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ABSTRACT

The fundamental question pertaining to the Pleistocene features of the New York City region is: "Did one glacier do it all? or was more than one glacier involved?" Prior to Fuller's (1914) monographic study of Long Island's glacial stratigraphy, the one-glacier viewpoint of T. C. Chamberlin and R. D. Salisbury predominated. In Fuller's classification scheme, he included products of 4 glacial advances. In 1936, MacClintock and Richards rejected two of Fuller's key age assignments, and made a great leap backward to the one-glacier interpretation. Subsequently, most geologists have accepted the MacClintock-Richards view and have ignored Fuller's work; during the past half century, the one-glacial concept has become a virtual stampede. What is more, most previous workers have classified Long Island's two terminal-moraine ridges as products of the latest Pleistocene glaciation (i. e., Woodfordian; we shall italicize Pleistocene time terms). Fuller's age assignment was Early Wisconsinan. A few exceptions to the one-glacier viewpoint have been published. In southern CT, Flint (1961) found two tills: an upper Hamden Till with flow indicators oriented NNE-SSW, and a lower Lake Chamberlain Till with flow indicators oriented NNW-SSE, the same two directions of "diluvial currents" shown by Percival (1842). In Boston, MA, and vicinity, C. A. Kaye (1982) found many tills having these same two inferred flow directions.

We here summarize our reasons for re-establishing Fuller's 4-glaciation classification and for rejecting a latest-Pleistocene age of Long Island's terminal-moraine ridges. Our analysis is based on our integrated regional studies of features glaciers eroded on bedrock, on the provenance implications of erratics and of indicator stones, on superposition of tills, and on the principle of "one glacier, one flow direction."

We accept as Woodfordian only the youngest till deposited by a glacier that flowed from NNE to SSW, down the Hudson Valley (the same direction as Flint's Hamden Till in CT). In the New York City region, such a till is gray to light brown in color, contains poikilitic mafic indicator stones from the Cortlandt Complex near Peekskill (which many may have confused with "trap rock" from the Palisades Sill) and erratics of Inwood Marble and other rocks from Westchester County, and totally lacks any erratics derived from the Newark Basin, which is situated on the W side of the Hudson. In our classification, we label the Woodfordian till and associated outwash by Roman numeral IV. Till IV is present in Queens and on Staten Island, but

is not present on much of Long Island; the terminal moraine of glacier IV lies along the S coast of CT (Flint and Gebert, 1974, 1976).

The next-older till, our III, was deposited by a glacier that flowed over the New York City region following a rectilinear course from NW to SE, across the Hudson Valley (the same direction as reported by Flint from the Lake Chamberlain Till in CT). In New York City, southern Westchester County, and western Long Island, Till III is a distinctive reddish-brown color from its content of pulverized Newark sedimentary rocks. Diagnostic indicator stones from outcrop belts NW of the Newark Basin include Lower Silurian Green Pond Metaconglomerate and Pennsylvanian anthracite coal (Sanders, 1974; Friedman and Sanders, 1978). In Long Island City (Queens), Woodworth (1901) found glaciated bedrock gneiss with striae and grooves oriented N25°W-S25°E overlain by reddish-brown materials forming the Harbor Hill Moraine. At Corona, Woodworth found reddish-brown sand underlying a gray till containing erratics of what he called "trap-rock." (We have not seen these but suspect that they may not be dolerite from the Palisades as one might suppose from his use of the term "trap rock." Other possibilities are indicator stones from the Cortlandt Complex, or Paleozoic amphibolites and or -mafic igneous rocks from SE New York and/or western CT. In any case, we classify this gray till as our IV, the Woodfordian).

Farther E on Long Island, in localities that lie outside the downflow path from the Newark Basin, Till III undergoes a dramatic lateral lithologic facies change. In localities that lie downflow from a "crystalline corridor" of bedrock exposed between the NE end of the Newark Basin and the SW end of the Hartford Basin in south-central CT, our Till III is not reddish brown, contains no Newark- or other erratics derived from NW of the Newark outcrop belt, but contains indicator stones of Inwood Marble and the Cortlandt Complex, as at Target Rock, for example. Still-farther E, the color of Till III becomes reddish brown once again as it contains erratics from the Hartford Basin of central CT and MA (for example on Gardiners Island). Reddish-brown till (our No. III?) occupies valleys eroded into the sandy S-dipping Gilbert-type deltaic foreset sediments that underlie the eroding cliffs at Sands Point and elsewhere on Long Island's north shore (Sanders, Merguerian and Mills, 1993; Sanders and Merguerian, 1994). At Caumsett State Park, these deltaic sediments contain abundant gravel including partly decomposed stones. We assign these to Fuller's Manhasset Formation and think the newly exposed relationships demonstrate that Fuller's pre-Wisconsinan age assignment was correct. Accordingly, we reject the Wisconsinan ages proposed by W. L. S. Fleming (1925) and by MacClintock and Richards (1936) for the Manhasset.

In the subsurface at Jones Beach, on the S shore of LI, the inferred nonmarine upper outwash (of Rampino, 1978 ms.; the Bellmore Formation of Rampino and Sanders, 1981) has been correlated with the Harbor Hill Moraine. We accept this correlation and assign both the upper outwash (Bellmore Formation) and Till III to the Early Wisconsinan.

The next-older glacial advance, our No. II, which also crossed the New York City following rectilinear flow paths from NW to SE, deposited tills having the same color-distribution pattern as deposits of glacier No. III. We think glacier No. II deposited the Ronkonkama terminal-moraine ridge. In the Jones Beach subsurface, the lower inferred outwash (of Rampino, 1978 ms.; the Merrick Formation of Rampino and Sanders, 1981) is separated from the upper inferred outwash (the Bellmore Formation) by the marginal-marine sediments of the Wantagh Formation (of Rampino and Sanders, 1981; the "20-foot clay" of Perlmutter, Geraghty, and Upson, 1959, Table 1, p. 420, p 422; Doriski and Wilde-Katz, 1983; and others of the U. S. Geological Survey). If the correlations of the two subsurface units of inferred outwash with the Harbor Hill- and Ronkonkama moraines are correct, then they imply that these two moraines were not deposited by the fluctuating margin of the same glacier (whatever its age), but by two different glaciers, as originally visualized by Upham (1879). The Wantagh Formation implies that these two outwash-connected glaciers were separated in time by an interval sufficiently long and with a climate sufficiently "nonglacial" so as to enable the sea to rise to close to its present level to deposit sea-marginal sediments. The age of the Wantagh Formation is not certain. Initially, Rampino and Sanders (1976) assigned it the mid-Wisconsinan and thought it is correlative with the Portwashingtonian warm interval of Sirkin and Stuckenrath (1980). In light of Wehmiller's amino-acid racemization results (reported in Ricketts, 1986), however, we now think the Wantagh is pre-Wisconsinan, possibly Sangamonian. If that is correct, then the next-older slot for the Ronkonkama Moraine and Till II is Illinoian.

We regard the newly exposed Gilbert-type delta foresets in Fuller's Manhasset Formation as deposits of proglacial Lake Long Island. The relationships at Montauk Point imply that this lake was there dammed on the S by the now-eroded Ronkonkama terminal-moraine ridge (Sanders and Merguerian, 1994). If this is correct, it implies that the age of these extensive proglacial-lake deposits is the same as that of the Ronkonkama Moraine, which we place in the Illinoian, the same age Fuller assigned. The extent of decomposition shown by the stones in the gravels at Caumsett State Park on the N shore of Long Island, however, suggests that the Manhasset Formation could be the product of a still-older glaciation, namely Kansan. If so, then the Long Island Lake must have been dammed on the S in part by a now-vanished terminal-moraine ridge that is older than the Ronkonkama.

Glacier III (and/or II; we cannot as yet distinguish between their erosive effects) sculpted the bedrock with prominent grooves trending NW-SE as found in Manhattan by Dr. L. D. Gale in 1828-29 (published in Mather, 1843), in Central Park by Hanley and Graff (1976) and in many parts of the New York City region by us (Merguerian and Sanders, 1988; 1991a, e; 1993a, c; 1994a; Sanders and Merguerian, 1991a, 1992). We ascribe the numerous effects of glacial flow oriented NW-SE, as reported from the erratics in the Brooklyn Botanical Garden (Gager, 1932) as shown on the Glacial Map of North America (Flint, 1945) and also as found by C. A. Kaye (1982) in Boston, MA, and vicinity to glacier(s) II and/or III.

Tills II and III, separated by a few meters of reddish-brown outwash of the kind deposited in a proglacial lake, are exposed in eroding bluffs along the E shore of the Hudson River at Croton Point Park, Westchester Co. At Enoch's Nose, they underlie yellowish-brown till IV that has been shaped into a drumlin whose long axis trends N-S; at Squaw Cove, they are overlain by gray varved clay containing scattered dropstones (assigned to the meltdown phase of glacial-episode IV); and at Teller's Point, they are underlain by a grayish-brown till (our Till No. I) containing indicator stones from the Cortlandt Complex and granitic rocks in which the feldspars have been totally decomposed to clay. Reddish-brown tills II/III underlie the terminal-moraine ridge being eroded in southern Staten Island; a prominent paleosol caps the upper reddish-brown till. The youngest unit in the coastal cliffs is a brownish loess (the "surficial loam"? of R. D. Salisbury (in New York City Folio of the U. S. Geological Survey).

The earliest glacier to leave its mark in New York City and vicinity (from our Episode I) flowed from the NNE to the SSW. It eroded the prominent rock drumlin at Fort Tryon Park, Manhattan, and many elongate rounded features eroded on the bedrock that constitute the smoothed, upglacier parts of typical roches moutonées but lack the diagnostic steep, quarried-and-plucked down-ice sides. We have been using the term "roche-moutonée structure" for these partial- or modified roches moutonées. Examples are known from Bear Mountain, Orange County; from FDR Veterans Hospital, Westchester County; and in various parks in New York City.

Glacier No. I deposited the gray-brown till that underlies red-brown till (No. II?) at Teller's Point, Westchester Co. and the gray-brown till at Target Rock, L.I., which contains "greenstone" indicator stones from the Maltby Lakes metavolcanics SW of New Haven [misidentified by Sirkin and Mills (1975) as Palisades Dolerite and thus assigned by them to a till that was deposited by a glacier that flowed NW-SE; the upper till here, deposited by a glacier that did flow from NW to SE, is gray and contains no Newark erratics but rather indicator stones, such as Inwood Marble and the Cortlandt Complex, derived from what we have called the "crystalline corridor" of southeastern NY and western CT].

At least two pre-Woodfordian glaciations are implied by the relationships at three localities on Staten Island: (1) Till, exposed in coastal cliffs eroded into a terminal-moraine ridge in southern Staten Island, containing but-minor quantities of decayed pebbles (only the "greenstones") and capped by a well-developed paleosol, yields provenance data which prove that at least one glacier flowed regionally across Staten Island from NW to SE (across the Hudson Valley, thus our Till II and/or III) not NNE to SSW, (down the Hudson Valley) with local diversions to the SE, the pattern inferred for the Woodfordian ice by R. D. Salisbury (1902) and accepted by many one-glacier advocates. (2) At the AKR Excavating Corp., much-decayed stones in outwash gravels that underlie comparatively fresh red-brown till and overlie Cretaceous sands imply a pre-Wisconsinan age (possibly a product of our Episode I). (3) Superposed glacial striae and -crescentic marks on the dolerite exposed at the Graniteville quarry are inferred products of two ice-flow directions: an older NW to SE (our II and/or III) cut by a younger NNE to SSW (our No. IV).

