botanical Garden (Figures 2, 38; Table 3) and eastward are in a key position with respect to CM's interpretation of the schists of Manhattan (Figures 16, 20). He and Baskerville (1987) have independently mapped the rocks here as belonging to the Hartland Formation. The Hartland Formation consists of a vast succession of metasedimentary rocks (that is, metamorphic rocks formed from protoliths that were sedimentary rocks). One of the diagnostic characteristics of the Hartland Formation is well-developed layering and overall aluminous composition. Various kinds of metamorphic rocks are present: muscovite schist and -gneiss with interlayers of mica granofels, quartz-feldspar gneiss, and amphibolite. The schistose- and gneissic members of the Hartland Formation contain minerals rich in aluminum. This implies that in the sedimentary protolith, clay minerals were abundant. The inferred abundance of clay implies further that the original sediments consisted of extremely fine size fractions.

The Hartland's interlayers of mica granofels and quartz-feldspar gneiss on the one hand, and of amphibolite, on the other, are inferred to have resulted from the metamorphism of turbidites and of basaltic extrusive rocks, respectively. In total, the Hartland Formation is thought to represent the products of metamorphism of a sequence of Lower Paleozoic rocks deposited in deep water adjacent to and east of the early Paleozoic shelf edge of the eastern North American continent (Merguerian, 1983b).

The limbs of the major folds into which the Hartland has been deformed trend roughly N30°E. Dips are steep in both of the possible directions for fold limbs having such a trend: (1) toward the northwest and (2) toward the southeast. The rocks are well foliated and have been recrystallized. The metamorphic minerals present are products of dynamothermal metamorphic conditions that are classified as being medium- to high grade. Such grades of metamorphism imply temperatures such as those found at depths ranging down to 25 km. Rocks formed at such depths typically display folds and small bodies of granitic rocks, the latter implying that locally, the rocks were hot enough to have been partially molten. Altogether, the rocks display numerous features that form as a result deformation that took place when the rocks were in a ductile condition.

In Bronx Park and in the southern part of the Botanical Gardens, the stratigraphic units of the Hartland are clearly exposed. According to Baskerville's geologic map (1987), Cameron's Line cuts across the northern part of the park, near the bend in the Mosholu Parkway (we concur). North of Cameron's Line, a thin layer of the Manhattan Schist crops out, and north of the schist, a belt of the Inwood Marble. Immediately north of the park, the marble underlies a lake. Elsewhere in New York City, the Inwood Marble is the main valley-forming unit. We have already discussed this relationship between marble and lowlands in a previous section (Local Examples) that contains additional remarks about the Bronx River.

Glacial features noted in the Botanical Gardens include polished bedrock surfaces, roche-moutonnée structure, and glacial grooves, indicating at least three major glacial episodes: (1)

earliest movement from NNE to SSW; (2) movement from the NNW to SSE, and (3) movement from NNE to SSW. These are in keeping with our results from studies of glaciation in the region.

The following stops are all within the confines of the New York Botanical Gardens in the Bronx (Stop 3) and are numbered 3.1 through 3.12. Below, the twelve sub-stops of Stop 3 are described separately and plotted on a trail- and garden map issued by the Botanical Gardens and reproduced with our sub-stop numbers as Figure 39.

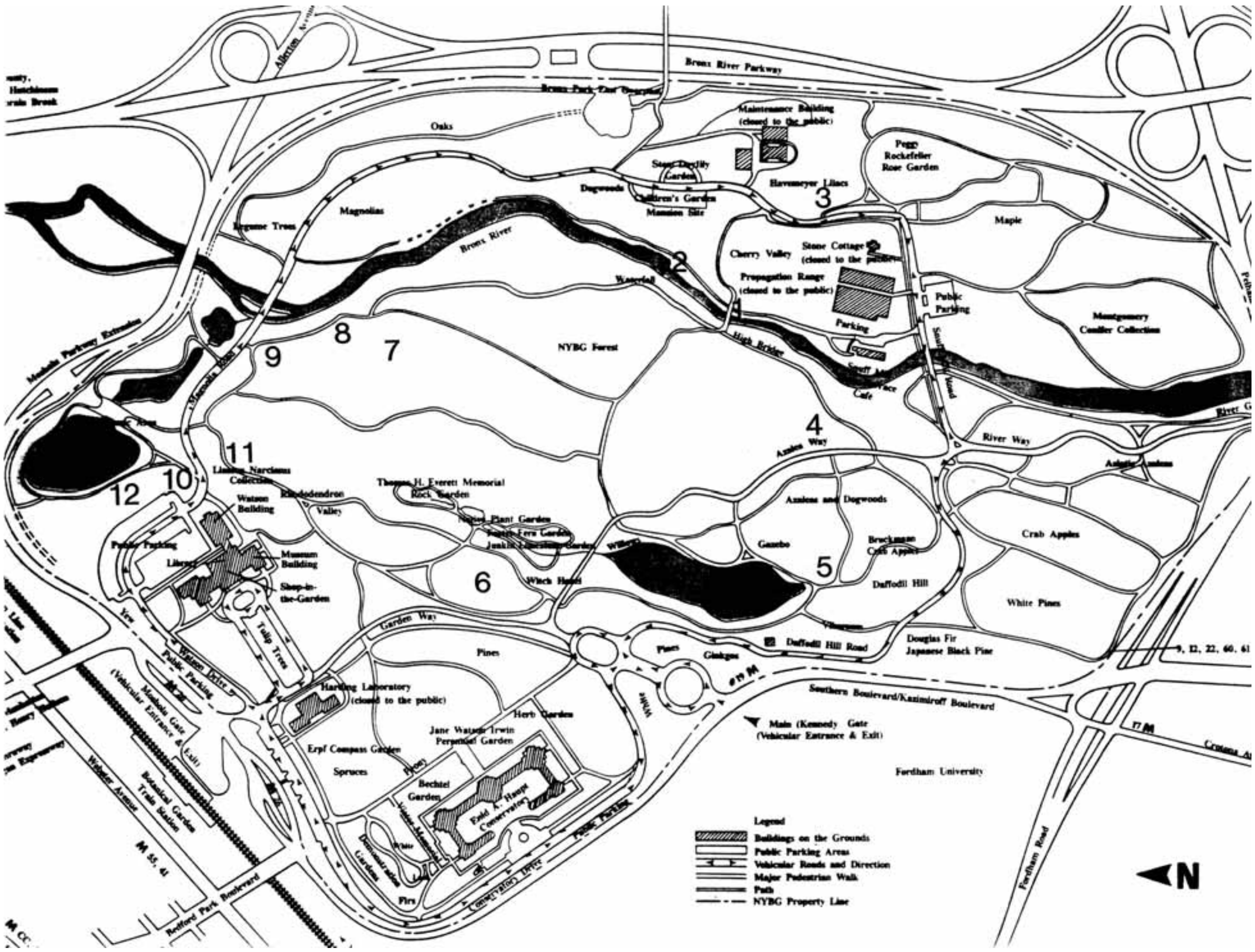


Figure 39 - Trail map of the New York Botanical Gardens showing the locations of sub-stops 3.1 through 3.12.

