DUKE GEOLOGICAL LABORATORY

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TRIPS ON THE ROCKS

Guide 03: Geology of Manhattan and the Bronx, New York

Trip 03: 20 November 1988; Trip 16: 21 April 1991

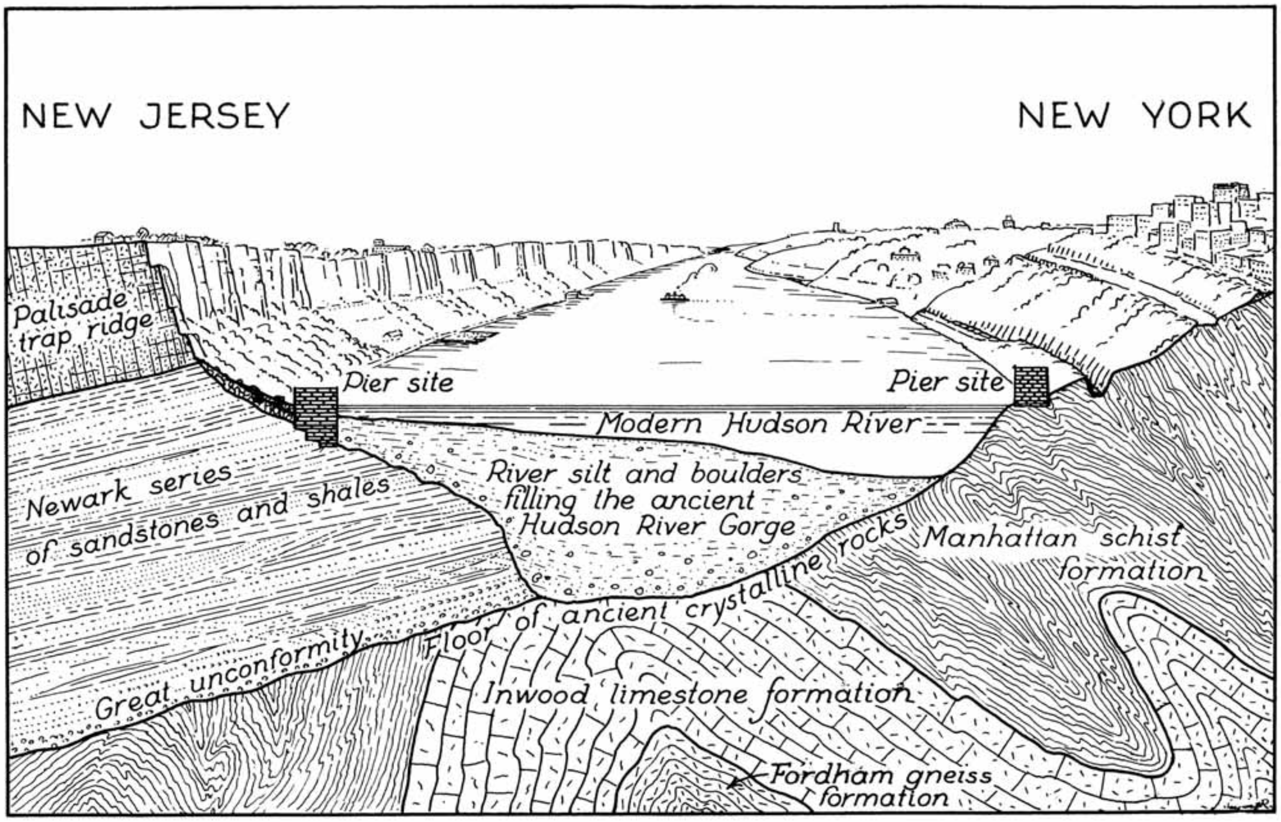

Figure 1 – Interpretive geological section across the Hudson River in the vicinity of the George Washington Bridge. (From Berkey, 1948.)

Field Trip Notes by:

Charles Merguerian and John E. Sanders

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INTRODUCTION

Long the center of commerce and culture in the United States, Manhattan is an island around which many geologic units and structural features coalesce. Manhattan's underlying lithology and durable crystalline structure has enabled the construction of enormous towering skyscrapers, rooted into the glacially sculpted crystalline rock (Figure 1, cover). First studied by naturalists in the 1700's, and by geologists in the 1800's and 1900's, the bedrock geology of the New York City area was mapped in systematic detail beginning in the mid- to late 1800's by W. W. Mather and F. J. H. Merrill, respectively. Merrill was the senior author of the United States Geological Survey New York City Folio (#83) published in 1902. In this work and in previous papers (1890, 1898a, b, c), Merrill outlined the basic stratigraphic- and structural framework that successive geologists would test, promote, and amplify upon.

Our field trip focuses on two aspects of the geology of New York City based on our individual and joint research efforts. For the past ten years, CM has concentrated his efforts on the Paleozoic bedrock geology of New York and the identification of 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 terranes and to explore the field evidence to support CM's new, more-complicated view of the stratigraphy and structure of Manhattan and 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 history and geomorphology of the New York City. Thus, our trip will concentrate on Layers II and VII as outlined in Tables 1 and 2.

Today's trip, a rerun of a similar trip conducted in the pouring rain in November of 1988, consists of seven easily accessible localities ("stops") in Manhattan and the Bronx (Figure 2). All of the outcrop areas are located in public parks or roadcuts that may be reached by car, bus, or subway. They have been chosen to best identify outcrops critical to our new interpretations of the bedrock and glacial geology of New York City. The seven localities are plotted on segments of the Central Park 7-1/2 minute quadrangle (Figure 3). A geological timescale is reproduced in Table 1 to help the reader follow the time-stratigraphic descriptions below.

Utilizing geologic maps and cross sections, the following section describes the geologic background of our trip route and presents, in historical perspective, the original geological concepts on the bedrock geology of New York City. The history of glacial investigations is outlined under the heading Layer VII. Thus, our combined research efforts allows us to present modern plate-tectonic interpretations on the Paleozoic bedrock geology of New York City and to identify the southernmost traces of the Taconic allochthon and to present evidence for superposed Pleistocene glaciation of the region.

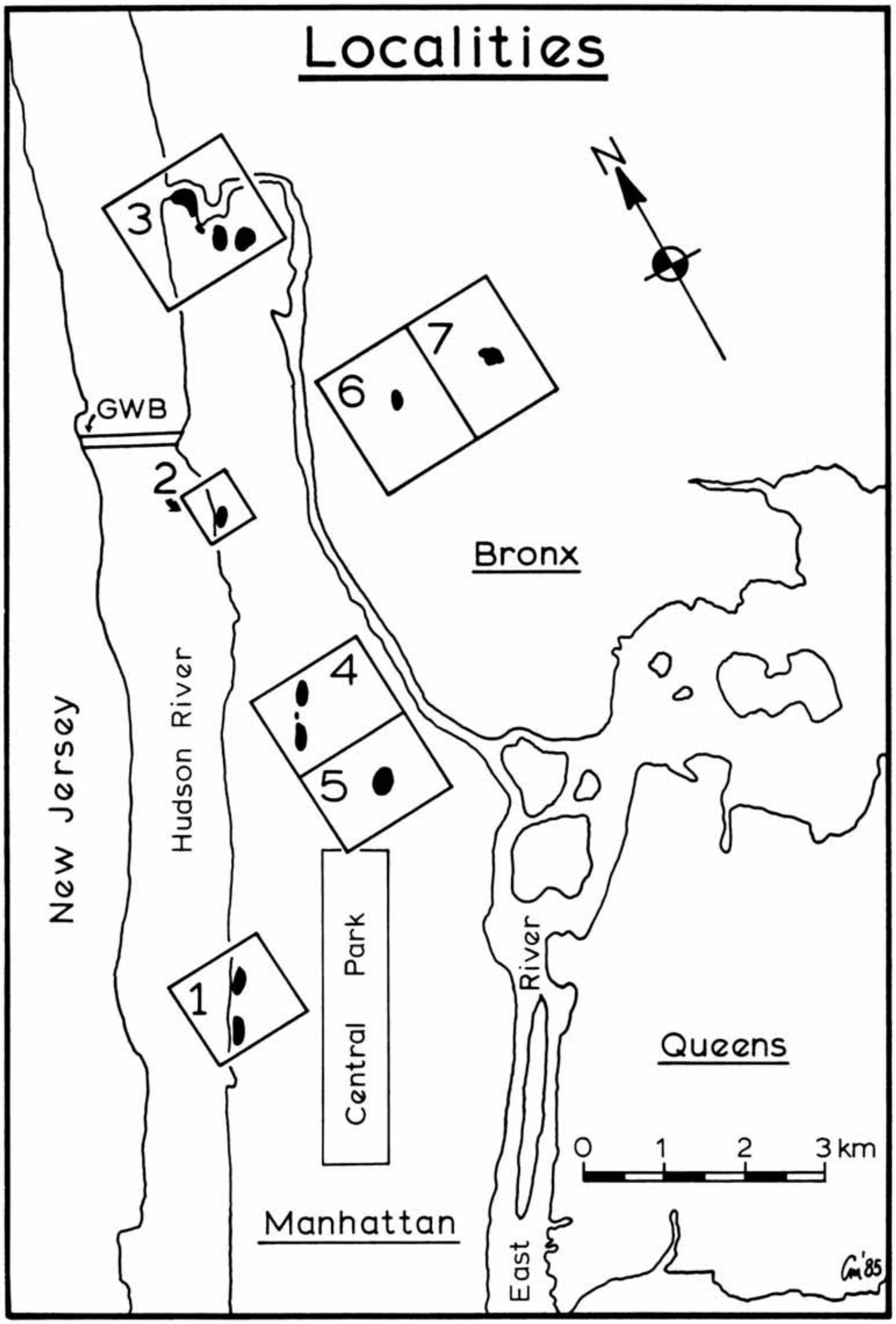


Figure 2 - Locality map of northern Manhattan and adjacent Bronx showing stop-number maps (numbered rectangles), each of which is enlarged on Figure 3.

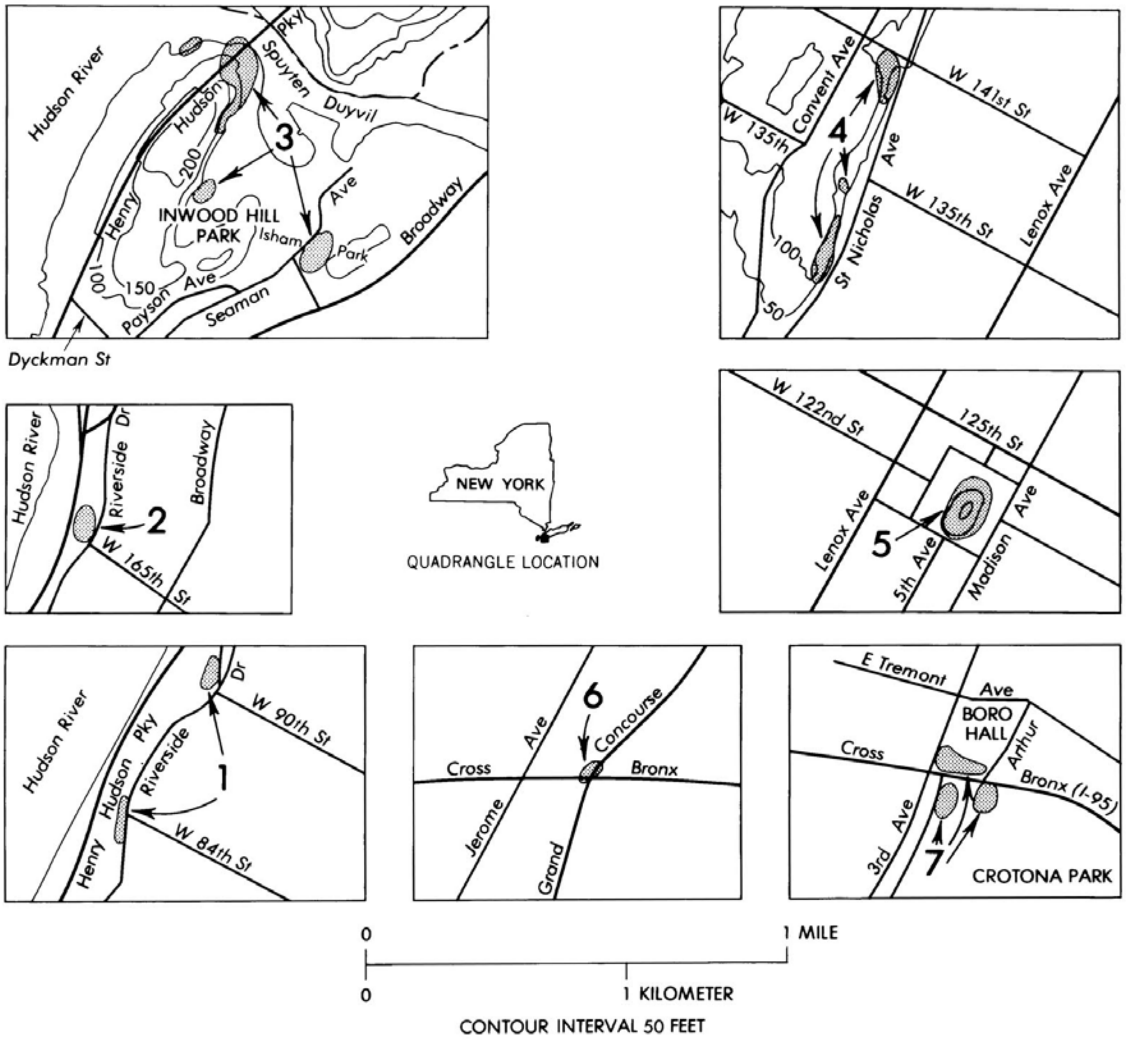


Figure 3 - Outcrop locations for trip stops (shaded areas) shown on segments of Central Park 7.5-minute topogographic quadrangle map of U. S. Geological Survey.

GEOLOGIC BACKGROUND

New York City is situated at the extreme southerly tip of the Manhattan Prong (Figure 4), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks that widen northeastward into the crystalline terranes of New England. Southward from New York City, the rocks of the Manhattan Prong plunge unconformably beneath Cretaceous sedimentary rocks and overlying Pleistocene (glacial) sediments. Figure 5, from Berkey (1933) illustrates the "pre-plate tectonics" surface distribution of bedrock- and surficial units in the New York City area based largely on formational contacts published in Merrill et al's Folio 83 (1902). The circled localities shown on Figure 5 are not those described on today's fieldtrip but are described by Berkey in his 1933 fieldtrip report for the International Geological Congress held in New York City.

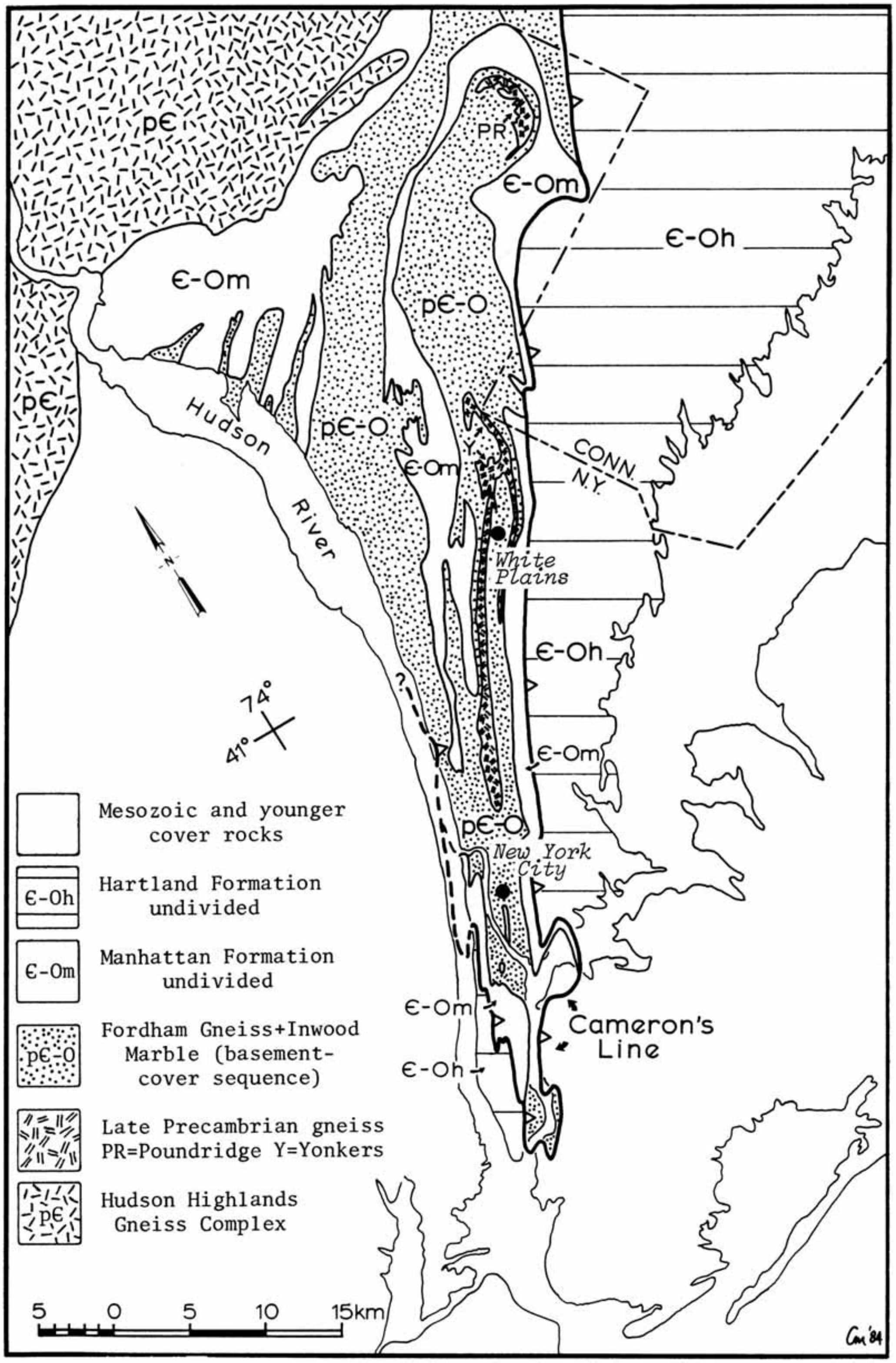


Figure 4 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted (Mose and Merguerian, 1985). See figure 39 for section A-A'.

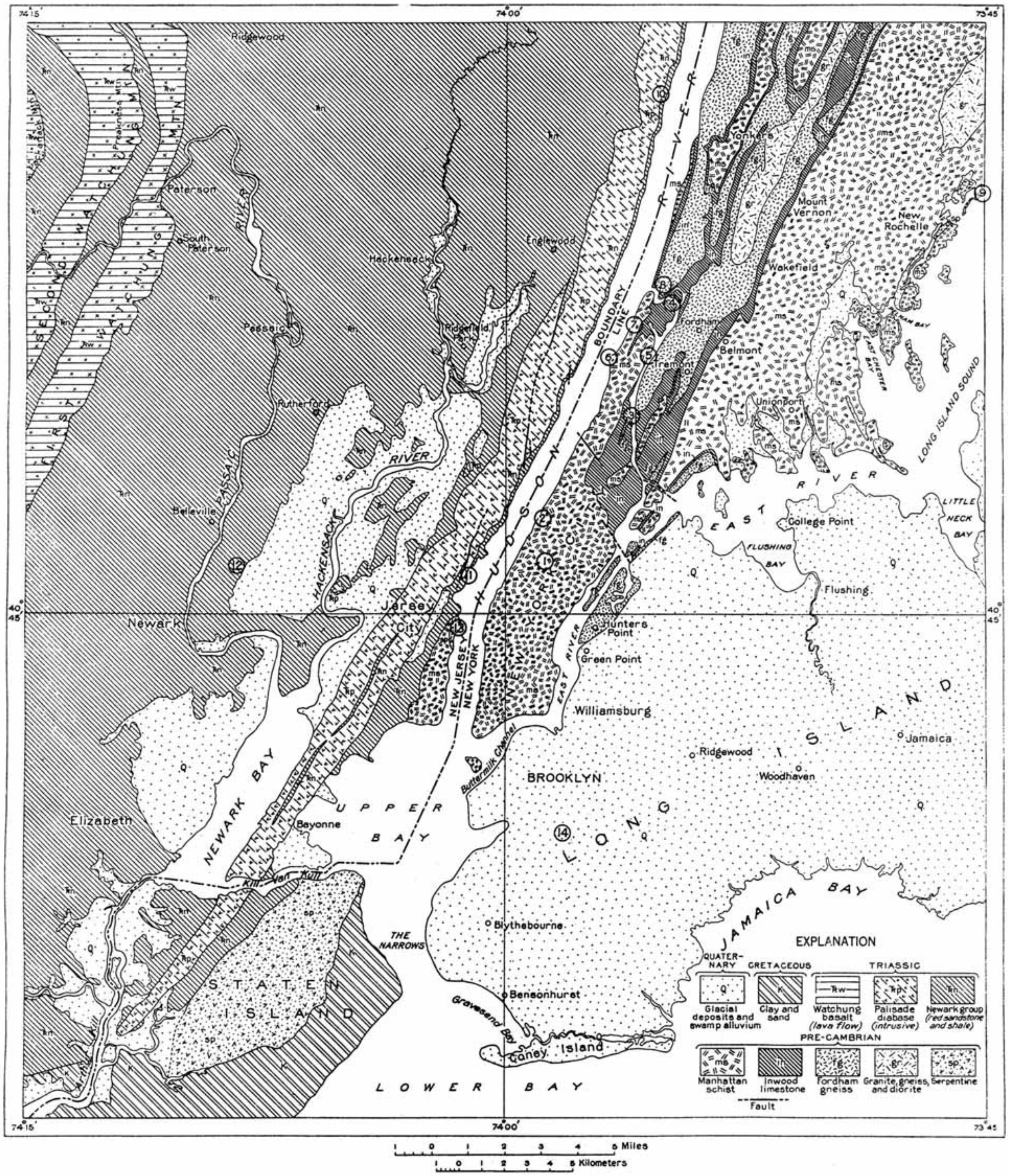


Figure 5 - Geologic map of New York City and adjacent part of New Jersey, generalized from U. S. Geological Survey Folio No. 83 (New York City, 1902). Circled numbers refer to trip stops on excursions offered by the 16th International Geological Congress, which met in the USA in 1933. (Berkey, 1933.)

A north-south generalized cross section from New Rochelle in Westchester southward across Queens to the Atlantic Ocean (Figure 6) shows the subsurface structure of the Cretaceous and younger deposits that crop out on Long Island and Staten Island. Note that the Cretaceous strata dip toward the south and are unconformably beveled by the essentially horizontal glacial deposits of Quaternary age. In the subsurface of Long Island, the Magothy Formation (Unit Km in Figure 6) is an important aquifer from which extensive supplies of drinking water are pumped on Long Island.

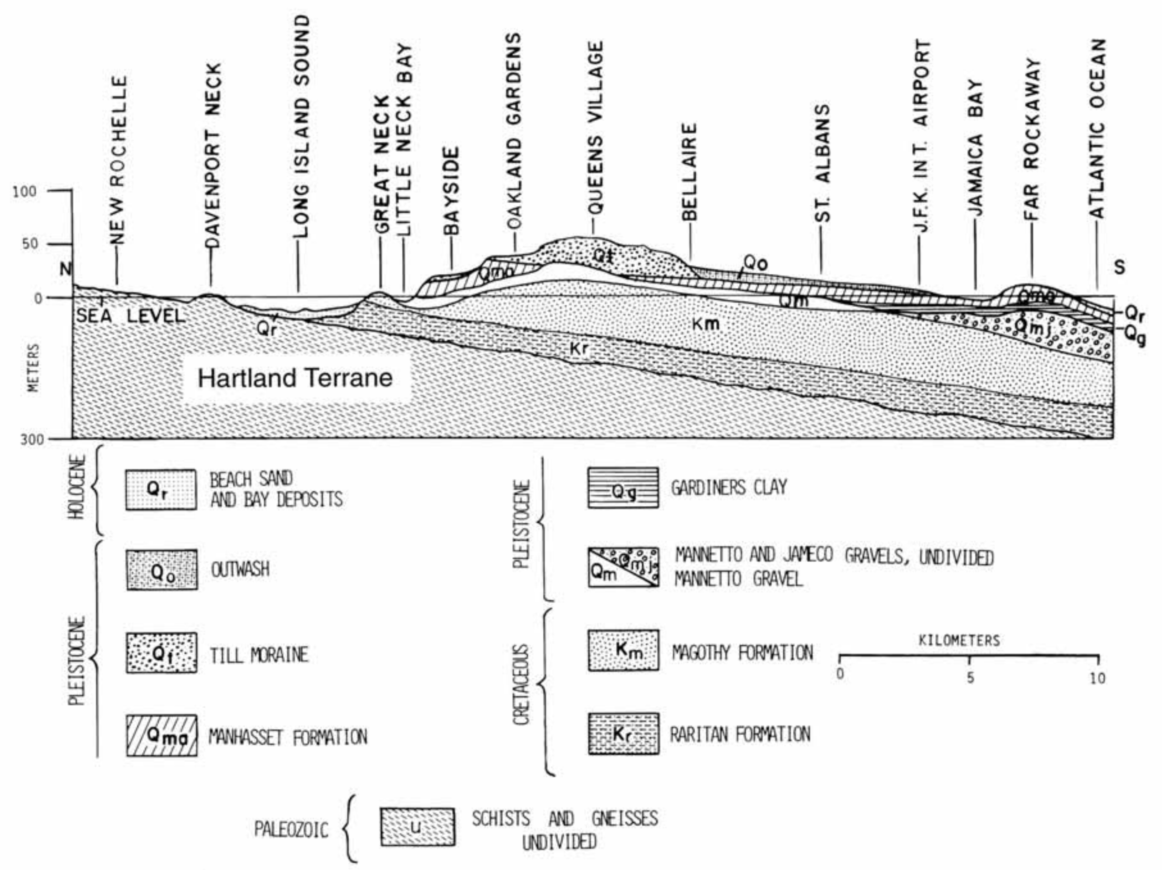


Figure 6 - North-south profile section from New Rochelle, Westchester County, New York, across Long Island Sound and Long Island, showing generalized relationships among Cretaceous coastal-plain strata and covering of Pleistocene deposits. (Baskerville, 1982, based on earlier publications of U. S. Geological Survey.)

West of Manhattan Island, in New Jersey, a series of gently west-dipping sedimentary rocks of Late Triassic to Early Jurassic ages rests depositionally on the deeply eroded bedrock of Manhattan. As indicated in the west-east cross section from New Jersey to the Bronx (Figure 7), the westward tilted Mesozoic sedimentary rocks of the Newark Basin have been intruded by the Palisades intrusive sheet whose tilted and eroded edge forms prominent cliffs along the west margin of the Hudson channel. Together, the Mesozoic sequence overlies a pre-Triassic planation surface (surface of unconformity) that projects out of the Hudson River valley 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 simplistic, folded layer-cake structural model of the bedrock sequence.

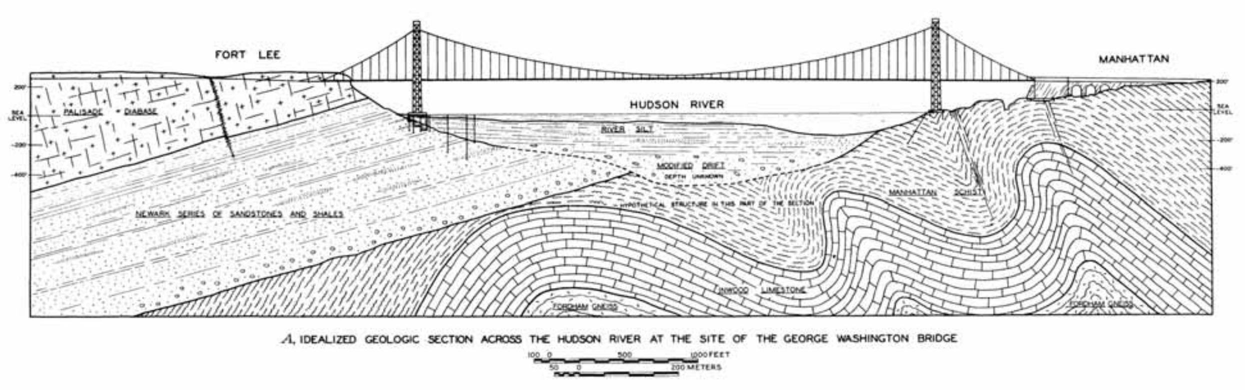


Figure 7 - East-west profile-section across Hudson River at George Washington bridge, showing geologic relationships determined from study of exposed rocks and of borings made for the footing of the western tower of the bridge. (Berkey, 1933, pl. 8, fig. A.)

BEDROCK UNITS

Under this section we describe the history of bedrock investigations, details of the geology of Layers I, IIA, and IIB, the specifics of the metamorphic geology of New York City, and brief descriptions of younger Layers III, and V.

History of bedrock geologic investigations

The earliest written record on the geology of New York City comes from a report 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 are limited to the mineralogy, lithology, and topography of Manhattan and the New York City area (including Long Island) but his report did not include a geologic map. S. L. Mitchill (1798) wrote "A sketch of the mineralogical 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.

Maclure's (1817) water-colored regional map of the eastern United States (Figure 8) adopted the rock stratigraphic nomenclature of the Werner and the Neptunists (not a punk rock band but an early "school of geology" that envisioned an oceanic origin for all rocks). Maclure, in fact, considered all of the metamorphic rocks of New England (and the entire Appalachian belt, for that matter) to represent 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, our Layer IIA(W) in Table 2, is known as the Cambrian to Ordovician Inwood Marble and correlatives.

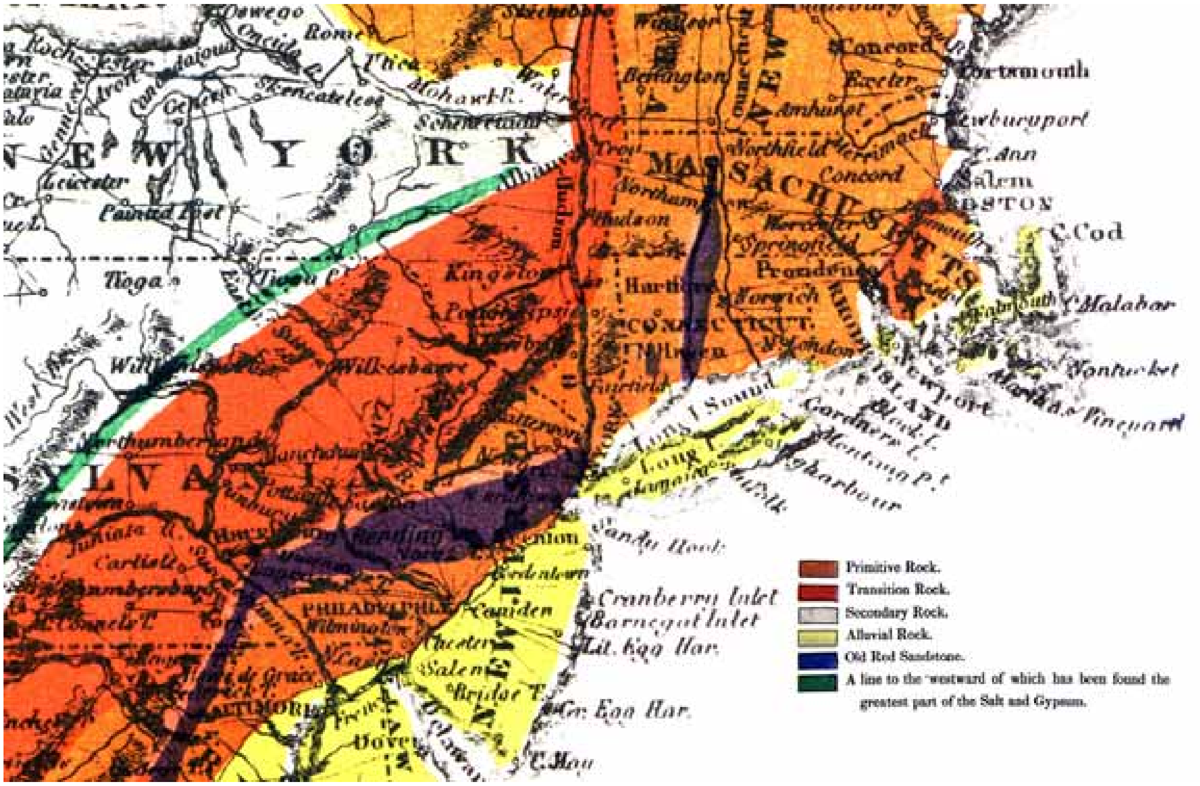


Figure 8 - Northeastern part of William Maclure's geologic map of the United States (1817).