We infer that on Staten Island are products of at least 3, possibly 4, glacial advances. We regard their ages as: Kansan (?) or even Nebraskan (?) for the much-decomposed outwash at AKR; Early Wisconsinan +/- Illinoian (?) for the coastal exposures of "terminal-moraine" materials derived from the NNW (capped by a well-developed paleosol and including a giant "erratic" slab of displaced Cretaceous sediments); and Wisconsinan (Woodfordian) for the till overlying the striae trending NNE-SSW at Graniteville. We do not know the location on Staten Island of any Woodfordian terminal-moraine ridge. Elsewhere, this ridge follows the south coast of Connecticut.

We have not yet turned up any absolute-age data that would settle the age assignments of our multiple-glacier interpretation and that would totally destroy the one-glacier-did-it-all view which we think is not correct. However, we think the case we have made for the pre-Woodfordian age for the Harbor Hill Moraine is very compelling. If we have correctly interpreted the subsurface relationships Rampino (1978 ms.) established at Jones Beach, then Long Island's two world-famous terminal moraines were not only not made by the fluctuating margin of the Woodfordian glacier, as has been universally believed for many years, but were made by two different glaciers whose appearance on Long Island was separated by an interglacial episode when the glacier retreated back into Canada and the sea rose nearly to its present level.

At present, the best hope for settling our chronological impasse is amino-acid-racemization analysis of shells from the Wantagh Formation. Our inference is that the Wantagh is Sangamonian, but as noted above, it could be mid-Wisconsinan or even Yarmouthian.

INTRODUCTION

This article has been written to provide regional geologic background about the Pleistocene sediments in the New York City region (Figure GG-1) against which what will be seen at four of the stops on the New Jersey Geological Association's Staten Island field trip can be evaluated. In writing it, we have been mindful that geological field guides are unique vehicles for disseminating field data that tend not be be accepted for publication elseswhere. Herein we present many such results from our continuing field investigations that have spanned twenty-five years.

In this article we: (1) briefly summarize selected items from the large geologic literature about local Pleistocene stratigraphy and -glacial history; (2) present our credentials and background and reasons for studying New York City's glacial history and offer a new stratigraphic classification; (3) summarize our field results under the headings of (a) inferred directions of glacial flow based on eroded bedrock in the New York City region, (b) directions of glacial flow inferred from sediments (erratics and indicator stones and long axes of drumlins), (c) discussion of the ice-flow evidence, and (d) stratigraphic superposition of tills and Pleistocene sediments; and (4) a summary of the glacial geology of Staten Island with respect to our proposed stratigraphic classification.

SUMMARY OF SELECTED GEOLOGIC LITERATURE ABOUT LOCAL PLEISTOCENE STRATIGRAPHY AND -GEOLOGIC HISTORY

In our review of previous work, we make no attempt at complete coverage. Moreover, in this section we include only major articles about the stratigraphic relationships with emphasis on the number of glaciations and the glacial history particularly with respect to the ages of the terminal-moraine ridges. We defer our attempts to evaluate these previous results until after we have presented our own results. We include some previous results on orientations of striae and on indicator stones alongside our own work.

Work Done Prior to 1914: Concept of One Glacial Episode is Born

In this category we include published work by L. D. Gale (1828-29, published in Mather, 1843), by James Gates Percival (1842) in Connecticut; by Mather (1843), by Warren Upham (1879), by T. C. Chamberlin (1883); by R. D. Salisbury (Salisbury, 1902, 1908; Salisbury and others, 1902; Salisbury and Peet, 1894; Peet, 1904); and by J. B. Woodworth (1901). Because of the difficulty in locating many of these old references, we quote from some of them at length. (Fuller, 1914, p. 4-19 summarizes all of the pre-1914 literature on Long Island Pleistocene sediments.)

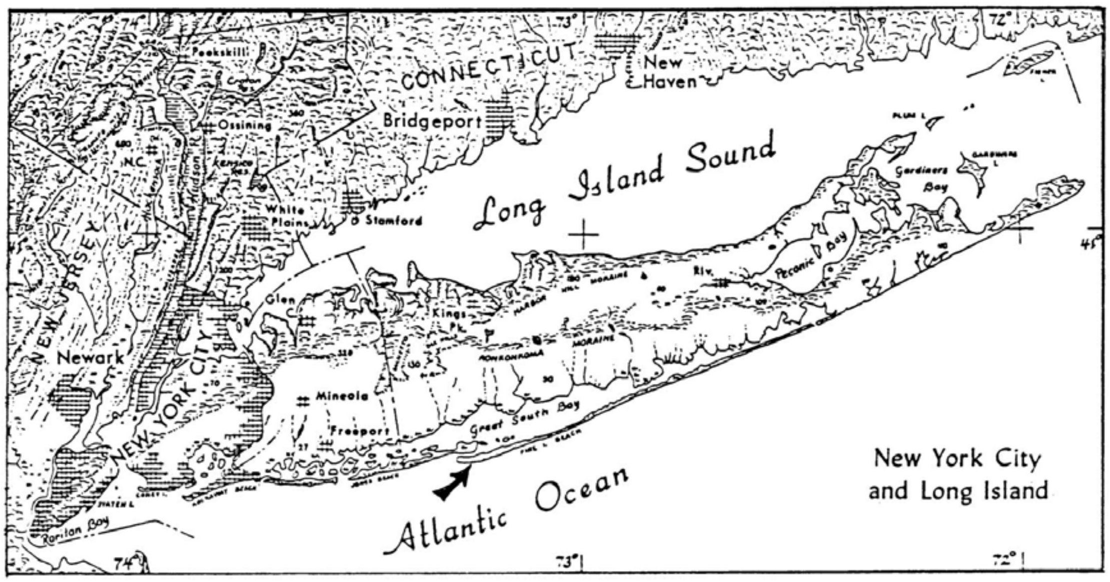

Figure GG-1. Physiographic sketch map of Long Island and vicinity showing the locations of localities mentioned in text. (J. A. Bier, 1964.)

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 Dr. L. D. Gale. Modern geologists would ascribe these to the effects of now-vanished glaciers. But in the early 19th century, these were considered to be products of the great flood of Noah; they were named "diluvial scratches and furrows".

Back then, 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 was able to study Manhattan Island in a more-or-less natural condition. Gale's street references can be taken directly; few buildings were present, and probably the ones to which he does refer have been long removed.

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 his use of the term "diluvial." L. D. Gale (1839, Geological Report of New-York; New-York island; published in Mather, 1843, p. 209-210):

"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.

"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'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: trying to force fit all data into 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.

Independently of and nearly simultaneously with Gale's survey of Manhattan, that great genius of Connecticut geology, James Gates Percival, was mapping the geology of the state of Connecticut. Percival was well acquainted with both the bedrock and what we would now refer to as the Pleistocene deposits. As did Gale, Percival classified these as "Diluvium," or the "unstratified (sic) materials," and contrasted them with the Alluvium, "those arranged in strata." Percival (1842, p. 453-456) cited many examples of distinctive kinds of rocks that had been displaced from NW to SE:

> "The greater part of the Diluvium was apparently deposited by a general current, traversing the surface from N. N. W. to S. S. E. This is satisfactorily indicated both by the bowlders, scattered over the surface, or imbedded in the diluvial earth, and by the smaller fragments included in the latter, as well as by its general character (sic)." (Percival, 1842, p. 453).

Percival emphasized that knowledge of the composition of the bedrock was absolutely essential for reconstructing the directions of the "diluvial currents:"

> "In order to determine the direction of the diluvial currents, a particular knowledge of the local character (sic) of the rocks, as indicated in the account already given of the different local formations, is indispensable. Several of these local formations are so peculiar in the character (sic) of their rocks, that the latter cannot be mistaken, to whatever distance they may have been transported. These, by the distribution of their bowlders and fragments, furnish conclusive evidence that the more general (sic) direction of the diluvial current was S. S. E." (Percival, 1842, p. 454)

Despite the numerous examples he cited that demonstrate transport from NW to SE, Percival reported that some rocks had been moved from NNE to SSW. As did Gale in Manhattan, Percival supposed that this transport to the SSW had resulted from local deflections of the general SSE-flowing diluvial current:

> "Although the general direction of the diluvial current was apparently S. S. E., yet in some instances, from local obstructions, its course was deflected to a S. S. W. direction. This is most distinctly obvious along the Western border of the larger Secondary formation, where blocks and fragments of the Trap and Sandstone of that formation are accumulated, sometimes quite abundantly, in such a direction from their apparent source." (Percival, 1842, p. 457).

In contrast to both Gale and Percival, the single flow event most later workers invoked was from the NNE to the SSW. They called upon aberrations from this "main-flow" direction to explain the scratches and furrows that trend NW-SE.

Mather (1843) described the geology of Long Island emphasizing strata exposed in the north-shore cliffs (Figure GG-2). At Lloyd's Neck, a storm exposed dipping strata that had been truncated and are overlain by horizontal strata. Mather was not able to interpret these strata as any modern geologist would do. After all, Mather's date of publication preceded general acceptance of the concept of Pleistocene continental glaciation and was 42 years before G. K. Gilbert (1885) presented his analysis of the topographic features of lake shores in which he proposed the terms topset, foreset, and bottomset as the three kinds of lacustrine deltaic strata formed along the shores of ancient Lake Bonneville, Utah (and 47 years before Gilbert's Lake Bonneville monograph appeared in 1890).

Mather used the name "Long Island Formation" informally for the sediments that he thought underlie most of the island; he assigned this formation to the Tertiary. Mather's term has been abandoned, but we are considering the feasibility of reviving it for the extensive suite of pre-Wisconsinan sediments deposited in a lake the occupied much of what is now Long Island. (We refer to it as Long Island Lake and discuss it in a following section.) Mather mentioned the two prominent curvilinear ridges now known to be terminal moraines, but he did not realize they were of glacial origin.

Warren Upham (1879) mapped and discussed Long Island's two terminal-moraine ridges and associated outwash plains (Figure GG-3). He inferred that each had been built at the margin of a separate glacier. (Upham recognized two tills throughout southern New England and on Long Island.) He noted that on Long Island, till is abundant W of Roslyn and generally absent to the E.

T. C. Chamberlin (1883; 1885; 1895a, b) laid the foundation for the stratigraphic classification of North American Pleistocene deposits. He described the conditions at the margin of the continental glacier in terms of lobes and inferred that the main axis of concentrated flow in eastern New York state had been down the Hudson Valley (1883, map following p. 346). He reviewed the previous work on the Long Island terminal moraines and outwash plains but differed with Upham's assignment of these to two separate glaciers. Based on the lack of differential erosion and dissection of the associated outwash plains, Chamberlin argued that both the terminal-moraine ridges and associated outwash plains were products of the latest glacial episode. Chamberlin's argument has been nearly universally accepted.

R. D. Salisbury and associates mapped the glacial geology of New Jersey and reported ice-flow indicators oriented not only NNE-SSW, as they expected, but also NW-SE, which they did not expect. Early in the studies of the glacial deposits, Salisbury concentrated on the flow indicators on the Palisades ridge. The position of the Palisades ridge was critical with respect to Chamberlin's view that a main axis of accelerated ice flow had been down the Hudson Valley. Chamberlin supposed that within the margins of an ice sheet are localized zones within which the ice flows faster than it does in adjacent areas. At such places of localized faster flow, he imagined that the ice-flow "stream-lines" would be crowded close together. On either side of such supposed zones of concentrated flow, the ice tends to spread out toward each side. Chamberlin had illustrated this concept by sketching a map of ice-flow indicators in the region surrounding Lake Michigan (Figure GG-4).