STOP 3.1 - Hartland Formation on the east side of Bronx River beneath Hester Bridge.

Beneath the footing for the Hester Bridge, steeply foliated biotite-garnet-sillimanite gneiss and migmatitic gneiss of the Hartland Formation (Ꞓ-Oh) bears a gentle southward-plunging L_3 lineation. The foliation is oriented N24°E, 74°NW. Rocks here are not typical of Hartland in that they are not well layered and do not contain granofels. Beneath the bridge, a spectacular example of rectilinear root wedging follows a prominent joint pattern in the bedrock. The Bronx River is here flowing in a steep post-glacial canyon that may be fault- and/or joint controlled. On the west side of the river, the rocks are exposed in subvertical cliffs that extend upward about 25 m above the water level. In our previous discussion (under the heading "Local examples") we argue that the steepness and lack of glacial effects mandates a YOUNG, post-glacial age for the diversion of the Bronx River and development of the canyon. (See Figure 38.)

STOP 3.2 - Migmatitic Hartland Formation on east side of Bronx River at waterfall area.

The rocks here form a part of the Hartland Formation with internal layering on the scale of 4- to 6 cm and 4 mm spangly muscovite locally on the foliation surface. CM suspects that the tabular- to blocky mica booklets may be the result of retrograde metamorphic replacement of aluminosilicate minerals as similar relationships were encountered on Manhattan in rocks of similar grade. Small K-feldspar-bearing pegmatitic sill-like intrusives are found parallel to the foliation (oriented N25°E, 90°). Two dolerite erratics are visible suggesting NW- to SE-directed glacial motion.

STOP 3.3 - Roche-moutonnée structure in the Hartland Formation.

The Hartland Formation is here sculpted into a classic roche-moutonée structure with a gentle up-glacier side and a steep down-glacier side. As such, this asymmetrical erosional indicator mandates glacial flow from N15°E toward S15°W (Our Glacier I or IV in Table 3). The development of the steep, down-glacier side of the roche moutonnée was undoubtedly facilitated by the subvertical A-C joints which formed perpendicular to the local F_3 fold axes in the Hartland.

Of additional interest here to students of geology is the structure of the Hartland which is deformed by south-plunging F_3 folds. Here, in contrast to Stop 3.1, the metamorphic rocks are well layered and are more typical of the Hartland Formation throughout New York City and New England. The Hartland is vertically foliated in a direction N16°E with the S_2 and S_3 fabrics subparallel. On the east side of the outcrop a 2-m-thick pegmatite sill with a quartz core has intruded parallel to the coplanar S_3 foliation and the primary layering (S_0 through S_2) in the Hartland. At the south end of the exposure the pegmatite crosscuts the metamorphic fabric at a high angle and locally, at the north end, includes a 30-cm-long foliated xenolith of Hartland gneiss with diffuse borders. The pegmatite is thus post-tectonic with respect to the F_3 folds and the regional foliation. The diffuse xenolith borders suggests that the temperature of the country rock and intrusive were roughly equivalent which further implies that the intrusion took place at depths equivalent to the metamorphic zone of the country rock. Sillimanite- and kyanite-grade rocks form in the depth range of 20-25 km. Where you putting all that overburden, Vern?

Locally, the F_3 folds deform cm-scale pegmatitic- and quartzose segregations which were sweated out and intruded parallel to the older S_2 regional foliation. The F_3 fold is tight- to isoclinal in outline with an axial surface oriented parallel to the S_2 regional foliation (N16°E, 90°) and a S15°W plunge at 03°. Note the spectacular "textbook" development of Z-, M-, and S-folds around the eastern-, northern-, and western portions of the southward-plunging synformal fold.

STOP 3.4 - Stratigraphy of the Hartland Formation and evidence for glaciation.

Here, the Hartland Formation contains massive muscovite-biotite-plagioclase-quartz granofels layers 1 to 1.5 m thick intercalated with mica schist bearing conspicuous garnet-kyanite-sillimanite-quartz nodules up to 1 cm in size. Bedding and subparallel foliation are oriented N21°E, 83°NW, the result of transposition of the S_3 and older fabrics. Together these lithologies are interpreted as metamorphosed turbidites (now granofels) and interbedded shale (now schist) that were evidently deposited in a deep-water oceanic setting prior to their metamorphism [Layer II(A)E in Table 2].

The evidence for glaciation is here in the form of a huge glacial erratic of the Fordham Gneiss perched upon the glacially polished outcrop surface. Etched into the surface are prominent glacial grooves oriented from N26°W to S26°E (our Glacier II or III in Table 3). They are parallel to the overall asymmetry of the outcrop with smoothed, gentle NW slopes and jagged, steep SE ledges. The gentle, polished NE-facing slopes suggest that the outcrop may also have been sculpted in a direction parallel to the strike of the foliation (N21°E). The associated jagged SW edge of this suspected roche moutonnée may have been strongly modified by the more-obvious effects of the younger, SE-directed glaciation.

STOP 3.5 - Shallow early structures in the Hartland Formation and evidence for two glaciations.

This low-relief outcrop contains superposed structural- and glacial features and offers the most in geology for very little investment in real estate. Bedding and the early foliation in the Hartland create an enveloping surface oriented N52°W, 20°SW, defined by a contorted sequence of interlayered schist, thin granofels, and their subparallel metamorphic foliation. The F_2 folds are reclined (plunge down the dip of the foliation) and are isoclinal in outline with axial surfaces parallel to bedding and the S_2 foliation. Flattened into the S_2 foliation are kyanite-sillimanite-quartz nodules. The nodules and the enclosing foliation are folded by upright, south-plunging F_3 folds with axial surfaces oriented N17°E, 90°. These structural relationships and relative dating chronology are identical with those found by Merguerian (1983b) in Manhattan and elsewhere in western Queens and the Bronx.

The overall shape of this glacially sculpted outcrop displays the erosional effects of two glaciations from different directions. The prominent N22°W to S22°E glacial grooves (Glacier II or III) here cut across an older roche-moutonnée structure (Glacier I) oriented from N26°E to S26°W. Thus, we here have combined evidence suggested from earlier stops indicating glacial flow from two contrasting directions. Of no great surprise to On-The-Rockers (but of some lament in the scientific community), these field data are in total support of the multi-directional glacial interpretaton for the New York area suggested by Sanders and Merguerian (1991a, b).

STOP 3.6 - Elephant Rock--a trunkful of crescentic- and lunate gouges, erratics, and striae in deformed Hartland rocks.