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]), together provide a thorough account of the glacial- and bedrock geology of Manhattan in the format of a street-by-street diary before many buildings were constructed. Gale's diary, in Mather (1843, p. 581-604), provided the first detailed report on the orientation of structure and lithology of Manhattan Island (without a map, unfortunately) including boring data and construction costs. Gale's (1839) observations (previously conducted in 1828-1829) on glacial features are outlined in a later section.

The first geologic map of the New York City area was published in Mather's treatise on the Geology of the First District of New York in 1843. Drawing heavily from Gale's investigations, Mather's map of Manhattan (Figure 9) shows the distribution of Primary granite, gneiss, "limestone of New York County", serpentine (on Staten Island), and alluvial sand and marshland. His detailed map of Manhattan (Figure 10) shows the topography and limited orientation data on the bedrock strata. Mather's Plate 3 included two geologic cross sections (reproduced in Figure 11) that illustrated the structure of New York City in sections parallel and perpendicular to strike. The sections are not very detailed but show depth to bedrock at numerous places and indicate that the substrate of New York City consists of granite and gneiss.

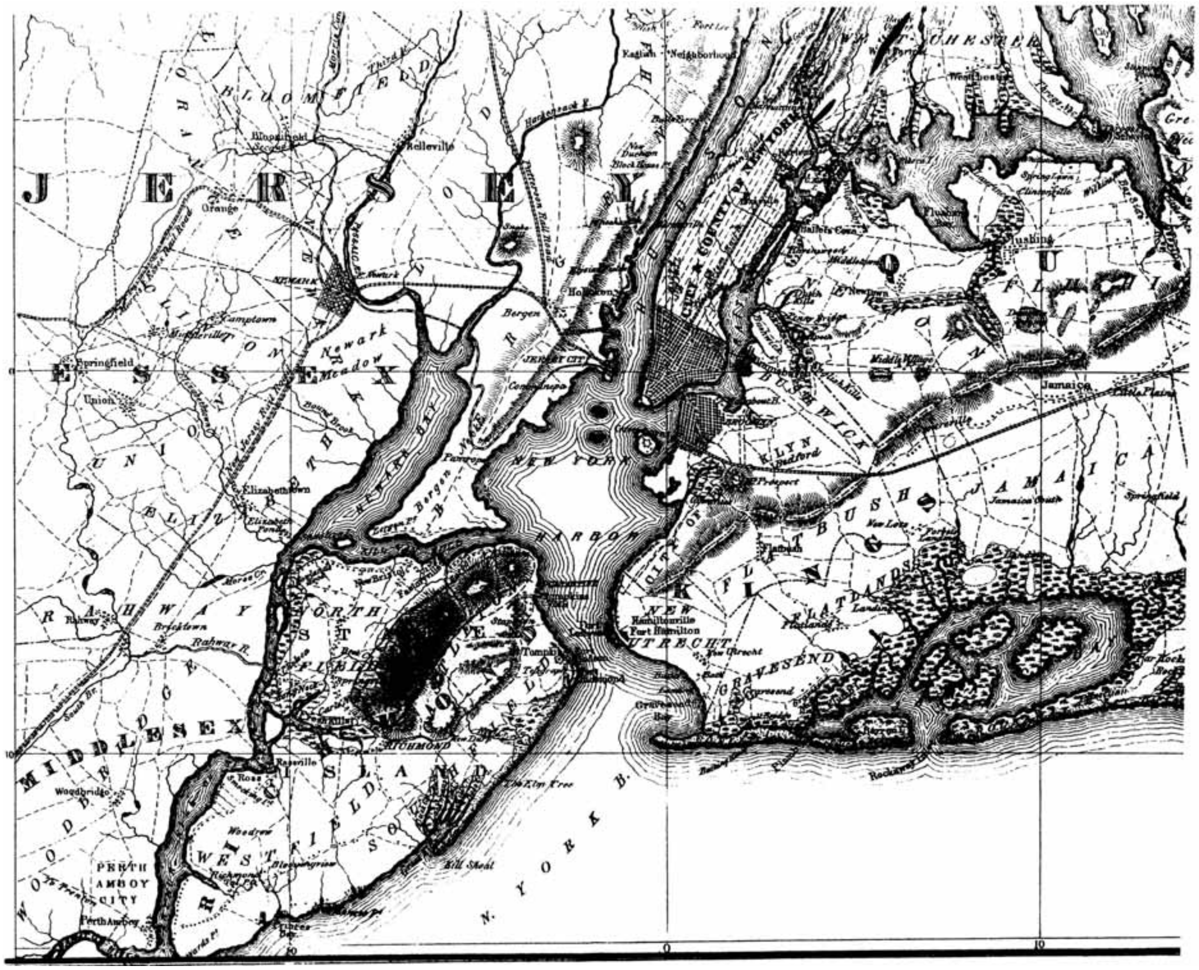


Figure 9 - Portion of Mather's (1843) map of New York City and vicinity that accompanied his report on the First Geological District of the State of New York. Notice that the built-up area of Manhattan is confined to the southwestern part of the island.

A north-south geologic section of Manhattan or New York Island accompanied a 114-page report by Issachar Cozzens in 1848. Reproduced in Figure 12, Cozzens' section shows a continuous granite substrate overlain by gneiss, limestone, amphibolite, serpentine, and glacial "diluvium". For an excellent review of American geology from the late eighteenth to late nineteenth centuries, the interested reader is urged to consult George P. Merrill's book on the history of geology (1924).

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 J. 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; reproduced here as Figure 13).

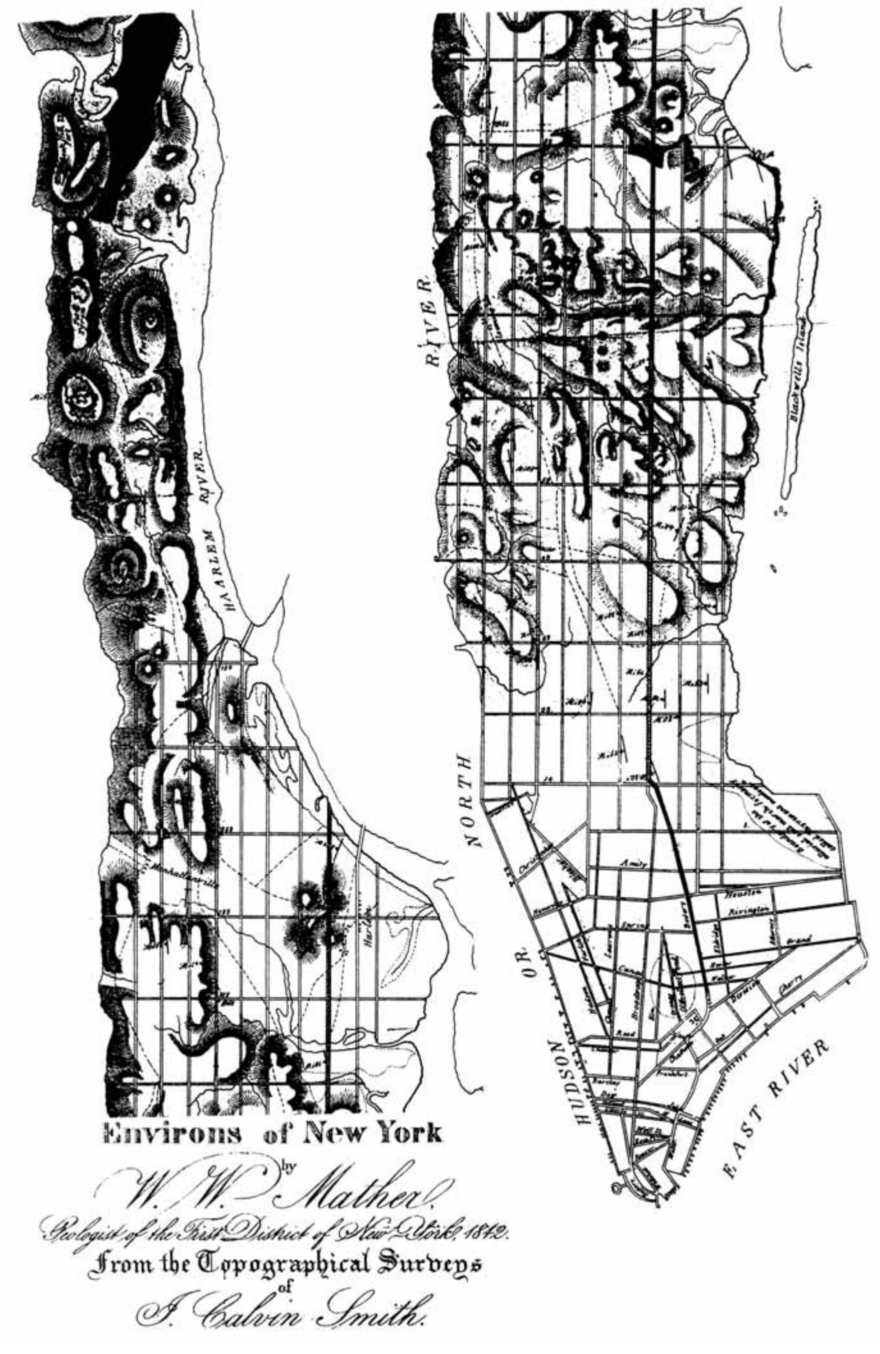


Figure 10 - Mather's (1843) map of Manhattan showing topography (hachures) and former natural drainage lines based on the work of J. Calvin Smith and with geological notations from L. D. Gale's surveys.

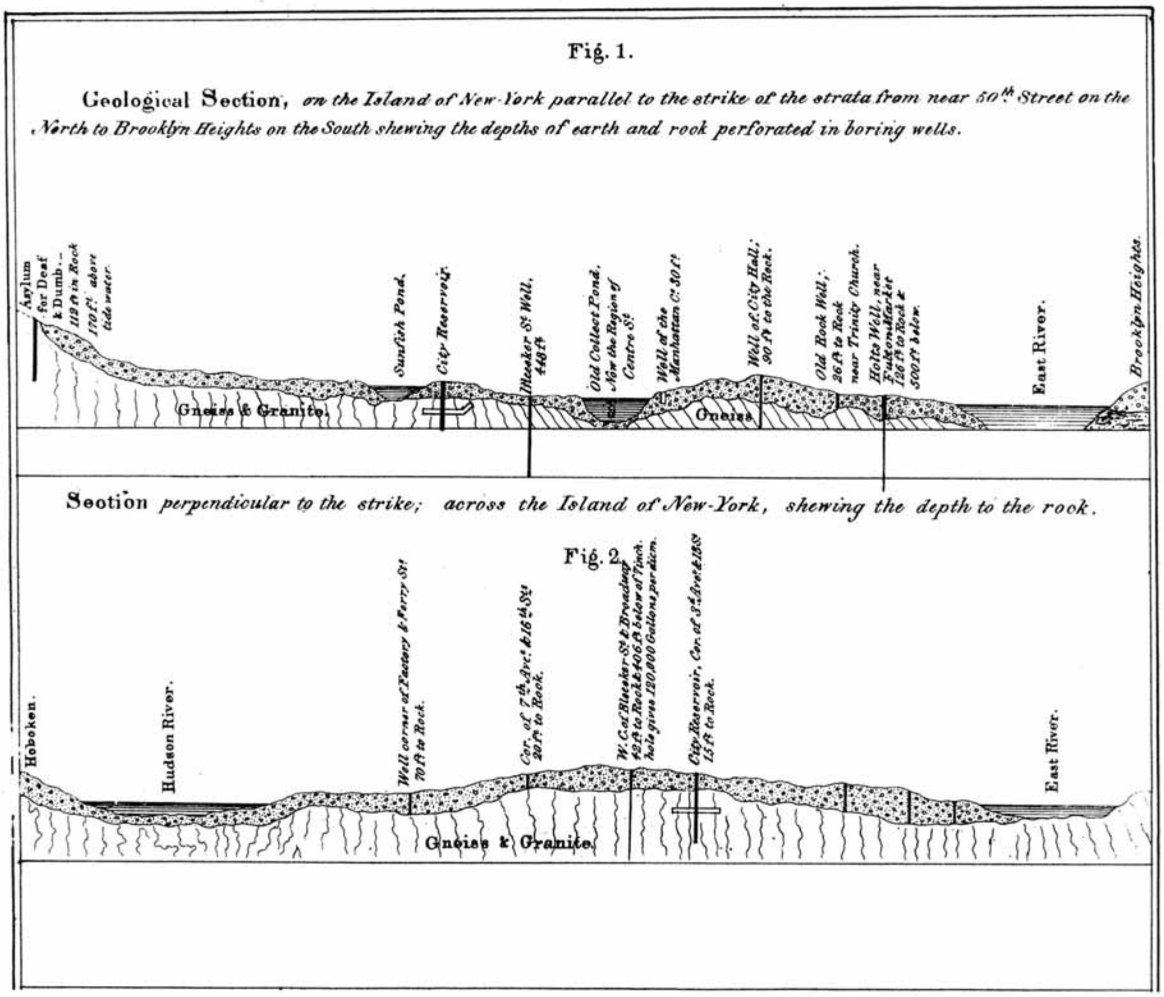


Figure 11 - Profile-sections of Manhattan and Brooklyn showing depth to bedrock based on borings. Upper section is parallel to strike of the rocks and extends from 50th Street, Manhattan (at L) across the East River to Brooklyn Heights. Lower section crosses lower Manhattan through old City reservoir (3rd Ave. and 13th St.) from Hoboken on the west (L) to the East River (R). (Mather, 1943, pl. 3, figs. 1 and 2.)

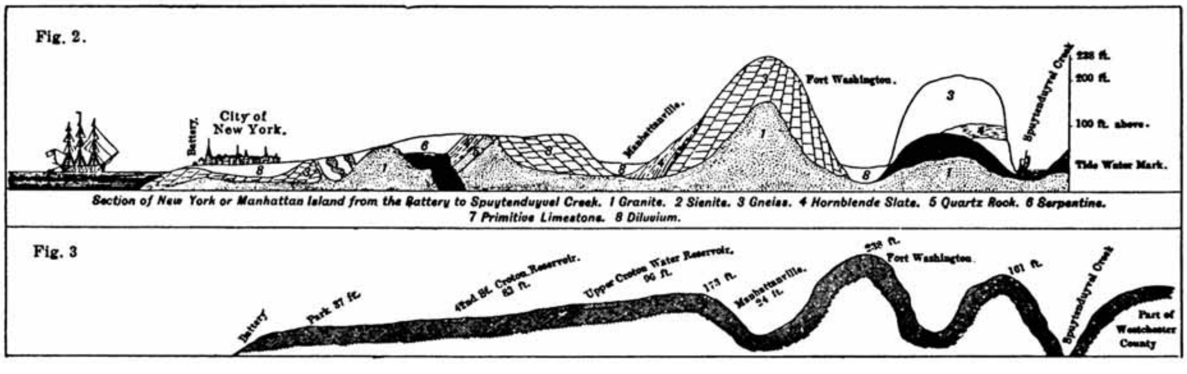


Figure 12 - N-S profile of Manhattan, from Battery (L) to Spuyten Duyvel Creek (R), showing shape of land surface (shaded, below) and inferred geological relationships as determined by Issachar Cozzens (above; G. P. Merrill, 1924, fig. 43, p. 238, from Cozzens, 1848, reference not in our bibliography).

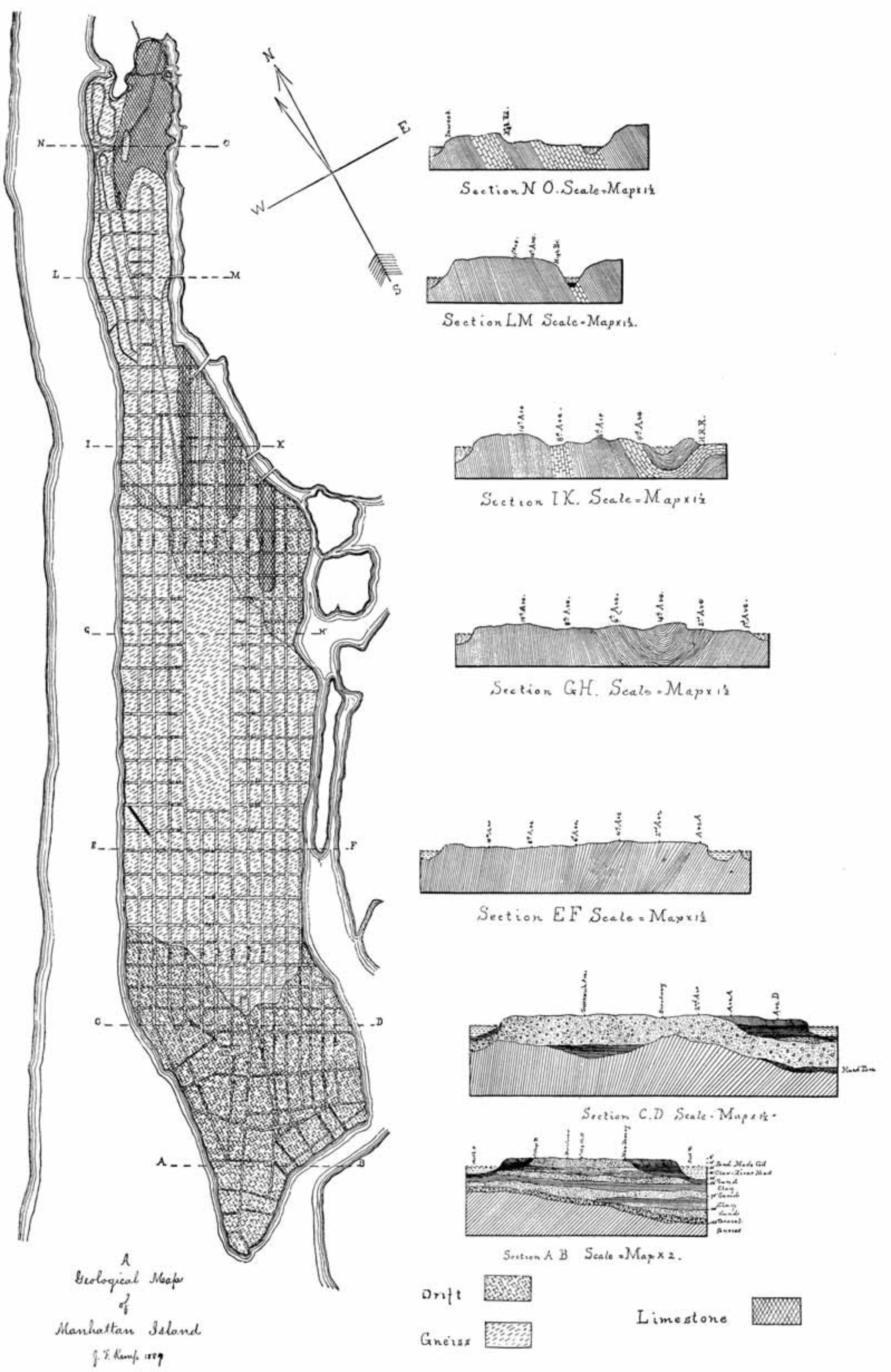


Figure 13 - Geological map and profile-sections drawn parallel to streets, Manhattan, with subsurface relationships in southwestern part based on borings. Notice that the scale of the profile-sections does not match that of the map. (J. F. Kemp, 1887.)

In 1890 (p. 390), Merrill named the Manhattan Schists 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. An obscure 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 Schists, the Inwood limestone, Fordham Gneiss, and the Yonkers Gneiss. Later, in 1902, Merrill and coworkers correctly correlated the Fordham gneiss with Precambrian sequences of the Hudson Highlands. Formal removal of the significantly older Fordham and Yonkers gneisses from the "Manhattan Group" had to await the refinement and application of radiometric dating techniques and detailed mapping 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.

Merrill, in concert with other geologists (1902), published the first comprehensive geologic map of New York City in their United States Geological Survey New York City Folio (#83). 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. From the top down, the Hudson Schist is successively underlain by the Stockbridge dolomite (Cambrian to Silurian), the Poughquag quartzite (Cambrian), and finally the Fordham Gneiss (Precambrian). Thus, the layer cake was served up (un-iced and without coffee), the general age assignments were made (the reader should substitute Ordovician for Silurian above), and the regional lithostratigraphic correlation between the metamorphic rocks of New York City and those of southeastern New York were made. 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 and enabled the development of massive engineering construction projects including power generation, water supply, transportation, and sewage disposal.

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 (1925, 1926, 1927, 1930, 1933), helped form our modern views on the bedrock geology of New York City and vicinity. In 1933, Berkey directed preparation of a guidebook for field trips in New York City held in connection with the 16th International Geological Congress meeting in Washington, D. C., which included 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 (basically a recap of his classic 1911 New York State Museum Bulletin publication on the geology of the New York City aqueduct).

In the post-International Geological Congress period, 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 number of scientific publications on the geology of New York City including Murphy and Fluhr (1944), Berkey (1948), Berkey and Fluhr (1948), and a great number of internal engineering reports by Berkey, Fluhr, W. O. Crosby and H. R. Blank which are listed and described in an important geotechnical summary by Fluhr and Terenzio (1984). A multitude of engineering reports, maps, and boring logs by individual private, state, and municipal agencies provide a wealth of information on the geology of New York City. These include the "rock data map" of Manhattan that was organized by J. J. Murphy, the engineer who was appointed to design the West Side Highway. He began by assembling all the data from the thousands of borings available to him in the mid-1930s. The project eventually involved a staff of geologists that were 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).

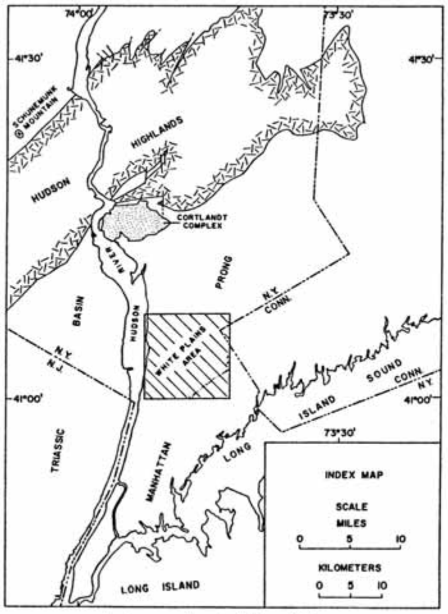
In addition, we list the efforts of Singstad (1944), deLaguna (1948), deLaguna and Brashears (1948), Suter, deLaguna and Perlmuter (1949), Perlmuter and Arnow (1953), Blank (1934, 1972, 1973), Binder (1975, 1978) and a host of others which can be tracked down at the Engineering Society Library near First Avenue and 46th Street in New York City. Note that boring logs and engineering data on municipal contruction projects are archived at the New York City Subsurface Exploration Section, 1 Centre Street, New York, New York.

The geologic work of the 1950s and 1960s included detailed mapping in the vicinity of New York City by Norton and Geise (1957) on the Lowerre Quartzite and by Langer and Bowes (1969) and Bowes and Langer (1969) on the polyphase deformation of the Manhattan Schist. 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, 1959), Paige (1956), Prucha (1956, 1959), Prucha, Scotford, and Sneider (1968), Scotford (1956), Lowe and Schaffel (1958), Schaffel (1958), Hall (1968a,b; 1969), Seyfert and Leveson (1968, 1969), and by Ratcliffe and Knowles (1969). Early, typically inaccurate attempts at radiometric dating of metamorphism 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 intrusion of 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, was held at the New York Academy of Sciences in Manhattan. Lowe (1959) edited a series of papers 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. Based largely on the work of Paige (1956), Hall (1968a, b, c), Lowe (1949, 1950, and 1959), Ratcliffe (1968), and Ratcliffe and Knowles (1968), "de-Grouping" of the New York City Group of Formations occurred. 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 for an unconformity between the Precambrian rocks of the Fordham and overlying Paleozoic rocks of the Lowerre-Inwood-Manhattan sequence in the Manhattan Prong (Figures 14, 15). The combination of isotopic data and paleontologic evidence proved the Early Paleozoic age of the Inwood Marble. Based on superposition, the Manhattan Schist was considered younger than the Inwood but pre-Silurian based on regional relationships and the late medial Ordovician age of the Taconic unconformity. 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. Isotopic age determination (Grauert and Hall, 1973) yielded a 1.1 Ga (Proterozoic Y) age for the Fordham based on U-Pb analyses on zircons from the Fordham gneiss.



Index map for the White Plains area.

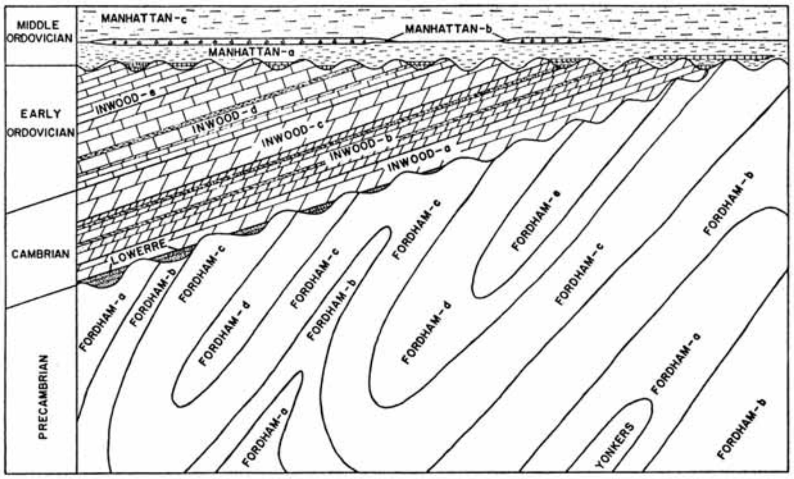
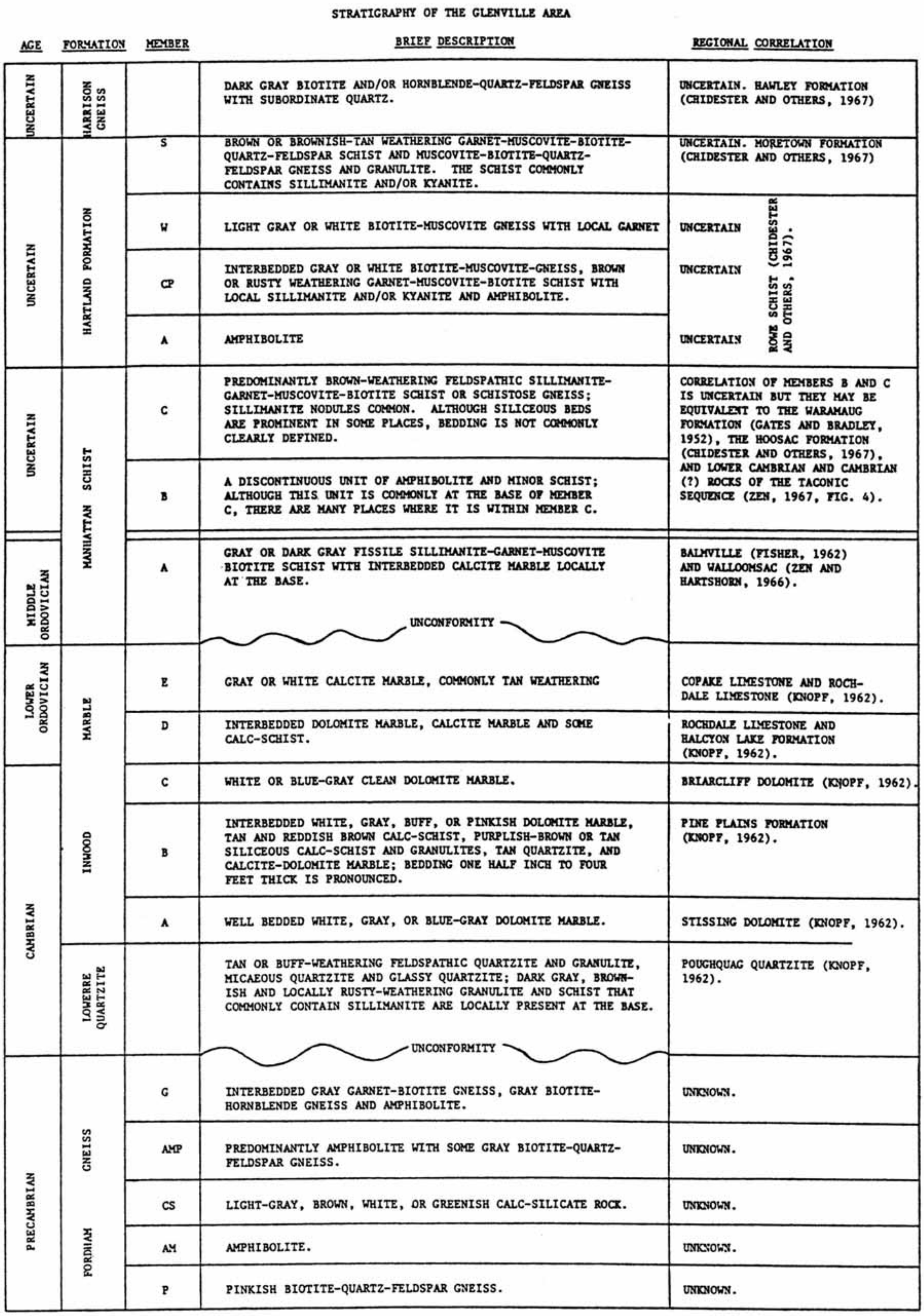


Figure 14 - Index map showing location of White Plains area (diagonal lines) and schematic profile-section showing inferred relationships among members of the Fordham Gneiss, Inwood Marble, and Manhattan Formation. (Leo Hall, 1968.)



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.	BALMVILLE (FISHER, 1962) AND WALLOOMSAC (ZEN AND HARTSHORN, 1966).
			UNCONFORMITY	
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.	POUGHQUAG QUARTZITE (KNOPF, 1962).
			UNCONFORMITY	
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 15 - Correlation chart of the metamorphic rocks of southeastern New York (Hall, 1968a, b, c).

Based on his work in the Glenville area of Westchester County, Hall (1968a, b, c; 1976, 1980), proposed subdivisions of the Manhattan Schist into lithically variable members (designated by letters A, B, and C) and correlated parts of the Manhattan Schist with Cambrian rocks of the Taconic allochthon of eastern New York State (See Figure 15.) 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 New York City. rather significant differences in stratigraphic- and structural interpretation can be found in these studies.

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 suggests that the Manhattan Schist exposed in Manhattan and the Bronx is a lithically variable sequence consisting of three, mappable, roughly coeval, structurally complex, tectonostratigraphic units. Merguerian's investigations agree, in part, with designations proposed by Hall (1976, 1980), but indicate the presence of a hitherto-unrecognized, structurally higher schistose unit that is a direct lithostratigraphic correlative of the Hartland Formation of western Connecticut (Merguerian, 1981, 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 geology of the East River. In 1986, Merguerian organized a conference on the Geology of Southern New York at Hofstra University, in Hrempstead, 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 Medial 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)

Precambrian 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 highly deformed metamorphic-, metaigneous-, and igneous rocks that dip southward, buried beneath the Paleozoic and younger strata of the central United States. These basement rocks do crop out on the surface in occasional upwarps, faults, 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 16). 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. They also occur 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 suspect that many of these exist as a result of combined terminal-stage, latest Paleozoic Appalachian overthrusting as well as post-Jurassic faulting and compression (Sanders, 1982; Merguerian and Sanders, 1991).