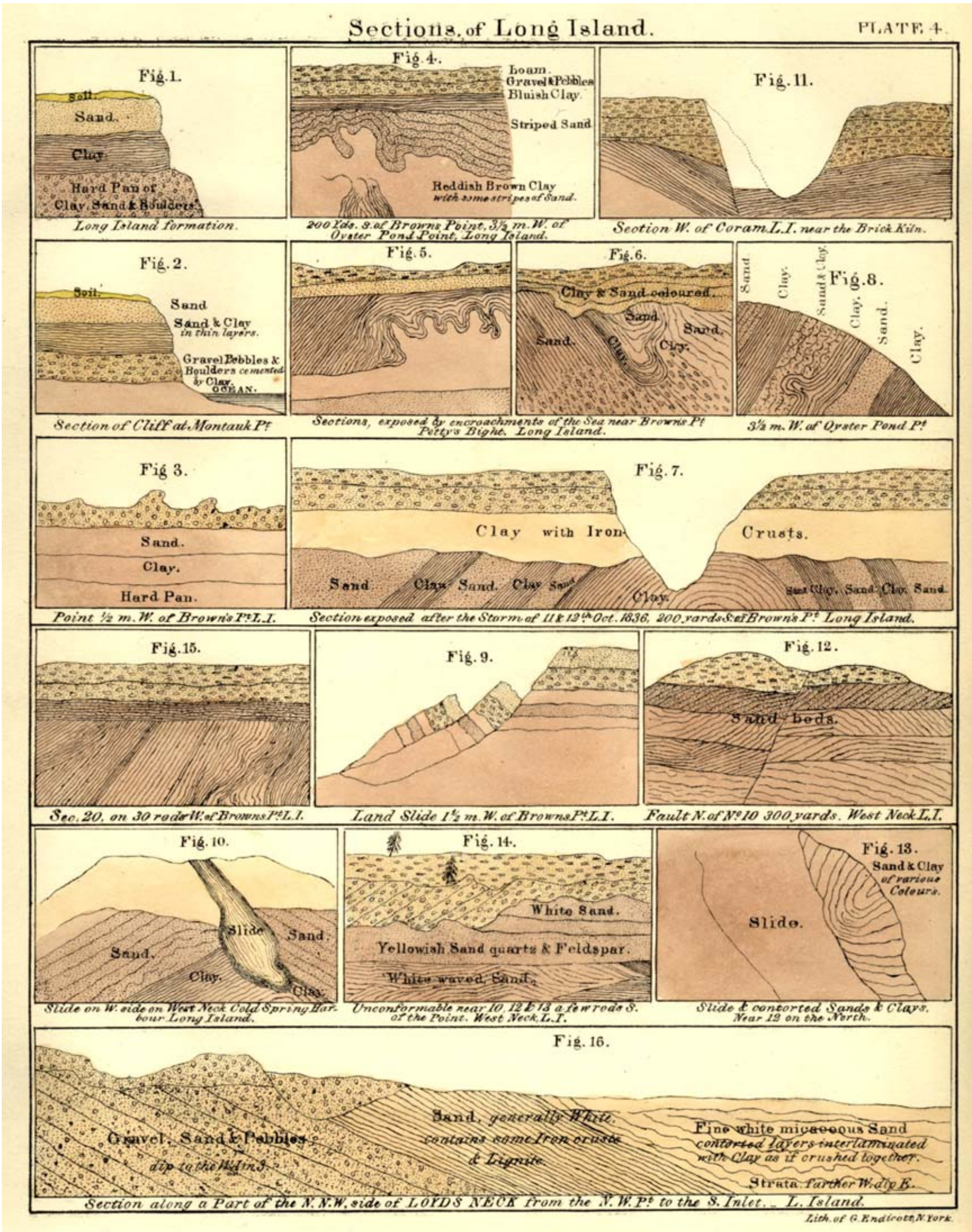

Figure GG-2. Mather's profile-sections of Long Island. Lloyd's Neck on the North shore cliffs is discussed in text. (Mather, 1843, Plate 4, fig. 16.)

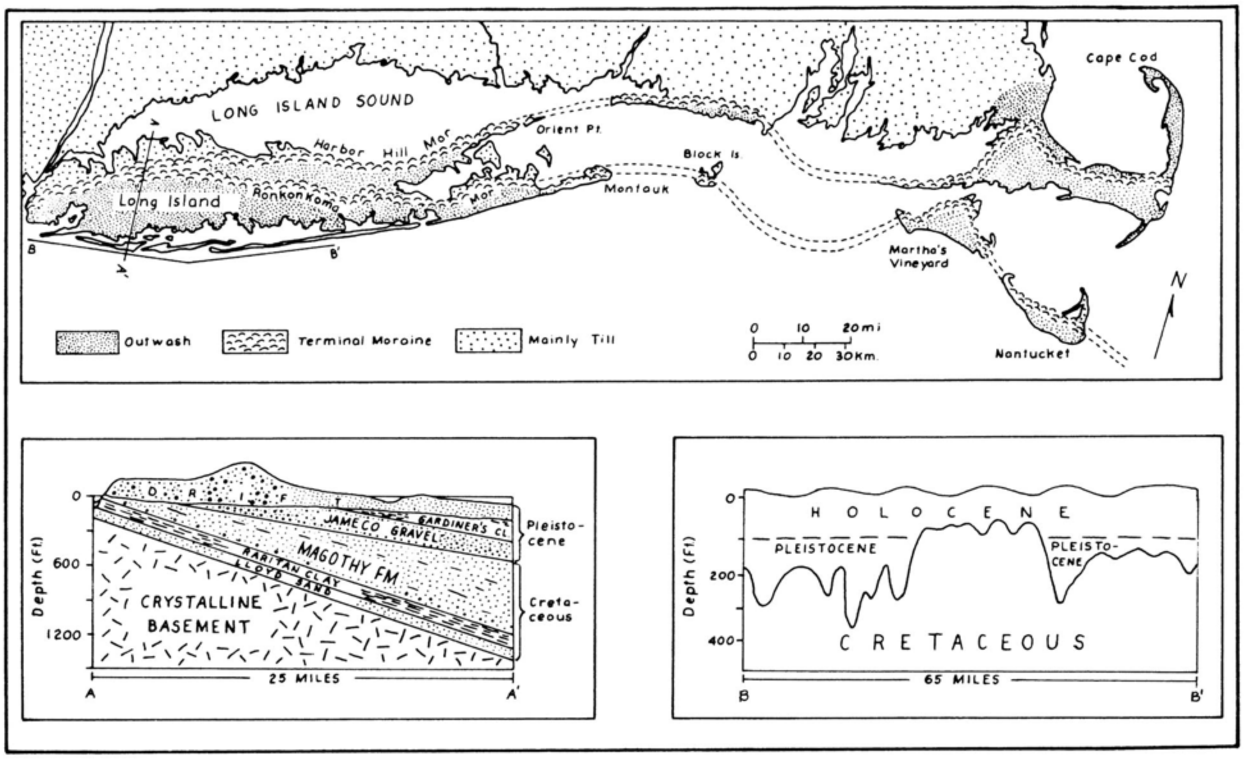

Figure GG-3. Map of Long Island and vicinity showing the locations of the two terminal moraines and profile sections showing subsurface relationships. (Wolff, Sichko, and Leibling, 1987, fig. 14.3, p. 128.)

Salisbury accepted Chamberlin's flow model. But if the zone of fast ice flow had followed the Hudson Valley, as Chamberlin had supposed, then divergent flow across the Palisades ridge should have been from NE to SW. Salisbury and Peet went to considerable trouble to study the glacial geology of the Palisades ridge. After they found virtually all the ridge-crest striae indicating glacial flow from from NW to SE and none from the predicted NE to SW, Salisbury reconciled the situation by shifting the axis of the presumed accelerated flow westward and placing it in the Hackensack Valley. From this inferred zone of concentrated flow down the Hackensack Valley, Salisbury and assistants (1902) thought that the ice had flowed toward the SSE over the Palisades ridge and Manhattan, and toward the SSW over the crests of the Watchung Ridges in New Jersey (Figure GG-5). This was consistent with their findings that glacial-flow indicators over the Watchung ridges had been predominantly from the NNE to the SSW, the predicted flow direction for the Palisades ridge for a fast-flow axis located either in the Hudson Valley or the Hackensack Valley.

Salisbury admitted that the regional distribution of erratics of the distinctive Silurian Green Pond Conglomerate from northwestern New Jersey and the divergent orientations of the glacial grooves and -scratches constituted anomalies to this explanation of marginal-flow divergence within a single glacier. Salisbury acknowledged that another succession of events which could explain the distribution of erratics of Green Pond Conglomerate involved two glaciations, but he merely mentioned the possibility of two contrasting glaciers.

"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).

All of Salisbury's work on the glacial deposits of New Jersey was based on the flow pattern shown in Figure GG-5. He published it repeatedly in various folios that the U. S. Geological Survey published in the region (New York City, Passaic, Franklin Furnace).

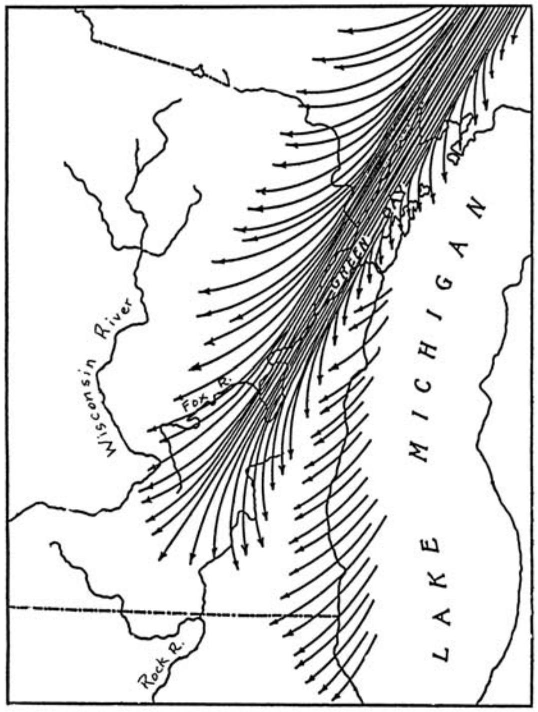

Figure GG-4. Sketch map of area west of Lake Michigan (mostly in Wisconsin, but including parts of Michigan and Illinois), showing concept of divergent flow from a narrow zone (centered above Green Bay, Wisconsin) of rapid flow within an ice sheet. (R. D. Salisbury, 1902, fig. 31.)

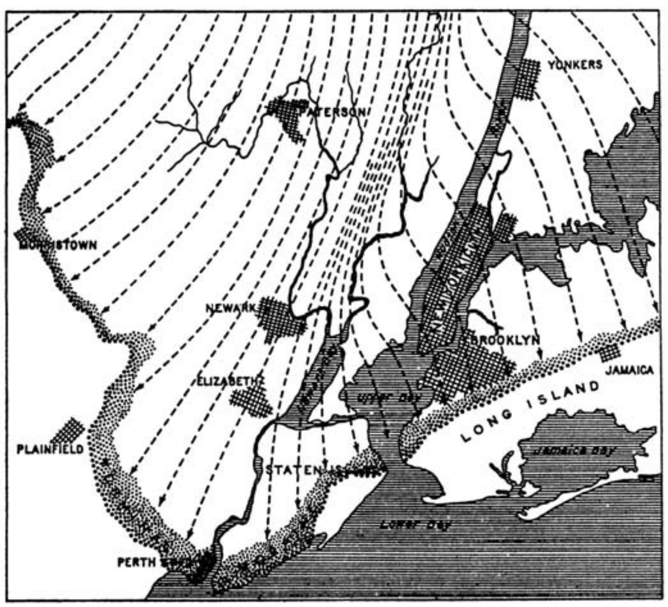

Figure GG-5. Map of northeastern New Jersey and southeastern New York showing inferred flow lines within the latest (and supposedly the only) Pleistocene glacier that reached the New York City region. Further explanation in text. (R. D. Salisbury, in Merrill and others, 1902, fig. 12, p. 13; also 1908, fig. 11; also, H. B. Kummel, 1933, fig. 13, p. 66.)