The most-obvious glacial feature at this stop is the enormous, split erratic boulder of Yonkers Gneiss on the NE part of the exposure near the entrance to the Rock Garden. The presence of the Yonkers is here constrains ice-flow direction in that exposures of the Yonkers are limited to areas directly north and east of us. Accordingly, this boulder was NOT transported by ice flow from the NW; it must have been deposited by our Glacier IV from the NNE. (See Table 3.) Because subsequent glaciers tend not to leave pre-existing erratics in place, the mere presence of this Yonkers Gneiss boulder (if it is indeed the Yonkers!) mandates the Glacier-IV interpretation.

Evidence of glacial flow from the NW (Glacier II and/or III) in the form of roche-moutonnée structure and a plethora of photogenic glacial striae oriented N23°W to S23°E is abundant. If one walks toward the western part of the outcrop, one encounters hard evidence for the older, SSW-directed glaciation (Glacier I). Here, roche-moutonnée structure, crescentic-, as well as lunate gouges together indicate glacial flow from N22°E to S22°W. These older glacial features are clearly crosscut by striae oriented NW to SE and roche-moutonnée features described above. As described below, the development of crescentic- and lunate gouges was undoubtedly the result of emphatic structural control of the subhorizontal S_2 foliation in the Hartland Formation.

The orientation of the S_2 foliation in the Hartland is here subhorizontal; it is similar to its orientation at our previous stop. Because of differential weathering susceptibility of the minerals aligned in the foliation an inherent weakness is established in the bedrock. Thus the early foliation in the Hartland, delineated by a penetrative foliation, subparallel granofels interlayers and quartzose segregations, evidently exerted a controlling influence on the local development of glacial gouges. We suspect that such favorable structural settings "stubbed the toe" of the advancing glacier and promoted frost-generated mechanical plucking. Of structural interest, shallow south-plunging F_3 Z-folds deform the older S_2 foliation and related subparallel features. The axial surfaces of the F_3 folds are oriented N15°E, 90°, consistent with measurements made elsewhere in the Gardens.

STOP 3.7 - Lincoln Rock - Two glacial directions and local flow divergence.

Lincoln rock is the highest natural point in the New York Botanical Gardens and consists of highly glaciated rocks of the Hartland Formation in the form of a steep-walled rock drumlin. The older glacial feature (Glacier I) is the overall NNE- to SSW-oriented roche-moutonnée structure of this large roche moutonnée with its steep, well-polished NNE side and jagged, glacially plucked SSW side. Glacial striae related to this event are oriented N13°E to S13°W. Superimposed on these features are glacial grooves oriented N32°W, a divergence 6° to 10° from our earlier measurements of the SE-directed flow of Glaciers II and/or III. We suggest that this is a local westward divergence caused by the unusually steep-walled outcrop. The foliation in the Hartland is oriented N15°E, 80°SE.

STOP 3.8 - Well layered (mylonitic?) Hartland cut by a prominent joint set.

The most-obvious structural features in this exposure are the well-developed joint set oriented N67°W, 67°SW. The joints are spaced, on average, from 5 to 6 cm and cut the outcrop into an obvious blocky form. Typically, such profuse development of joints in an outcrop alerts the budding (an appropriate term for the Botanical Garden) field geologist to "be on the alert" for a fault having an orientation parallel to one set of joints. Commonly, however, faults are easily eroded and do not show up in outcrop. Rather, they are found by duplication- or omission of geologic units and/or geomorphic expression. Here, we argue that the change in flow orientation of the adjacent Bronx River to the southeast may be the result of offset by a northwest-trending fault that parallels one of the sets of joints.

Speaking of faults, the foliation in the Hartland Formation (N13°E, 77°NW) is quite well layered compared to exposures observed thus far. Such highly laminated metamorphic textures are typical of mylonites, ductile-fault rocks produced at significant depths around fault zones. As such, we may be dangerously close to Cameron's Line, a ductile fault that separates the Hartland Formation on the east and southeast from rocks of the Manhattan Formation on the west and northwest. Clearly, the evidence at this outcrop is not sufficiently overwhelming to enable CM to be absolutely certain of this but it is time to start looking for supporting evidence. We hope to convince you, in subsequent stops, that Cameron's Line does, indeed, reside in the Bronx beneath the public parking lot (in the vicinity of Watson Drive and Magnolia Road) in the northwestern park border, as was first suggested by Baskerville (1987).

STOP 3.9 - Dolerite erratics.

Just a quick stop to see a few dolerite erratics. Remember that dolerites are medium-textured mafic rocks from the Palisades Sill. As such they indicate NW- to SE-directed glacial flow across the New York City area. We have today seen ample evidence of glacial flow (Glaciers II and/or III) from this direction.

STOP 3.10 - Manhattan Schist Formation.

Adjacent to the parking lot are rocks that CM argues do not the Hartland but part of a vast sequence of Cambrian to Ordovician metamorphosed strata known as the Hoosac and Waramaug formations farther north in Massachusetts and Connecticued and as the middle unit of the Manhattan Schist (Ꞓ-Om) in New York City. In contrast to the Hartland Formation, which is typically gray-weathering, well layered and rich in muscovite with abundant quartzose granofels and greenish amphibolite layers, the Manhattan is brown- to maroon in weathered color, tends to be massive and richer in biotite, contains little to no granofels, and includes thin layers of blackish amphibolite. Further distinctions are summarized in the section of geologic background and can also be found in Merguerian (1983a, 1985, 1987). Here, the Manhattan is massive and brown in weathering color and consists of magnetite-bearing kyanite-biotite-garnet-quartz-plagioclase schist. The foliation (a composite of the S_2 and S_3 foliations) is oriented N20°E, 65°NW. If this lithologic call is correct, then Cameron's line must exist somewhere between Stops 3.8 and 3.10. But let's look at some adjacent outcrops to help define the position and configuration of the presumed ductile-fault surface.

STOP 3.11 - Hartland Formation and amphibolite float.

Just across from Stop 3.10, on the south side of Magnolia Road, occurs an outcrop typical of the Hartland Formation with a 40-cm-thick layer of biotite-quartz granofels. The S_3 foliation is here oriented N23°E, 90° and is parallel to the layering (bedding) in the granofels unit. Cameron's Line must be isoclinally folded and rotated into parallelism with the S_3 foliation in order to "fit it in" between Stops 3.10 and 3.11. Of additional interest here is a float block of amphibolite (nothing like a chocolate ice cream float!) meaning that the rock is not bedrock but "floating" in the regolith. The angular nature of the block and typical "Hartland look" suggest that it has not been "floated" very far.

STOP 3.12 - Mylonitic Manhattan Formation and the elusive Inwood Marble.