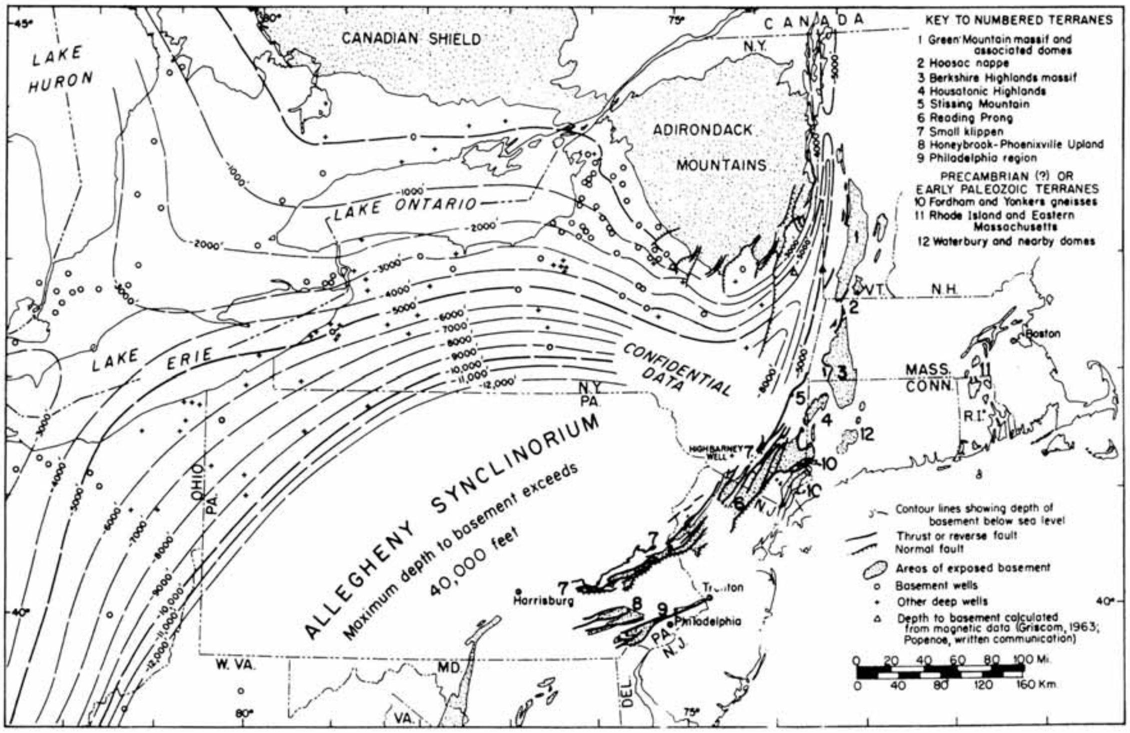


Figure 16 - Configuration of Proterozoic surface and areas of exposed basement (Isachsen, 1964).

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 Figure 4.) The Highlands gneisses are composed of complexly deformed layered feldspathic gneiss, schist, amphibolite, calc-silicate rocks, and massive granitoid gneiss of uncertain stratigraphic relationships that 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.

In the Pound Ridge area (PR in Figure 4), 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. Subunits in the Fordham are cut by Proterozoic Z granitic gneiss (the Pound Ridge Gneiss and correlative Yonkers Gneiss [Y in Figure 4] farther south in Westchester County), and 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 unconformable relationship (Patrick Brock, personal communication) with the Grenvillian basement sequence. The Yonkers Granitic Gneiss has yielded ages of 563+30 Ma (Long, 1969) 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 Brock (1989) 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 has identified an easterly, metamorphosed volcaniclastic facies of Proterozoic Z igneous activity whose probable vent 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 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 17) 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!

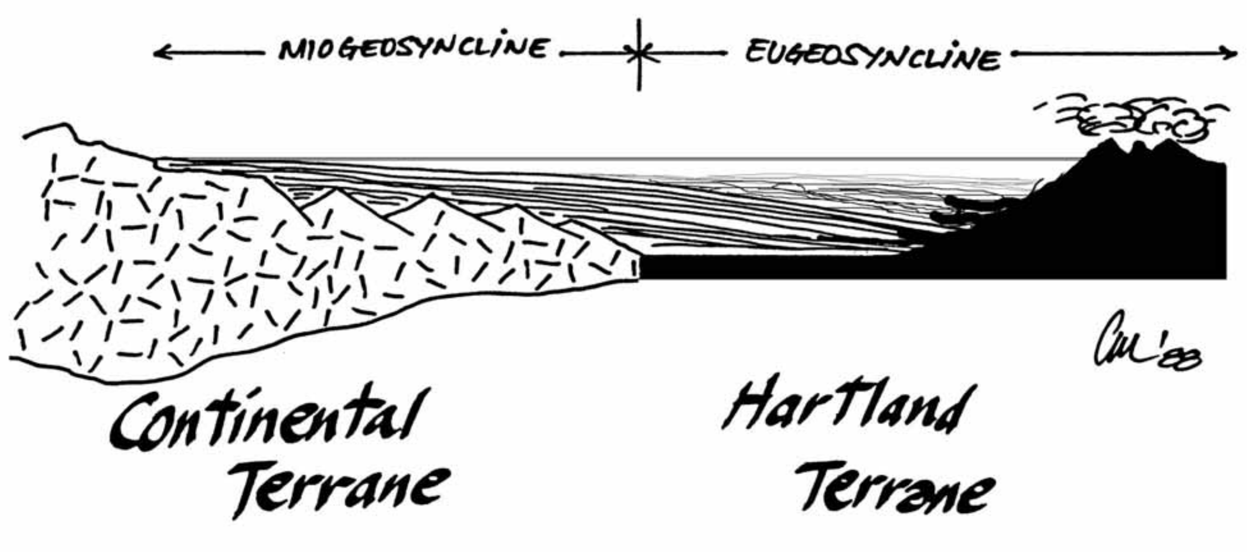


Figure 17 - Diagrammatic sketch of the passive margin of eastern North America in Early Paleozoic time showing the contrast in miogeosynclinal and eugeosynclinal depositional areas.

We will not stop to examine the Fordham Gneiss today, but on the last legs (Stops 6 and 7) of our fieldtrip route, we will pass outcroppings and will view the Fordham "from afar" at the north end of Inwood Park (Stop 3).

Layers IIA and IIB: Cambro-Ordovician strata

As we examine rocks in Manhattan and 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 18) and which featured a carbonate-platform interior that was bordered on the east by a continental-rise prism of fine-grained terrigenous sediment and an oceanward volcanic source [Layers IIA(W) and (E)]; and (2) products of an actively converging continental margin [Layer IIB], which commenced later in the Ordovician Period and extended through at least the end of the Ordovician period. This 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 slope reversal and geographic rearrangements. The first event in this changed tectonic situation was the emplacement of the Taconic allochthon, whereby the the fine-grained terrigenous sediments of Layer IIA(E), deposited in the vicinity of the ancient continental rise and oceanward, were displaced physically above carbonates and clastics of the continental platform [Layers IIA(W) and IIB]. Associated with this Taconic overthrust was deep subsidence and the establishment of an active, synorogenic foreland basin [Layer IIB] above Layer IIA. The evidence for this change consists of a karst landscape at the top of the Layer IIA clastic-carbonate succession and the eventual covering of this karst surface with graptolite-bearing shales of Layer IIB (Figure 18). A complicating factor is that the Taconic allochthon was 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 deposited in this foreland basin.

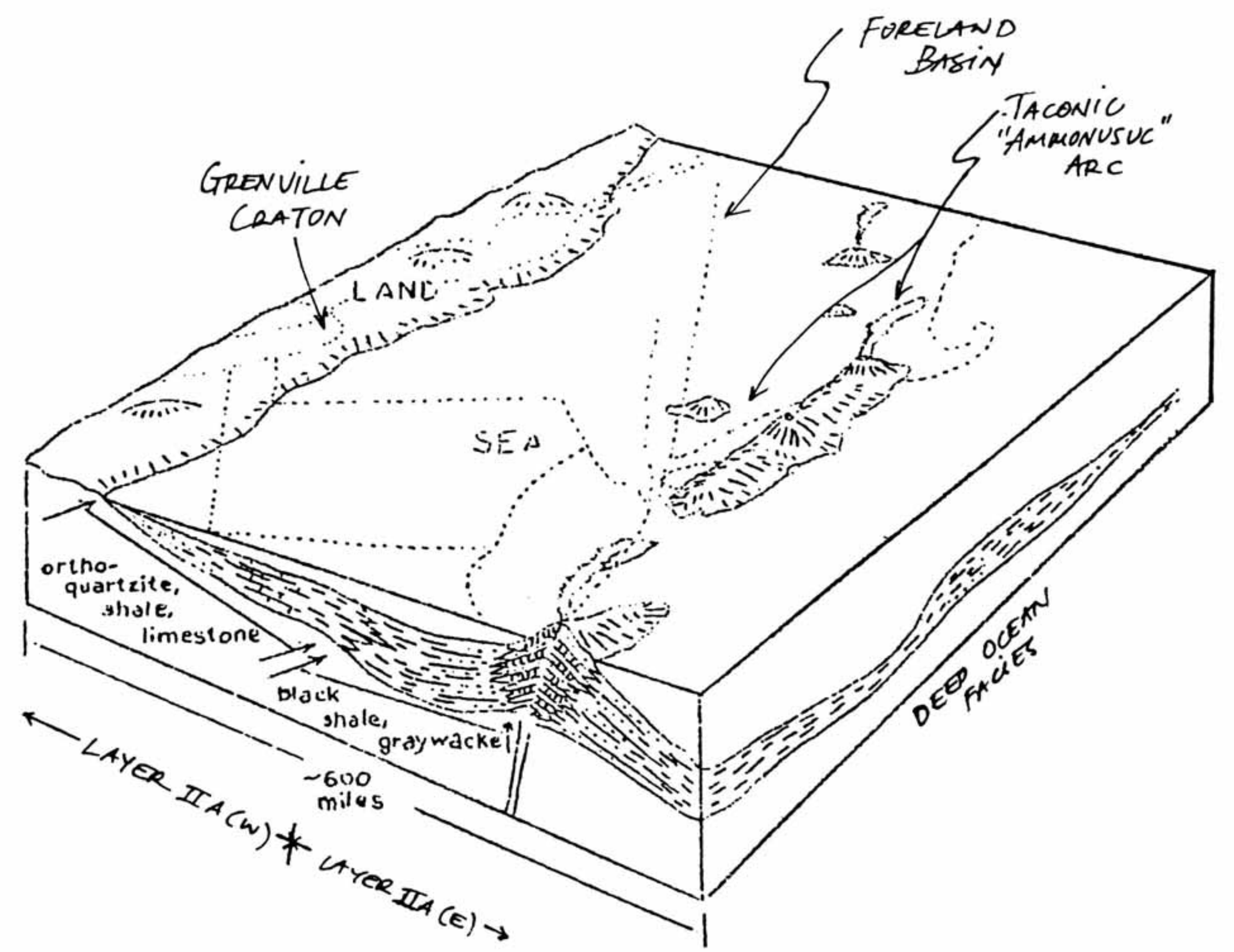


Figure 18 - Block diagram showing the Early Paleozoic continental shelf edge of embryonic North America immediately before the deposition of Layer IIB. Current state outlines are dotted. The depositional areas for Layers IIA(W) and IIA(E), and the position of the Taconic arc and foreland basin are shown.

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 Wappinger Group (local name taken from Wappinger Falls, south 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 19) 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, it consists of dolomite rocks of Cambrian and Early Ordovician ages and is underlain by Lower Cambrian quartzose clastic rocks. 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.

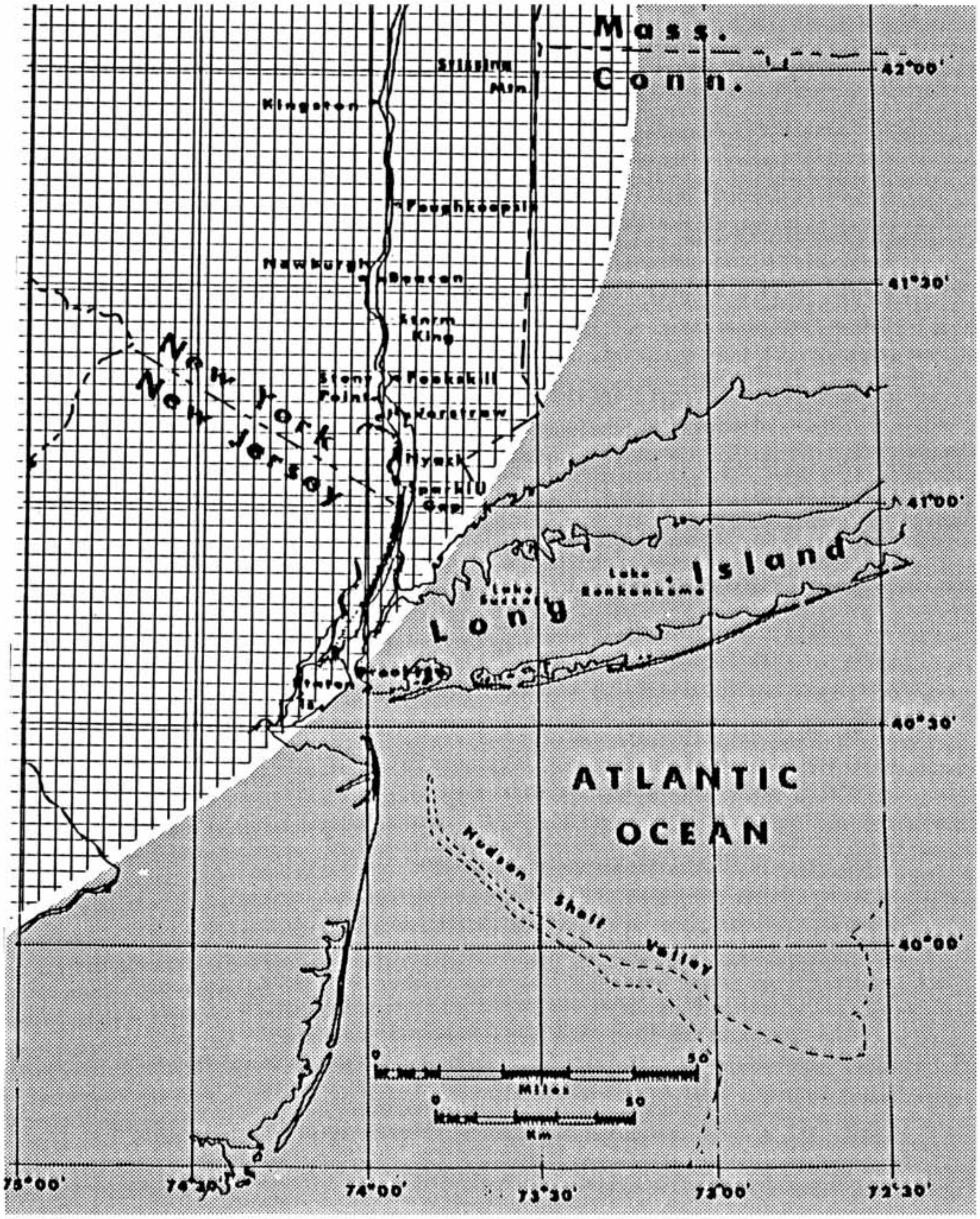


Figure 19 - Boundary between carbonate platform (pattern of squares) and deeper-water area to the east where terrigenous sediments were deposited (shaded), during the Cambrian and early part of the Ordovician periods. JES diagram.

BEDROCK STRATIGRAPHY OF NEW YORK CITY

The bedrock underlying Manhattan includes the Fordham Gneiss, Lowerre Quartzite, Inwood Marble, and various schistose rocks formally included in the Manhattan Schist. As a result of construction as well as of its very local deposition, the Lowerre is no longer exposed on the surface. As described earlier, important stratigraphic relationships for the Manhattan Prong were developed by Leo M. Hall in the White Plains area, New York (See Figures 14, 15.), indicating that the Fordham is much older than the overlying Paleozoic rocks of New York City. Hall's mapping in White Plains showed that subunits of the Fordham are truncated by both the Cambrian Lowerre and the Cambro-Ordovician Inwood Marble. This field data verified the existence of the surface of unconformity suggested by the isotopic age dating of Grauert and Hall (1973).

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 4) and thus represent metamorphosed sedimentary rocks 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, 1983) or Hutchinson River Group (Seyfert and Leveson 1969, Baskerville 1982). 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 4) which became accreted to North America during the Medial Ordovician Taconic orogeny (Hall, 1979; Merguerian 1979, 1983; Merguerian and others, 1984; Robinson and Hall, 1979). 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 has established subdivisions of the Manhattan Schist into two basic units. The autochthonous Manhattan A, which was originally deposited above the Inwood marble and the allochthonous (transported rocks not found where deposited) Manhattan B and C members. Hall (1976) suggested that the Manhattan B and C (interlayered amphibolite unit) were Early Cambrian (or possibly older) in age, part of the eugeosyncline (Layer IIA(E) in our scheme) and were deposited below aluminous schist and granofels of the Hartland Formation. In Figure 4, Manhattan A is included in the basement-cover sequence (pꞒ-O) and Manhattan B and C are designated Ꞓ-Om. Merguerian (1983, 1985) interprets the Manhattan B and 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.

Strong evidence for three subdivisions and possibly allochthony within the Lower Paleozoic schists exists in New York City (Merguerian, 1981, 1983; 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 sequence (Ꞓ-Om) and as the eugeosynclinal deep-water oceanic Hartland Formation (Ꞓ-Oh), not as the stratigraphically-youngest unit as suggested in all "pre-plate tectonics" bedrock interpretations!

Based on detailed mapping, the schist on Manhattan Island is subdivided into three, lithologically distinct, structually imbricated, lithostratigraphic units of kyanite- to sillimanite metamorphic grade that plunge toward the south (Figure 20). 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-grained, 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 (1968) because it "looks like it" and is found interlayered with the underlying Inwood at two localities (Stops 3 and 6), 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 a middle Ordovician age to the 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) that forms the bulk of the "schist" exposed on the Island of Manhattan (Stops 2-5, 7, and most Central Park outcrops - Figures 2, 3). The middle schist unit consists of rusty- to sometimes maroon-weathering, medium- to coarse-grained, 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 (Hall, 1976; Merguerian, 1981, 1983). 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.

The structurally highest, upper schist unit (Ꞓ-Oh) is dominantly gray-weathering, fine- to coarse-grained, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, gneiss,and granofels with cm- and m-scale layers of greenish amphibolite+garnet (Stop 1). The upper schist unit, which based on CM's study of over 500 outcrops, and a multitude of drill cores, and construction excavations, underlies most of the western- and southern third of Manhattan, is lithologically identical to the Cambrian and Ordovican Hartland Formation of western Connecticut and southeastern New York. On this basis, they are considered correlative; 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 21). 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.

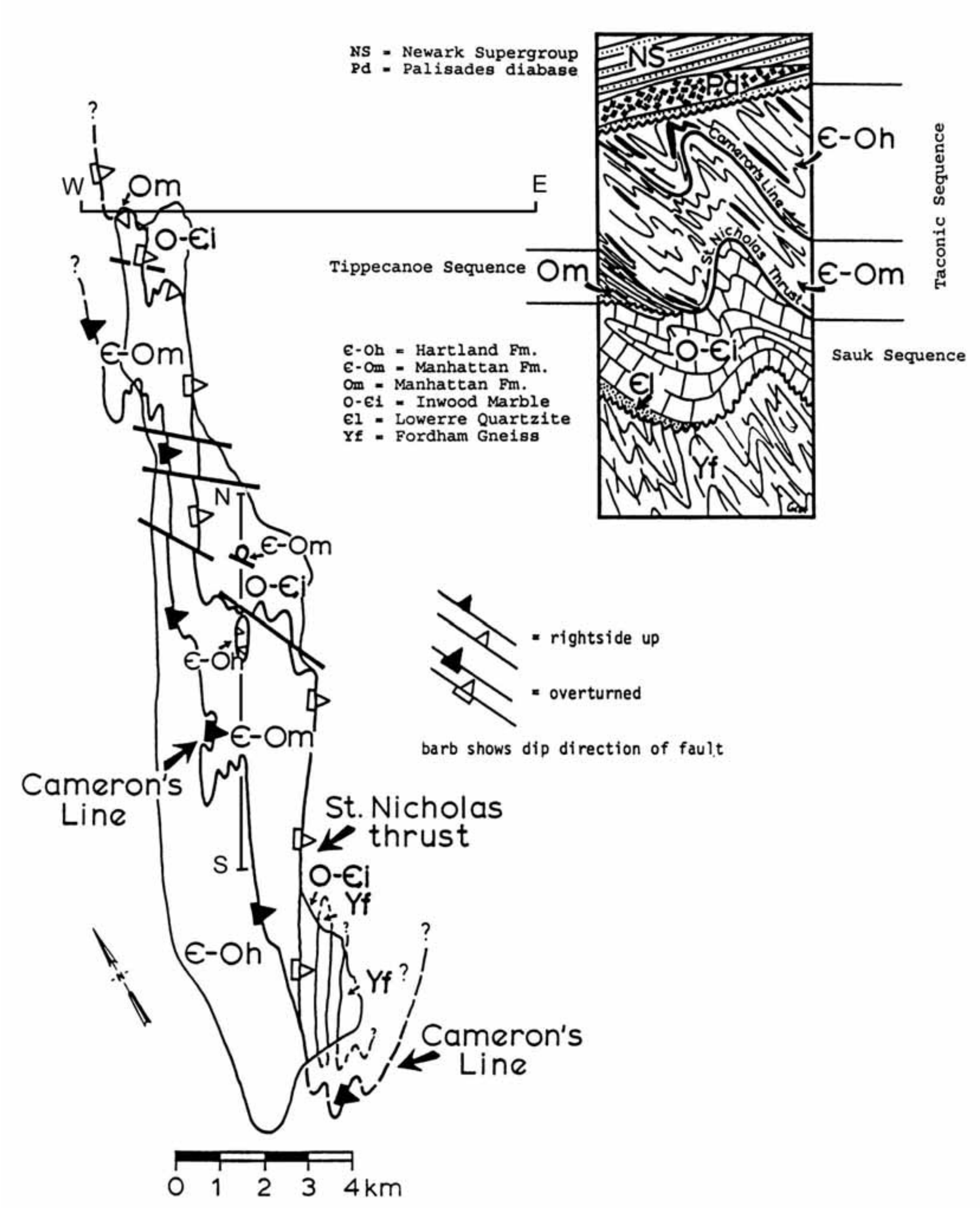


Figure 20 - Geologic map of Manhattan Island showing a new interpretation of the stratigraphy and structure of the Manhattan Schist. Drawn and mapped by C. Merguerian.

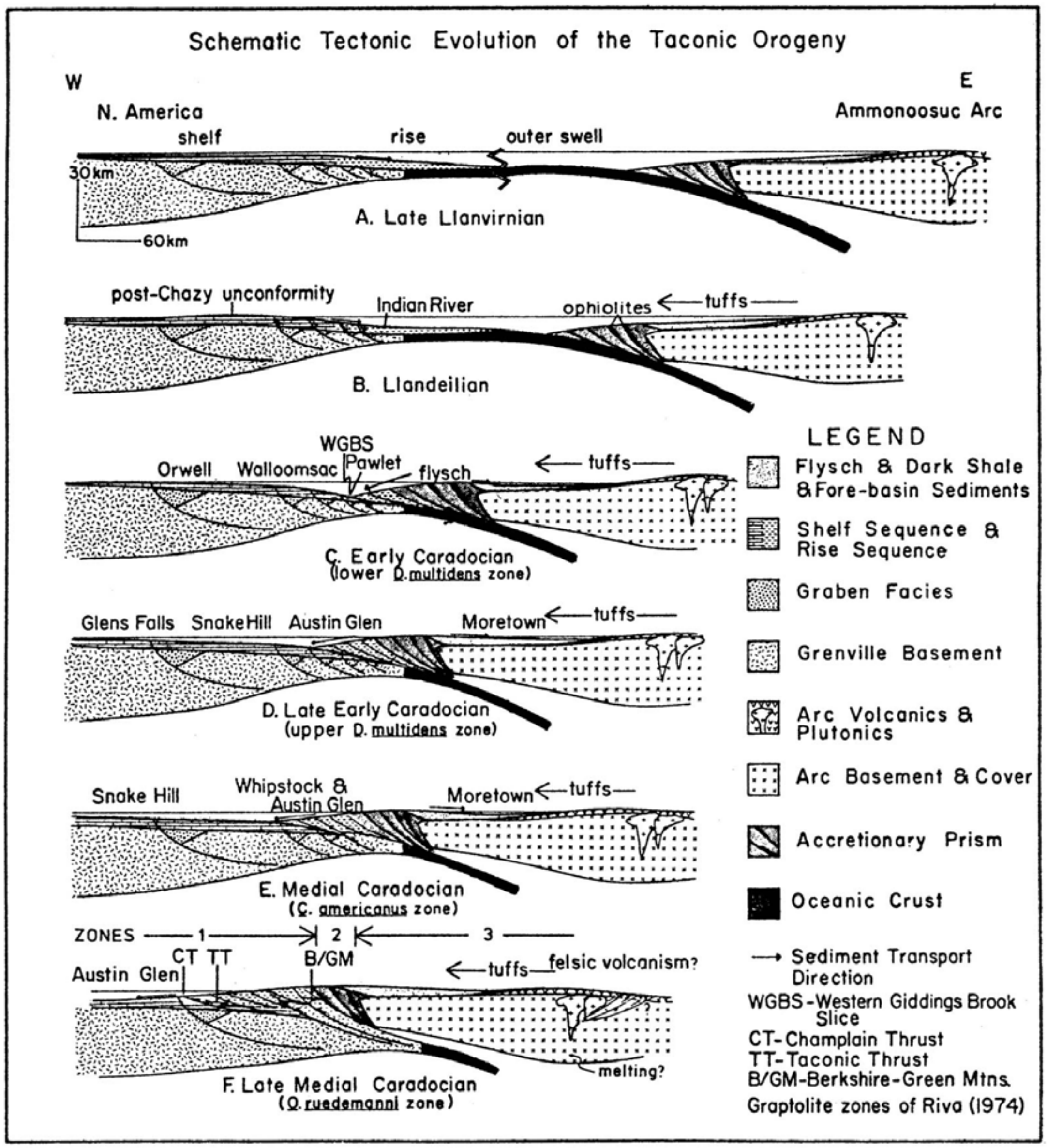


Figure 21 - Sequential tectonic cross sections for the Taconic orogeny in New England. From Rowley and Kidd (1981).

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.

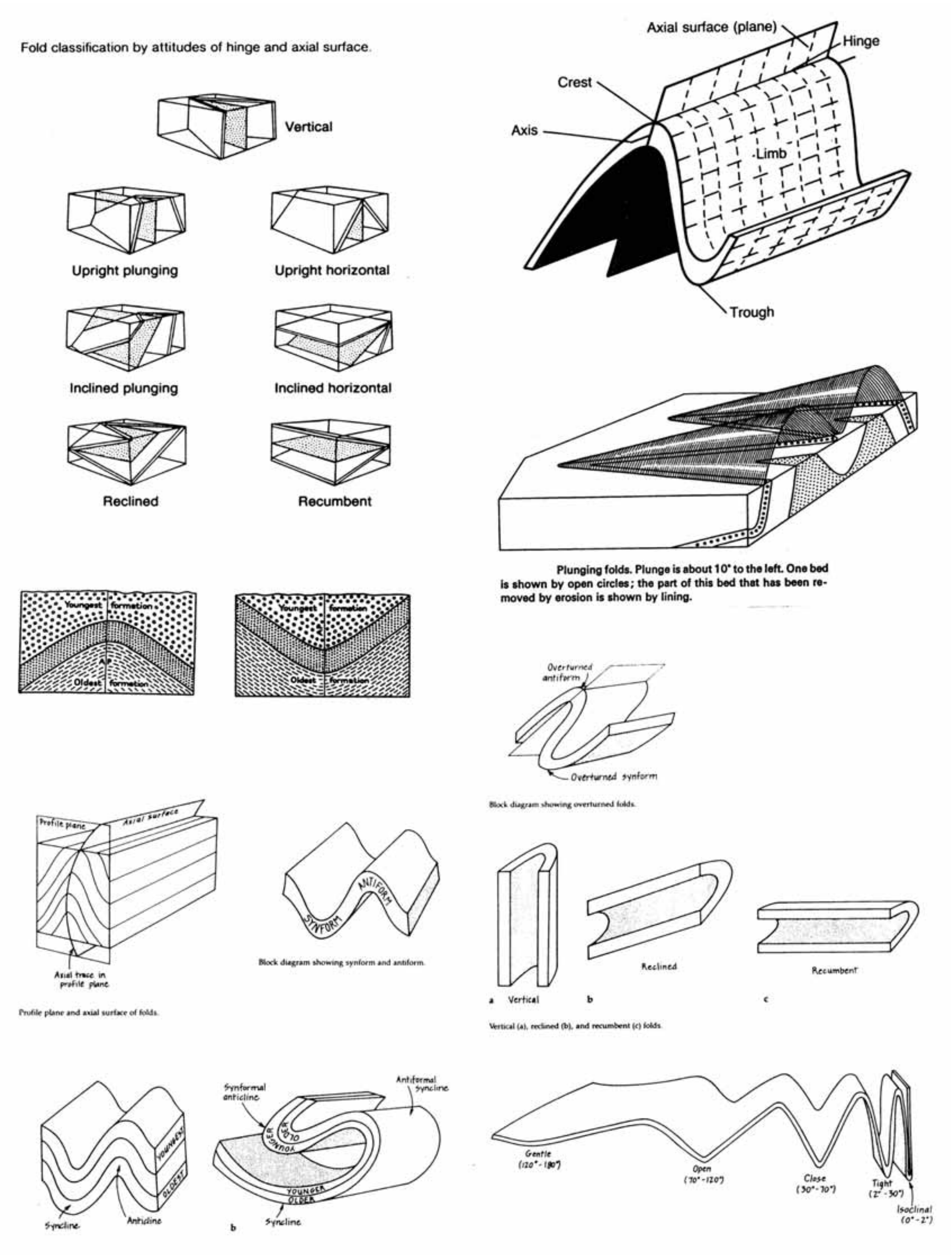
Folds

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, rocks behave in a ductile fashion. 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 22, 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 22 the fold is deformed about a vertical axial surface and is cylindrical about a linear fold axis that 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.

Realize that in the upright folds shown in Figure 10, 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. Minerals can also align in a linear fashion producing 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.



Fold classification by attitudes of hinge and axial surface.

Plunging folds. Plunge is about 10° to the left. One bed is shown by open circles; the part of this bed that has been removed by erosion is shown by lining.

Block diagram showing overturned folds.

Profile plane and axial surface of folds.

Block diagram showing synform and antiform.

Vertical (a), reclined (b), and recumbent (c) folds.

Figure 22 - Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the text.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine tilting of the axial surface, to form inclined or overturned folds, or a sub-horizontal axial surface, to form recumbent folds, all accomplished by keeping the fold axis horizontal (Figure 22). In addition, we can keep the axial surface vertical and alter the plunge 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 episodes of deformation (D_n), folding (F_n), foliation (S_n), and metamorphism (M_n), 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 two groups, the S'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 axis.

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 orientations 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 stress. 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 in 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 and that situated above the fault plane, the hanging wall (Figure 23). 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 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 imagine shearing 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 23) with the fault plane showing slickensides oriented subhorizontally. Left-lateral and right-lateral motion directions are possible and the trick is to imagine standing on one block facing across the fault plane to the other block. If the other block appears to move to the left, fault is left-lateral and vice versa. Convince yourself that it matters not which block you choose to observe from! Naturally, complex faults show movements that can show components of dip-slip and 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 above 10 km, is accompanied by seismicicity 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. The identification of such ductile fault rocks in complexly deformed terranes can be accomplished 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), which 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.

Surfaces of Unconformity

Surfaces of unconformity mark temporal gaps in the geologic record and commonly result from periods of uplift and erosion. Such uplift and erosion is commonly caused during the terminal phase of regional mountain-building episodes. Our field trip will clearly show you deformed middle Ordovician slates of the Taconic autochthon overlain by essentially flat-lying to gently tilted Siluro-Devonian carbonate rocks of Layer III. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure 24), such surfaces represent mysterious intervals of geologic time (usually ascribed to uplift and erosion) where we really do not have a clue as to what went on! By looking elsewhere, the effects of a surface of unconformity of regional extent can be recognized and piecemeal explanations of evidence for filling in the missing interval may be found.