Woodworth (1901) reported on the Pleistocene geology of Queens County. About inferred directions of flow of the glacier(s), he wrote:

> "Frontal moraines mark the position of the ice front. The motion of the ice, at least near its margin, will tend to be toward that front; hence, since (sic) the moraine in this part of the island trends to the south of west, forming a lobate line across this region and that adjacent in New Jersey, glacial striae in this part of the island should run to the east of south. A number of ledges of gneiss in Long Island City meet (sic) this requirement."
>
> "The southeastward movement of the ice on this side of the Hudson valley is further attested by the drift. The moraine from Brooklyn as far east as Oyster Bay contains trap boulders, the nearest known site of which rocks is in the Palisade trap ridge on the west bank of the Hudson river.
>
> "Stratified red sands, also undoubtedly derived from the area of Triassic red sandstones now found only on the west bank of the Hudson, occur in a section by the roadside from Corona to Astoria, being there overlain by 8 or 9 feet of gray till... " (Woodworth, 1901, p. 652),
>
> With respect to divergent flow directions, Woodworth wrote:
>
> "This fanning of the ice sheet to the eastward on the east side of the lower Hudson and to the westward on the west side is consistent with the form of the moraine across the mouth of the river. The axis of the lobe thus indicated has been fixed by Salisbury on the west side of the Palisade trap ridge. (ftn. 1)

Footnote 1: "Salisbury, R. D. N. J. geol. sur. An. rep't state geol. for 1893. 1894, p. 161." (Woodworth, 1901, p. 653).

Woodworth discussed ancient glacial lakes that lay between the high parts of Long Island and/or a terminal-moraine ridge on the S and the glacier itself on the N and sandy/gravelly delta deposits built into such lakes. He included, as Plate 8, a photograph by Heinrich Ries of Gilbert-type delta foresets and -topsets taken in the large Port Washington sand pit during the early days of its active phase. In Figure GG-6 we have modified Woodworth's figure 9 (p. 658) to show a gap between the ice front and a terminal moraine on the S which could serve as a dam to hold in the water of a proglacial lake. Woodward's map and text clearly indicate that is what he had in mind even though in his figure 9, he showed other relationships.

Woodworth also discussed examples of older gravels assigned to the Columbia Formation (p. 624-637) that include an interstratified thin unit of boulder-bearing till (his "boulder clay bed" of p. 627). He described it as follows:

> "The boulder clay bed. In many of the coastal sections on the north shore an unstratified (sic) mixture of pebbles, sand and clay in a bed varying from 3 to 10 feet in thickness may be seen in a position to indicated that it is interstratified with these older gravels; but it is only in the sand pits on Hempstead bay that a bed of this character (sic) is fully revealed. About half way up the bluff, or about 100 feet above the bay, there is a bed of boulder clay from 2 to 3 feet thick, traceable in all the pits open in 1900 south of Bar beach. The matrix of this bed is an unctuous dark blue (sic) clay locally sandy or gravelly. Scattered through it and sometimes in close contact with each other (sic) are glaciated boulders ofter over (sic) 1 foot in diameter and numerous pebbles attesting the glacial origin of the deposit. Several large boulders examined in 1901 by Dr. F. J. H. Merrill and the writer were recognized by the first named as having been transported in all probability from the Adirondacks. Other small boulders carrying Silurian fossils indicated their origin in the Hudson Valley north of the Highlands. The longest journey made by these materials appears to exceed 200 miles."

In summary, it is clear that by early in the twentieth century, T. C. Chamberlin and R. D. Salisbury had stamped on the glacial geology of the New York City their one-glacier view with flow deviation at the margin based on the behavior of inferred ice lobes. Lost in the shuffle were J. B. Woodworth's important contributions, especially that his older series of gravels and interbedded till form a foundation upon which the Harbor Hill moraine was deposited and with respect to his proof that the direction of flow of the glacier which had deposited the Harbor Hill Moraine had been from NNW to SSE and to his clear evidence for multiple glaciation based on the older unit of interstratifed till and gravels as seen in sand pits and north-shore coastal cliffs.

A note about language: Salisbury and Woodworth always used the term striae as the plural for glacial scratches, whereas T. C. Chamberlin adopted the plural of the attribute word "striation" and wrote "striations." In the interests of being gramatically correct, we accept

Salisbury and Woodworth and reject the "striations" of T. C. Chamberlin and his legion of followers.

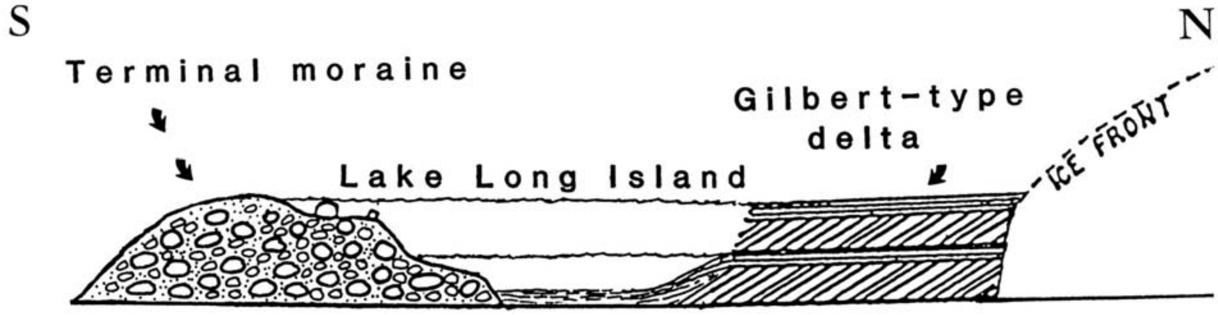

Figure GG-6. Schematic profile-section showing Gilbert-type deltas on N side of Lake Long Island, which formed in the lowland beteen the ice front on the N and the terminal-moraine ridge on the S. Two levels are shown: the lower at +40 feet and the upper at +80 feet (referenced to modern sea level). Highlands of Long Island, underlain by Cretaceous strata, could also serve as a dam for the lake on the S side. (Sanders and Merguerian, 1994, fig. 1, p. 103; adapted from Woodworth, 1901, fig. 9, p. 658.)

Fuller's (1914) Monographic Results: Four Glacial Episodes

The fundamental study of the stratigraphy of the glacial deposits in the New York metropolitan region is Fuller's (1914) monumental treatise on the geology of Long Island. Fuller found deposits that he interpreted as products of 4 glacial advances; between some of the glacial sediments, he found nonglacial strata. Table GG-1 shows the names- and stratigraphic relationships of Fuller's units. Notice his assignment of the Harbor Hill Moraine and the Ronkonkoma Moraine to the post-Illinoian (Early Wisconsinan); he inferred they are both younger than the Vineyard unconformity but assigned them to the Early Wisconsinan. (Later workers changed Fuller's age assignment from Early Wisconsinan to latest Wisconsinan, or Woodfordian).

Fuller inferred that during the Vineyard erosion interval, which he assigned to the Sangamonian, streams had eroded the deep north-facing valleys. Although Fuller did not discuss the relationship between glaciation and low sea level as contrasted with interglacial conditions and high sea level, he did realize that the extensive valley erosion he assigned to this interval required that base level be relatively low with respect to Long Island. He attributed the low base level to uplift of Long Island.

Fuller applied the name Manhasset formation (with upper Hempstead gravel member, middle Montauk till member, and lower Herod gravel member) to the "Columbia formation" of Woodworth. Because, as mentioned, Fuller inferred that the extensive network of north-flowing valleys had been cut into the Manhasset Formation, he classified this formation as being older than the Vineyard erosion interval. Fuller assigned the Manhasset to the Illinoian. Fuller drew many sketches of strata exposed in coastal cliffs. Among these, he illustrated examples of

Manhasset Formation showing one-directional dips (Figures GG-7 and GG-8). We discuss these further in a following section.

Early	Harbor Hill Terminal Moraine	
Wisconsinan G	Ronkonkama Terminal Moraine	
Sangamonian I	Vineyard Fm. (marine deposits and peat);	
	surface of erosional unconformity with relief of ca. 300 ft.	
		Hempstead Gravel Member
	Manhasset	"Ice-erosion" unconformity
Illinoian G	Formation	Montauk Till Member
		"Ice-erosion" unconformity
		Herod Gravel Member
	Jacob Sand	
Yarmouthian I	Gardiners Clay	
Kansan G	Jameco Gravel	
Aftonian I	Unconformity surface of great erosion	
Pre-Kansan G	Mannetto Gravel	

Table GG-1. Fuller's stratigraphic classification of the Pleistocene deposits of Long Island. G, glacial; I, interglacial. (Fuller, 1914, p. 20.)

The next-older unit in Fuller's classification is the Jacob Sand. Fuller took the name from Jacob Hill, "a high point on the north shore of Long Island, 8 miles northeast of Riverhead, near which the formation is well exposed" (Fuller, 1914, p. 107).

The Gardiners Clay grades upward into Jacob Sand which Fuller described as:

> "In its most characteristic (sic) form the Jacob sand consists of exceedingly fine sands, mainly quartz flour, but with many grains of white mica and some of dark-colored minerals. In color the sands commonly range from a very light gray to yellowish (sic) and buff tints, but where laminae of true clay are present they may be stained reddish externally. They are everywhere clearly stratified, although individual beds several

feet thick and appearing structureless to the eye are encountered. When wet most of them are somewhat plastic but lack the toughness of true clay; all are decidedly gritty to the teeth and most of them to the touch. Interbedded with the fine varieties of the Jacob deposits are some more distinctly (sic) sandy beds, usually buff or yellowish, and several feet thick, in which particles of fairly fresh granitic minerals can be recognized" (Fuller, 1914, p. 107).

Fuller (1914, p. 113) assigned the Jacob Sand to the Illinoian, but considered it to be transitional between the interglacial Yarmouthian Gardiners Clay below and overlying Illionian glacial materials of the Manhasset Formation.

"There is reason to believe that the change in deposition, as was pointed out in the discussion of the source of the material (p. 107), was caused by the advent of glacial silts brought down from the north during the advance of the Montauk ice, but long before it invaded the region under discussion" Fuller (1914, p. 113).

Fuller (1914, p. 92) gave the name Gardiners clay from "Gardiners Island, situated between the North and South flukes at the east end of Long Island, on which several clay beds with included sands are well exposed at a number of points."

"On western Long Island, where the formation reaches its maximum development, the Gardiners clay consists of irregular dark-colored beds alternating with layers (sic) or lenses of sand and fine gravel and attaining near Brooklyn an aggregate thickness of 150 feet. In this region the clays, unlike those in the localities farther east, grade downward through glauconitic (sic) and locally fossiliferous sand into the Jameco gravel, representing in fact transitional deposits. The clays themselves consist of a very fine silt, dark from the contained organic matter and carrying more or less lignitized wood. The included sandy layers are commonly from 5 to 10 feet thick and at some places have yielded fossil remains (Fuller, 1914, p. 93).

"The great body of the Gardiners clay rests upon the Jameco gravel, but along the borders of the Jameco next to the Cretaceous land mass, especially along the edges of the great depression in the vicinity of Jamaica Bay, the clay laps up on the eroded surfaces of the

Cretaceous and Mannetto (fig. 57) or even upon the metamorphic rocks (fig. 62), with sharp erosion (sic) and overlap unconformities (sic) (Fuller, 1914, p. 94).