The attitude of the Manhattan Schist observed at Stop 3.10 is repeated here; the brown- to red-brown weathering Manhattan (Unit Є-Om) displays a massive but hackly appearance. Unlike other outcrops in the park (with the exception of the outcrop of Hartland at Stop 3.8), these rocks possess a penetrative mylonitic foliation with elliptical quartzose augen (flaser structure) and sheared-out F_2 folds defining the S_2 foliation. Some of the shearing may have resulted from deformation during the F_3-folding episode but the penetrative mylonitic texture is quite distinctive. We agree with Baskerville (1987) that the appearance of the lowland immediately north of us (Twin Lakes and ponds east of Picnic Area) is underlain by the less-resistant Inwood Marble. The lack of exposed carbonate is typical for our humid-temperate climate and therefore we must resort here, in the absence of drill-core data, to negative outcrop evidence (the valley) to prove the existence of the marble.

STOP 4 - Hutchinson River Group of North and South Twin Islands, near Orchard Beach, Pelham Bay Park. [UTM Coordinates: 602.4E / 4525.0N, Flushing quadrangle.]

Orchard Beach is one of Robert Moses' grand designs. Figure 40 compares the situations BM (before Moses) and AM (after Moses). The sand forming the crescentic beach was barged here from Rockaway Inlet. The bathhouse was built as elegantly as possible following the guidelines limiting the uses of the federal money that largely paid for the construction costs. Interested readers should consult Robert Caro's (1972) book for a description of the pre-Moses land use and of a field "brainstorming" session held here by Moses and his staff.

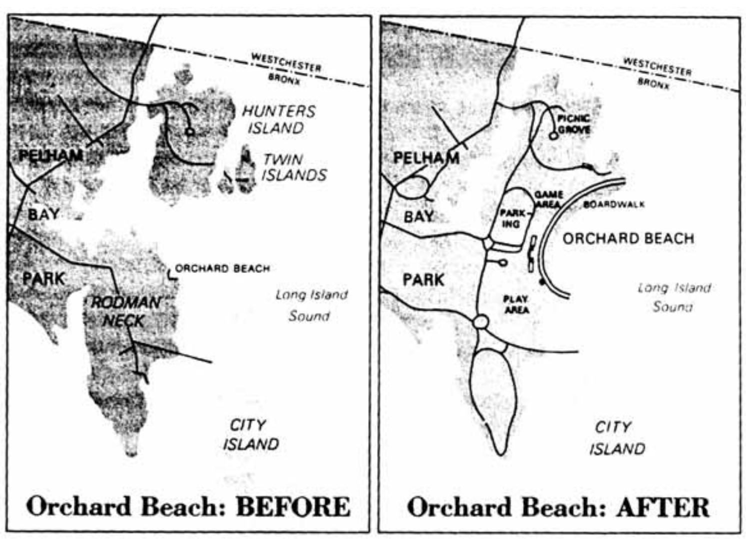


Figure 40 - Maps comparing Orchard Beach before and after Robert Moses did his number on this place in 1934. (Caro, 1974, p. 366.)

Rocks of the Hutchinson River Group are fully displayed on glaciated pavements (look for glacial features) on South and North Twin Islands to the north of Orchard Beach in Pelham Bay Park in the Bronx. Described by Leveson and Seyfert (1969), and Seyfert and Leveson (1968, 1969), these high- to medium- grade metamorphic rocks include gneiss, schist, and amphibolite all showing ample evidence for partial melting (fusion) forming mixed igneous- and metamorphic rocks known as migmatites. Of additional geologic interest, many pegmatites and veins of quartz occur. A geologic map of the region is reproduced in Figure 41.