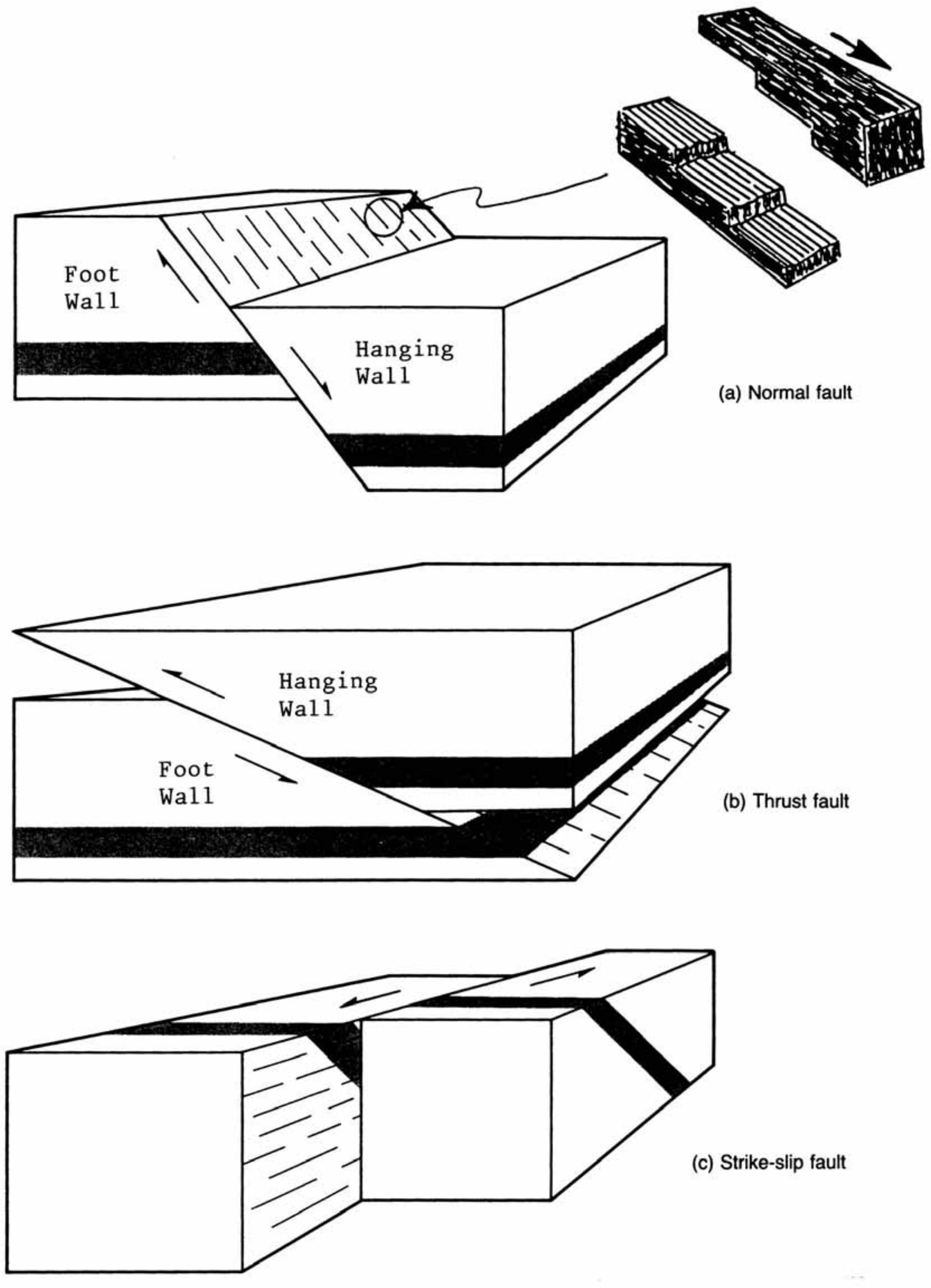


Figure 23 - Composite diagram from introductory texts showing the three main types of faults.

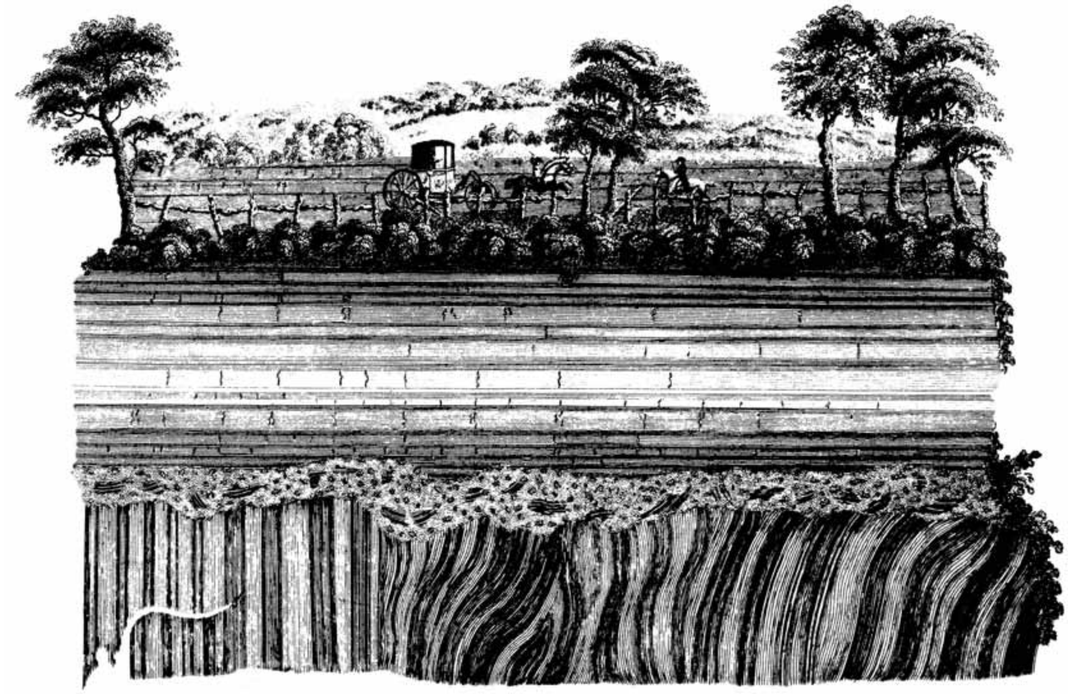


Figure 24 - Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's "Theory of the Earth", (1795).

Sedimentary Structures

During deposition in a variety of environments, primary- and secondary sedimentary structures can develop above, below, and within strata. During normal deposition, or settling from a fluid in a rainfall of particles, massive sequences of essentially poorly stratified sequences result. The presence of stratification implies a change in deposition and as a result most geologists appreciate the significance of layering in sedimentary rocks as marking CHANGE in big letters, be it a change in source area, particle size, or style of deposition. Thus, bedding can best be viewed as marking the presence of mini-surfaces of unconformity (diastems). During high-energy transport of particles, features such as cross beds, hummocky strata, asymmetric current ripple marks, or graded beds result. Cross- and hummocky bedding, and asymmetric current ripple marks are deposited by moving currents and help us unravel the paleocurrent directions during their formation. Graded beds result from a kind of a "lump-sum distribution" of a wide range of particles all at once (usually in a gravity-induced turbidity flow). Thus, graded beds show larger particle sizes at the base of a particular layer "grading" upward into finer particles.

Secondary sedimentary features are developed on already deposited strata and include mud (or desiccation) cracks, rain- drop impressions, sole marks, load-flow structures, flame structures, and rip-up clasts. The last three categorize effects produced by a moving body of sediment on strata already in place below. A composite diagram illustrating these common structures is reproduced in Figure 25.

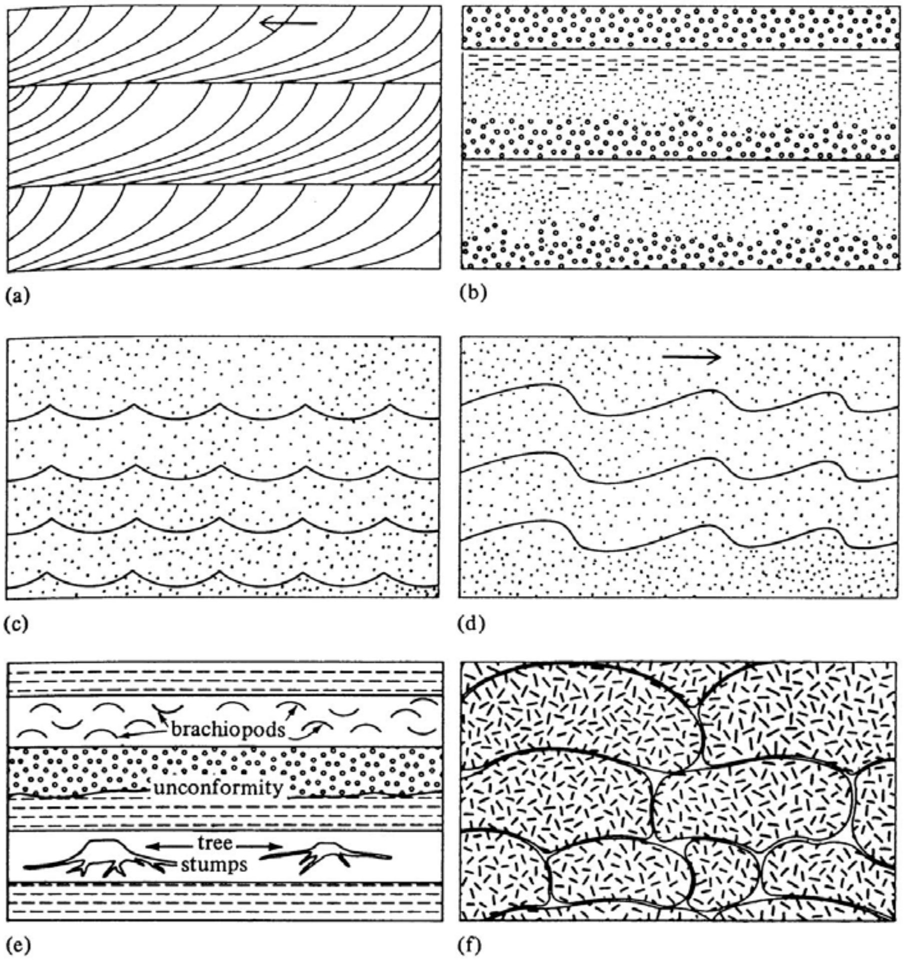


Figure 25 - Diagrammatic sketches of primary sedimentary structures used in determining topping (younging) directions in stratified rocks.

Together, these primary- and secondary sedimentary structures help the structural geologist unravel the oft-asked field questions - namely.... "Which way is up?" and, "Which way to the package store?" The direction of younging strata seems obvious in horizontal- or gently tilted strata using Steno's principle of superposition, but, steeply tilted-, vertical-, or overturned beds can be confidently unravelled and interpreted structurally only when the true topping (stratigraphic younging) direction is known. As we will demonstrate on this field trip, simple observations allow the card-carrying geologist to know "Which way is up" at all times.

Structures in Sedimentary- vs. Metamorphic Rocks

In metamorphic terranes, simple sedimentary observations will not allow the card-carrying geologist to know "Which way is up" at all. Rather, because of the intense transposition and flow during ductile deformation, stratification, fossils for age dating, tops and current-direction indicators are largely useless except to identify their hosts as sedimentary protoliths. Thus, according to CM, "at the outcrop scale, metamorphism can best be viewed as the great homogenizer". The increase in temperature and pressure and presence of chemically active fluids often severely alters the mineral compositions and textures of pre-existing rocks. As such, in many instances, typical soft-rock stratigraphic- and sedimentologic analysis of metamorphic rocks are not applicable.

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 (D_1-D_3) followed by three or more episodes of open to crenulate fold phases (D4-D6+). The synmetamorphic juxtaposition of the various schist units occurred very early in their structural history based upon relationships found in Manhattan.

The base of the middle schist (Ꞓ-Om) is truncated by a ductile shear zone, here informally named the St. Nicholas thrust (open symbol in Figure 20). The thrust is exposed at Stops 3, 4, and 5. The upper schist unit (Ꞓ-Oh) is in probable ductile fault contact with the middle schist unit along Cameron's Line in the Bronx (Stop 7) and in Manhattan. However, this conclusion is based upon regional stratigraphic evidence; 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 (F_1+F_2). The F_1 folds are inferred from a locally preserved S_1 foliation. An annealed highly laminated mylonitic texture occurs at the thrust zone (Merguerian, 1988). 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 (S_2) 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. Stereograms (Figure 26) show the distribution of 245 poles to S_2, F_2 fold axes and L_2 lineations as measured in the field (Merguerian, unpublished data).

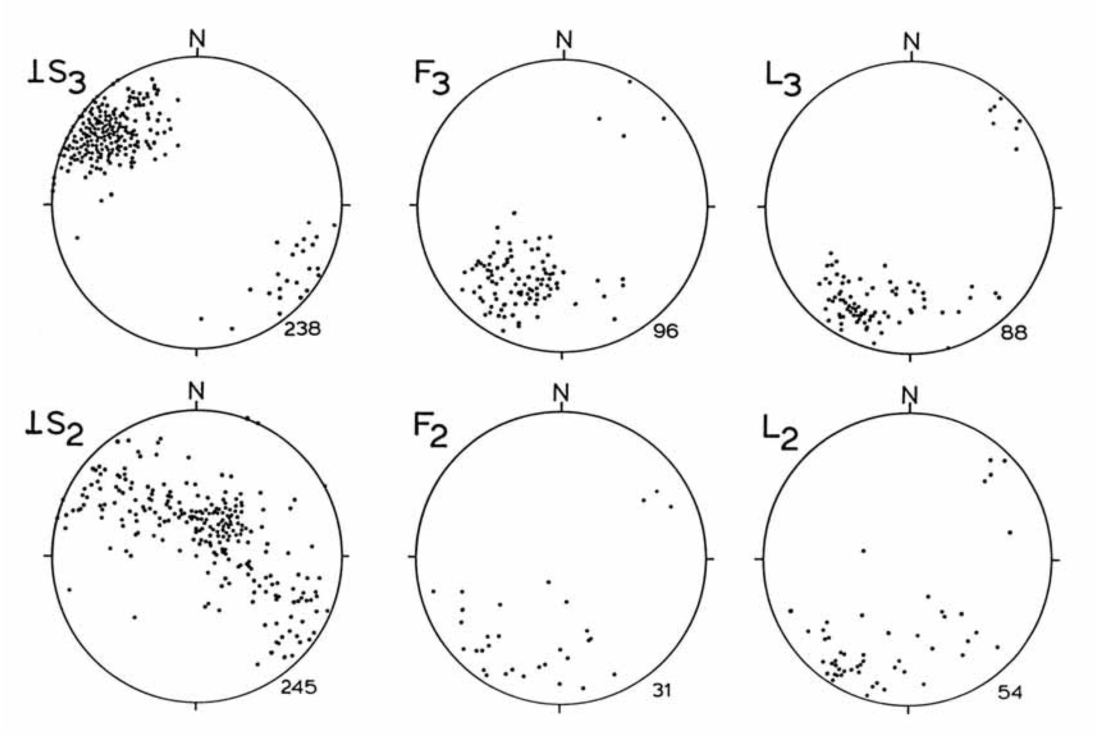


Figure 26 - Equal area stereograms showing the distribution of poles to S_2 and S_3, the orientation of F_2 and F_3 fold hingelines, and the orientation of L_2 and L_3 lineations. The number of plotted points indicated to the bottom right of each stereogram. (Merguerian, unpublished data).

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 20). 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. Stereograms (Figure 26) show the distribution of 238 poles to S_3, F_3 fold axes and L_3 lineations as measured in the field (Merguerian, unpublished data). Note the great-circle distribution of poles to S_2 and how the pole to that great circle corresponds to the concentration of F_3 axes.

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

The localities described below offer critical evidence for new structural interpretations of the Paleozoic schists exposed in New York City. Figure 27 presents simplified W-E and N-S structure sections across the New York City area. Keyed to Figure 20, the sections illustrate the complex structural- and stratigraphic picture that CM's recent studies have enabled him to make.

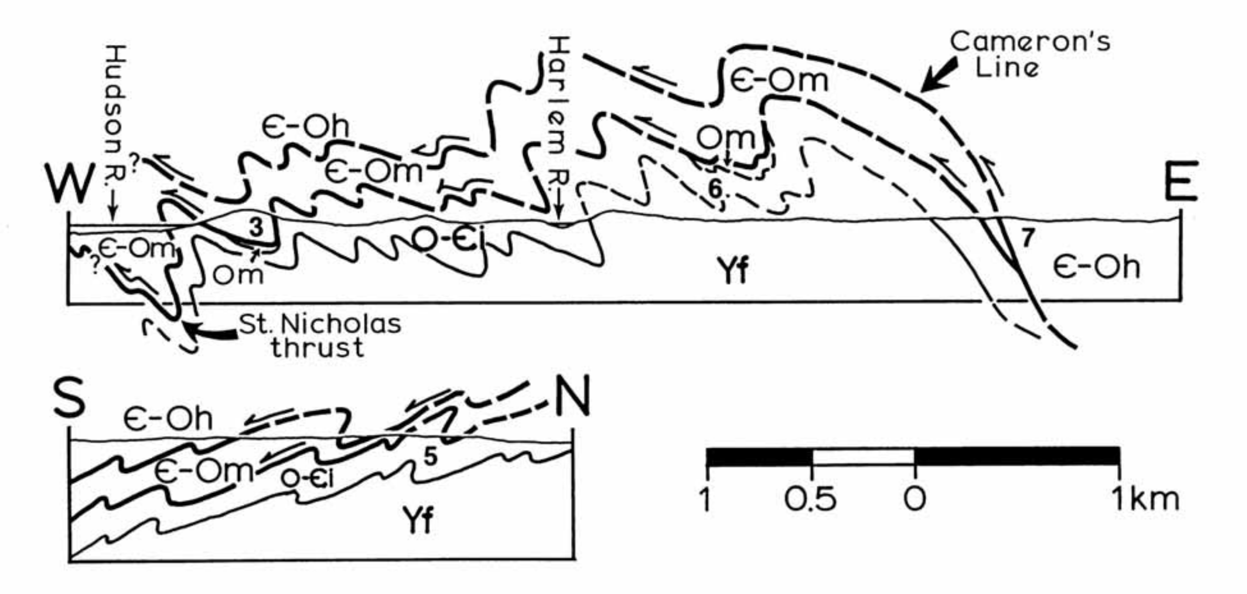


Figure 27 - Geologic cross sections across Manhattan and the Bronx showing the distribution of various tectonostratigraphic units in New York City and folded ductile faults (Cameron's Line and the St. Nicholas thrust). Symbols defined on Figure 20. (C. Merguerian, unpublished data).

The W-E sections shows 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-lower schist unit basement-cover sequence. The major F_3 folds produce digitations of the structural- and lithostratigraphic contacts that dip gently south, downward out of the page toward the viewer. The N-S section illustrates the southward plunge of lithostratigraphic units exposed in central Manhattan and the effects of the late NW-trending upright folds.

Figure 28 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, 1986; and unpublished data). This section is keyed to Figure 4. 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 schistose rocks of the Hartland (?), identifies the ductile fault known as Cameron's Line in two places with repetition resulting from brittle faulting, shows complex folding of the Inwood Marble (members A and B), and shows how in the vicinity of New York City, Cameron's Line places foliated schistose rocks structurally against the Fordham Gneiss. Thus, along the length of Cameron's Line from western Connecticut to New York City, the Hartland may be in structural contact with stratigraphically deeper bedrock units.

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.

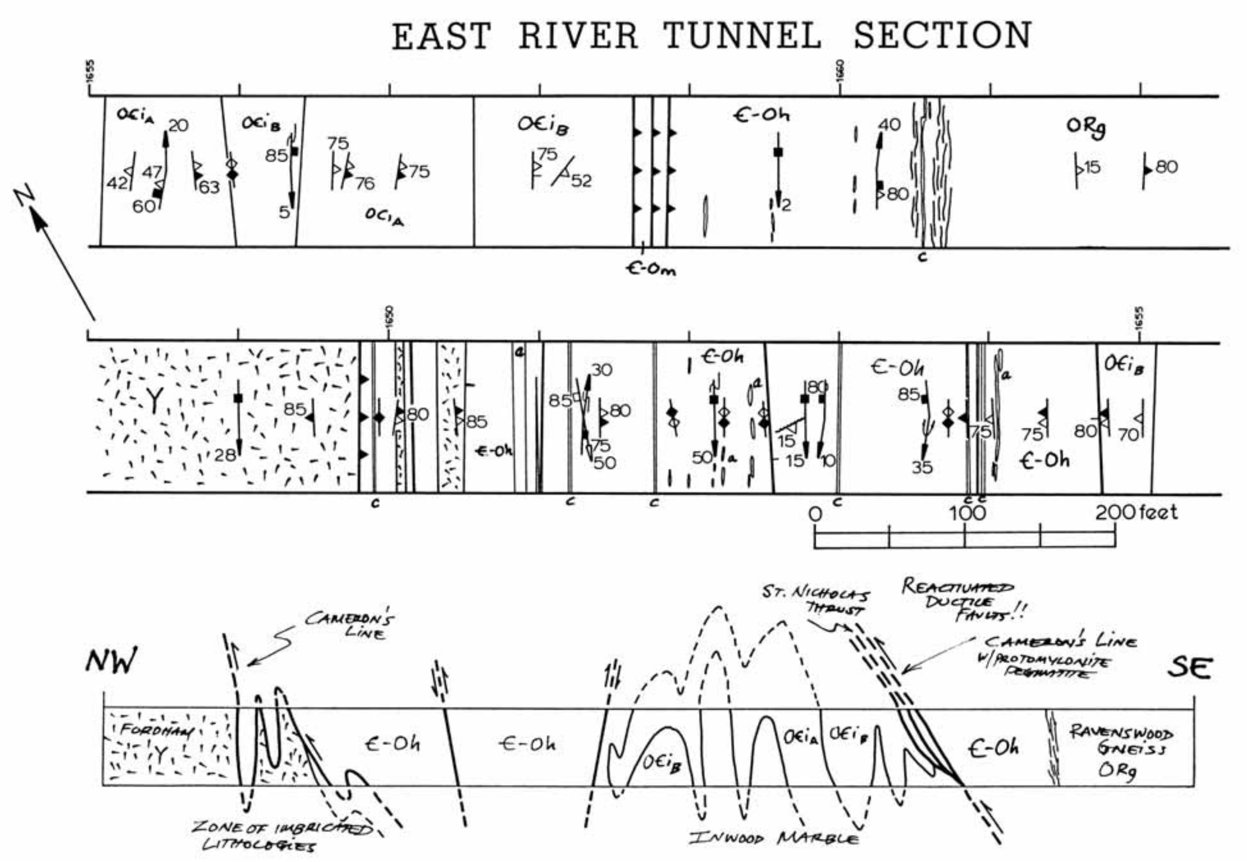


Figure 28 - Geologic map and section of the bedrock exposed in the New York City water tunnel beneath the east channel of the East River between Roosevelt Island and western Queens. (Merguerian, unpublished data).

The Geology of Cameron's Line

According to Eugene Cameron (of Cameron's Line fame) in a confidential personal communication with 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 autochthonous Proterozoic Y and Z gneiss and overlying lower Paleozoic quartzite and marble (shallow-water sedimentary strata [Layer IIA(W)] formed originally 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 (1983) is interpreted as an internally sheared imbricate thrust package that marks the former site of a deep-seated accretionary complex or subduction zone. It 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, 1981). Hartland rocks (Unit Є-Oh in New York City) are correlative with metamorphosed eugeosynclinal (deep- water deposition) Cambrian to Ordovician rocks found along strike northward into New England (Figures, 29, 30). The allochthonous portion of the Manhattan Schist (Unit Ꞓ-Om) is directly correlative with rocks of western Connecticut and Massachusetts along the east flank of the Berkshire and Green Mountains massifs.

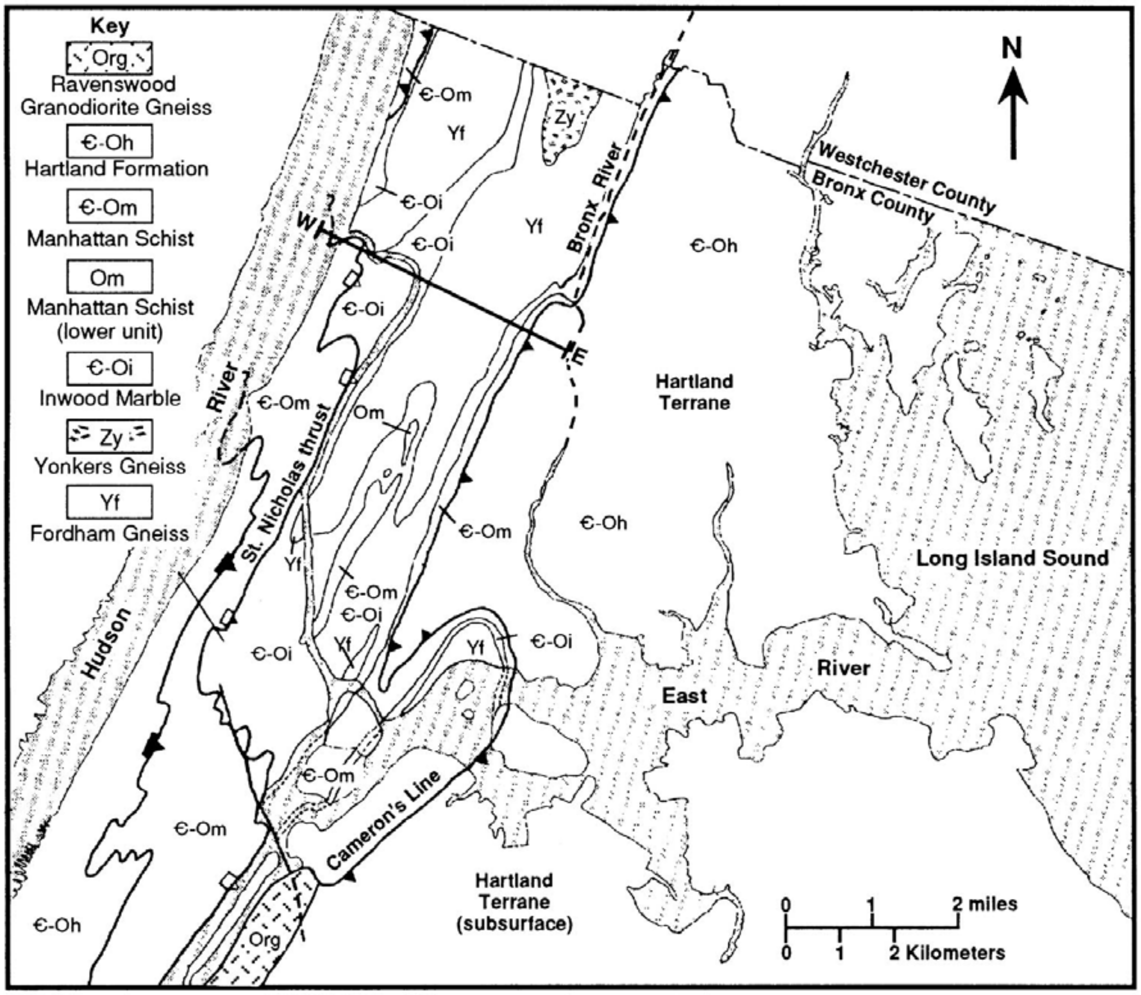


Figure 29 - Geologic map of Manhattan and the Bronx showing the geometry and distribution of Cameron's Line, the Hartland Terrane, and the Ravenswood Granodiorite (Merguerian and Baskerville, 1987).

Numerous lower Paleozoic calc-alkaline plutons occur 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, 1985).

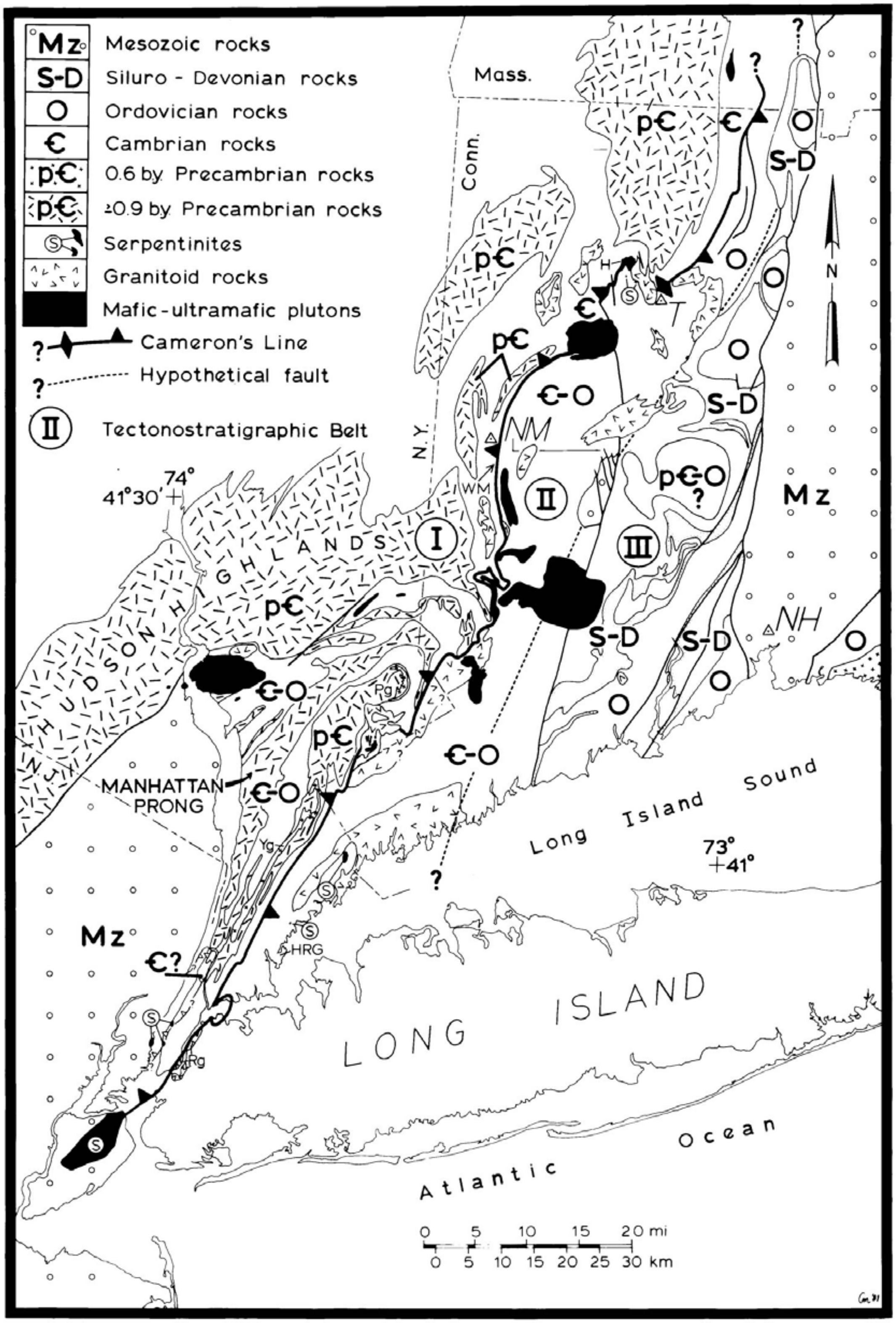


Figure 30 - Geotectonic map of New England showing Cameron's Line and the distribution of northeast-trending tectonostratigraphic units (Merguerian, 1983).

In western Queens, the Ravenswood Granodiorite of Zeigler (1911) crops out. (See Figure 29.) Field relationships indicate that the Ravenswood is a foliated metaplutonic rock (hornblende gneiss) which encloses foliated screens and xenoliths of coticule-bearing Hartland rocks in the water tunnel beneath western Queens and in surface exposures in Long Island City (Merguerian, unpublished data). 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 D_2 regional fabric and the aligned S_2 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 21.) 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 (Figures 6 and 30).

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.

Faults and Seismicity

It is generally agreed by all geologists and seismologists that earthquakes produce dislocations known as faults and that 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 Cameron's Line and the St. Nicholas thrust, five northwest-trending brittle faults are indicated on CM's geologic map of Manhattan north of 125th Street (Figure 20) and Lobeck (1939) shows the two of the major faults of Manhattan south of the 125th Street fault (Figure 31). 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.

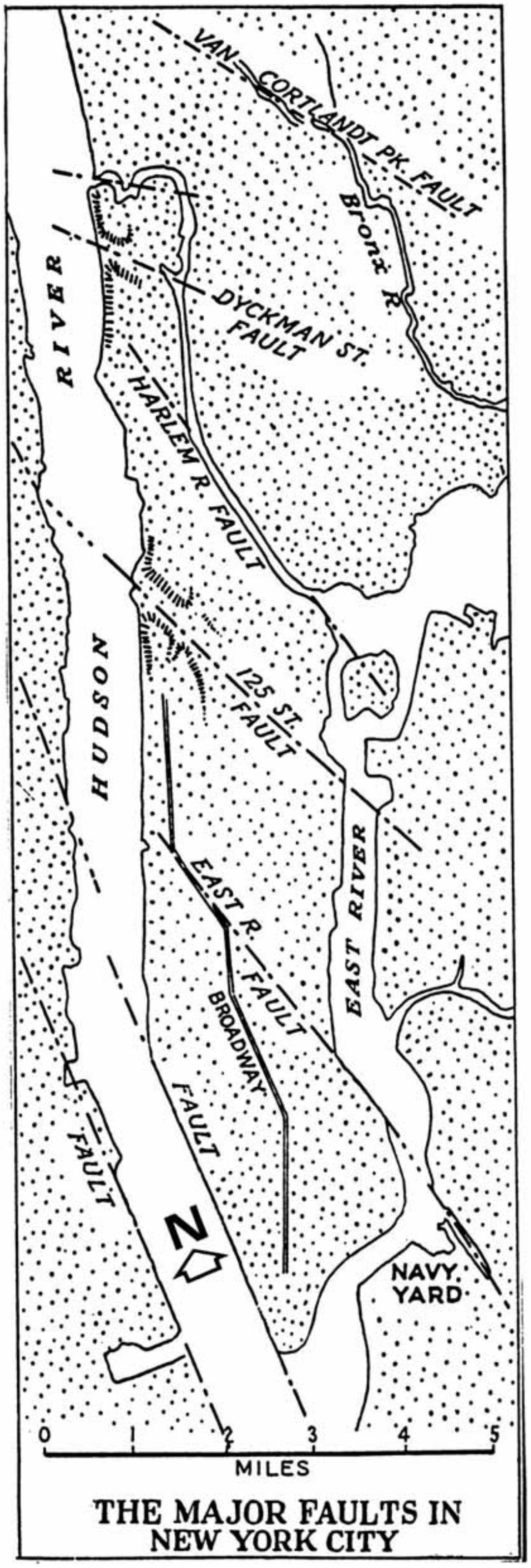


Figure 31 - Map of Manhattan showing major faults inferred on the basis of subsurface data in water tunnels and physiographic relationships. (A. K. Lobeck, 1939.)