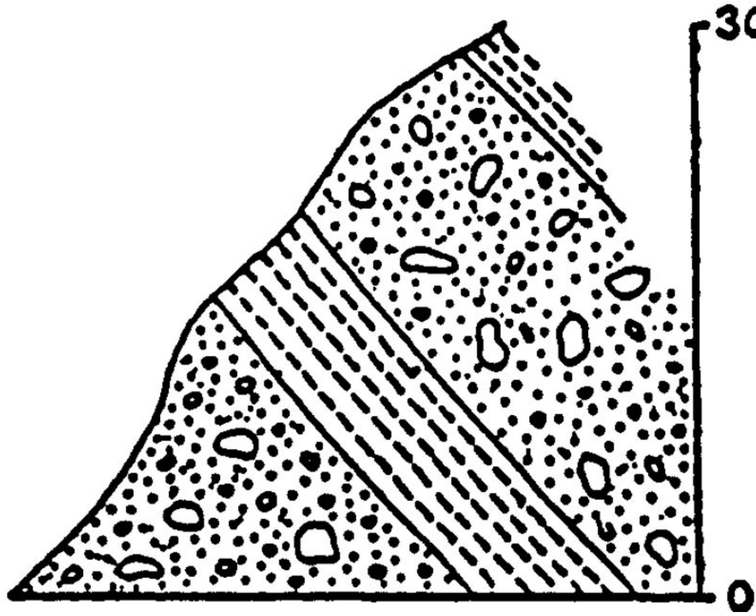

Figure GG-7. Fuller's sketch of exposure 1 mile west of Rocky Point, Montauk showing dipping diamictons and intercalated well-bedded strata. Based on what is exposed at Caumsett State Park, we infer that all these dipping layers are deltaic strata, the diamictons being products of subaqueous debris flows, not tills. (M. L. Fuller, 1914, fig. 156, p. 143.)

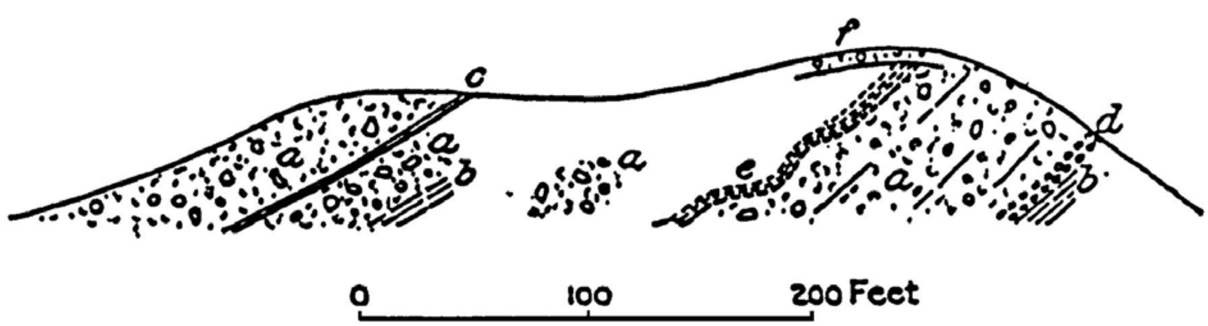

Figure GG-8. Fuller's sketch of exposure 0.5 mi S of Cullodan Point, Montauk, showing a dipping succession of diamictons and well-bedded strata and overlain by a horizontal till (f, at top; "Wisconsin till" in Fuller's caption. Other letter notations, after Fuller, are: a, "Montauk till member"; b, clayey sand; c, clay; d, gravel, and e, sand. (M. L. Fuller, 1914, fig. 157, p. 143.)

In all of the localities where the Gardiners Clay is visible at the surface, evidence of ice-thrust deformation is unmistakeable (Fuller, 1914, p. 96-102, figs. 65-86).

Fuller's two oldest units, the Jameco Gravel and Mannetto Gravel, are known mostly from wells. They form valley fills. The oldest valleys on Long Island, the pre-Mannetto valleys, were completely filled in by the Mannetto Gravel (Fuller, 1914, p. 44). The Jameco Valley cuts the Mannetto Gravel; it in turn has been filled in by the Jameco Gravel, which filled the valley and obliterated it as a landscape feature.

Fuller took the name Jameco Gravel "from the Jameco pumping station, near Jamaica South, 3 miles south of Jamaica, in western Long Island," where Veatch first recognized and named these deposits from deep wells.

> "The Jameco gravel, although it has not been definitely recognized at the surface at any point on Long Island, has been encountered in a considerable number of wells. In its type locality, in the area extending from Jamaica Bay northward toward Whitestone, it occupies a broad //(p.86) depression in the underlying rocks (either Cretaceous or Mannetto). It is easily recognized in the wells in this locality because of its striking dissimilarity to all other Pleistocene beds (except the Montauk till member of the Manhasset formation) and to the Cretaceous formations. The difference between the Jameco gravel and the Mannetto gravel is especially marked. Although the older beds are prevailingly light-colored (sic) and composed principally of quartz, the Jameco is generally a very coarse dark-colored gravel containing a predominance of granitic pebbles with a few streaks of black (sic) or other dark sands or finer silts..."
>
> "Where lithologic characteristics are not determinative, the formation is recognized by its position beneath the fossiliferous Gardiners clay" (Fuller, 1914, p. 85-86).

"The Mannetto gravel was named from the Mannetto Hills (West Hills), on the crest of which just west of Melville some of the best exposures of this gravel on the island were found" (Fuller, 1914, p. 80).

Fuller described the Mannetto as follows:

> It "consists of stratified (sic) and in some places cross-bedded gravels composed mainly of well-rounded pebbles of quartz from half

> an inch to an inch in diameter mixed with coarse yellowish quartz sand, but carrying everywhere a few deeply weathered granitic pebbles and scattered large bowlders of crystalline rock, also deeply weathered or disintegrated. It includes a few thin intercalated beds of yellowish clay. The granitic fragments can usually be crushed by the finger or by a slight blow of a hammer, and even the quartz is far more friable than fresh fragments. The quartzose (sic) and stained character (sic) of the gravels, the deep weathering of the pebbles, and the complex flow and plunge (sic) structure are the distinguishing features of the formation " (Fuller, 1914, p.80).

We note a distinctive anomaly in the relationships Fuller described for the Jameco and contrasted with the Mannetto gravels. Both are prominent subsurface units in western Long Island where the upper unit, the Jameco, fills a major depression eroded in the Mannetto and is therefore the younger unit. Fuller reported that the Jameco is not known at the surface on Long Island. By contrast, the type locality of the Mannetto is on the surface in the Mannetto Hills.

The key feature that Fuller used to identify the Mannetto is the decayed granitic pebbles. Such decayed pebbles can originate in two ways. (1) They can be distinctive erratics, indicator stones, for example, of a region of pre-glacial decayed bedrock, such as is found in the northernmost 500 feet of the Garrison tunnel of New York City's Catksill aqueduct (Berkey and Rice, 1921, p. 101-103; Berkey and Fluhr, 1948); or (2) they can be the result of intensive in-situ chemical weathering after deposition and thus indicate great age.

Two indices of the first alternative are that (a) the pre-glacial (probably even pre-Late Cretaceous; Blank, 1978) decomposition of the feldspars was accompanied by the dissolution of quartz; and (b) other stones do not show comparably advanced states of decomposition.

The key feature of the second alternative is that all stones display the effects of advanced stages of decomposition. We have not checked the surface exposures that Fuller assigned to the Mannetto Gravel for dissolution of quartz, but have noticed a contrast in states of decomposition: only in the granitic rocks has the feldspar turned into clay. In other kinds of pebbles, only the effects of incipient decomposition are visible. Therefore, the decay of the feldspars should not be considered a badge of extremely ancient age (as we have previously supposed).

Given the validity of the first alternative, we raise the possibility that the Mannetto Gravel of the surface exposures may not be correlative with the subsurface unit Fuller assigned to the Mannetto Gravel in wells from western Long Island. This possibility would be highly likely if the degree of decomposition of the pebbles in the subsurface units assigned to the Mannetto is more or less uniform throughout in contrast to decay of granitic pebbles only in the surface exposures. Whatever is the outcome of this discussion about the Mannetto, the message is clear: decayed feldspars by themselves do not necessarily prove an early Pleistocene age.

Work Done After 1914: Most Return to the Single-glacier Hypothesis, But Multiple Glaciers Do Rear Their Ugly Heads Again

In the mid-1930's, W. L. S. Fleming (1935) and MacClintock and Richards (1936) published their analysis of the Pleistocene record. Both rejected several key age assignments in Fuller's stratigraphic classification. Fleming argued that the age of the Manhasset Formation is Wisconsinan; he invoked several Wisconsinan glacial advances to account for the Montauk Till and changed the age assignment of Long Island's famous terminal moraines from Early Wisconsinan (Fuller's interpretation) to Late Wisconsinan. MacClintock and Richards led the multitude back to the one-glacier view that Fuller had thought he had buried. Not only did they move Fuller's Manhasset Formation up into the Wisconsinan but also they shifted the Gardiners Clay from the Yarmouthian interglacial, where Fuller had placed it, into the Sangamonian (but MacClintock and Richards weaseled by allowing as how the age of this clay might be partly Sangamonian and partly Yarmouthian).

According to Sirkin:

> "...the Gardiners Clay, was believed to represent an Early Pleistocene interglacial (Fuller, 1914) and was subsequently placed in the Sangamonian Interglacial Stage (MacClintock and Richards, 1936). In historical usage, a variety of fine-grained sediments of both fresh water (sic) and marine orgin have been called the Gardiners Clay. These strata, which have been observed in surface exposures and well sections, can vary considerably from the original fossiliferous marine sediments of the type section (Upson, 1968; Sirkin and Mills, 1975). Gustavson (1976) has shown that certain so-called Gardiners Clay units contain fossil faunas quite unlike the fauna from the type section, while (sic) Sirkin and Stuckenrath (1980) indicate that some strata identified as Gardiners Clay could be of Portwashingtonian age, particularly in the absence of radiometric ages for either the original or the presumably correlative units.
>
> "The inclusion of such strata in the Woodfordian moraines only show that they predate (sic) the Woodfordian advance. As a surface deposit, the Manetto Gravel, although well weathered, is probably Woodfordian outwash (Sirkin, 1971), derived from deeply weathered

granite and granite gneiss in Connecticut. The Jameco Gravel and the Gardiners Clay as recognized in well section are undoubtedly post-Cretaceous and probably represent Late Pleistocene deposits that are older than the overlying glacial deposits" (Sirkin, 1982, p. 38).

MacClintock and Richards experienced difficulty in recognizing Fuller's Montauk Till Member of the Manhasset Formation and did not accept Fuller's stream-dissection hypothesis for the origin of the north-facing valleys. According to Fuller, streams of post-Manhasset age eroded valleys into the Manhasset Formation. Because Fuller thought this interval of erosion correlated with the Sangamonian interglacial age, he assigned the pre-erosion Manhasset Formation to the Illinoian. By contrast, MacClintock and Richards argued that the valleys had not been stream eroded, but were left as depressions (somewhat analogous to giant kettles) because they had been occupied by tongues of glacial ice. While the ice tongue remained in what is now the valleys, thick bodies of outwash sand were aggraded in between. After the ice had melted, valleys appeared. Valleys having such an origin are not younger than the adjoining sands, but of the same age. We prefer Fuller's interpretation.

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 a self-generating 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.

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 tend to obliterate all traces of the older one, Flint opposed the multiple-glacier hypothesis. Accordingly, he argued that all the striae must have been made by only one glacier, the youngest one.

On the Glacial Geologic Map of North America, Flint (1945) mapped the two contrasting flow directions, one from the NNE to the SSW and the other from NW to SE. Figure GG-9 show examples from the upper midwest and from SE New England that demonstrate glacial flow from the NW to the SE.

The first post-Fuller challenge to the one-glacier-did-it-all school of thought came from one of the staunchest one-glacier partisans, Richard Foster Flint (1961). In south-central Connecticut, Flint found two tills in direct superposition. He gave the name Hamden Till to the upper till, whose flow indicators imply glacier movement from NNE to SSW. He proposed the name Lake Chamberlain Till for the lower till, whose flow indicators showed glacier movement from NNW to SSE.