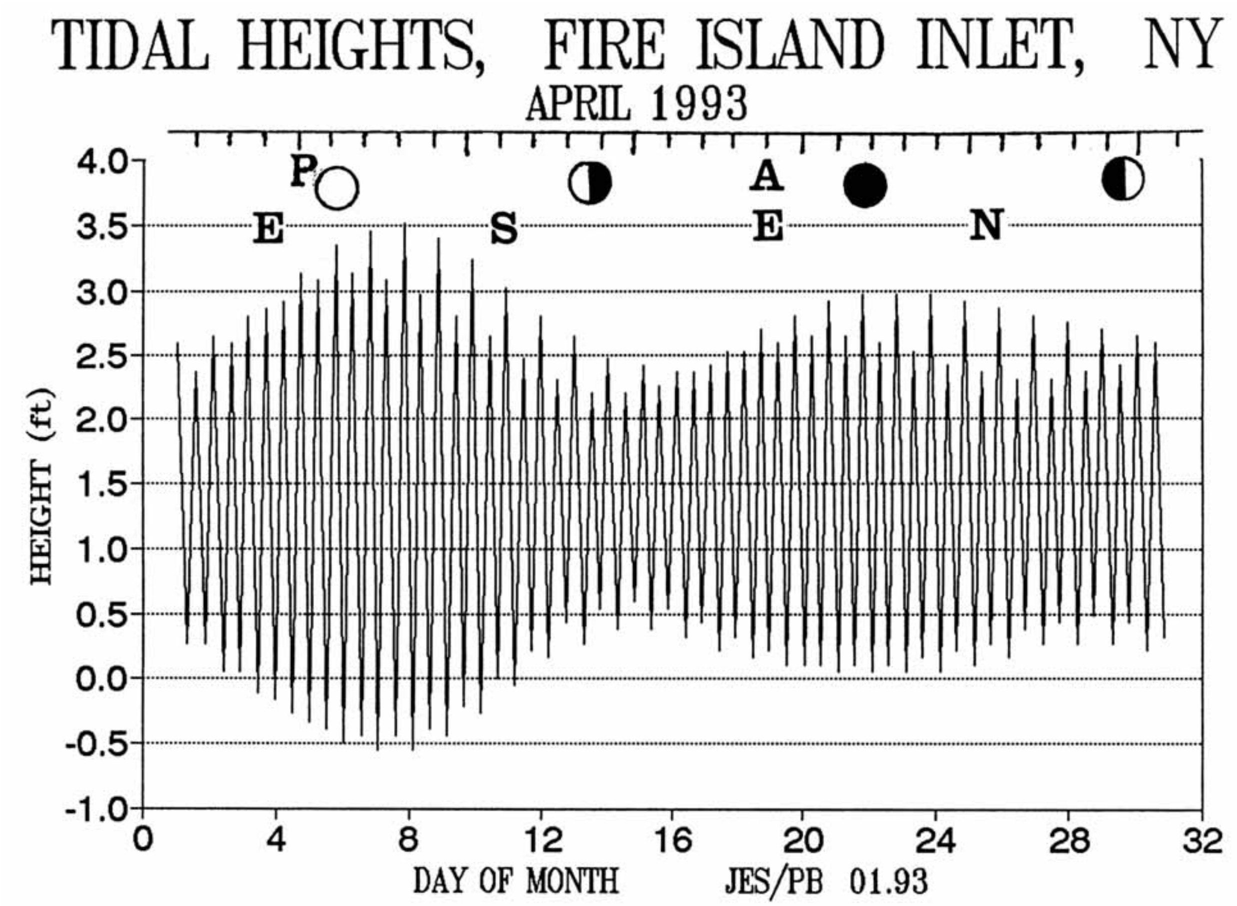


Figure 41 - Graphic display of predicted tidal heights at Fire Island Inlet including astronomic data for the Moon (shown by letters and symbols added by hand at top). A, apogee; P, perigee; S, maximum south declination; E, Moon over Earth's Equator; N, maximum north declicnation; open circle, Full Moon; darkened circle, New Moon; partially shaded circles, quarter phases. The maximum tidal amplitudes are associated with the near coincidence of perigee and the Full Moon at Passover. We do not know the time(s) when the scarp was cut in the till at Orchard Beach, but presume that it happened during one or more of these higher-than-normal spring tides. (J. E. Sanders and Peter J. R. Buttner, program in Quattro Pro based on 1993 NOAA tidal-height tables for Sandy Hook, NJ, which also include the astronomic data.)

The glacial features of South Twin Island are remarkable and take the form of glacial striae oriented N32°W, glacial polish, and roche-moutonnée structure (these features related to our Glacier II and/or III in Table 3). A boulder of ultramafic rock from the Cortlandt Comp[lex in Peekskill, New York can be found at the southern end of the South Twin Island exposure near Orchard Beach. This discovery mandates glacial advance from the NNE (Glacier IV in Table 3). In addition to these features, a thin red-brown till, consisting of rounded boulders set in a reddish-brown matrix of poorly sorted sand, silt, and clay, was extensively exposed as a byproduct of the erosion of a wave-cut scarp during the higher-than-normal spring tides accompanying the perigee-syzygy Full Moon of Passover (06 April 1993). We do not know the exact date of the erosion, but can bracket it as being between 01 April when CM visited here with his class and 17 April when the Hofstra beginning-geology class trip stopped here. Figure 42 shows the predicted lunar-tidal heights for Fire Island Inlet for April 1993 (based on Sandy Hook, NJ). Judging from the newly visible features in the bedrock, we estimate that scarp retreat during the storm ranged from 3 to 5 m.

Before the scarp was cut, a sod-covered slope extended down to the bedrock pavement. Beneath the red-brown till are clear NW-SE-trending glacial grooves on the bedrock surface. Here, then, is a second example of red-brown till resting on striated bedrock, as in the Queens localities described by Woodworth (1901). We have seen many examples of red-brown till and many other examples of striae oriented NW-SE, but this is the first example we have seen of these two features together.

At the extreme north end of South Twin Island, glacial erosion by two different glaciers has produced what we suggest is a double roche moutonnée. Here, the bedrock shows evidence of being been sculpted by ice that flowed initially from NNE to SSW (Glacier I) and subsequently from the NW to the SE (Glacier II and/or III). Similarly, just E of the jetty, a roche moutonnée with long axis oriented NNE-SSW has been cut across by grooves trending NW-SE.

For the purposes of mapping, Seyfert and Leveson (1968) have subdivided the metamorphosed bedrock into two major units: (1) a "Felsic Unit" and (2) a "Mafic Unit." The "Felsic Unit" includes 95% feldspathic gneiss and 5% sillimanite schist and underlies roughly 50% of North Twin Island and most of South Twin Island. Contacts between the felsic gneiss and -schist are gradational over distances of several mm to 10s of cm. The gneisses consist of quartz, plagioclase (An33), and biotite with minor garnet, muscovite, microcline, sillimanite, magnetite, and apatite. The schist unit, although of minor importance volumetrically, consists of plagioclase, quartz, biotite, sillimanite, microcline, and garnet with subordinate magnetite and muscovite. The calculated chemical composition of the "Felsic Unit" suggests that their protoliths were interlayered graywackes and shales although CM would not discount the possibility that they are largely of volcaniclastic origin.

The "Mafic Unit" includes amphibolite, diopside-epidote amphibolite, and plagioclase-biotite gneiss together with subordinate calcite- and plagioclase-rich layers. The amphibolites consist of medium-textured hornblende and plagioclase (An37) together with minor biotite, quartz, magnetite, and apatite. Garnet occurs locally as porphyroblasts in layers parallel to the hornblende-plagioclase foliation. On South Twin Island, the "Mafic Unit" is represented by amphibolite. By contrast on North Twin Island, the lithologies within the "Mafic Unit" include diopside-epidote amphibolite, plagioclase-biotite gneiss, and calcite- and plagioclase-rich layers. Contacts between the felsic- and mafic units are interpreted as original stratification (bedding) that has been strongly modified by folds and faults. The calculated chemical composition of the mafic unit suggests that the protoliths of the rocks within it are similar to olivine basalt. Therefore, these are interpreted as mafic lava flows, -sills, and/or -tuffs that were emplaced prior to metamorphism.