CM's detailed mapping in the water tunnels beneath Manhattan and the East River in the period from 1983 to 1985, has identified a multitude of brittle faults that fall into two broad categories - those that trend northeasterly (parallel to the length of Manhattan) and those that transect the island of Manhattan at a high angle with a northwest trend. 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 quartz, calcite, pyrite, and zeolite minerals. Thus, New York City is cut into blocks by the intersection of these two important fault sets. CM is currently 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 by July of 1991.

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 of NE trend. A case in point was mapped in the east channel of the East River (Merguerian, 1985), 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 Fordham (Figure 32). CM interprets that this overprinting indicates a change from strike-slip to oblique-normal slip movement.

Figure 32 - Photograph of a left-lateral strike-slip fault exposed in the New York City water tunnel beneath the east channel of the East River between Roosevelt Island and western Queens. The fault is oriented N20°W, 67°NE and shows 7 cm of left-lateral offset in a quartz segregation within the Fordham Gneiss Formation.

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 (Figure 33), cuts orthogonally across the tunnel line and the foliation in the schist and thus beautifully displays the 125th Street fault. CM was amazed to observe in the overhead roof of the tunnel that enormous blocks of the Manhattan, which remained internally coherent within the zone of sheared rock, showed up to 90° of rotation about a vertical axis. Clearly, this observation indicates that along the 125th Street fault, some of the motion has been strike slip.

Figure 33 - Photograph of the 125th Street fault as exposed in the subsurface of Manhattan in the water tunnel built roughly 250 m beneath Amsterdam Avenue. Note the sharp demarkation of the fault. The photo, by Carl Ambrose of the NYC DEP, covers roughly 7 m in vertical dimension and shows the presence of ventilation, compressed air, and electrical conduits along the top and bottom and bolted rock straps to hold up the fractured bedrock. (NYC Bureau of Water Supply photo.)

The 19 October 1985 earthquake in Ardsley, Westchester County, shook up the scientific community and the engineering community as well, when a Richter magnitude 4.0 earthquake woke light sleepers early on a Saturday morning. 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 episodic slip along a fault with a northwest trend, identical to those mapped in Manhattan by CM! 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".

The Taconic Problem in New York City

The "Taconic problem" (or "problems" as we might more aptly express it to be consistent with the plural used by John Rodgers (1989) in the title of his review article: "The Taconic controversies") refers to the geologic interpretations of the age(s) of the predominantly terrigenous and fine-textured (or pelitic) Lower Paleozoic sedimentary rocks and their metamorphosed equivalents that underlie the Taconic Range of eastern New York and of the relationships of these pelitic rocks to their neighboring rocks, many of which are likewise of Early Paleozoic age but consist of carbonate rocks. We continue by describing the Taconic range. Then follows a review some of the history of the geologic investigations.

The Taconic range (the "Taconics") designates a series of rolling hills that extend for about 240 km, from near Poughkeepsie, New York to north of Rutland, Vermont (Figure 34). At their widest point, the Taconics are 40 km across and therefore form an impressive, if not somewhat topographically subdued, physiographic province nestled east of the Devonian Catskills and Precambrian Adirondack mountains and west of the Berkshire and Green Mountain Precambrian massifs.

Based on topographic expression, the metamorphic grade of the rocks, relative structural position, and stratigraphic relationships, the Taconics are subdivided into an eastern belt (high Taconics) and a western belt (low Taconics). The high Taconics not only reach to higher elevations, but within them, the rocks are of higher metamorphic grade, and higher structural positions than the Taconic rocks exposed farther west in the low Taconics.

Early in the history of geologic studies, during the First Geological Survey of the State of New York, in the 1830s and 1840s, a sure way to guarantee one's entry into "geologic heaven" was to propose a new geologic system. Proposals to establish two new systems within the Paleozoic were made by New York's first geologists. Ebenezer Emmons proposed the "Taconic" system for the thick body of terrigenous pelitic rocks underlying the Taconic range, and James Hall, the "New York" system, for the strata underlying the Catskills and vicinity.

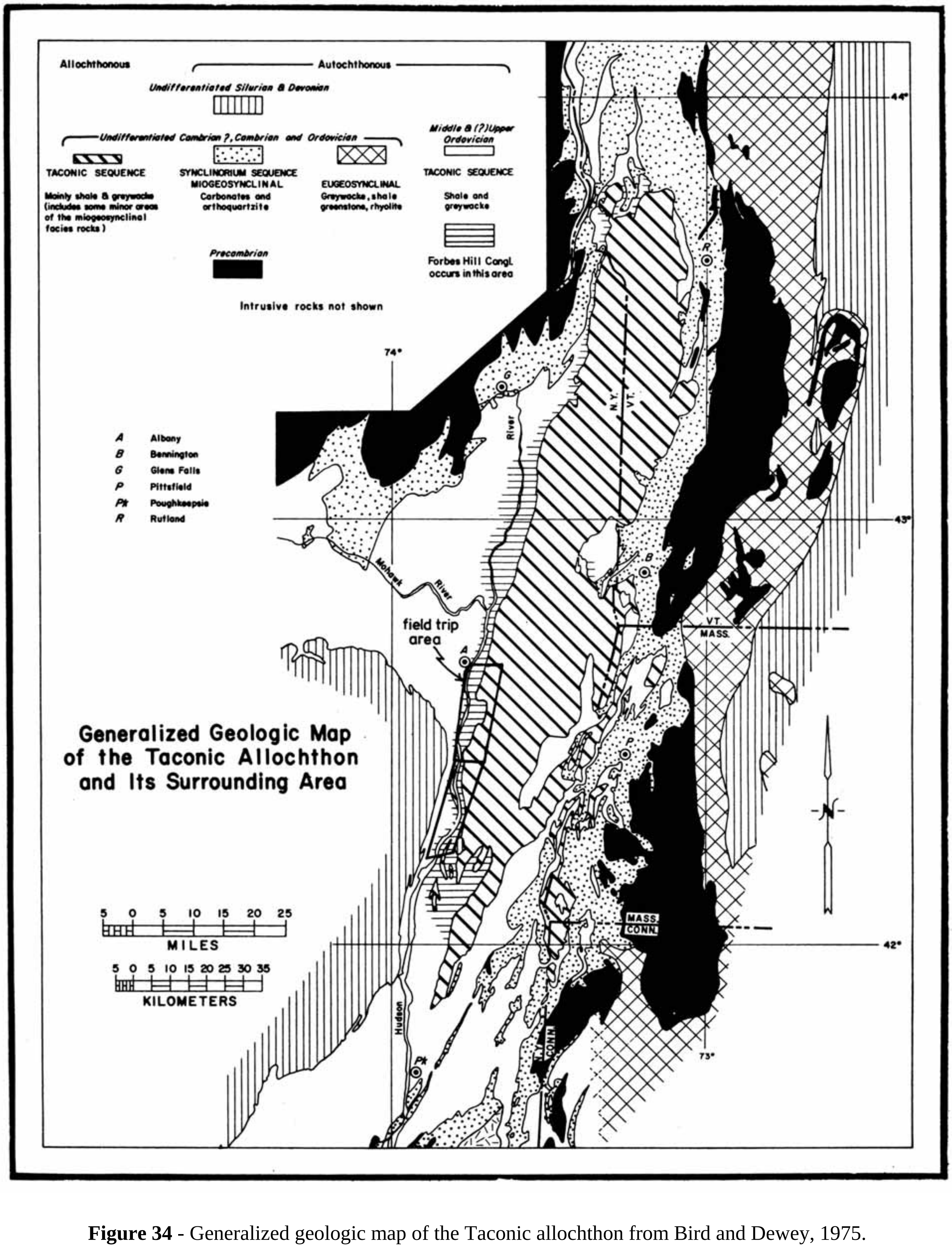


Figure 34 - Generalized geologic map of the Taconic allochthon from Bird and Dewey, 1975.

The "Taconic controvery" No. 1 centered on whether or not the rocks championed by Emmons did indeed represent strata deposited during a span of geologic time not yet identified by the European geologists who were busy naming new systems, many of which have been incorporated into the worldwide geologic time chart and thus should appropriately be accorded the exalted status of a new geologic system.

The strata within Hall's proposed "New York System" proved to be the same age as the rocks to which Sedgwick and Murchison (1838) had designated as Devonian System. Before this identity of the "New York System" and Devonian was known, Hall did everything he could to enhance the chances for having his "New York System" adopted. At the same time, he was eager to scuttle the rival Taconic System being touted by Emmons. Hall "sandbagged" Emmons at every turn, including making an incorrect identification of a key fossil found by Emmons (the only known example of such an error by New York's eminent first State Paleontologist).

The upshot of "Taconic controversy No. 1" was that the name Taconic was retained as a designation for all the terrigenous pelitic rocks, but the term was not adopted as a geologic system. Instead, the ages of the Taconic strata were found to span most of Cambrian and Early Ordovician time. Despite the efforts of its early geologists, neither of the proposed new systems based on New York rocks "made the cut."

"Taconic controversy No. 2" has pendulated back and forth and has not stopped moving. In order to explain what "Taconic controversy No. 2" is all about, we need to be specific about names and inferred ages. In our attempt to review this complex problem, it is useful to make use of terms that include large bodies of related rocks. For this purpose, we shall combine our scheme of "layers" as in Table 2 with the names of Sequences (in the sense of Sloss, 1963) as recently applied in eastern New York by Guo, Sanders, and Friedman (1990). Sloss proposed the concept of Sequences for strata underlying the North American craton that are set off from other groups of strata by a surface of unconformity of regional extent. The oldest of these he named the Sauk Sequence; it overlies the Precambrian basement and includes the carbonate rocks of our Layer IIA(W). The age range of the Sauk Sequence is from Cambrian (Early, Medial, or Late, depending on locality) through Early Ordovician. The carbonate rocks of the Sauk Sequence typically are dolomitic. Overlying the Sauk Sequence, and separated from it by a surface of unconformity of continent-wide extent is the Tippecanoe Sequence. The basal strata of the Tippecanoe Sequence are of Medial Ordovician age; they consist of limestones as contrasted with the Sauk dolostones. Above the basal limestones, the Tippecanoe Sequence consists of fine-textured pelitic rocks; these form Layer IIB of our Table 2.

The Taconic Sequence [Layer IIA(E) of Table 2] designates the terrigenous pelitic rocks the lower part of which are the same age as the carbonate rocks of the Sauk Sequence (Early Cambrian to Early Ordovician). Terrigenous pelitic rocks of the Taconic Squence were found in structural positions above the Sauk Sequence carbonates. Such an arrangement is the basis for the interpretation that a large Taconic overthrust had displaced the Taconic strata westward on the order of 100 km or more. (See summary in Kay, 1937.) The displaced Taconic strata were thus considered to constitute a vast allochthon.

Complications have arisen over the age span of the upper part of the Taconic Sequence. The issue is whether or not the upper part of the Taconic Squence spans the same range as the lower part of the Tippecanoe Sequence (Medial Ordovician).

Further understanding requires the reader to become familiar with some of the names of the subdivisions of the Middle Ordovician limestones of the lower part of the Tippecanoe Sequence and of some graptolite zones.

Early in the twentieth century, the Middle Ordovician limestones of the lower Tippecanoe Sequence in New York State were organized as follows:

Trenton

Middle Ordovician Black River Lowville Limestone in Upper Part

Chazyan

The key graptolites belong to a distinctive fauna associated with the genus Nemagraptus. The pendulating problem is the correct age of this diagnostic Nemagraptus fauna. In New York, the Nemagraptus fauna was found in the Normanskill Shale; in Tennessee, this fauna characterizes the Athens Shale. The issue is not whether the Normanskill correlates with the Athens Shale, but rather how to fit both the Normanskill and the Athens into a correct time-stratigraphic scheme. Wherever one of these formations is assigned, the other has to go with it.

The way to determine the correct position of a particular faunal zone is to study stratigraphic successions that are as complete as possible and to analyze the distribution within these successions of the contained fossil assemblages. As far as graptolites go, a long-standing tendency has existed for American paleontologists to assign particular graptolites to a higher stratigraphic position than British and Canadian specialists tend to do. A further way to check on the age assignments is to compare information obtained from strata containing graptolites (usually dark-colored shales) with that obtained from strata containing other fossils, for example brachiopods and trilobites in the limestones.

The age of the Normanskill Formation lies at the heart of the pendulating "Taconic controversy No. 2." JES would go so far as to contend that on the first swing of the pendulum, the initial controversy over the correct age of the Normanskill delayed any rational understanding of the Taconic strata for more than fifty years. We are now in the midst of the second swing of the pendulum. JES wonders if another 50 years will elapse before the matter is resolved.

The first swing of the pendulum involved a careful and comprehensive paleontological effort not likely to be duplicated ever again. The individual who carried out this great effort was Rudolf Ruedemann. Early in his studies of the Normanskill Formation, Ruedemann found the distinctive Nemagraptus fauna. Intercalated within the Normanskill Formation, Ruedemann found a peculiar formation that he named the Rysedorph Hill Conglomerate. The Rysedorph Hill Conglomerate contains fossiliferous limestone pebbles. Ruedemann collected a wagon load of these pebbles, took them to his house and broke them apart in search of fossils. To do this, he would heat the pebbles in the oven of his kitchen stove and then take a pair of tongs and plunge the hot pebbles into a bucket of cold water. The pebbles would break along any fossils within. Some of the pebbles contained Early Trentonian fossils. Given such fossiliferous pebbles, Ruedemann (1901b) concluded that the age of the Normanskill must be post-Early Trentonian. Indeed, he inferred that the age of the Normanskill fauna is Late Trentonian (in the older sense shown above; not Late Trentonian of G. A. Cooper, 1956). On the face of it, one would think that Ruedemann's results would have settled all questions about the stratigraphic age of the Normanskill Formation and the Nemagraptus fauna.

However, things were not that simple. And why? Because one of Ruedemann's contemporaries was a crusty character named E. O. Ulrich. Mr. Ulrich was a powerful individual and he thought that he understood the stratigraphic relationships of the Ordovician strata in northeast Tennessee beyond any shadow of doubt. There, the Athens Shale underlies a distinctive fine-textured limestone that looked just like the Lowville Limestone of New York. Indeed, it had been given the name Lowville. Most workers were happy both with this name and the interpretation that accompanied it, namely, that the formation was the same age as the New York Lowville. Therefore, whatever underlay the Lowville had to be of Chazyan age. Accordingly, Ulrich was convinced that the correct age of the Nemagraptus fauna of the Athens Shale of Tennessee (and also the Normanskill of New York) was Chazyan. In the face of Ruedemann's new data about the Early Trentonian age of the Nemagraptus fauna, one might have supposed that Ulrich would have reevaluated his faith in the Lowville Limestone situation. (As it later worked out, Cooper and Cooper in 1946 showed that the limestone in Tennessee is much younger than Ulrich thought, i.e., it is a correlative of the New York Trenton, not the New York Lowville.) But, Ulrich was Ulrich, and he thundered down on poor Ruedemann. Ulrich's message: THE NORMANSKILL IS CHAZYAN--period, exclamation point!

As long as the terrigenous Normanskill strata were assigned a Chazyan age, then the Normanskill had to be considered as belonging to the Taconic Sequence and thus to be a part of the Taconic allochthon (i. e., terrigenous strata same age as and above the carbonates). By contrast, if the age of the Normanskill initially assigned by Ruedemann and supported by W. B. N. Berry (1960, 1962, 1963, 1973) (i.e., post-Lower Trenton) is considered to be correct, then the Normanskill belongs to the Tippecanoe Sequence. Accordingly, its position above carbonates need not involve the Taconic allochthon. Instead, Trentonian-age Normanskill beds are parts of the autochthonous terrigenous strata that unconformably overlie the basal limestones of the Tippecanoe Sequence. Indeed, Berry's reaffirmation of Ruedemann's initial Trentonian age assignment of the Normanskill formed the basis of what was thought to be the "solution" to the "Taconic problem" (Zen, 1961, 1963, 1967; Sanders, Platt, and Powers, 1961; Platt 1962; Theokritoff, 1964).

In the face of Ulrich's dogmatic assertion, Ruedemann actually abandoned his original correct assignment of the age of the Normanskill as Late Trentonian. Every time Ruedemann wrote about this, he would quote Mr. Ulrich as "authority" for a Chazyan assignment. As a result, much of Ruedemann's geologic mapping turned out to be wrong. Everywhere he showed the supposedly Chazyan-age Normanskill, he had to map an overthrust at its base where it was in contact with the Cambro-Ordovician carbonates (whose topmost unit was the Lower Trenton Limestone).

One can only wonder at what private thoughts must have been dancing around inside Rudolf Ruedemann's head each time he was forced to "knuckle under" in print to Ulrich by reciting that Mr. Ulrich said the age of the Normanskill is Chazyan. Perhaps Ruedemann soothed his conscience by including his persistent disclaimers that the Normanskill might be as young as "Black River." (Ruedemann was thus trying to bring the Normanskill up in the column where he thought it belonged, but did not want to get Mr. Ulrich's back up by going as high as Trenton.)

How much farther along New York stratigraphy and -structure would have been if Ruedemann had been a more-combative individual. Scientific progress would have been greatly served had Ruedemann stood up on his hind legs on the age of the Normanskill and told E. O. Ulrich to go right straight to hell on this matter (and could have made that remark stick). As it was, Ruedemann lacked the courage of his correct scientific conviction, and the whole subject was a mess until W. B. N. Berry straightened it out in the 1960's. [Because of the likelihood that large-scale overthrusts took place in the Hudson Valley region during the Late Paleozoic deformation, it needs to be emphasized that an authochthonous structural position with respect to the Late Ordovician deformation does not preclude an allochthonous position during the Late Paleozoic deformation.]

In 1973, the pendulum took another swing. Following the graptolite zonation advocated by Jean Riva (a Canadian; note Ruedemann's comment above about the "Empire" propensity in graptolites), Rickard and Fisher (1973) published a paper advocating a "born-again" Chazyan age assignment for the Normanskill. It would be one thing if they had just published such a paper. Despite W. B. N. Berry's written comment that no basis existed for the Rickard and Fisher correlations, these two. being firmly entrenched in the New York State Geological Survey in Albany, were able to incorporate their disputed interpretation about the Chazyan age of the Normanskill into the second edition of the New York State geologic map. On this map, the strata in all localities previously mapped as Normanskill are indicated as belonging to the Taconic allochthon. In JES's opinion, this 1970 New York State geologic map incorporates all the errors of Ruedemann's mapping based on E. O. Ulrich's fiat about the Chazyan age of the Normanskill.

In the remainder of this discussion about how the status of the Taconic controversy affects the geologic relationships in New York City, we shall proceed on the proposition that the 1901 Ruedemann view as reinforced by W. N. B. Berry and others is correct. In other words, for the age of the Normanskill, we vote Trentonian; we totally reject the Ulrich-Riva-Rickard-Fisher-and anybody else's Chazyan assignment. As far as the rocks go, this means that in any region along the former passive continental margin which later experienced the conversion to a convergent margin, the following predictable relationships exist. At the bottom, basement. Above this, the Sauk Sequence, in eastern areas, beginning with Lower Cambrian. In the Sauk Sequence, dolomitic carbonates prevail (at least in areas closest to the former continental interior), but quartz sandstones are present at the base and at many levels higher up.

Above the regional surface of unconformity at the top of the Sauk Sequence are the limestones of the basal Tippecanoe Sequence. Collectively, the entire Sauk Sequence and the basal Tippecanoe limestones are the Cambro-Ordovician carbonates [our Layer IIA(W)]. Then comes another surface of unconformity along which more karst features formed; the shallow sea floor emerged and was subjected to the effects of rainfall and subaerial exposure. Then, the "plug" literally was "pulled" and the region subsided by thousands of meters. Deep-water terrigenous sediments, the Normanskill and equivalents, were deposited unconformably above the limestones. Such terrigenous sediments above carbonates resulted from rapid subsidence and deposition. These terrigenous sediments were not overthrust into their positions above the carbonates; they are younger than the carbonates. But, overthrusting is but a stone's throw (in time) away. While these Normanskill terrigenous strata were being deposited, the Taconic allochthon moved into high gear. The older terrigenous strata, namely the Taconic Sequence, whose age extends back to the Early Cambrian from whatever point within the Medial Ordovician the allochthon set forth upward and westward, plowed across the Normanskill sea floor.

Now, in a position structurally above the carbonates, the displaced older terrigenous pelitic strata [Taconic Sequence, our Layer IIA(E)] join with the in-situ younger terrigenous strata (Normanskill part of the Tippecanoe Sequence, our Layer IIB). The result is a great body of terrigenous strata above a great body of carbonates. After the whole has been subjected to regional metamorhism, the result is marble below and schists above. As a first approximation, one would suppose that all the schists are younger than the marble. This is exactly the interpretation formulated by the Merrill and his colleagues when they proposed the name Inwood Marble and Manhattan Schist. But, if the marble and the schists are metamorphosed rocks that are part of the "Taconic problem," then structurally above the marbles are two categories of schists: (1) those whose protoliths were deposited there as part of the Tippecanoe Sequence (Normanskill; our Layer IIB), which are younger than the marble; and (2) those whose protoliths were transported there as part of the Taconic allochthon [the Taconic Sequence, our Layer IIA(E)], whose age span is virtually the same as that of the marbles (exactly so for the bulk of the Taconic Sequence, but allowing for some to be younger at the top, namely whatever material kept on accumulating in the deep basin while the carbonates to the west were being eroded and while some parts of the Normanskill were being deposited).

In the CM view of things, the "good old Manhattan Schist" is the metamorphosed equivalent of the Normanskill strata (i. e., that part whose protoliths were truly in situ, belong to the Tippecanoe Sequence, and were deposited unconformably above the basal Tippecanoe limestones), whereas 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 Normanskill-age schists and another, for the overthrust marble-age schists. You pays your money, and you takes your choice.

The Taconic Orogeny

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 460-400 Ma were intruded. (See Table 1.) As mentioned, while the deep-water turbidites and related sediments of the Martinsburg Formation were accumulating, the Taconic allochthon was emplaced, with much of the thrust plate moving along the former sea floor. To many geologists, subscribing to the older thinking (Zen, 1967; Bird and Dewey, 1975; Ratcliffe and others, 1975) (Figure 35) 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 21) 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 due to continentward overthrusting of a subduction complex formed between the oceanward-facing continental margin sequence and the encroaching Taconic arc (Figure 21). The main argument for gravity-induced sliding of allochthons, the presence of olistostromes and wildflysch conglomerates on the western, leading edge of the Taconic allochthon, are now interpreted as deposits of forethrust olistostromes in front of an overriding accretionary wedge. 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, slivers of Cambro-Ordovician carbonate have been mapped and identified within the base of Taconic sole thrusts by Zen and Ratcliffe (1966) and by Ratcliffe and others (1975).

In Newfoundland, thick slices of oceanic lithosphere (i.e., an ophiolite succession) have been thrust over the Cambro-Ordovician shallow-water platform carbonates. Detrital chromite, a mantle-derived chromium oxide, probably shed westward during subaerial exposure of ophiolitic slabs, has been found in the flysch deposits associated with the Newfoundland "Taconics". One possibility, not yet confirmed, is that New England Taconian overthrusts transported granitic basement westward above the sedimentary strata-only Taconic allochthon, and that subsequent erosion completely removed any and all such slice(s) of granitic basement on the overthrust block. This possibility is mentioned here because an overthrust block composed of granitic basement rocks could have provided a supply of coarse quartz to form the Lower Silurian Green Pond-Shawangunk-Tuscarora-Clinch sheet of sandstones and local conglomerates at the base of Layer III. Alternatively, the thick quartzose deposits could have been formed from reworked bull quartz veins found along the Taconic thrust faults (JES thinks this is a lot of bull, quartz!), or from eroded pegmatites associated with the roots of the Taconic volcanic arc. The parent deposit of all this Silurian-age quartz is, as yet, a mystery.

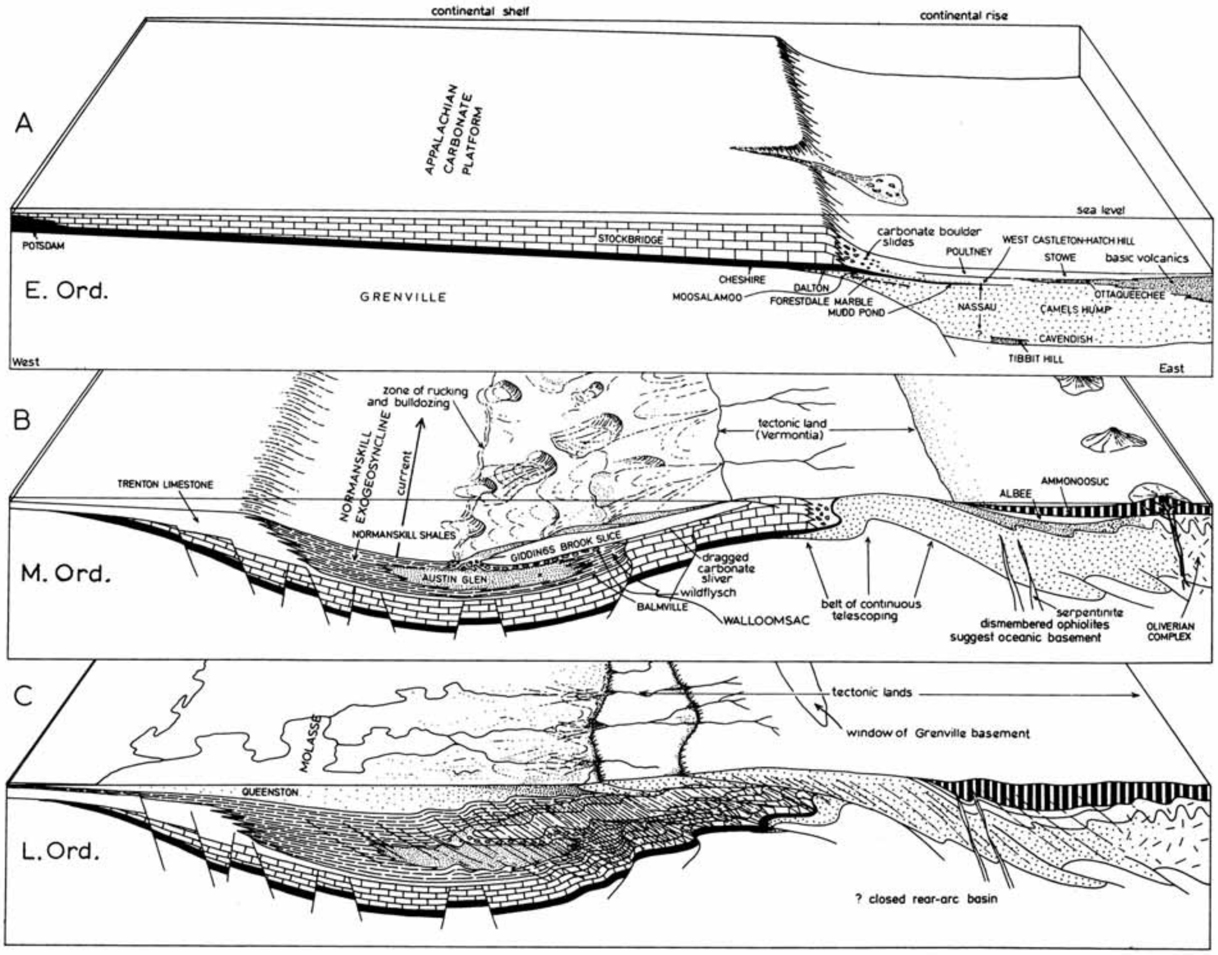


Figure 35 - Sequential block diagrams illustrating Ordovician tectonism and emplacement of Taconic slides as envisioned by Bird and Dewey, 1975.

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 occurs.

Post-Taconic Crustal Disturbances

Following the Taconic orogeny, the rocks of southeastern New York were effected by a number of Paleozoic mountain-building disturbances which involve folding, metamorphism, and faulting (both high- and low angle). As summarized on Tables 1 and 2, the Acadian orogeny of Devonian age produced folds; rocks were deeply buried and regionally metamorphosed; and the Peekskill Granite as well as other granites were intruded. In addition, in the rocks of Layer III, the Acadian orogeny produced high-angle reverse faults and possibly low-angle thrusts. After the Acadian orogeny, southeastern New York underwent an episode of continued uplift and erosion. In the Permian Period, however the terminal phase of the Appalachian orogeny occurred. (Some geologists, wishing to downplay the concept that the Paleozoic Era was brought to a close by a majestic Appalachian orogeny, propose to trivialize, even abandon the term Appalachian, and in its place, to establish the Alleghanian.) The effects of the Late Paleozoic orogeny are best observed in the southern Appalachians and in Rhode Island where rocks of late Paleozoic ages have been folded, faulted, intruded, and metamorphosed. In these widely separated areas, low-angle overthrusts involving basement, and coincident folding of sedimentary cover rocks is well documented. In addition, coal in Pennsylvanian-age strata in Rhode Island has been raised to the rank of graphite and in eastern Connecticut, granites were intruded.

Armchair geologists (or plate pushers) conjecture that the Acadian orogeny was driven by continentward subduction of ocean crust to the oceanward side of the Taconian arc-continent collision zone. Thus, the Acadian orogeny, basically a brief, thermal event, could be visualized as the result of Andean-type subduction. Following a period of strike-slip displacement of geologic terranes, the "big one", as Fred Sanford would say, occurred. The Appalachian orogeny is thought to have been the result of a continent-continent collision between North America and Africa to close out the Paleozoic Era. Deep seismic- reflection profiles across the southern Appalachians documents the significance of low-angle overthrusts of crystalline basement rock. In some cases, layered reflectors (probably Paleozoic sedimentary strata), are trapped beneath the huge overthrust sheets. Clearly, the effects of late Paleozoic low-angle thrusting cannot be discounted in southeastern New York just because the post-Devonian strata were here eroded (or not deposited).

There are obviously many post-Taconic events to explain the multitude of folds and low- to high-angle faults found to affect Taconic rocks throughout southeastern New York. In addition to these of Paleozoic age, remember (Table 1) that during the Triassic and Jurassic, North America and Africa split apart again with renewed normal and strike-slip faulting. Commonly, the rejuvenation of plate motions reactivates pre-existing weak zones in the Earth's crust. Thus, it is not uncommon to find faults with complex, movement histories that may, in fact, record protracted Taconic, Acadian, Appalachian, as well as Newarkian tectonic activity. In the field, we shall attempt to identify and discuss these post-Taconic structures and develop the idea that high-angle faulting and block uplifts (horsts) and downwarps (grabens) can cause abrupt changes in lithology and metamorphic grade. Steep metamorphic gradients, truncated low-angle thrust faults, and rapid lithologic variations may be the result of such faulting.

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 36). 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). A sequence of poorly bedded silt and turbidites formed outboard of the shelf on quasi-continental "transitional" crust (middle unit of the Manhattan Schist - Ꞓ-Om) and in the deeper oceanic environment, deep-water shale, turbidite, and intercalated volcanic rock accumulated on oceanic crust in the vicinity of a volcanic archipeligo (Hartland Terrane - Ꞓ-Oh). (See Figure 18.)

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 30) 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.

Layer III: The Siluro-Devonian Carbonate and Terrigenous Strata

In the aftermath of the Taconic orogenic event which involved an arc-continent collision resulting in continent-scale overthrusting of deep-water eastern Taconic strata over shallow-water western carbonates, folding, local metamorphism, and mafic (alkalic) intrusive igneous activity, uplift and erosion created a planation surface atop which Silurian and Devonian strata were eventually deposited. This surface of unconformity is marked by the contrast between the underlying deformed Taconic slates and the overlying, subhorizontal Silurian and younger carbonate and clastic rocks.