Despite Flint's results, Sirkin (1968, 1971, 1977, 1982) has attached to his noteworthy paleobotanical contributions a strong adherence to the one-glacier interpretation. Because he disagreed with some of Fuller's correlations, Sirkin swept aside all Fuller's work. Because we think Wehmiller (in Ricketts, 1986) has destroyed one of the keystones of Sirkin's interpretation, namely the supposedly mid-Wisconsinan Portwashingtonian warm interval (the amino-acid-racemization results suggest an age of 200,000 yr for the shells that gave a radiocarbon age of about 40,000 yr BP), we accord Sirkin the same treatment that he applied to Fuller (1914) and for the same reasons. [For further discussion of the problem of contrasting ages between these two dating methods in specimens from Port Washington, Long Island, see Muller and Calkin (1993, p. 1841), and for the Pleistocene deposits at Sankaty Head, Nantucket Island, MA, see Oldale and others (1982).]

We think that Sirkin's Roslyn Till probably is the same till that Upham (1879) noticed in extreme western Long Island and also the "trap-rock"-bearing gray till at Corona mentioned by Woodworth (1901). Like Sirkin, we assign the Roslyn Till to the Woodfordian (our Till IV); unlike Sirkin, we interpret the Roslyn Till as being younger than the Harbor Hill Moraine (which we assign to our Till III and place in the Early Wisconsinan).

In his study of the Quaternary sediments in the Boston area, Kaye (1982) found deposits that he ascribed to several Wisconsinan glaciers. Kaye's inferred flow directions of these Boston glaciers are virtually identical to those that we infer 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).

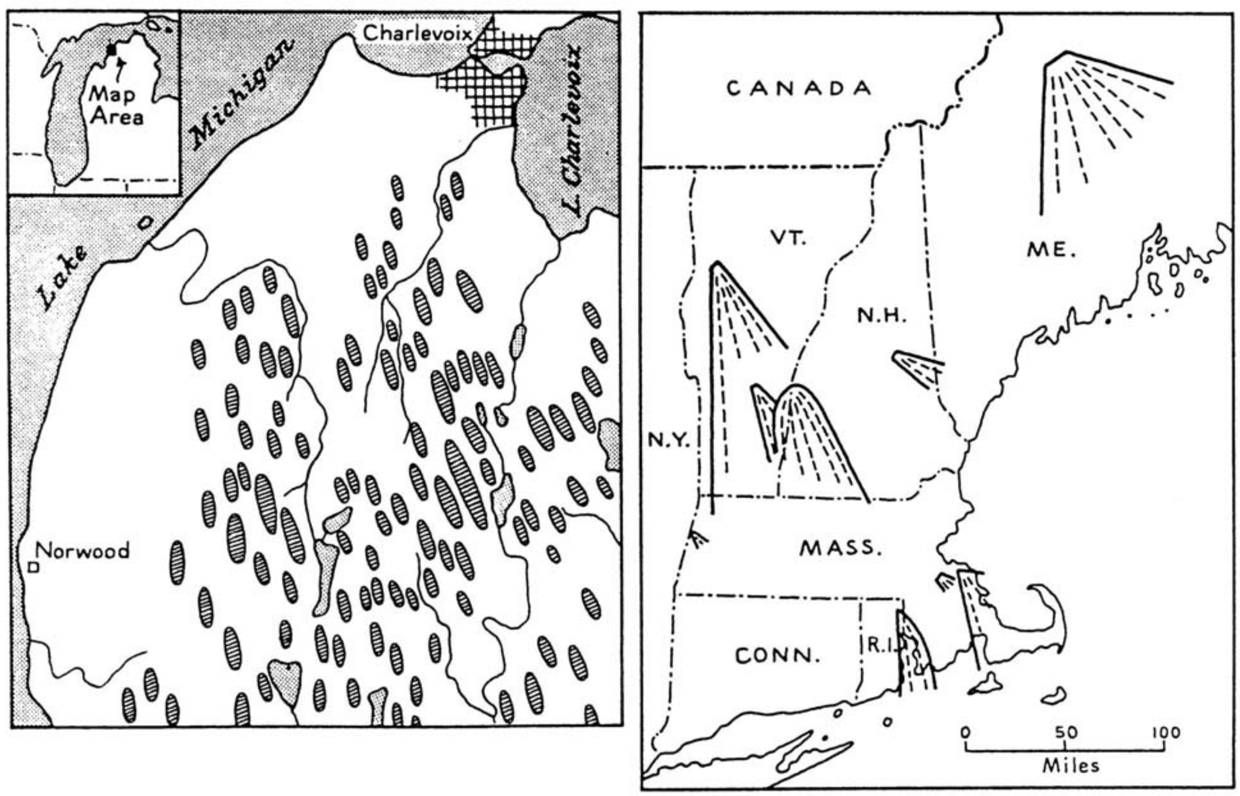

Figure GG-9. Sketch maps showing other regions in the United States where glacier flow was from NW to SE.
A. Swarm of drumlins south of Charlevoix, MI. (Frank Leverett, and F. B. Taylor, 1915, p. 311; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-20, p. 188.)
B. Boulder trains in New England, 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.)

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°

Recently, Sirkin has moderated his one-glacier viewpoint. In an open-pit mine at Sanford Hill, in the central Adirondacks, Muller, Sirkin, and Craft (1993) described two tills separated by 3.6 m of brown Tahawus lake- or pond clay containing wood fragments older than 55,000 radiocarbon years B. P. that were exposed in 1963 in the National Lead Company's (now NL Industries) open-pit mine. They assigned the Tahawus Clay to the Sangamonian; according to them, it contains "an interglacial pollen record, the first one identified in northeastern New York" Muller, Sirkin, and Craft, 1993, p. 163).

In their summary of the glacial events in New York State, Muller and Calkin (1993) did not recognize any pre-Wisconsinan tills in the New York City region. They wrote: "The pre-Wisconsinan record involves saprolith and till in the Adirondack Mountains, marine clay on Long Island, multiple tills at Fernbank, Otto, and Gowanda, and major drainage derangement of the Allegheny River" (Muller and Calkin, 1993, p. 1829).

After summarizing the amino-acid-racemization results, they continued:

> "...it is difficult to escape the conclusion that two temporally distinct stratigraphic units are involved. Indeed, Stone and Borns (1986) propose that the name Gardiners Clay be reserved for brown marine clay and silt (sic) with interbedded sand and gravel of probable Sangamonian to Eowisconsinan age (Table 3). This action clarifies the age of the Gardiners Clay, and implicitly acknowledges the probability that marine clays of both Sangamonian and pre-Sangamonian age are present" (Muller and Calkin, 1993, p. 1830).

OUR WORK

We subdivide this section into two parts: (1) a narrative of our background and credentials for investigating the glacial deposits in the New York City region, and (2) a summary of our interpretation of the stratigraphic framework of the Pleistocene deposits in the New York City reigon.

Background and Credentials of Investigators

In 1949-50 Sanders (hereafter abbreviated JES) took the late Professor Richard Foster Flint's graduate course in Geomorphology and Glacial Geology and for 10 years (1954-1964) was a faculty colleague of Flint's at Yale University. In the late 1950's and early 1960's, JES mapped the bedrock geology of several 7.5-minute quadrangles in and around New Haven at the same time as Flint was mapping the surficial deposits. They undertook several joint field conferences during which Flint interested JES in looking for and recording the orientations of features on bedrock surfaces that are valuable in determining the direction of flow of a glacier. JES found this a logical extension of his interest in the features made in sediments that enable directions of paleocurrents to be inferred, a topic he began to study during 1954 while a postdoctoral fellow working in Europe with the late Professor Ph. H. Kuenen, of the University of Groningen, The Netherlands (Kuenen and Sanders, 1956).

In 1964 JES moved to New York. He continued to work closely with Flint as a co-author of the Longwell, Flint, and Sanders Physical Geology textbook published in 1968. In 1968, JES began teaching the introductory geology course in the Department of Geology at Barnard College, Columbia University. Guided by Ina Alterman, a City College graduate then a graduate teaching assistant in the Department of Geology, Columbia University, JES started to examine local features at Fort Tryon Park (Figure GG-10) and the Palisades, places where many generations of geology students had been taken on required half-day field trips. One of the first things that JES noticed was the prominent evidence at both localities of striae and grooves made by a glacier that had flowed from about N15°W to S15°E. In search of what the experts on Pleistocene geology had made of such evidence, JES read into the geologic literature on the Pleistocene geology of the New York City region. In the writings of H. B. Kümmel (1933) and of R. D. Salisbury (1902, 1908; Salisbury and others, 1902), JES found how Salisbury, one of America's foremost specialists on Pleistocene geology, had explained this evidence of glacial flow from NW to SE. (See Figures GG-4 and GG-5.) JES thought Salisbury's explanation, which had been accepted by Kümmel and many other geologists, was somewhat unusual, but initially found no reason to challenge it.

Three other developments caused JES to change his position with respect to the Salisbury explanation. (1) In the summer of 1969, JES and son Thomas accompanied John Burger and his son David on a two-week canoe trip in the International Boundary Waterways Wilderness Area in northern Minnesota. One rainy day, they paddled past a splendid example of a roche moutonée comparable to the one shown in Figure GG-11. JES vividly recollected Richard Foster Flint's efforts to find an outstanding photograph of a roche moutonée for use in the Physical Geology textbook and how Flint had finally settled on the one shown. Accordingly, JES kept on the lookout for other examples of roches moutonées that he could photograph on a fair-weather day. To his surprise, he found no other examples as typical as the one passed during the rain. A few nights later, we camped on a bedrock knoll whose surface had been glaciated. Next morning when we studied it closely, we found that it had been shaped by glacial-ice flow from two directions nearly at a right angle. The typical jagged, quarried-and-plucked downglacier side created by earlier ice flow from the NE to the SW had been destroyed by later ice flow from NW to SE. Being mindful of the standard version of the North American ice sheets during the Pleistocene (Figure GG-12), JES asked John Burger if local Pleistocene geologists had noticed what we had seen and if so, how they explained it. Burger was puzzled. When we returned to Beloit, Burger took JES to visit a local limestone quarry, where the stripped surface of the bedrock near the quarry faces displayed crossed sets of striae, one oriented NE-SW and the other, NW-SE, the same directions of flow that had sculpted the bedrock knolls we had seen on the canoe trip. Both of us left the quarry in a puzzled state of mind.

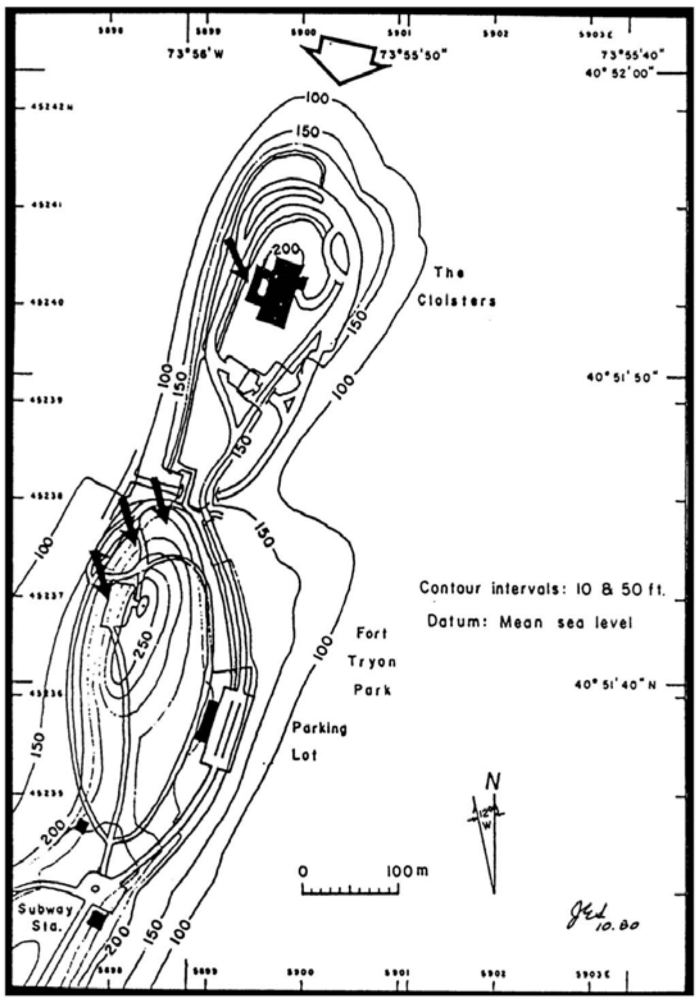

Figure GG-10. Enlarged topographic map of the Cloister area, Fort Tryon Park showing the two rock drumlins oriented NNE-SSW. Enlarged from USGS Central Park 7.5-minute quadrangle by JES.)