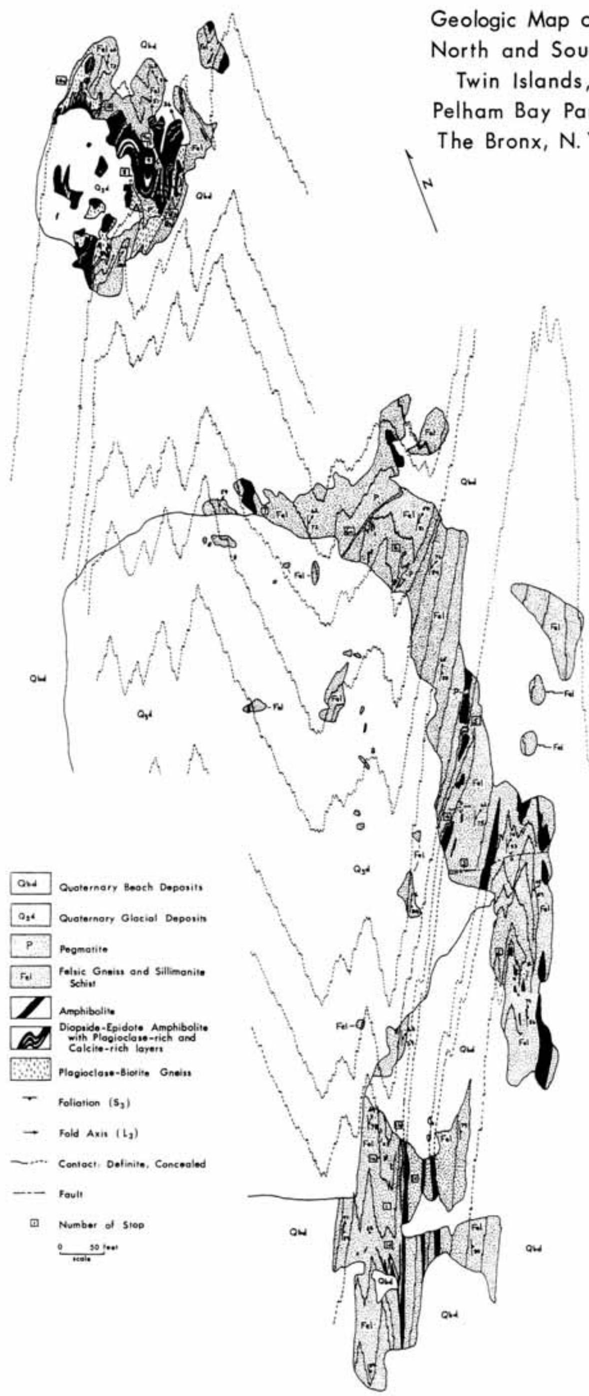


Figure 42 - Geologic map of North and South Twin Islands, Pelham Bay Park, The Bronx, New York. (Seyfert and Leveson, 1968.)

The Hutchinson River Group, which is correlative with the Hartland Formation of western Connecticut and southeastern New York, has been intensely deformed under high- to medium-grade metamorphic conditions. Mapping by C. Merguerian in 1981-83 showed the presence of at least four sets of superposed folds, two early stages of isoclinal folds (F_1 and F_2), followed by tight F_3 folds, that were gently warped by open F_4 folds. Based on similarities in structural style and -orientation compared to sequences mapped in New York City and western Connecticut on either side of Cameron's Line (Merguerian, 1985a, 1986b), the F_1 and F_2 fold phases are superposed and probably progressive. Significant shearing parallel to the axial surfaces of F_1 and F_2 folds has resulted in folds with sheared-out limbs and has created beautiful interference patterns. In addition, pegmatitic sweat-outs and bull-quartz veins injected parallel to S_2 are omnipresent. Together these create local migmatite. The enveloping surface of the composite $S_1 + S_2$ foliation trends roughly N54°W, 60°SW, a bit steeper but of identical strike to older fabrics in coeval rocks mapped in Manhattan by Merguerian (1983a).

The F_3 folds deform the penetrative $S_1 + S_2$ foliation and as a result are quite obvious in outcrop. The axial surfaces of the F_3 folds trend N30°E, and their axes dip 75°SE to vertical. The plunge of F_3 axes is dominantly S to SE at roughly 45° to 60° but variable as a result of differences in the original orientations of S_1 and S_2 foliations and younger, F_4 warps. The F_3 axes are obvious as mineral streaks on the S_2 foliation and as the long axis of boudins. On North Twin Island, the ductility contrasts with the surrounding felsic units has resulted in extensive boudinage of the mafic rocks; the final product of this deformation is sheared boudins.

The F_4 folds are larger than outcrop scale but show up as broad open warps of preexisting structures and a slip cleavage oriented roughly N85°E, 80°NW. Again, the similarities in structural sequence and orientation between these rocks and those mapped by CM in New York City are striking: all four fold phases can be recognized in both regions.

Thus, as described earlier, the rocks of the Hutchinson River Group are interpreted as the remnants of an ocean basin adjacent to the Early Paleozoic shelf edge of North America and fringed by a volcanic arc [Layer IIA(E) in Figure 14]. During our walk over the glaciated pavement, see if you can identify the various rock types, folds, faults, joints, deformational structures, and glacial features discussed above.

ACKNOWLEDGEMENTS

This field guide was prepared utilizing data gathered from outcrops, tunnels, and construction excavations in Manhattan together with some additional data from the Bronx provided by Dr. Charles A. Baskerville of the U. S. Geological Survey. CM thanks the late Dr. Leo M. Hall and Dr. Nicholas M. Ratcliffe helpful discussions in developing the lithostratigraphic views presented here on the schists of Manhattan. Additional lithologic information from CM's study of Hofstra University's Metropolitan New York Drill Core Collection helped verify geologic contacts mapped in the field.

We thank Dr. Patrick W. G. Brock of Queens College for his critical comments on the 1991 version of this guidebook. Many of the improvements in this version of the guide are the result of his careful reading and comments. CM and JES were assisted in the field by Diane Dennis, James Harris, Norma Iturrino, P. LaJuke, and Ernest P. Worrell and received abundant subsurface data from local municipal agencies and engineering firms too numerous to mention here individually.

We thank Robert Heinisch (Director - Security) and Jean Skully (Supervisor - Education Department) for their help in facilitating today's field-trip visit and allowing us to use vehicles on the Garden grounds. Remember - Don't step on the Roses!

We sincerely hope that you've enjoyed today's field trip!

TABLES

Table 01 - GEOLOGIC TIME CHART

(with selected major geologic events from southeastern New York and vicinity)

ERA Periods (Epochs)	**Years (Ma)**	**Selected Major Events**
CENOZOIC		
(Holocene)	0.1	Rising sea forms Hudson Estuary, Long Island Sound, and other bays. Barrier islands form and migrate.
(Pleistocene)	1.6	Melting of last glaciers forms large lakes. Drainage from Great Lakes overflows into Hudson Valley. Dam at The Narrows suddenly breached and flood waters erode Hudson shelf valley. Repeated continental glaciation with five? glaciers flowing from NW and NE form moraine ridges on Long Island.
(Pliocene)	6.2	Regional uplift, tilting and erosion of coastal-plain strata; sea level drops. Depression eroded that later becomes Long Island Sound.
(Miocene)	26.2	Fans spread E and SE from Appalachians and push back sea. Last widespread marine unit in coastal-plain strata.
MESOZOIC	66.5	
(Cretaceous)		
	96	Passive eastern margin of North American plate subsides and sediments (the coastal-plain strata) accumulate.
	131	(Passive-margin sequence II).
(Jurassic)		Baltimore Canyon Trough forms and fills with 8,000 feet of pre-Cretaceous sediments.
		Atlantic Ocean starts to open. Newark basins deformed, arched, eroded.
	190	Continued filling of subsiding Newark basins and mafic igneous
(Triassic)		activity both extrusive and intrusive. Newark basins form and fill with non-marine sediments.