The Silurian and Devonian strata of eastern New York State mark an important succession of basal terrigenous clastics (including the Shawangunk Formation, High Falls Shale, and Binnewater Sandstone), overlain by waterlimes of the Manlius and Rondout Formations which grade upward into a magnificent collection of carbonates of the Helderberg Group of Devonian age. The carbonates, together, form an impressive carbonate bank analagous to the present-day Bahama Banks off of the southeastern United States.

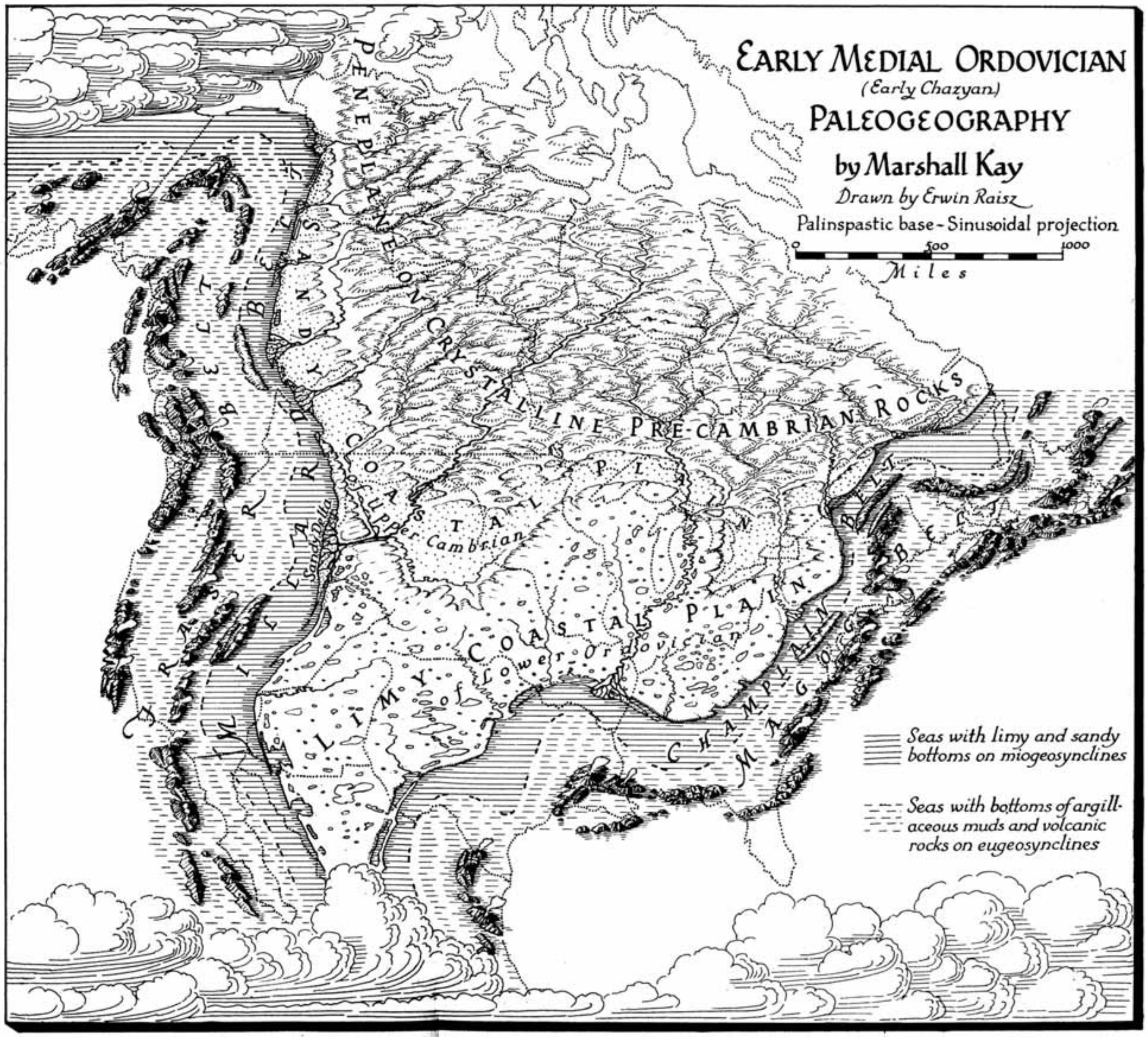


Figure 36 - Paleogeographic map of North America in Early Paleozoic time (Kay, 1951).

Gradually, the carbonate succession was replaced by conglomerate, chert, siltstone, shale, and eventually coarse clastics that grade upward into the famous Catskill redbeds or "Old Red Sandstone". Thus, the Catskill fan-delta complex was built upon the carbonate bank as uplift and erosion of the Acadian orogenic belt (in New England) shed coarse clastics continentward and eventually, but not without occasional marine incursions, built up an intracontinental delta. So the next time your friends invite you to go to "the Catskill Mountains" be sure to correct your friends, resolutely, by informing them that "they're not mountains, they are a dissected, uplifted fan-delta complex!"

Layer V: Newark Basin-Filling Strata

The tilted and eroded remnants of the Newark strata are exposed along the west side of the Hudson River, from Stony Point south to Staten Island. As shown on the diagonal cut-away slice in Figure 37, the Newark strata generally dip about 15° to the northwest.

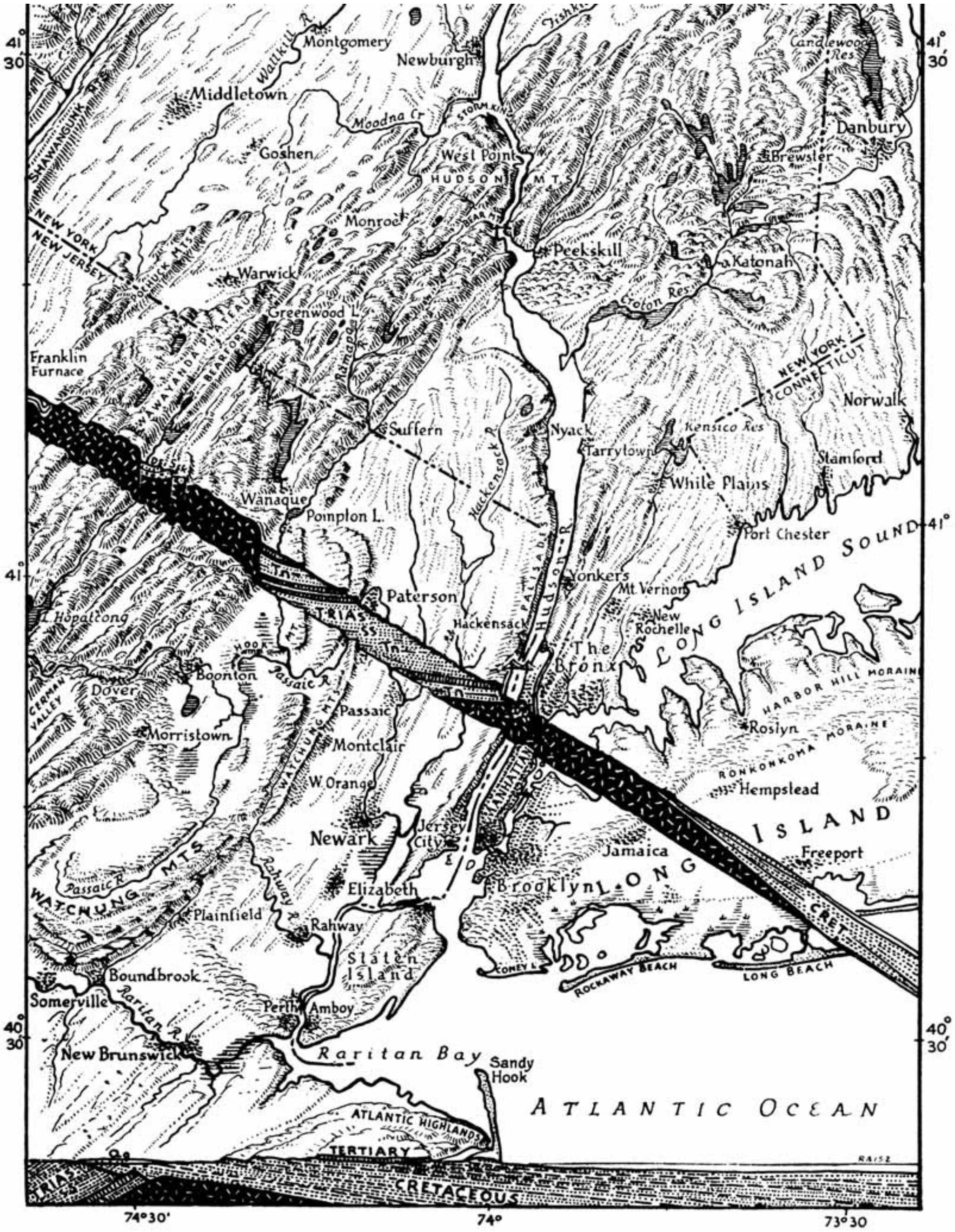


Figure 37 - Physiographic block diagram of the lower Hudson River region (drawn by E. Raisz).

The formal stratigraphic name for the Newark strata is Newark Supergroup. Included are various sedimentary formations, of which the basal unit is the Stockton Arkose. Above it is the Lockatong Formation, the unit into which the Palisades Sill has been intruded. Higher up are other sedimentary units and three interbedded sheets of mafic extrusive igneous rock (ancient lava flows), whose tilted edges are resistant and underlie ridges known as the Watchungs. The age of the sedimentary units beneath the oldest extrusive sheet is Late Triassic. The remainder of the formations are of Early Jurassic age.

The Newark sedimentary strata were deposited in a fault-bounded basin truncated on the northwest by the Ramapo fault (Figure 37) to which the sea never gained access. In this basin, the filling strata were deposited in various nonmarine environments, including subaerial fans, streams, and shallow- and deep lakes. Lake levels varied according to changes in climate (Olsen, 1980).

After the Newark strata had been deeply buried, they were elevated and tilted, probably during a period of mid-Jurassic tectonic activities. They were then eroded and truncated to form a surface upon which the Upper Cretaceous and younger coastal-plain strata of Layer VI were deposited.

Layer VII: QUATERNARY SEDIMENTS

The Quaternary sediments include: (1) the Pleistocene deposits made by continental glaciers that formerly flowed across the region and various bodies of outwash that were deposited when the glaciers melted; and (2) Holocene sediments that were deposited during the Flandrian submergence, which took place as the continental glaciers disappeared.

Pleistocene Deposits

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 and asymmetric features created by glaciers, and outwash.

Till And Asymmetric Features Created By Glaciers

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 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. We discuss these two kinds of deposits at greater length in the following paragraphs.

An important point to be determined in studying a glacial deposit is which way the glacier flowed. Because glaciers create scratches and even large grooves on solid bedrock, it is usually a straightforward matter to infer ice-flow direction. It is along the trend of the linear grooves, striae, and other elongate features.

In some places, the ice created various crescentic marks (Flint, 1971, p. 95; G. K. Gilbert, 1906; S. E. Harris, 1943; P. MacClintock, 1953). The use of crescentic marks for inferring the direction of ice flow is based on 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. Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the direction of flow (Figure 38).

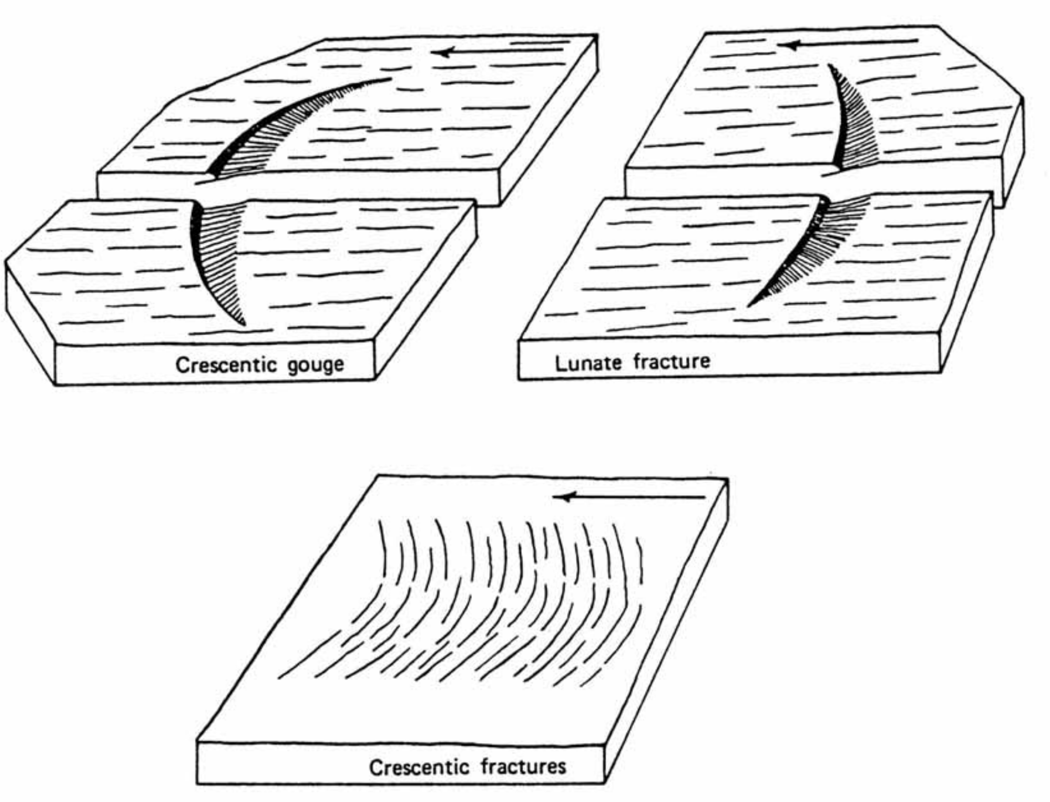


Figure 38 - Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

Glaciers also sculpt larger-scale asymmetric relief features in the bedrock known as roche moutonnée (Figure 39). 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 39)].

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 40). 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 consisting 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.)

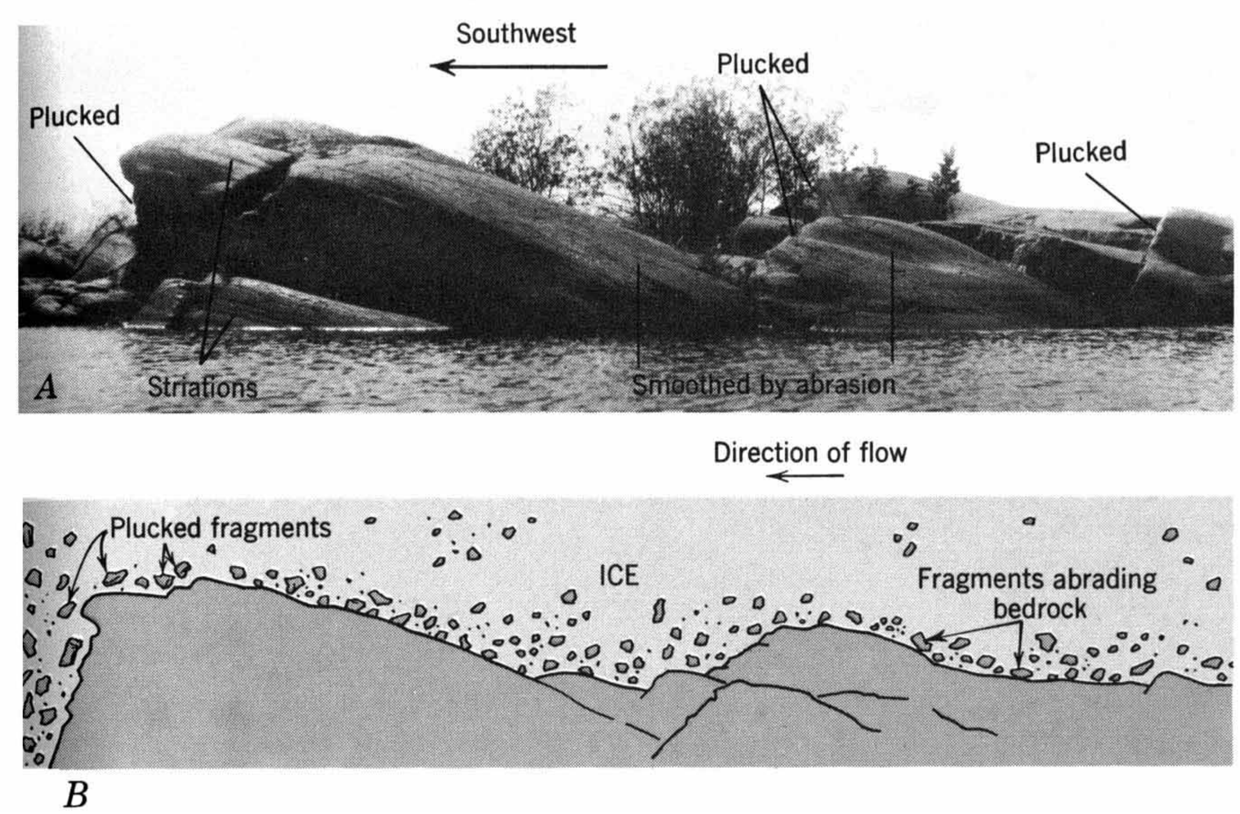


Figure 39 - Roche moutonnées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roche moutonnées sculpted in Proterozoic granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnées beneath a glacier.

Direction of flow may also be inferred by studying provenance; that is, the source of the particles in the deposits. 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.

L. D. Gale's study of "Diluvial scratches and furrows" carried out in 1828-1829.

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). At that time, most of the present-day streets had been laid out, but only a few buildings existed north of what is now known as Lower Manhattan. Therefore, Gale's street references can be taken directly, but one has to realize that either no buildings were present, or the ones to which he does refer have probably been long removed.

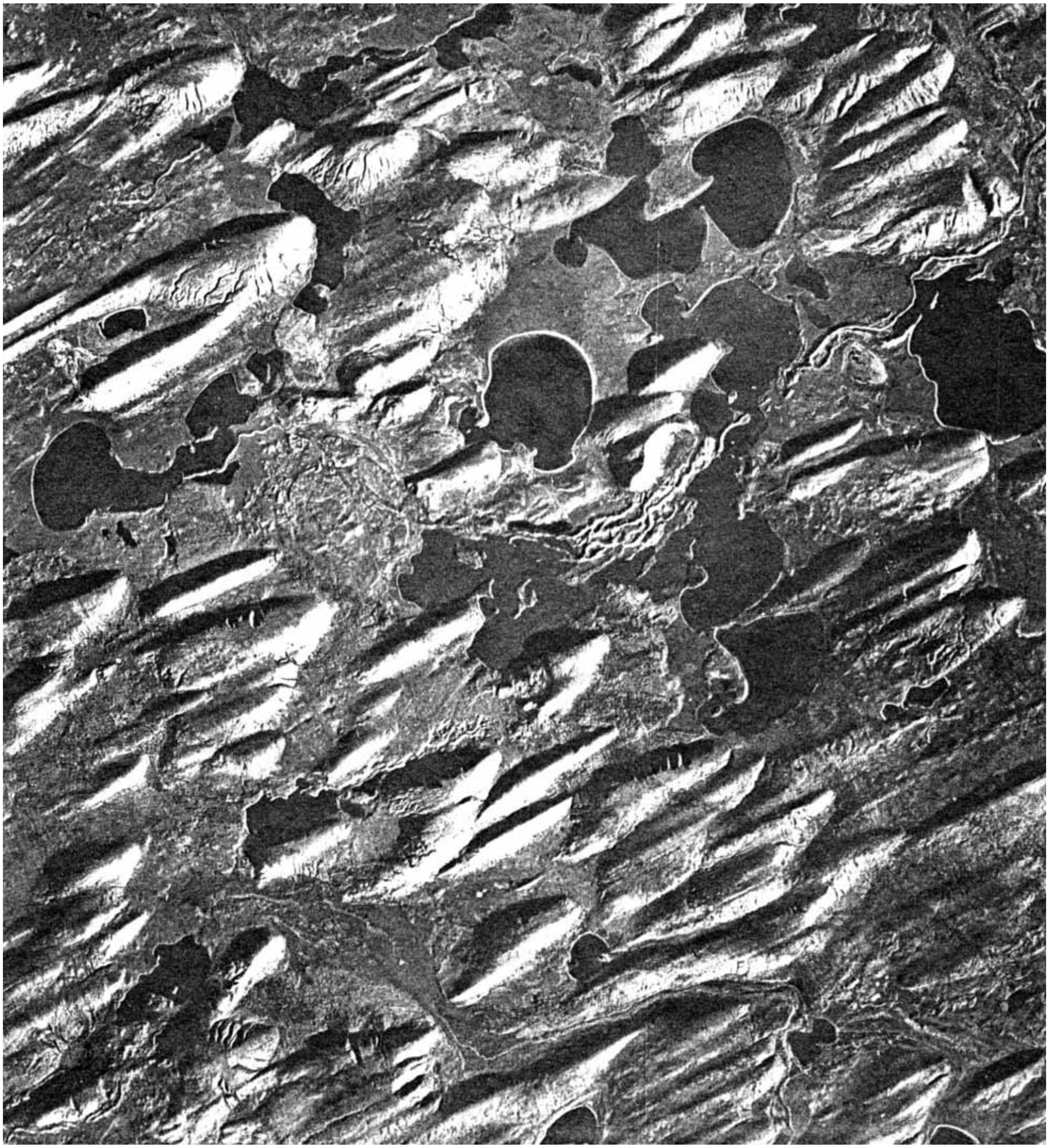


Figure 40 - Swarm of drumlins viewed from vertically above in aerial photograph, northern Saskatchewan, Canada, created by a glacier that flowed from NE (upper right) to SW. The small circular lakes give the scale; their diameters are about 1 kilometer. The thin, curvilinear light-toned features extending 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.)

As was common in his day, Gale supposed that the grooves and scratches had been made by water currents, perhaps assisted by icebergs. The presumed significance of water is implied in the use of the term diluvial. L. D. Gale (1839, Geological Report of New-York; New-York island; in Mather, 1843, p. 209-210): (p. 209.)

> "Diluvial grooves and scratches have been found in every section of the island, from Sixteenth-street on the south, to 200th-street on the north, (or to the southern termination of the limestone;) and from the banks of the Hudson on the west, to Harlem river on the east. The furrows generally are most distinct where the rock has been recently uncovered, and least where it has been long exposed to the action of the elements. They have been found on the highest rocks, and at the lowest tide-water marks, being a difference of more than one hundred feet perpendicular height. The furrows are always most strongly marked on the northwestern slopes of the hills, and least so on the southeastern. In many instances they are very distinct on the western and northwestern slopes, extending to the highest point of the rock; but no traces are to be seen on the eastern and southeastern slopes, although both slopes are equally exposed.
>
> "Direction of the furrows. Observations of the diluvial furrows were made in between sixty and seventy different places on the island. Taking together the whole series of observations, the general course of the current was from northwest to southeast, or north forty-five degrees west, but varied in the extremes from north twenty-five degrees west to north forty-eight west, making a difference of twenty-three degrees. Of the whole series of observations, thirty-nine were north forty-five degrees west, twelve varied from north forty-five degrees west (seven being north thirty-five degrees west), two were north forty-eight degrees west, and a few scattering ones varying from north thirty-five degrees west to north forty-five degrees west. (JES query: did they know about magnetic declination?)
>
> "Abundance of the furrows. The furrows occur most abundantly in the middle portions of the island, between the city and the Harlem and Manhattanville valley, somewhat less in the western, and least of all in the eastern.

"Direction of the furrows in particular neighborhoods. Half of all the places where the furrows were noticed were in the middle portion of the island, in the line of the Eighth avenue from Sixtieth-street to 105th-street, where without exception the direction is north forty-five degrees west. About one fourth of all are on the west side, and vary but little from north thirty-five degrees west; and about one-eighth on the eastern side, where the direction varies from north twenty-five degrees west to north thirty-five degrees west. In connection with this subject, I have examined the surface of the greenstone on the neighboring shores of New-Jersey (sic), and find their grooves and scratches abundant, and their general direc-/ (p. 210): tion is north forty-five degrees west. Hence it appears, that the diluvial current which once swept over this island from northwest to southeast, on reaching the western shore, was deflected southward, as by the action of some force at a right or some other angle to its course; and that the same current, before it reached the middle of the island, again assumed a southeasterly direction, but was again diverted southerly on approaching the eastern shore. That some portion of the current was diverted southerly on reaching the western shore of the island, is evident, not only from the diluvial furrows, but from the boulders of anthophyllite found in large numbers in the lower part of the Eighth avenue near Fifteenth-street, a distance of two miles in a south-southwest direction from the only locality whence they could have proceeded. Again, the white limestone of Kingsbridge has been distributed along the eastern shore of the island, in a direction almost due south of the only locality in the vicinity where it is found in place; whereas had they been carried in the general direction of the current, they would have been deposited eastward in Westchester county, as before stated.

"Magnitude of the furrows. The size of the furrows varies in the same and different localities. Sometimes they are the finest scratches, not more than a line in diameter horizontally, and of the smallest appreciable depth; from this they increase

> to grooves four inches deep and eighteen inches in horizontal diameter. In a few cases, they are furrows, or rather troughs, more than two feet wide and six or eight inches deep. A case of the latter kind occurs on Eighth avenue, between Seventy-ninth and Eight-first-streets; and one of the former on the west side of the island, on the very banks of the Hudson, five hundred yards north of Mr. John H. Howland's country seat (near Ninety-seventh-street).
>
> "Convenient places for examining the diluvial furrows. The nearest places to the city for examining the furrows are at the junction of Twenty-second-street and First avenue, south of the Almshouse yard; and again about half a mile northward at Kip's bay, at the junction of First avenue and Thirty-fifth-street. Both of these localities will soon be destroyed by grading the streets. Some of the most interesting localities have been made known by cutting through Eighth avenue, from Bloomingdale road, at or near Sixtieth-street, to Harlem and Manhattanville valley at 105th-street; these locations are on both sides of the avenue, and very conspicuous. Another, equally interesting in many respects, is on the banks of the Hudson west of the Bloomingdale road, about six miles from the city, and about six hundred yards northwest of Burnham's hotel. The interest excited by this locality arises from the fact, that the furrows ascend from beneath the lowest tide water, up to an elevation of seventy feet in three hundred or four hundred feet distance." (Gale, 1839, p. 197, 199).

Gale's observations clearly suggest the effects of two contrasting flow directions, (a) nearly all the "diluvial scratches and furrows" indicating flow from the NW to the SE and (b) the displacement of indicator erratics (the anthophyllite-bearing rock and the white limestone) showing transport from the NNE to the SSW. Yet his interpretation of his data was that of a single event, which he expressed as "the diluvial current." Gale tried to show how the changes in flow of a single such current could account for both the regional trends of the scratches and furrows on the smoothed bedrock and the displaced indicator erratics. In this regard, Gale began a pattern that would be followed by most subsequent students of the "diluvial" deposits: trying to account for all the disparate observations by invoking only a single transport event. But Gale's single transport event differed significantly from the one favored by later investigators. Gale concluded that his single "diluvial current" had flowed from NW to SE and he sought aberrations in this flow direction to account for the displacement from NNE to SSW of indicator erratics. In contrast, the single flow event for most later workers was taken to be from the NNE to the SSW; they invoked aberrations to explain the scratches and furrows that trend NW-SE.

Other Ideas about Multiple Ice-flow Directions

Several interpretations of these two sets of ice-flow indicators are possible. The two ideas analyzed here are: (1) that various changing conditions caused the direction of flow of a single ice sheet to shift with time, and (2) each set of flow directions was made by a single glacier having only one dominant flow direction.

(1) 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.

As indicated previously, L. D. Gale's initial investigation of the "diluvial scratches and furrows" on the surface of the bedrock on the then-undeveloped central and northern parts of Manhattan resulted in the discovery of direct evidence of what would now be considered to have been 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. 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 41). 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 42). 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:

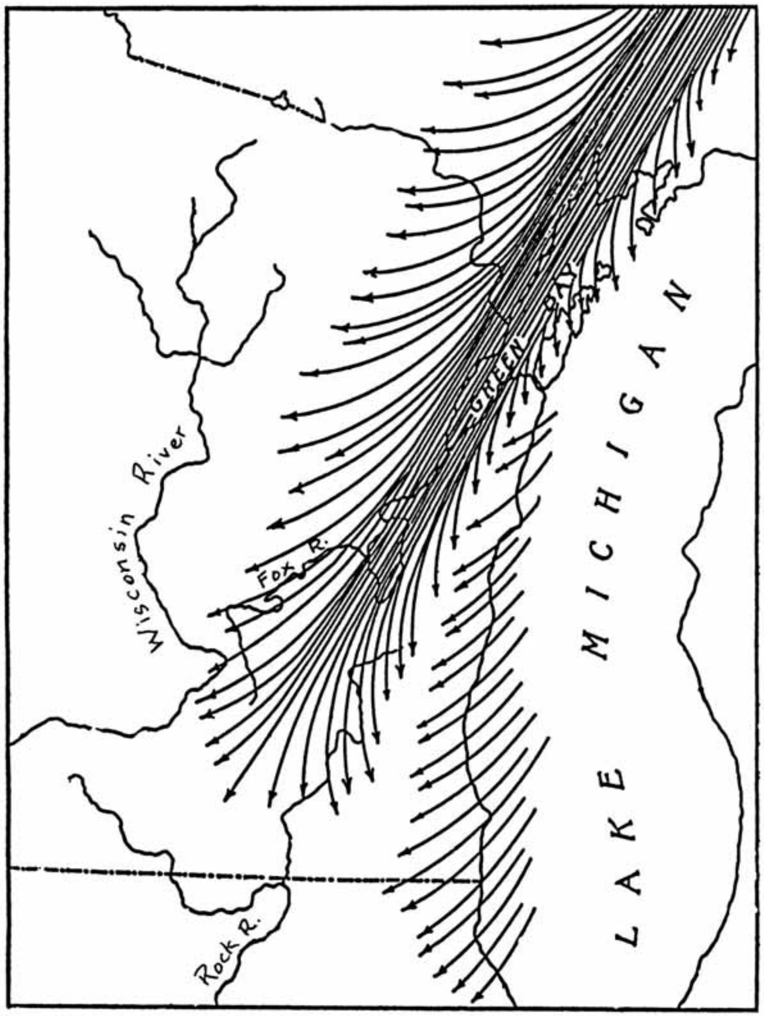


Figure 41 - Sketch map of area west of Lake Michigan (mostly in Wisconsin, but including parts of Michigan and Illinois), showing concept of divergent flow from a narrow zone (centered above Green Bay, Wisconsin) of rapid flow within an ice sheet. (R. D. Salisbury, 1902, fig. 31.)

> "No single Green Pond mountain conglomerate bowlder has been found on the ridge. West of Hackensack, such bowlders are found in abundance, and this in spite of (sic) the fact that in New Jersey the movement of the ice along the Green Pond mountain range was to the southwest, approximately parallel to the range itself. Glacial movement in this direction could not have carried bowlders from the New Jersey part of the the Green Pond mountain formation to the Hackensack valley. It would seem that the conglomerate ledges which furnished the Hackensack valley bowlders must have lain somewhere north of New Jersey, in the axis of the ice lobe, or

perhaps a little to the west of it, and that the bowlders derived from this ledge were carried southward in the direction of ice movement, and finally out of the valley onto the highlands to the west by the westerly-diverging currents, but that they were not brought within the influence of easterly diverging currents, and therefore were not carried eastward upon the Palisades ridge. Another hypothesis which would equally well explain the distribution of the Green Pond mountain conglomerate bowlders, but for which there is no demonstrative evidence at hand, is that these bowlders were carried southeastward from their parent ledges by an earlier ice movement, the movement in the last epoch being to the southwest over or along the Green Pond mountain formation. A good deal may be said for this suggestion. The distribution of these bowlders has not been studied beyond the State of New Jersey" (Salisbury, 1894, p. 180).