(2) In 1970, based on material in Schuberth's (1968) book, JES worked up a one-day Palisades/Staten Island field trip to be included as part of a new course on the Natural History of the New York City region offered in alternate years jointly with faculty colleagues in the Department of Biology, including the late Donald R. Ritchie, Chairman, who had kept up a life-long interest in geology. One of the localities included on our trips was Princess Bay (Stop 6 on today's trip). On the beach we found examples of many kinds of rocks that had been washed out of the reddish-brown till exposed in the eroding bluff; before us lay the materials for virtually a complete course in petrology. Among the washed-out erratics were two varieties that qualify as indicator stones: (A) the Lower Silurian Green Pond Conglomerate from the Appalachian fold-thrust belt in NW New Jersey. (One particularly distinctive kind, featuring small, white, rounded, uniformly sized quartz pebbles about 4 mm in diameter set in a dark-reddish brown hematitic matrix, prompted Professor Ritchie to name it the "braunschweiger-sausage" rock). (B) Small angular erratics of anthracite, which we found by studying the eroding face at close range. Both these kinds of indicator stones demonstrate that glacial flow from NW to SE had been not local and curved (as implied by the flow lines in Figure GG-5) but regional and rectilinear (Figure GG-13). JES subsequently interested Joanne Bourgeois in studying the erratics here for her Senior Thesis (Bourgeois, 1972 ms.)

(3) Alexandra Gardiner Tufo (now Goelet) enrolled in the course on the Natural History of New York City and as one of the trips, invited the class to visit her family home on Gardiners Island. The eroding cliffs on the E side of Gardiners Island display reddish-brown till featuring abundant erratics from the Newark-age rocks of the Connecticut valley belt in central Connecticut and -Massachusetts (now designated as the Hartford basin). A Pleistocene glacier could have transported these erratics to Gardiners Island only if it had flowed regionally from NW to SE.

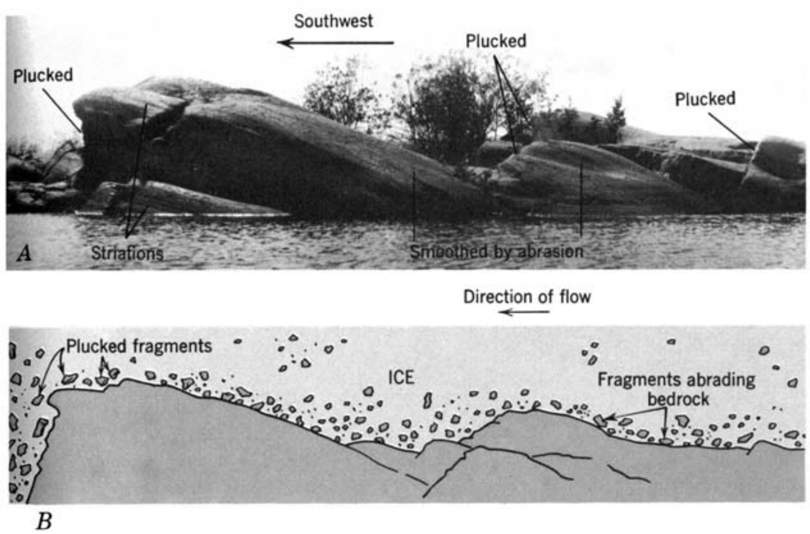

Figure GG-11. Roches moutonées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roches moutonées sculpted in Proterozoic granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roches moutonées beneath a glacier.

Figure GG-12. Map of North America showing a 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).

JES began to think about the Pleistocene history of New York City in terms of two glaciers, possibly the same two that Flint (1961) had described in southern Connecticut: an older glacier that had flowed from NW to SE and a younger one that had flowed from NNE to SSW and that Long Island's prominent terminal-moraine ridges had not been deposited by ice flowing from NNE to SSW, the direction assigned to the latest glacier, but rather by a glacier that had flowed from NW to SE (Sanders, 1974).

The thousands of engineering borings through the thick bodies of sediment underlying the Hudson, Hackensack, and other strike valleys that trend NE-SW disclosed evidence for only a single glaciation. 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 (Berkey, 1933, 1948; Berkey and Healy, 1912; Berkey and Fluhr, 1948; Lovegreen, 1974 ms.).

Rampino (1978) examined the numerous vibracores collected along the routes of the outfall pipes from the sewage-treatment plants being built for Nassau County and for Suffolk County in the vicinity of Jones Beach on the S shore of Long Island (Figure GG-14). These cores provided the basis for recognizing three new formations (Figure GG-15). A lower nonmarine sand unit, interpreted as outwash, was named the Merrick Formation. It was separated by coastal marine (intertidal- and bay) deposits, the Wantagh Formation, from an upper sandy nonmarine unit of inferred outwash, the Bellmore Formation (Rampino and Sanders, 1981). They correlated the inferred upper outwash (the Bellmore Formation) with the Harbor Hill Moraine and the lower inferred outwash (the Merrick Formation) with the Ronkonkama Moraine.

JES and Rampino (1978) presented a paper at the Northeastern Section of the Geological Society of America on proposed revisions is the Pleistocene stratigraphy of the New York City region. The response from the reigning "experts" on Pleistocene geology was a massive yawn.

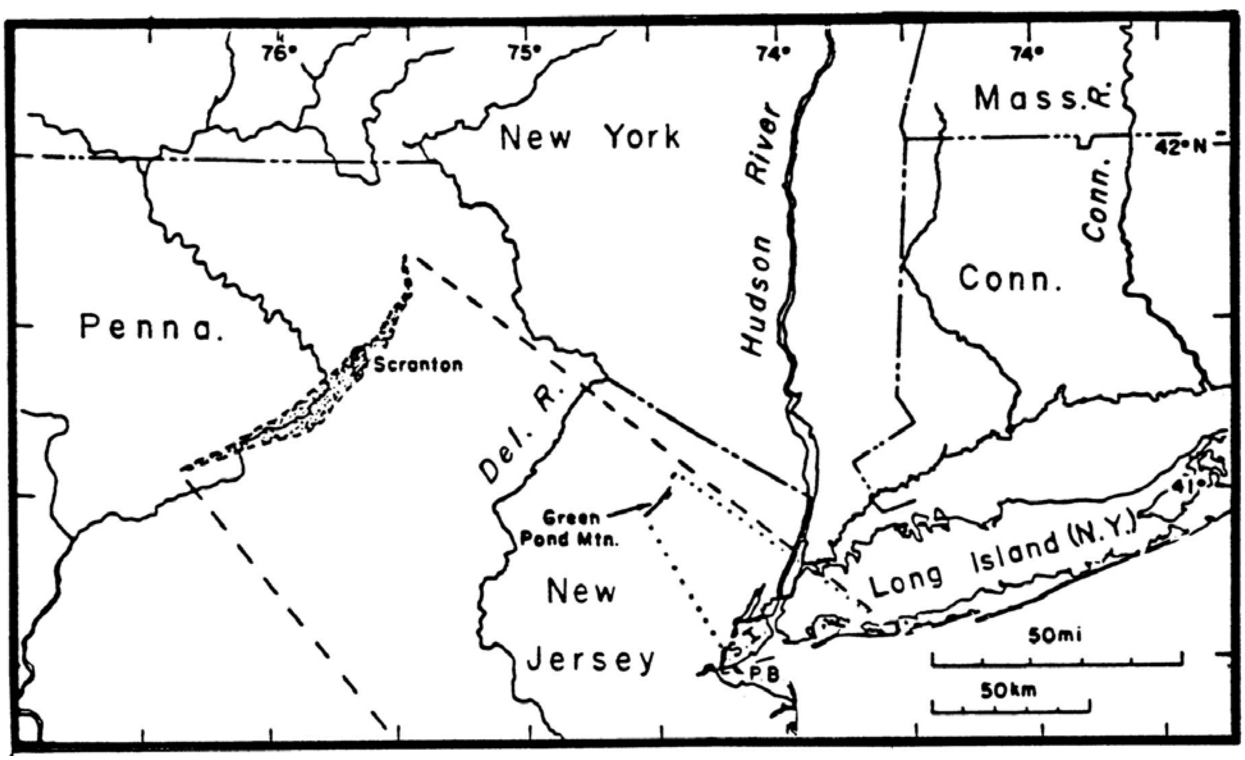

Figure GG-13. Distinctive indicator stones found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten Island; P. B. = Princess Bay. (Friedman and Sanders, 1978, fig. 2-1, p. 27; Friedman, Sanders, and Kopaska-Merkel, 1992, Box 2.2 fig. 1, p. 48.)

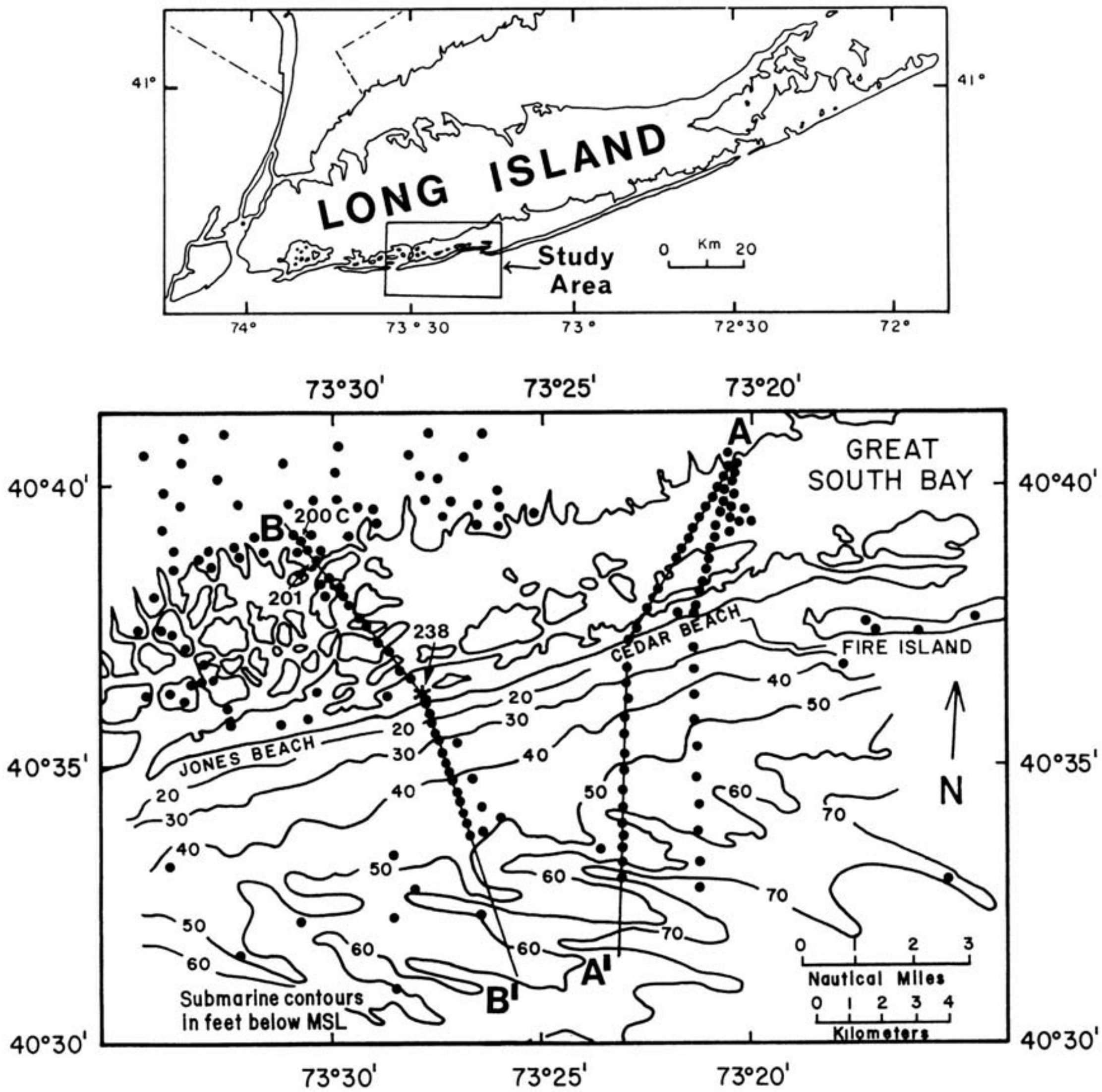

Figure GG-14. Index map, location of Jones Beach profile-sections. (Rampino and Sanders, 1981, fig. 3, p. 118.)