PALEOZOIC	245	
(Permian)		Pre-Newark erosion surface formed.
	260	**Appalachian orogeny.** (Terminal stage.) Folding, overthrusting, and metamorphism of Rhode Island coal basins; granites intruded.
(Carboniferous)		Faulting, folding, and metamorphism in New York City area. Southeastern New York undergoes continued uplift and erosion.
(Devonian)	365	**Acadian orogeny.** Deep burial of sedimentary strata. Faulting, folding, and metamorphism in New York City area. Peekskill Granite and Acadian granites intruded.
(Silurian)		
	440	**Taconic orogeny.** Intense deformation and metamorphism.
	450	Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line). Arc-continent collision.
(Ordovician)		Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata. Ultramafic rocks (oceanic lithosphere) sliced off and transported above deposits of continental shelf.
(Cambrian)		Shallow-water clastics and carbonates accumulate in west of basin (= Sauk Sequence; protoliths of the Lowerre Quartzite, Inwood Marble, part of Manhattan Schist Fm.). Deep-water terrigenous silts form to east. (= Taconic Sequence; protoliths of Hartland Formation, parts of Manhattan Schist Fm.). (Passive-margin sequence I).
PROTEROZOIC		
	570	Period of uplift and erosion followed by subsidence of margin.
(Z)	600	Rifting with rift sediments, volcanism, and intrusive activity. (Ned Mountain, Pound Ridge, and Yonkers gneiss protoliths).
(Y)	1100	**Grenville orogeny.** Sediments and volcanics deposited, compressive deformation, intrusive activity, and granulite facies metamorphism. (Fordham Gneiss, Hudson Highlands and related rocks).
ARCHEOZOIC		
	2600	No record in New York.
	4600	Solar system (including Earth) forms.

Table 02 - Generalized Descriptions of Major Geologic "Layers", SE New York State and Vicinity

This geologic table is a tangible result of the On-The-Rocks Field Trip Program conducted by Drs. John E. Sanders and Charles Merguerian between 1988 and 1998. In Stenoan and Huttonian delight, we here present the seven layer cake model that has proved so effective in simplifying the complex geology of the region. Under continual scrutiny and improvement, we provide this updated web-based information as a public service to all students and educators of geology. We encourage any comments, additions, or corrections. References cited can be sought by following this link.

LAYER VII - QUATERNARY SEDIMENTS

A blanket of irregular thickness [up to 50 m or more] overlying and more or less covering all older bedrock units. Includes four or five tills of several ages each of which was deposited by a continental glacier that flowed across the region from one of two contrasting directions: (1) from N10°E to S10°W (direction from Labrador center and down the Hudson Valley), or (2) from N20°W to S20°E (direction from Keewatin center in Hudson's Bay region of Canada and across the Hudson Valley). The inferred relationship of the five tills is as follows from youngest [I] to oldest [V]. [I] - Yellow-brown to gray till from NNE to SSW, [II] - red-brown till from NW to SE, [III] - red-brown till from NW to SE, and [IV] - yellow-brown to gray till from NNE to SSW, and [V] - red-brown till from NW to SE containing decayed stones (Sanders and Merguerian, 1991a,b, 1992, 1994a, b; Sanders, Merguerian, and Mills, 1993; Sanders and others, 1997; Merguerian and Sanders, 1996). Quaternary sediments consist chiefly of till and outwash. On Long Island, outwash (sand and gravel) and glacial lake sediment predominates and till is minor and local. By contrast, on Staten Island, tills and interstratified lake sediments predominate and sandy outwash appears only locally, near Great Kills beach.

[Pliocene episode of extensive and rapid epeirogenic uplift of New England and deep erosion of major river valleys, including the excavation of the prominent inner lowland alongside the coastal-plain cuesta; a part of the modern landscape in New Jersey, but submerged in part to form Long Island Sound].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER VI - COASTAL-PLAIN STRATA (L. Cretaceous to U. Miocene; products of Passive Continental Margin II - Atlantic).

Marine- and nonmarine sands and clays, present beneath the Quaternary sediments on Long Island (but exposed locally in NW Long Island and on SW Staten Island) and forming a wide outcrop belt in NE New Jersey. These strata underlie the submerged continental terrace. The basal unit (L. Cretaceous from Maryland southward, but U. Cretaceous in vicinity of New York City) overlaps deformed- and eroded Newark strata and older formations. Also includes thick (2000 m) L. Cretaceous sands and shales filling the offshore Baltimore Canyon Trough. At the top are Miocene marine- and coastal units that are coarser than lower strata and in many localities SW of New Jersey, overstep farther inland than older coastal-plain strata. Capping unit is a thin (<50 m) sheet of yellow gravel (U. Miocene or L. Pliocene?) that was prograded as SE-directed fans from the Appalachians pushed back the sea. Eroded Newark debris is present in L. Cretaceous sands, but in U. Cretaceous through Miocene units, Newark-age redbed debris is conspicuously absent. This relationship is considered to be proof that the coastal-plain formations previously buried the Newark basins so that no Newark-age debris was available until after the Pliocene period of great regional uplift and erosion. The presence of resistant heavy minerals derived from the Proterozoic highlands part of the Appalachians within all coastal-plain sands indicates that the coastal-plain strata did not cover the central highlands of the Appalachians.

[Mid-Jurassic to Late Jurassic episode of regional arching of Newark basin-filling strata and end of sediment accumulation in Newark basin; multiple episodes of deformation including oroclinal "bending" of entire Appalachian chain in NE Pennsylvania (Carey, 1955), and one or more episodes of intrusion of mafic igneous rocks, of folding, of normal faulting, and of strike-slip faulting (Merguerian and Sanders, 1994b). Great uplift and erosion, ending with formation of Fall-Zone planation surface].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER V - NEWARK BASIN-FILLING STRATA (Upper Triassic and Lower Jurassic)

Newark-age strata unconformably overlie folded- and metamorphosed Paleozoic strata of Layer II and some of the Proterozoic formations of Layer I; are in fault contact with other Proterozoic formations of the Highlands complex. Cobbles and boulders in basin-marginal rudites near Ramapo Fault include mostly rocks from Layers III, IIB, and IIA(W), which formerly blanketed the Proterozoic now at the surface on the much-elevated Ramapo Mountains block. The thick (possibly 8 or 9 km) strata filling the Newark basin are nonmarine.

In addition to the basin-marginal rudites, the sediments include fluvial- and varied deposits of large lakes whose levels shifted cyclically in response to climate cycles evidently related to astronomic forcing. A notable lake deposit includes the Lockatong Formation, with its analcime-rich black argillites, which attains a maximum thickness of about 450 m in the Delaware River valley area. Interbedded with the Jurassic part of the Newark strata are three extrusive complexes, each 100 to 300 m thick, whose resistant tilted edges now underlie the curvilinear ridges of the Watchung Mountains in north-central New Jersey. Boulders of vesicular basalt in basin-marginal rudites prove that locally, the lava flows extended northwestward across one or more of the basin-marginal faults and onto a block that was later elevated and eroded. The thick (ca. 300 m) Palisades intrusive sheet is concordant in its central parts, where it intrudes the Lockatong at a level about 400 m above the base of the Newark strata. To the NE and SW, however, the sheet is discordant and cuts higher strata (Merguerian and Sanders, 1995a). Contact relationships and the discovery of clastic dikes at the base of the Palisades in Fort Lee, New Jersey, suggest that the mafic magma responsible for the Palisades was originally intruded at relatively shallow depths (roughly 3 to 4 km) according to Merguerian and Sanders (1995b).