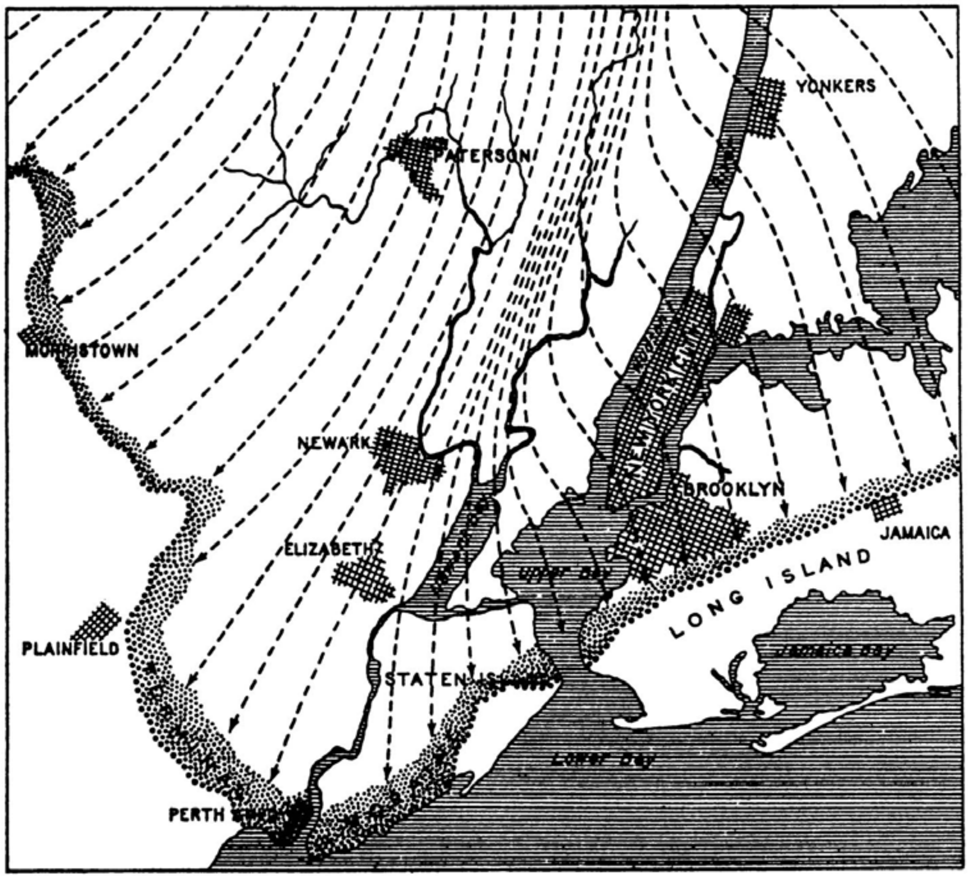


Figure 42 - Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (U. S. Geological Survey, Passaic Folio, No. 157, Figure 11, 1908, rendering of R. D. Salisbury).

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.

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.

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.

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.

Striae, crescentic marks, directions of asymmetry of roche moutonnées, long axes of drumlins, and indicator stones all show 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.

Figure 43 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.

Figure 43 - 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).

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 42).

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. By contrast, the borings from valleys that trend NW-SW display a more-complicated succession of sediments. JES infers that these complex sediments in the fillings of valleys that trend NW-SE are products of glaciers that flowed from NW to SE that that would tend to deepen valleys having orientations parallel to their direction of flow. Any sediments that were deposited in valleys trending NW-SE would tend to be preserved from destruction by ice flowing from NE to SW. By contrast, any such complex deposits that may have been deposited in valleys trending NE-SW would have been especially vulnerable to total removal by a glacier flowing from NE to SW.

From studying the stratigraphic relationships, provenance, grooves and crescentic gouges on bedrock surfaces, directions of asymmetry of roche moutonnées and of drumlins, JES proposes an alternative view. In the JES scheme of things, the flow indicated in Figure 42 is not the product of one glacier, but of more than one (two, possibly more). Figures 44 and 45 show how JES interprets the glaciers in the same area of Figure 42. In Figure 44, 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 45 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 44. The latest glacier, shown in Figure 45, 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.

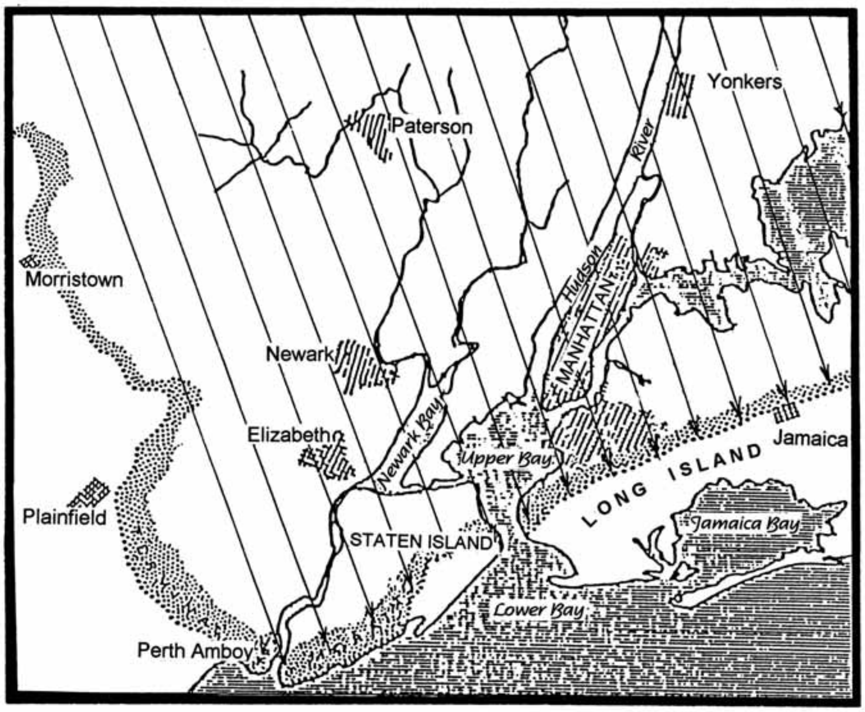


Figure 44 - Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders).

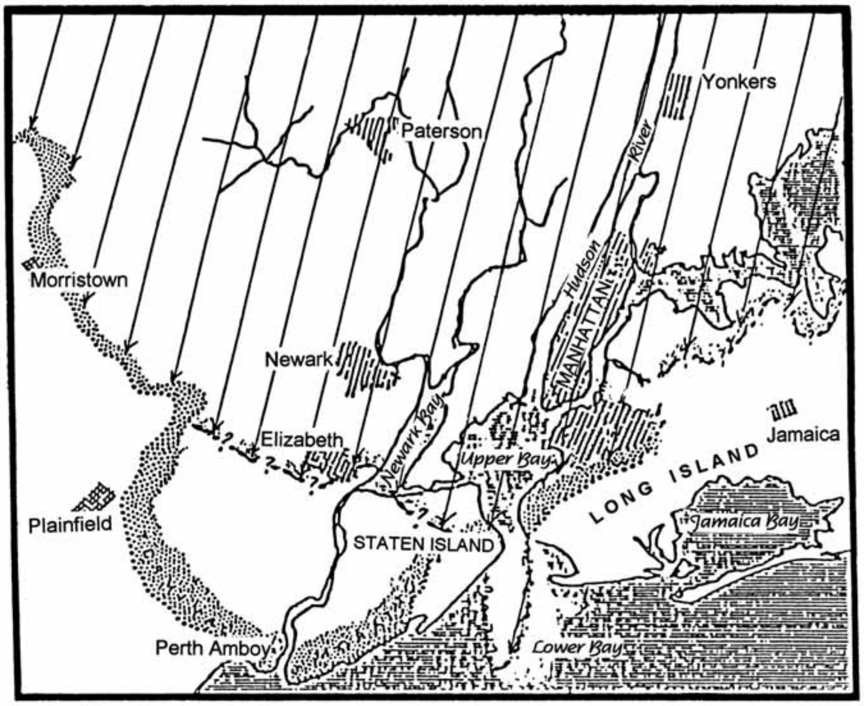


Figure 45 - Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

The distribution of erratics derived from as far away as the anthracite district in eastern Pennsylvania (Figure 46) in the red-brown tills and -outwashes in localities east of the Hudson River (as in New York City and Westchester County, New York) lends strong support to the JES interpretation shown in Figures 44 and 45, as contrasted to Figure 42. The finding by JES of natural erratics of anthracite in the red-brown till in the Hudson Valley 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).

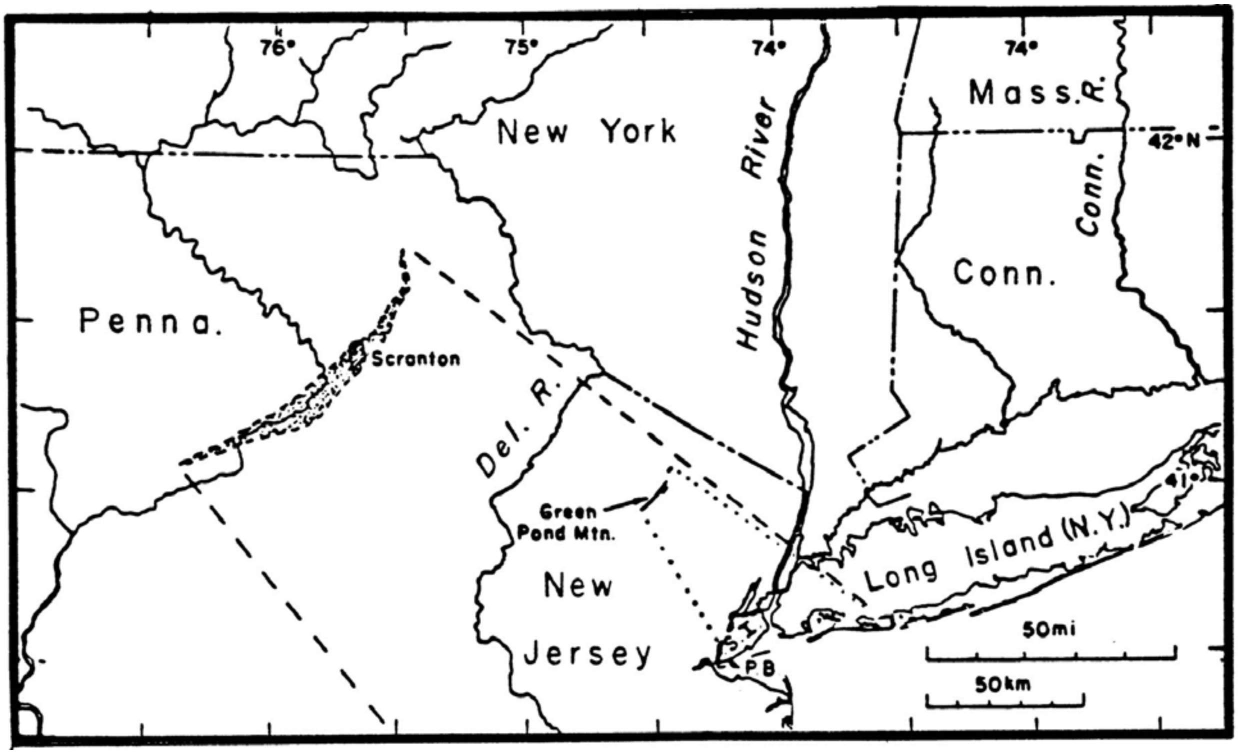


Figure 46 - Distinctive erratics found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten Island; P. B. = Princess Bay. (Friedman and Sanders, 1978, Figure 2-1, p. 27.)

Evidence for glacial flow from the NW to the SE is not confined to the territory near New York City. Figure 47 shows examples based on swarms of drumlins near Charlevoix, Michigan (northwestern part of southern peninsula) and on indicator stones in New England.

Stratigraphy of Pleistocene Sediments

The stratigraphy of glacial deposits is worked out by noting the relationships among till, outwash, and sediments that have nothing at all to do with a glacier and, in fact, were deposited under a climate regime that is nonglacial. In a coastal area such as New York, glacial deposits are interstratified with marginal-marine deposits. This has resulted from the relationship between growth of continental ice sheets and the volume of water in the ocean basins. Professor

R. A. Daly, of Harvard, once described this relationships between glacial ice and the water of the oceans as one of "robbery and restitution." By robbery, he meant the locking up of the water in the glaciers. By restitution, he meant the return of the water to the oceans when glaciers melted. Although the exact climate settings involved in these changes are not as well known as one might suppose, it is well established that when the glaciers reached their maximum extents, the sea was at its lowest stand, a level around 75 m lower than now.

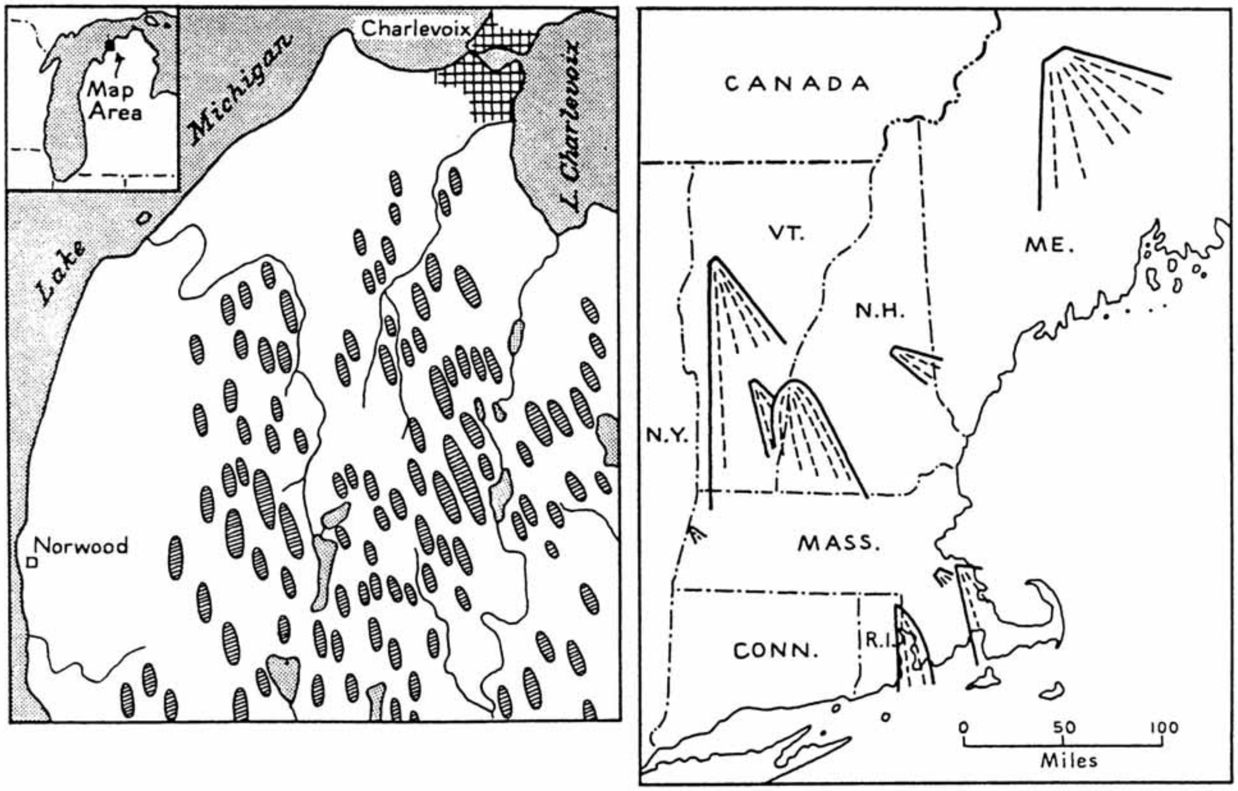


Figure 47 - Sketch maps showing other regions in the United States where glacier flow was from NW to SE.
A. Swarm of drumlins south of Charlevoix, Michigan. (Frank Leverett, and F. B. Taylor, 1915, p. 311; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-20, p. 188.)
B. Boulder trains in New England, 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. 190.)

The most-critical evidence for interstratification of glacial- and nonglacial sediments comes from borings in the general vicinity of Jones Beach. Here, sandy strata interpreted as outwash deposited during times of emergence are interbedded with fossiliferous marginal-marine strata deposited during a submergent episode. (Rampino, 1978 ms.; Rampino and Sanders, 1976, 1980, 1981a, b; Figures 48, 49).

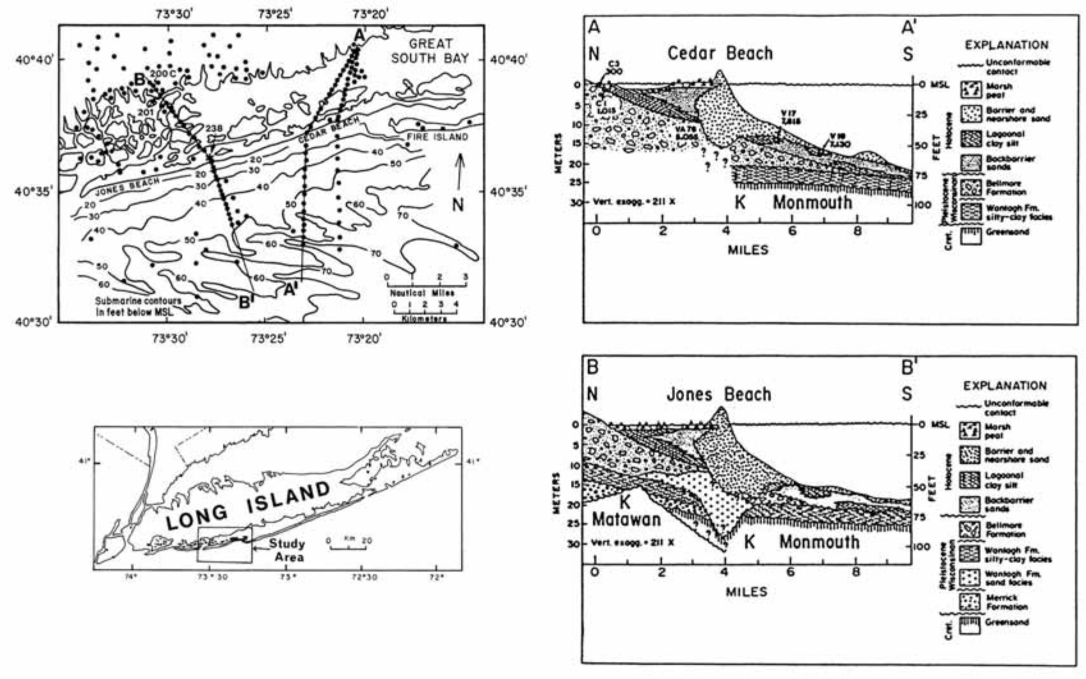


Figure 48 - Index map showing locations of profile-sections across the south shore of Long Island.

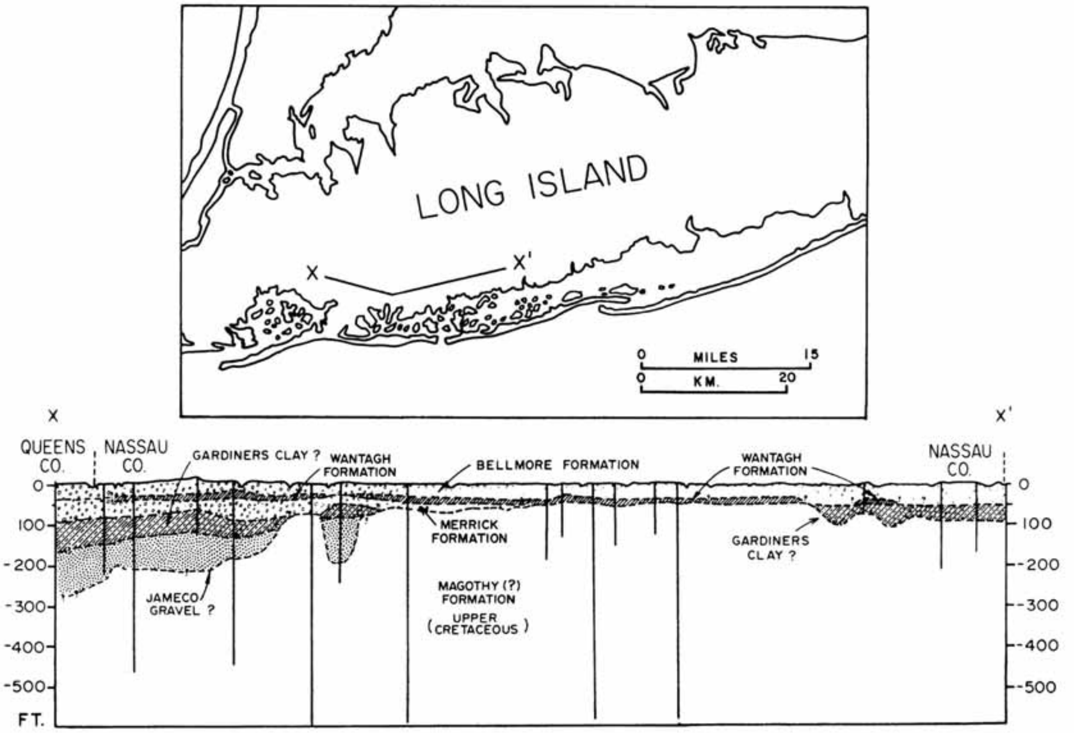


Figure 49 - Subsurface relationships in southwestern Long Island shown by data from water wells. Line XX' on map locates profile section at bottom. Wantagh Formation is marginal-marine deposit known informally among geologists of the Water Resources branch of the U. S. Geological Survey as the "20-foot clay." (Data from wells from U. S. Geological Survey; stratigraphic interpretation by Rampino, 1978 ms.)

Field studies by JES and CM in connection with preparation of guidebooks for these On-The-Rocks trips have turned up evidence which is completely at odds with the prevailing "one-glacier (or possibly at the most, two)" view of the Pleistocene sediments in New York City and vicinity. JES and CM visualize relationships as shown in Table 3. The two most-drastic changes shown in Table 3 as compared with "conventional wisdom" are: (1) based on provenance and thickness of weathering rinds on stones, JES and CM infer that the latest glacier, the Woodfordian, which flowed down the Hudson Valley (the second one from the Labrador, flow direction NNE to SSW, thus indicated by LII in the table) did not reach most of Long Island, but rather left its end moraines along the south coast of Connecticut (Flint and Gebert, 1974, 1976; situation depicted in Figure 45); (2) An ancient till containing decayed granitic stones (thus matching the descriptions of Fuller's Manetto Gravel) and evidence of flow from NNE to SSW (indicated as LI in Table 3) is present on Long Island (discovered by JES and CM after storm erosion and some digging at Garvies Point), on Staten Island, and at the S end of Tellers Point, Croton Point Park. Elsewhere, the former erosive activities of this inferred early glacier are shown by rock drumlins having long axes oriented NNE-SSW that have been remolded by ice flow from NW to SE.

The two sandy formations in the subsurface of southern Long Island (Merrick below, Bellmore, above) separated by the interglacial Wantagh Formation (= the "20-foot clay" of various authors from the U. S. Geological Survey Water Resources Division) have been interpreted as belonging to the same glacial meltdown episodes during which Long Island's two prominent moraines were fashioned. Thus, Bellmore goes with the Harbor Hill Moraine; Merrick, with the Ronkonkama Moraine. If this coupling of inferred outwash sediments and moraines is correct, then it implies that the age of the Harbor Hill moraine is no younger than medial Wisconsinan and that of the Ronkonkama, probably youngest Illinoian. Such a correlation represents a significant shift of these two moraines downward in the geologic time scale from the position assigned to them by Fuller (and everybody else), namely, the latest Wisconsinan.

How these newly proposed correlations fare in the future will probably depend to a considerable degree on careful sedimentologic study of the samples from the myriad of engineering borings that have been made over the years in New York City and vicinity. From these newly proposed correlations, specific, checkable hypotheses about the provenance and degree of alteration of minerals can be made. The time for testing is at hand.

In addition to ripping up individual fragments from the material over which it passes, a glacier may also deform the strata it overrides. One of the Pleistocene glaciers profoundly affected some of the Upper Cretaceous strata: it stripped several large thin slabs (up to 0.5 km in one dimension and a few tens of meters thick) away from their pre-glacial positions and incorporated them as great thrust slices in the till.

Comparison of Pleistocene Sediments of the New York City Region with Those of Boston, Massachusetts

In the foregoing discussion of the stratigraphy of the Pleistocene formations and of the previous interpretations of the Pleistocene sediments of the New York City region, mention was made that the one-glacier view for the Wisconsinan was given strong support by the engineering borings from the major valleys in the New York City region, which trend NE-SW (such as the Hudson and Hackensack valleys). Borings from such valleys show one till overlain by outwash overlain by Holocene estuarine sediments. (See Figure 1.) As a result, the "standard" interpretation has been that of a single Wisconsinan glacier that is inferred to have deposited both of the moraine ridges on Long Island. Also summarized are the provenance data and how they fit with the directions of striae and grooves cut into the bedrock. The conclusions reached by JES are the same as those reached by Clifford Kaye (1982) from his study of the Quaternary sediments in the Boston area. Kaye found evidence of several Wisconsinan glaciers. The flow directions of these Boston glaciers inferred by Kay are virtually identical to those JES infers for the ancient glaciers in the New York City region. To quote from Kaye's paper:

> "The direction of ice flow in the Boston Basin and adjoining uplands was studied by means of the orientation of striations (sic) and grooves on the bedrock surface, the orientation (sic) of the long axes of drumlins, the direction of transport of erratics in till, and the direction of thrusting and overturning of bedding in glacially deformed drift. These data range through 360 degrees in azimuth. Analysis of this confusing message shows the existence not of an ever-shifting ice current but of at least four separate and distinct ice currents of different ages. Three of these flowed fairly rectilinearly, but one (the last) was multicomponent and marked by strong lobation" (1982, p. 31).

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°

Outwash

As mentioned previously, outwash consists of stratified sediments deposited by the meltwater from a glacier. In the region of today's trip, most of the outwash has been submerged; it lies beneath the estuarine sediments deposited by the rising sea. But, no account of the geologic history of the New York City region would be complete without a discussion of the freshwater lakes that occupied the Hudson valley from the time when the last glacier disappeared (about 13,000 years ago) until the sea invaded the area (about 11,000 years ago).

When the most-recent of the Wisconsinan glaciers (the Woodfordian, reaching a maximum about 14,000 yr ago, and beginning its rapid disappearance starting about 13,000 yr ago), had attained its southernmost limit, it completely covered the basins now occupied by the Great Lakes (Figure 50, a). By 13,000 yr ago, the retreating ice had uncovered the south end of today's Lake Michigan basin and much of the basin of modern Lake Erie. The only outlet available was situated at Chicago, via the Illinois River into the Mississippi and Gulf of Mexico (Figure 50, b). By about 10,500 yr ago, the ice had melted out of the basins of Lake Michigan, Lake Erie, and Lake Ontario, but still covered the eastern part of the basin of Lake Superior and the northern part of the basin of Lake Huron. The St. Lawrence outlet was plugged; hence, the water drained out of Lake Ontario into the Mohawk, then eastward to a large lake that occupied the Hudson Valley and adjacent lowlands (Figure 50, c). Counts of varves (sediments deposited in a year) in the proglacial-lake clays at Little Ferry, New Jersey (Reeds, 1926, 1927, 1933) showed that this arrangement lasted for at least 2,550 years. The south end of this narrow lake was formed by the natural dam of the Harbor Hill moraine. Two factors, dates not well known, contributed to the demise of this Hudson Valley lake: (1) the dam burst at The Narrows, and the surge of water is thought to have eroded the Hudson Shelf Valley; (2) the ice melted out of the St. Lawrence lowland, making possible the modern-day discharge route into the Gulf of St. Lawrence, Canada (Figure 31, d).

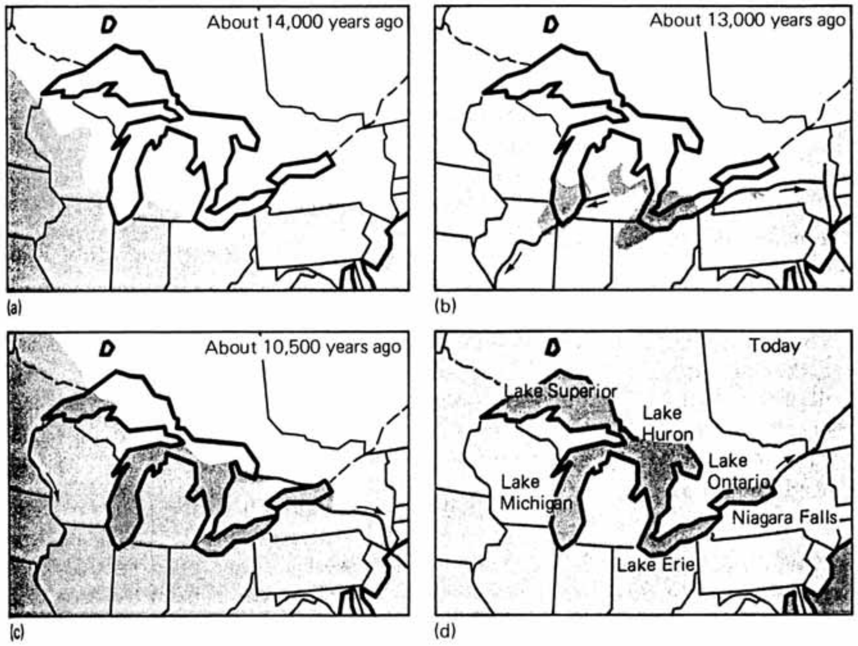


Figure 50 - Sketch maps showing Great Lakes at Wisconsinan glacial maximum, at two stages during deglaciation, and at present. (From F. B. Taylor, in Frank Leverett and F. B. Taylor, 1915, (b), pl. 17 facing p. 392; (c), pl. 19 facing p. 400; redrawn by J. E. Sanders, 1981, fig. 13.34, p. 333.)
(a) Maximum of Wisconsin glacier (in white).
(b) Early stage of deglaciation; outlet to Gulf of Mexico via Illinois River at Chicago, Illinois, and Mississippi River.
(c) Later stage of deglaciation; St. Lawrence lowland still blocked by remnant of glacier; outlet from Lake Erie via Niagara Falls into Lake Ontario, thence eastward via Mohawk Valley into Lake Hudson/Albany, which was dammed at south end by terminal-moraine ridge.
(d) Conditions today; outlet from Lake Ontario into St. Lawrence lowland, within which the water flows northeastward into the Atlantic Ocean via the Gulf of St. Lawrence, northeastern Canada (not shown).

Hogwash

Under this facetious heading JES would rank all interpretations of the pre-Woodfordian Pleistocene continental ice sheets that mention "lobes" and "fishes."

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, Trier, and S. C. Williams, 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.

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. 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 51a, d) or from the building of "embankments" (Figure 51c, 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 52).

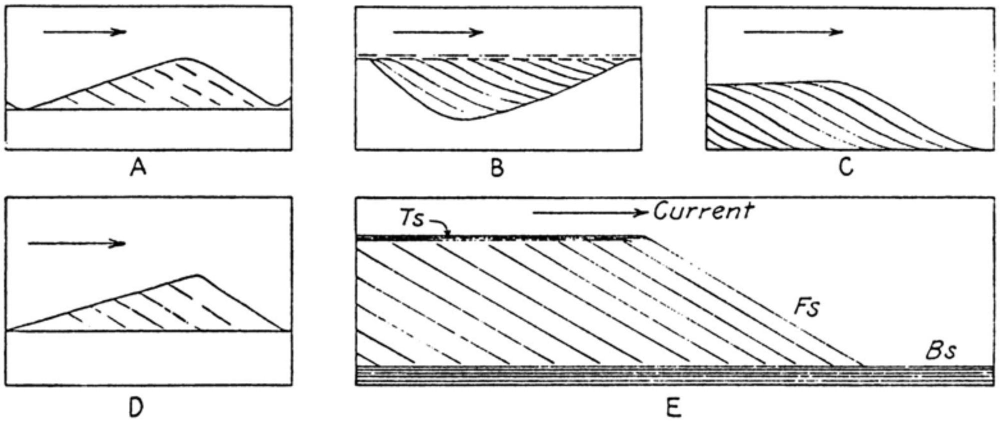


Figure 51 - Sketches of cross strata dipping to the right and formed by current flowing from left to right.
A and D, Longitudinal profiles through individual bed forms that have migrated to the right (downcurrent) by at least one
wavelength, thus preserving as internal cross strata many former downcurrent 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.)

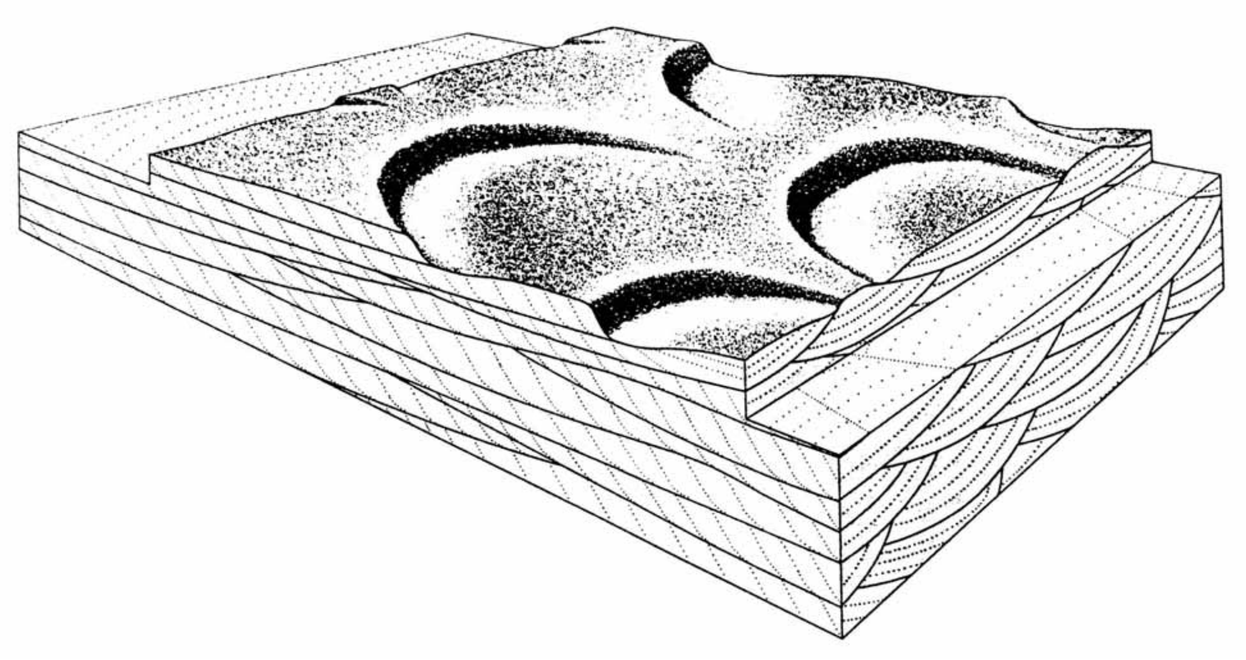


Figure 52 - Block diagram showing trough-type cross strata formed by downcurrent migration of lunate megaripples. Current from upper left to lower right. (H. E. Reineck and I. B. Singh, 1980, fig. 52, p. 43.)

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 53a). 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 53b). Such a stream is known as an antecedent stream; it is older than the axis it has cut across. Another possiblity is superposition (Figure 53c). 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.

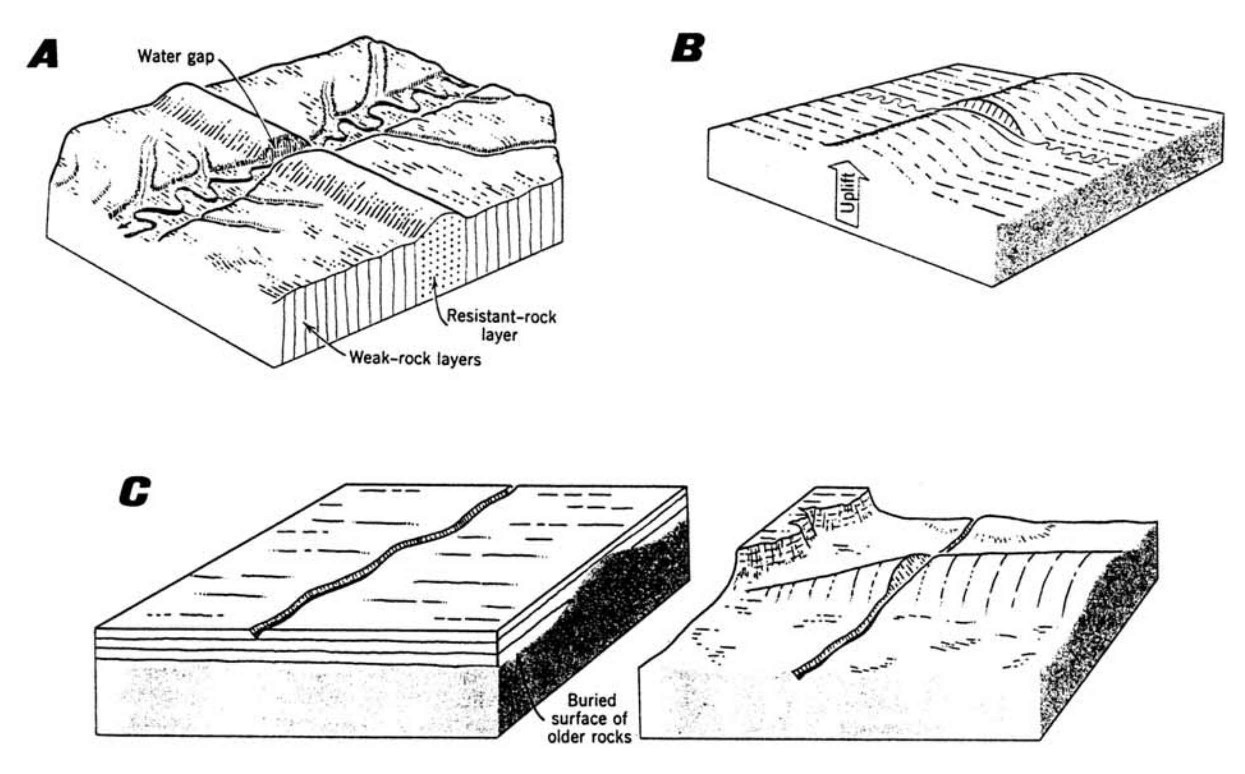


Figure 53 - Drainage anomalies associated with cross-axial stream flow, schematic block diagrams. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969: A, fig. 10-12, p. 225; B, fig. 10-15, p. 227; C, fig. 10-16, p. 227.)
A. Stream cuts a water gap through a ridge formed by resistant rock.
B. Stream 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

In the drainage history of the New York City region, the oldest clear-cut evidence dates from the Late Triassic-Early Jurassic, when the Newark basin was being filled. Reference to the physiographic diagram of Figure 37 shows the morphologic expression in today's landscape of what is left after elevation and erosion of the Newark basin-filling strata. The longer of the two profile-sections (the one that extends diagonally across the middle of the page) displays the existing arrangement of the basin-filling strata (eroded base in contact with the metamorphic complex of the Manhattan prong, northwest dip along the line of this profile-section, and abrupt ending on the northwest against the Ramapo fault).

The northwest-dipping Newark strata end abruptly along a line at the base of the Ramapo Mountains. Geologic analysis indicates that this line marks a fault, the Ramapo fault, which has been active for more than a billion years (Ratcliffe, 1971). During Late Triassic and Early Jurassic time, this fault separated an actively elevated block on the northwest from an actively subsiding block on the southeast. From the elevated block came sediment composed almost entirely of Paleozoic formations. The sediments were transported to the southeast and accumulated to form the Newark Supergroup. Near the Ramapo fault, these sediments are coarse; but, with distance from this fault, they become finer. Cross strata also indicate that ancient streams flowed from the northwest to the southeast. By contrast, both provenance data and the cross strata prove that some of the sediments composing the basal strata of the Newark Supergroup, namely the gray arkoses within the Stockton Formation, were derived from the southeast and were deposited by rivers that flowed westward, a direction that is down the present-day dip of the strata (Glaeser, 1966; Klein, 1969). This general pattern of sediment supply and transport directions has been further supported by geochemical provenance studies based on determining radiometric ages of the feldspars (Abdel-Monem and Kulp, 1968).

One of the major mysteries associated with the Newark basin-filling strata is what happened (and when) to disrupt the drainage and to end the episode of sediment accumulation in the Newark basin. The drainage pattern that began with the initial elevation of the marginal blocks and initial subsidence of the basin block fed sediments into the basin. This drainage pattern persisted for perhaps 30 million years. Then, something happened to disrupt it. Sanders (1963) argues that the elevation of the central part of the formerly subsided basin block, as indicated by the modern-day dip of the strata, was the event which changed the drainage pattern and caused the basin-filling strata to be eroded. As a result of this change, the Newark basin changed from being an importer of sediment into a condition of being an exporter of sediment.

As the Newark strata were elevated and eroded, a strike valley is inferred to have formed along their base. A strike valley is a linear- or curvilinear valley whose axis is parallel to the strike of non-horizontal strata. An example of a strike valley is the Hudson Valley between Stony Point, New York, and a point opposite Hoboken, New Jersey. (Figure 54; no label appears on Figure 54 for Hoboken, but the short sector of the river under discussion is the north-south segment just east of the "y" in the label for Jersey City.) At Hoboken, the Hudson makes about a 15-degree bend to its left (facing downriver). In so doing, it flows out of the strike valley at the base of the Newark Supergroup. However, the strike valley continues to the SSW. It goes under Jersey City, western Staten Island, and into New Jersey. (See Figure 37, profile-section along the bottom margin of the map, just above the 30' of the label for 74° 30'). The fact that this basal-Newark strike valley passes beneath the coastal-plain strata proves that the initial age of this valley is pre-Late Cretaceous. How long the Hudson has flowed in it is not securely known. Presumably, this whole strike valley is the same age throughout. It has been reoccupied by the Hudson from Haverstraw to Hoboken. Another valley, not a strike valley and now completely full of sediment and thus hidden from view and that may pass beneath the cover of the coastal-plain strata, extends on a WSW trend out of New Haven harbor and into Long Island Sound (Haeni and Sanders, 1974; Sanders, 1989 ms.).

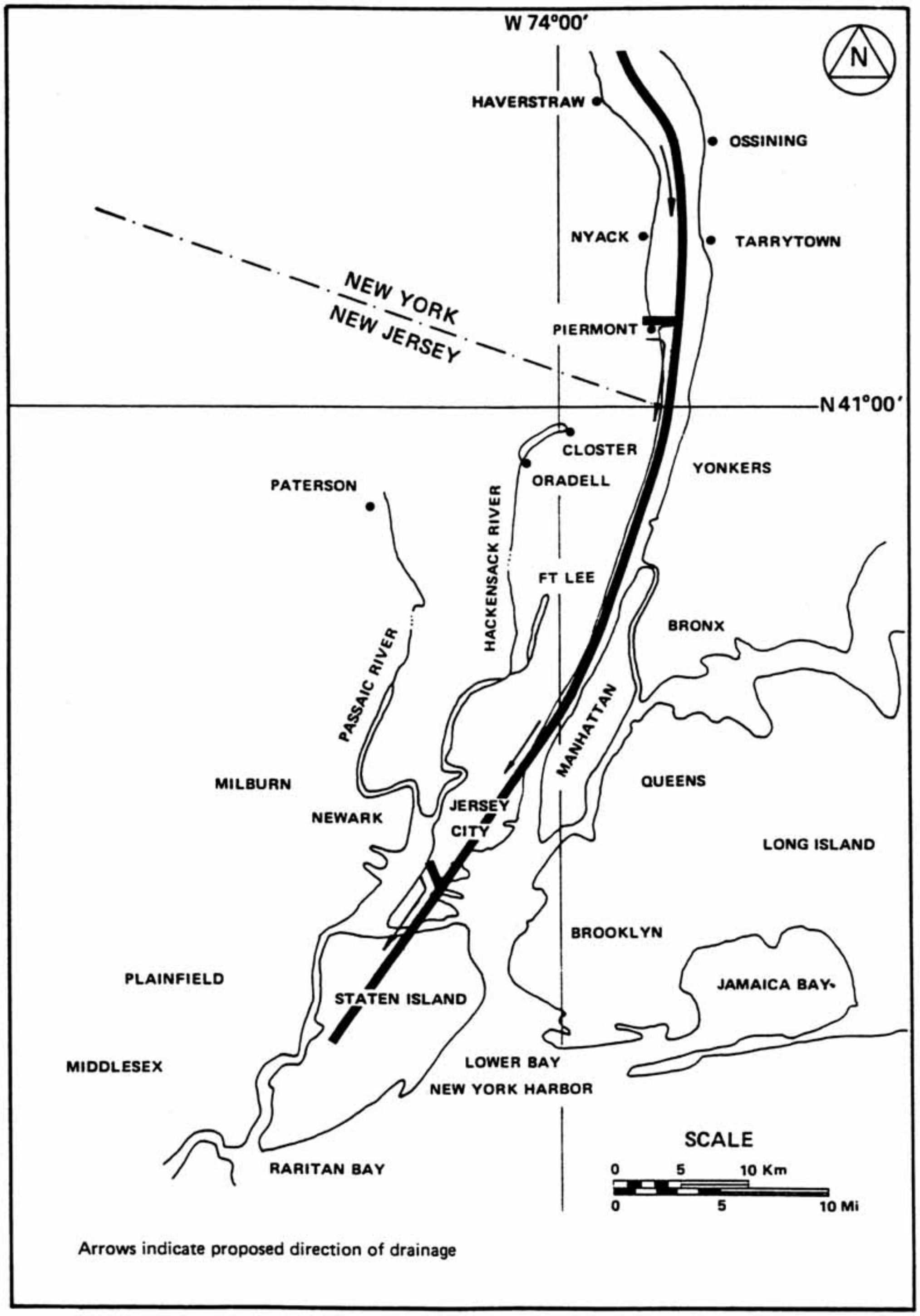


Figure 54 - Strike valley at base of Newark Supergroup as inferred during the late Cretaceous, after tilting and erosion of Newark strata (Layer V) but prior to submergence and deposition of coastal-plain strata (Layer VI). (J. Lovegreen, 1974 ms., Figure 19, p. 148).

A second strike valley exists at the base of the tilted and eroded coastal-plain strata. Locally, ocean water fills this basal-Cretaceous strike valley and we call it Long Island Sound. This valley and many others resulted from erosion associated with the post-Miocene elevation of the Appalachians and of New England and the accompanying drop of sea level.

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. The oldest probable lowland is the strike valley at the base of the Newark Supergroup, just described.

Locally, three rivers cross parts or all of the Hudson Highlands and thus might qualify as being cross-axial drainage anomalies. The Ramapo River begins at Central Valley, where NY 17 (the Quickway) branches off from the NY State Thruway, and flows southward to across the Ramapo Mountains to Suffern. The Thruway was built in the valley of the Ramapo River, part of which follows along the axis of a structural feature that has been named the Thruway graben (Jaffe and Jaffe, 1973). The Hudson River cuts a zig-zag course across the Highlands from Storm King to Peekskill. And, the Croton River, whose lower reach lies within the Manhattan Prong, cuts across the Highlands from Carmel into the Harlem Valley. Of these, only the course of the Hudson through the Highlands has been much discussed by geomorphologists. H. D. Thompson (1936) showed how the Hudson's course through the Highlands follows zones of weakness in the bedrock. To this JES would add the point about the parallelism of the zigs to one of the glacial-flow directions and of the zags to the other direction.

Buried valleys in the Hudson-Hackensack lowlands have been mapped by Lovegreen (1974 ms). This is the most-recent of several attempts to display the relief on the surface of the bedrock (Hobbs, 1905b; Berkey, 1910). The most-elaborate of these was the "rock data map" of Manhattan, organized by Murphy, (1940) and Murphy and Fluhr, (1944). Several prominent valleys trending NW-SE cross Manhattan Island at Dyckman Street and 125th Street. (See Figure 31.) The valley at 125th Street is known to coincide with a fault zone; the southwest-dipping gouge zone has been penetrated in the water tunnels. (See Figure 33 and description in an earlier section.)

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 New York City.

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

3) To examine the evidence for Cameron's Line and the St. Nicholas thrust.

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 (Fat Chance!)

LIST OF LOCALITIES ("STOPS") TO BE VISITED

Stop 1: Riverside Park
Stop 2: Outcrop at West 165th Street
Stop 3: Inwood Hill and Isham Park
Stop 4: St. Nicholas Park
Stop 5: Mount Morris Park
Stop 6: Grand Concourse and I-95, Bronx
Stop 7: Cameron's Line, I-95, Bronx

DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

The following seven stops (Figures 2, 3) 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 unknown 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 - Hartland exposures near West 90th to 91st streets [UTM Coordinates: 586.22E / 4516.00N, Central Park quadrangle] and between West 82nd to 85th streets [UTM Coordinates: 585.95E / 4515.50N, Central Park quadrangle], Riverside Park, Manhattan.

The Hartland Formation or upper schist unit (Ꞓ-Oh) crops out in Riverside Park from West 116th Street southward to West 75th Street. Described here are exposures near West 90-91st Streets and exposures from West 82nd-85th Streets. The northernmost outcrops consist of gray-weathering, well-layered and slabby to laminated, lustrous muscovitic schist containing interlayers of quartz-muscovite biotite granofels. Locally, l cm thick glassy quartzose layers and elliptical pods of recrystallized dark quartz occur.

The prominent 2-3 cm scale layering is due to mineralogic variation (bedding?) and subparallel S_1 + S_2 metamorphic recrystallization. The metamorphic layering is parallel to N48°E, 65°SE axial surfaces of long-limbed F_2 isoclinal folds plunging 60° into S28°E. A strong down-dip stretching lineation (L_2) composed of quartz ribs and streaked mica lies within S_2 and is deformed by F_3 folds. The F_3 folds are tight, south-plunging "s" folds with abundant shearing along their axial surfaces (S_3 = N37°E, 78°SE). L_3 intersection lineations and stretching lineations are parallel to F_3 hingelines which plunge 22° into S29°W and deform the L_2 lineations. S_3 is typically a transposition foliation with oriented mica and migmatite overprinting the older folds and related fabrics. Pre-, syn-, and post-D_3 pegmatites are found throughout the study area.

The southern outcrops of the upper schist unit are lithologically identical to the above except the layering is thicker (6-8 cm) and a laminated black-weathering, greenish-black biotite-amphibolite layer (l m thick) occurs near West 82nd Street. Together these outcrops illustrate the penetrative nature of F_3 isoclinal folds with their shallow southward plunges. Apparently the NW-trending, shallow SW-dipping enveloping S_2 metamorphic layering exerts a strong control on the orientation of F_3 hingelines despite the fact that significant transposition occurred during D_3. The average orientation of S_3 is N55°E, 75°SE with F_3 hingelines and sub-parallel L_3 lineations plunging 20° into S40°W. Late, open folds with axial surfaces trending N47°E, 90° are locally developed.

Several glacial features of interest are present here. The overall shape of the surface of the bedrock defines several roche moutonées. Not only are the rock surfaces rounded and smoothed on a large scale, but grooves and striae are present as well. The trends of these show that the ice flowed across the Hudson River, from NW to SE. We will refine this direction more closely by using a Brunton compass in the field. Consistent with such a flow direction is the color of the till, reddish brown, and the kinds of erratics present (dolerite from the Palisades Sill; anthracite coal from northeastern Pennsylvania; and possibly others).

STOP 2 - Middle schist unit (Ꞓ-Om) exposed at West 165th Street, Manhattan. [UTM Coordinates: 588.78E / 4521.44N, Central Park quadrangle.]

The middle schist unit (Ꞓ-Om), exposed here in a large outcrop west of Riverside Drive, consists of rusty- to gray-weathering, coarse-grained biotite-muscovite-plagioclase-quartz-kyanite-sillimanite-garnet-tourmaline gneiss and schist with 2-15 cm interlayers of quartz-biotite-garnet-kyanite-sillimanite granofels. The rock contains porphyroblasts of kyanite+sillimanite and garnet (up to l cm). Outcrops 350 m to the north show more typical rusty-weathering colors and abundant aluminosilicates. The middle schist unit also crops out throughout most of Central Park where detailed study of its various facies can be accomplished.

Structurally, at the south end of the outcrop, there is a clear example of a long-limbed intrafolial F_2 reclined fold refolded by F_3 "z" folds. Here, F_2 folds an S_1 biotite foliation and granitoid pods developed parallel to S_2 (and/or S_1) are folded by F_3. S_2 trends N54°E, 44°SE with F_2 plunging 40° into S19°E and S_3 trends N20°E, 75°SE with F_3 axes plunging 42° into S10°W. Excellent examples of type-3 interference patterns (Ramsay, 1962) are found on the sloping north-facing portion of the outcrop.

Several glacial features of interest are present here. The overall shape of the surface of the bedrock defines several roche moutonnées. This particular rock knoll probably was a splendid example of a roche moutonnée many years ago, but cannot be considered as such any longer. The diamond-drill holes along the rock face by the sidewalk indicate that the SE side of this knoll was blasted away to make way for the street and the sidewalk.

Not only has the rock surface been rounded and smoothed on a large scale, but grooves and striae are present as well. The trends of these show that the ice flowed across the Hudson River, from NW to SE. We will refine this direction more closely by using a Brunton compass in the field. Consistent with such a flow direction is the color of the till, reddish brown, and the kinds of erratics present (dolerite from the Palisades Sill; anthracite coal from northeastern Pennsylvania; and possibly others).

STOP 3 - Inwood Marble and Inwood-Manhattan contact, Isham and Inwood Hill Parks, Inwood section of Manhattan. [UTM Coordinates: 590.97E / 4524.72N, Central Park quadrangle and 590.66E / 4525.40N, Yonkers quadrangle, respectively.]

Inwood Hill Park is located in the extreme northwest corner of Manhattan Island. The park is bordered by Dyckman Street on the south, the Hudson River on the west, Spuyten Duyvil (Harlem Ship Canal) on the north, and Payson and Seaman Avenues on the east. Isham Park occupies the flat area northeast of Inwood Hill Park extending eastward to Broadway between Isham and West 214th Streets.

The area of Manhattan north of Dyckman Street is known as the Inwood section. Except for Inwood Hill Park, the region is underlain by the Inwood Marble (Ꞓ-Oi) marking the name-locality (originally called the Inwood Limestone by Merrill l890). Isham Park contains near continuous exposure of the Inwood Marble. Several lithologies occur such as coarse-grained dolomitic marble, fine-grained calcite marble, foliated calc-schist, and marble containing siliceous layers and calc-silicate aggregates that stand in relief as knots on the weathered surface. The marble ranges from white- to blue-white to gray-white. Depending on the amount of impurities it weathers gray or tan and produces a sugary-textured surface on outcrops that ultimately develops into residual calcareous sand. In addition, the outcrops illustrate differential weathering with dolomite-silicate units standing in high relief and calcite marble forming depressions.

The Inwood trends N45°E, 73°SE and forms the eastern overturned limb of a large F_3 synform which is cored to the west by the middle schist unit of Inwood Hill Park. Tight south-plunging F_3 folds are locally developed. Older structures are not obvious but do occur as F_2 isoslinal folds with shallow plunges. Abundant examples of boudinage of the siliceous and calc-silicate layers into lenses occur due to the marked ductility contrast between them and the surrounding marble.

Enter Inwood Hill Park following the past past the playground. The first prominent ridge is composed of kyanite gneiss and schist of the middle schist unit (Ꞓ-Om). Follow the path to where it curves around to the west side of the ridge and enters a valley underlain by a south-plunging F_3 antiform which exposes tan weathering, gray-white Inwood Marble striking N40°E, and dipping 58°NW.

Along the path going north (up-slope) along the westernmost ridge, massive, brown-weathering, blackish amphibolite of the middle schist unit crops out. Rocks exposed on the ridge (Ꞓ-Om) are massive muscovite-biotite-plagioclase-quartz-garnet-kyanite gneiss and schist with weathered kyanite+sillimanite nodules. The structure of the ridge is a south-plunging F_3 synform overturned toward the northwest. The S_3 foliation in the middle schist unit is related to F_3 folds with axial surfaces oriented N4l°E, 75°SE and south-plunging hingelines. The F_3 structures are superimposed on an older S_2 metamorphic layering which trends N50°W, 25°SW.

The contact between the middle and lower schist units (the St. Nicholas thrust) is exposed in a 20 m zone from beneath the Henry Hudson Bridge abutment to river level. Structurally beneath the middle schist unit a 0.5 m layer of mylonitic amphibolite is deformed by F_3 folds. Unlike the amphibolite in the middle schist unit above, which contains subidiobastic hornblende, this amphibolite has been retrograded by intense shearing in the S_2 foliation. Green hornblende porphyroclasts are set in an anastomosing S_2 foliation consisting of colorless clinoamphibole, biotite, and quartz ribbons.

Directly beneath the bridge, where a dirt trail leads down to the river, a coarse-grained gray-white calcite marble with differentially eroded calc-silicate nodules is exposed at low tide. It is unknown whether the marble exposed at the low-tide mark is an interlayer in the lower schist unit (Om) or the Inwood Marble.

Physically above the marble, the lower schist unit consists of biotite-quartz-plagioclase and kyanite with abundant garnet porphyroblasts. Here the lower schist unit contains an S_2 mylonitic foliation composed of mm-scale ribboned and polygonized quartz with recrystallized reddish pleochroic biotite. The S_2 foliation strikes N45°E, and dips 55°SE with a strong down-dip lineation plunging 50° in a S34°E direction. The thrust zone is structurally complex consisting of intercalated lithologies of the lower and middle schist units together with mylonitic amphibolite.

STOP 4 - St. Nicholas Park, west of St. Nicholas Avenue between West 129th and West 141st Streets. [UTM Coordinates centered on: 588.58E / 4518.74N, Central Park quadrangle.]

The St. Nicholas thrust (Figure 20) probably separates the middle schist unit from the Inwood Marble along the east edge of St. Nicholas Park situated west of St. Nicholas Avenue between West 129th and West 141st Streets. Excellent outcrops of the schist form the steep ridge of the park. The southernmost outcrops consist of rusty-weathering biotite- and muscovite-rich gneiss and schist with abundant aluminosilicate nodules, interlayered biotite-quartz-garnet granofels, and thin amphibolite. The Inwood Marble is not exposed but, based on drill core data, underlies the lowland immediately east of the park.

Outcrops atop the ridge on St. Nicholas Terrace contain flattened aluminosilicate layers folded by F_3 folds. Northward, F_2 isoclinal folds with subhorizontal axial surfaces are also deformed by F_3 folds. S_3 trends N30°E, dipping 70°SE and is locally warped by several generations of late crenulate and open folds.

A penetrative S_2 mylonitic layering occurs at the northeastern outcrop in the park. Tight to isoclinal F_3 folds deform and locally transpose the S2 mylonitic foliation into parallelism with S_3. In addition, the F_3 folds deform pegmatite sills intruded sub-parallel to S_2+S_1, thin lit-par-lit foliated syn-D_2 granitoids, aluminosilicate layers, and quartz veins. Due to the combined effects of D_2 and D_3 the rocks are locally migmatitic.

The contact between the middle schist unit and the Inwood Marble is never encountered but the presence of unusually penetrative S_2 fabrics in the schist at the eastern edge of the park and the apparent absence of the lower schist unit together suggest that the St. Nicholas thrust may be marked by the abrupt break in slope to the east.

STOP 5 - Mount Morris Park at West 122nd Street and Fifth Avenue. [UTM Coordinates centered on: 589.15E / 4517.28N, Central Park quadrangle.]

Mount Morris Park, centered at West 122nd Street and Fifth Avenue, consists of an erosional remnant of the middle schist unit (Є-Om) which forms a hill protruding above the Harlem Valley. The Inwood Marble crops out on the Madison Avenue side of the park. The marble is gray- to tan-weathering and contains schistose zones with layers and nodules of diopside+tremolite+ quartz. The middle schist unit is composed of rusty- and locally, maroon-weathering, gray, biotite-muscovite-plagioclase-quartz-kyanite-sillimanite gneiss and schist with kyanite layers, zones of porphyroblastic kyanite+garnet, and layers of biotite-quartz-plagioclase+garnet granofels.

The overall structure of the park is a south-plunging klippe of the middle schist unit produced by the superposition of an F_3 synform and a late, NW-trending synform (Merguerian, 1983). The klippe is terminated along its southern margin by a fault exposed at street level trending N69°W, dipping 84°SW. Slickensides in the fault surface are oriented N70°W @ 22° clearly indicating a strike-slip movement sense although a component of reverse motion is suggested by the presence of Inwood Marble to the south. The contact between the schist and

Inwood Marble is marked by 10° truncation of lithologic layering in the marble, extreme flattening, 2-3 cm scale annealed mylonitic layering, shearing and imbrication of lithologic units, and quartz veins.

Developed during thrusting and deformed by F_3 folds, the S_2 enveloping surface is variable but on average trends N30°W, 20°SW and marks the axial surface of reclined and isoclinal folds found both above and beneath the thrust contact. Disharmonic F_3 folds of mylonite developed at the thrust contact are exposed at the northern edge of the klippe. They trend N32°E, 80°NW to 70°SE and plunge 23° into S25°W.

STOP 6 - Grand Concourse and the Cross Bronx Expressway, The Bronx. [UTM Coordinates: 591.70E / 4521.95N, Central Park quadrangle.]

An excellent exposure of the lower schist unit occurs west of the Grand Concourse in an overpass above the Cross Bronx Expressway (I-95) (Om in Figures 2, 29). Here, fine- to medium-grained, massive but locally friable, tan- to brown-weathering muscovite-biotite-quartz-plagioclase-kyanite-sillimanite-garnet schist and granofels is found interlayered on the scale of 3-4 m with calcite and dolomite marble containing 2-3 cm diopside+tremolite calc-silicate and siliceous layers. Massive Inwood Marble occurs in the roadcut forming the south wall of I-95 beneath the overpass. This locality, together with exposures described earlier in Inwood Hill Park (STOP 3) and a few other outcrops south of I-95 paralleling the Grand Concourse (C. A. Baskerville, personal communication), are interpreted as the autochthonous (essentially in place) portions of the Manhattan Schist.

STOP 7 - St. Nicholas thrust and Cameron's Line, 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 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 (Є-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 Є-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. In early 2002, Pamela and Patrick Brock and I jointly found Om exposed in the NE corner of Crotona 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.

Dr. 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).

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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	(**Begin Atlantic Passive-Margin Stage 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.
(Triassic)	190	Continued filling of subsiding Newark basins and mafic igneous 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 and St. Nicholas Thrusr Zone). Arc-continent collision. Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata.
(Ordovician)		Ultramafic rocks (oceanic lithosphere) sliced off and transported structurally 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, Walloomsac Schist). Transitional slope/rise sequence (Manhattan Schist) and deep-water terrigenous strata (Hartland Formation) form to east. (= **Taconic Sequence**).
PROTEROZOIC		
	570	Period of uplift, rifting,and erosion followed by subsidence of margin and development of **Iapetan Passive-Margin Stage I**.
(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, marine)	Bellvale Fm., lower unit (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]. In NYC and throughout New England, dismembered ophiolite is common (Merguerian 1979; Merguerian and Moss 2005, 2007).

~~~~~~~~~~~~~~~~~~~**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. / Walloomsac Schist
Normanskill Fm. / Annsville Phyllite

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

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

LAYER IIA [W] - SAUK SEQUENCE	LAYER IIA [E] - TACONIC SEQUENCE
Western shallow-water platform	**Eastern deep-water zone**
(L. Cambrian - M. Ordovician)	(L. Cambrian-M. Ordovician)
Copake Limestone (Stockbridge,	
Rochdale Limestone (Inwood Marble)	
Halcyon Lake Fm.	
Briarcliff Dolostone	(Ꞓ-Oh) Hartland Fm.
Pine Plains Fm.	(Ꞓ-Om) Manhattan Fm.
Stissing Dolostone	
Poughquag Quartzite	
Lowerre Quartzite	
Ned Mtn Fm.	

[**Pre-Iapetus Rifting Event**; extensional tectonics, volcanism, rift-facies sedimentation, and plutonic igneous activity precedes development of Iapetus ocean basin. Extensional interval yields protoliths of Pound Ridge Gneiss, Yonkers granitoid gneisses, and the Ned Mountain Formation (Brock, 1989, 1993). 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. Followed by a period of uplift and erosion.

~~~~~~~~~~~~~~~~~~~~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).**
Illinoian(?)	**IIIA**	**NW to SE**	**Ronkonkoma Terminal Moraine and associated outwash (Merrick Fm. in Jones Beach subsurface).**
	IIIB		**Manhasset Fm. of Fuller (with middle Montauk Till Member; in lower member, coarse delta foresets (including debris flows) deposited in Proglacial Lake Long Island dammed in on S by pre-Ronkonkoma terminal moraine.**
	IIIC		
Yarmouthian			**Jacob Sand, Gardiners Clay.**
Kansan(?)	**IV**	**NNE to SSW**	**Gray till with decayed stones at Teller's Point (Croton Point Park, Westchester Co.); gray till with green metavolcanic stones, Target Rock, LI.**
Aftonian(?)			**No deposits; deep chemical decay of Till V.**
Nebraskan (?)	**V**	**NW to SE**	**Reddish-brown decayed-stone till and -outwash at AKR Co., Staten Island, and at Garvies Point, Long Island; Jameco Gravel fills subsurface valley in SW Queens.**
			Pre-glacial (?) Mannetto Gravel fills subsurface valleys.

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