Xenoliths and screens of both Stockton Arkose and Lockatong Argillite are present near the base of the sill. Locally, marginal zones of some xenoliths were melted to form granitic rocks (examples: the trondhjemite formed from the Lockatong Argillite at the Graniteville quarry, Staten Island, described by Benimoff and Sclar, 1984; and a "re-composed" augite granite associated with pieces of Stockton Arkose at Weehawken and Jersey City, described by J. V. Lewis, 1908, p. 135-137).

[**Appalachian terminal orogeny**; large-scale overthrusts of strata over strata (as in the bedding thrusts of the "Little Mountains east of the Catskills" and in the strata underlying the NW side of the Appalachian Great Valley), of basement over strata (in the outliers NW of the Hudson Highlands, and possibly also in many parts of the Highlands themselves), and presumably also of basement over basement (localities not yet identified). High-grade metamorphism of Coal Measures and intrusion of granites in Rhode Island dated at 270 Ma. Extensive uplift and erosion, ending with the formation of the pre-Newark peneplain].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

Mostly nonmarine coarse strata, about 6 km thick, including thick coals altered to anthracite grade, now preserved only in tight synclines in the Anthracite district, near Scranton, NE Pennsylvania; inferred to have formerly extended NE far enough to have buried the Catskills and vicinity in eastern New York State (Friedman and Sanders, 1982, 1983).

[**Acadian orogeny**; great thermal activity and folding, including metamorphism on a regional scale, ductile deformation, and intrusion of granites; dated at ~360 Ma].

LAYER III - MOSTLY MARINE STRATA OF APPALACHIAN BASIN AND CATSKILLS (Carbonates and terrigenous strata of Devonian and Silurian age)

(Western Facies)	**(Eastern Facies)**
Catskill Plateau, Delaware Valley monocline, and "Little Mountains" NW of Hudson-Great Valley lowland.	SE of Hudson-Great Valley lowland in Schunnemunk-Bellvale graben.
Kaaterskill redbeds and cgls.	Schunnemunk Cgl.
Ashokan Flags (large cross strata)	Bellvale Fm., upper unit
Mount Marion Fm. (graded layers,	Bellvale Fm., lower unit

marine)	(graded layers, marine)
Bakoven Black Shale	Cornwall Black Shale
Onondaga Limestone	
Schoharie buff siltstone	Pine Hill Formation
Esopus Formation	Esopus Formation
Glenerie Chert	
Connelly Conglomerate	Connelly Conglomerate
Central Valley Sandstone	
Carbonates of Helderberg Group	Carbonates of Helderberg Group
Manlius Limestone	
Rondout Formation	Rondout Formation
Decker Formation	
Binnewater Sandstone	Poxono Island Formation
High Falls Shale	Longwood Red Shale
Shawangunk Formation	Green Pond Conglomerate

[**Taconic orogeny**; 480 Ma deep-seated folding, dynamothermal metamorphism and mafic- to ultramafic (alkalic) igneous intrusive activity (dated in the range of 470 to 430 Ma) across suture zone (Cameron's Line-St. Nicholas thrust zones). Underthrusting of shallow-water western carbonates of Sauk Sequence below supracrustal deep-water eastern Taconic strata and imbrication of former Sauk-Tippecanoe margin. Long-distance transport of strata over strata has been demonstrated; less certain locally is proof of basement thrust over strata and of basement shifted over basement. In Newfoundland, a full ophiolite sequence, 10 km thick, has been thrust over shelf-type sedimentary strata].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER II - CAMBRO-ORDOVICIAN CONTINENTAL-MARGIN COVER (Products of Passive Continental Margin I - Iapetus). Subdivided into two sub layers, IIB and IIA. Layer IIA is further subdivided into western- and eastern facies.

LAYER IIB - TIPPECANOE SEQUENCE - Middle Ordovician flysch with basal limestone (Balmville, Jacksonburg limestones).

Not metamorphosed / Metamorphosed
Martinsburg Fm. / Manhattan Schist (Om - lower unit).
Normanskill Fm. / Annsville Phyllite

Subaerial exposure; karst features form on Sauk (Layer IIA[W]) platform.

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER IIA[W] - SAUK SEQUENCE

Western shallow-water
platform (L. Cambrian-
M. Ordovician)

Copake Limestone
Rochdale Limestone
Halcyon Lake Fm.
Briarcliff Dolostone
Pine Plains Fm.
Stissing Dolostone
Poughquag Quartzite
Lowerre Quartzite [Base not known]

LAYER IIA[E] - TACONIC SEQUENCE

Eastern deep-water zone
(L. Cambrian-M. Ordovician)

Stockbridge
or Inwood Marbles

(Є-Oh) Hartland Fm.
(Є-Om) Manhattan Fm.
(in part).

[**Pre-Iapetus Rifting Event**; extensional tectonics, volcanism, rift-facies sedimentation, and plutonic igneous activity precedes development of Iapetus [Layer II = passive continental margin I] ocean basin. Extensional interval yields protoliths of Pound Ridge Gneiss, Yonkers granitoid gneisses, and the Ned Mountain Formation (Brock, 1989, 1993). Followed by a period of uplift and erosion. In New Jersey, metamorphosed rift facies rocks are mapped as the Chestnut Hill Formation of A. A. Drake, Jr. (1984)].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER I - PROTEROZOIC BASEMENT ROCKS

Many individual lithologic units including Proterozoic Z and Y ortho- and paragneiss, granitoid rocks, metavolcanic- and metasedimentary rocks identified, but only a few attempts have been made to decipher the stratigraphic relationships; hence, the three-dimensional structural relationships remain obscure.

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

[**Grenville orogeny**; deformation, metamorphism, and plutonism dated about 1,100 Ma. After the orogeny, an extensive period of uplift and erosion begins. Grenville-aged (Proterozoic Y) basement rocks include the Fordham Gneiss of Westchester County, the Bronx, and the subsurface of western Long Island (Queens and Brooklyn Sections, NYC Water Tunnel #3), the Hudson Highland-Reading Prong terrane, the Franklin Marble Belt and associated rocks, and the New Milford, Housatonic, Berkshire, and Green Mountain Massifs.]

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

In New Jersey and Pennsylvania rocks older than the Franklin Marble Belt and associated rocks include the Losee Metamorphic Suite. Unconformably beneath the Losee, in Pennsylvania, Proterozoic X rocks of the Hexenkopf Complex crop out.

Table 03 – Proposed new classification of the Pleistocene deposits of New York City and vicinity (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).
	IIIA	NW to SE	Ronkonkoma Terminal Moraine and associated outwash (Merrick Fm. in Jones Beach subsurface).
Illinoian(?)	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 (?) Mannetto Gravel fills subsurface valleys.

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