Merguerian's (hereafter abbreviated CM) experience in mapping metamorphic- and igneous rocks in the southern part of the New England Appalachians and in the foothills metamorphic belt of the Sierra Nevada of California and adjacent regions has spanned more than twenty-five years. As an extension of his work on Cameron's Line and the bounding units in western Connecticut (Merguerian 1983a, 1985, 1987), CM has mapped all of the bedrock exposures in Manhattan (under the auspices of the U. S. Geological Survey branch of Engineering Geology during 1981-83) and has continued his research to the present (Merguerian, 1983b; 1986a, b; 1994; Merguerian and Baskerville, 1987; Merguerian, Baskerville, and Okulewicz, 1982). CM has led hundreds of geological field trips to Central Park and other sites in Manhattan and vicinity.

As a dyed-in-the-wool hard-rock geologist, CM would have never imagined working on the non-lithified "cover" that masks the more-interesting crystalline tectonostratigraphic terranes. His first nudge away from this hard-rock attitude was delivered during a graduate course in Pleistocene Geology at Columbia University taught by Professor Rhodes W. Fairbridge.

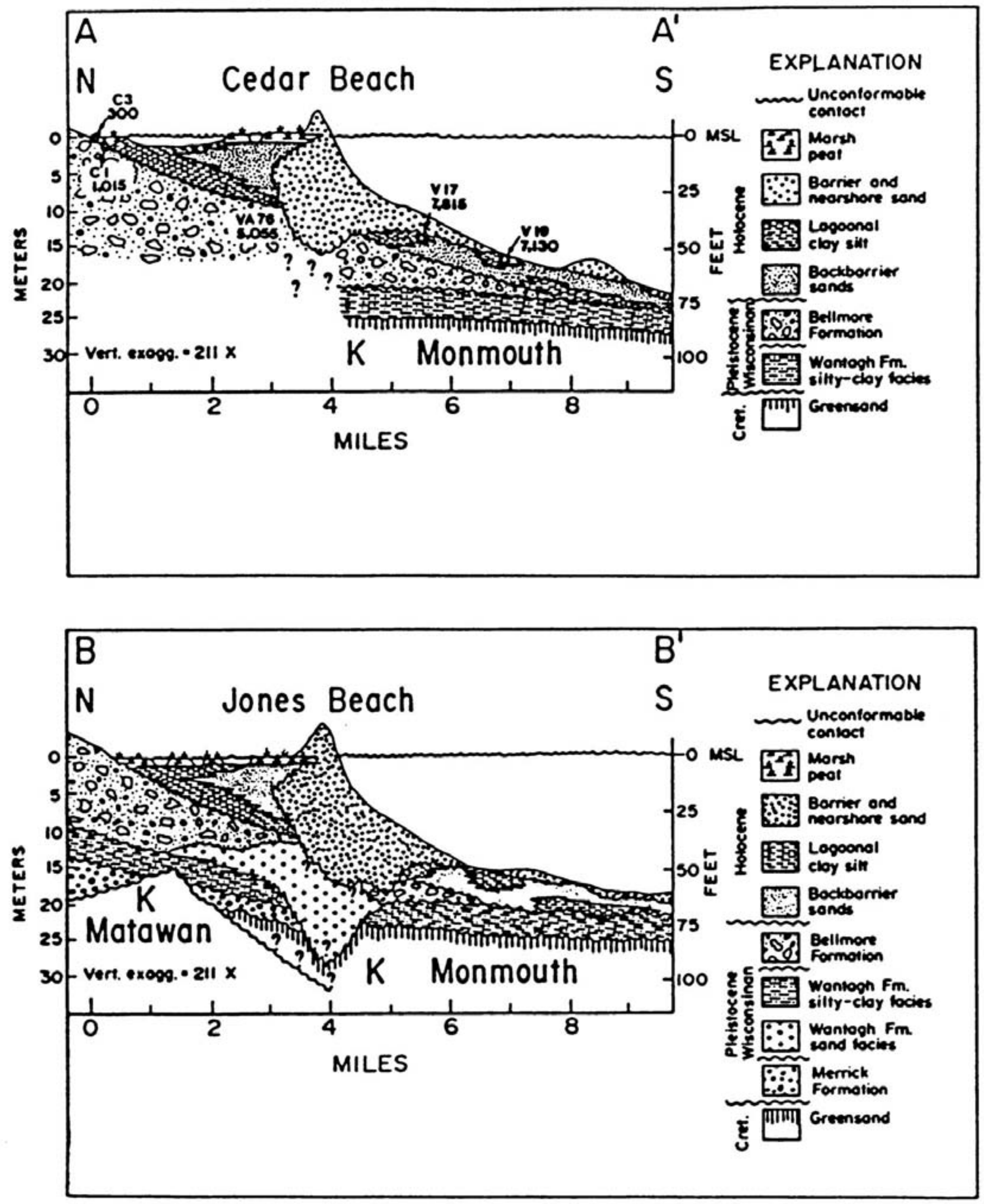

Figure GG-15. Profile-section subsurface of Jones Beach. (Rampino and Sanders, 1981, fig. 4, p. 119.)

Since 1987, our collaboration has given CM a new perspective and appreciation for soft-rock geology (as such, CM now feels that only mild heating to 600°C under 5 Kb pressure is needed to correct their soft character!). CM's main contribution to this project has been the identification of far-traveled erratics and indicator stones excavated and brought down from areas of his bedrock familiarity, the field measurement of superposed features of glacial erosion, and keeping JES on schedule for publication deadlines.

Our joint studies have been made starting in 1987 and are continuing in connection with preparations of guidebooks and the carrying out of many of our On-The-Rocks field trips for the Section on Geological Sciences of the New York Academy of Sciences (Merguerian and Sanders, 1988; 1989a, b, c, d, e, f; 1990a, b, c, d, d, e, f; 1991a, b, c, d, e, f; 1992b, c, d, e; 1993 a, b, c, d; 1994 a, b) and a special trip on the glacial geology of the north shore of Long Island for the Long Island Geologists (Sanders and Merguerian, 1991b). We have published abstracts of papers presented at meetings related to our joint research on the glacial history of the New York metropolitan area (Sanders and Merguerian 1991a; 1992; 1994; Sanders, Merguerian, and Mills, 1993).

We are now at work on the manuscript of a book on the geology of New York City and vicinity, a book on the Roadside Geology of New Jersey, and an introductory-level Geology lab manual based on materials that we have presented in the On-The-Rocks field-trip guidebooks.

Together we have focused on three aspects of the glacial geology: (1) features made by glaciers flowing over the bedrock (not an altogether new topic; geologists have been studying the orientations of small-scale glacial striae and -grooves in the New York City region for 166 years; we have concentrated on glacial features at all scales not only on the small-scale ones); (2) glacially displaced indicator stones [another topic on which many previous workers have expended first-class efforts locally; any edge we claim for ourselves falls in this department--between the two of us we are very familiar with the bedrock in the region over which the glaciers flowed, posssibly more so than many of the geologists who have specialized in study of the Pleistocene sediments on Long Island, for example. In this connection, we think our most-important contributions have been in our ability to distinguish between a common kind of mafic erratic (Palisades dolerite/diabase) from four potential look-alike rocks, (a) mafic- and ultramafic rocks from the Cortlandt complex near Peekskill; (b) Paleozoic dark-colored amphibolites from southeastern New York and western Connecticut; (c) Paleozoic mafic igneous rocks from western Connecticut; and (d) the Paleozoic metavolcanic rocks from southwest of New Haven, CT.; and (3) exposures of stratigraphic relationships [in this topic we have lucked into some "treasures" exposed in new excavations and in coastal cliffs that were severely eroded during storms, but then several of our predecessors, namely Mather (1843) and Fuller (1914) likewise studied storm-eroded coastal cliffs on Long Island; more importantly perhaps, we have been resolute diggers with trenching tools and routinely clear up the slope wash to see what is really under there--some of our contemporaries have been less inclined to use trenching tools and thus, we think, have made some serious mistakes in their interpretation of the slope wash). Our view parallels the U. S. Supreme Court's voting-rights decision: "one person, one vote." With respect to New York's glacial record, we paraphrase that Supreme Court ruling with "One glacier, one flow direction."

Our View of New York City's Pleistocene Stratigraphy

Table GG-2 shows our interpretation of the Pleistocene stratigraphic units in the New York City region. Although for the sake of completeness, we have included in Table GG-2 all of Fuller's units, we emphasize that our work has concentrated on tills and their directions of flow and has not dealt at all, for example, with the Gardiners Clay or with such important subsurface units as the Jameco Gravel and subsurface Mannetto Gravel. We have included the Gardiners Clay not because we have studied it but because we accept the Ricketts-Wehmiller result that the age of the Gardiners Clay is Yarmouthian, where Fuller (1914) assigned it and not Sangamonian, where the multitude following MacClintock and Richards (1936) has placed it and where Stone and Bornes (1986) would officially redefine it (a proposal that we totally reject).

The key to the changes we have made comes from our results from directions of flow. We argue that the youngest glacier (the Woodfordian; our No. IV) flowed along a direction that is parallel to the Hudson Valley (from about N10°E to S10°W). In the New York City area, the color of this till is gray or yellowish brown. The next-older till (our No. III) was deposited by a glacier that we think flowed from a direction that is across the lower Hudson Valley (direction from N25°W to S25°E). As mentioned previously, in his study of the Pleistocene deposits of Queens, J. B. Woodworth (1901) showed that the Harbor Hill moraine is associated with reddish-brown materials that rest on striated bedrock with striae oriented N25°W-S25°E. In our scheme of things, we think this means that the Harbor Hill moraine cannot possibly be of Late Wisconsinan age (i. e., Woodfordian, as most workers except Fuller believe), but must be at least one glacier older.

We are confident in our relative arrangements, but readily admit that we have assigned ages by the method of "counting down from the top" that is subject to change at the first whiff of solid chronostratigraphic data, of which we offer absolutely none. We still lack the definitive interglacial stratigraphic evidence necessary to destroy forever the one-glacier-did-it-all viewpoint that we think is erroneous.

In the following sections, we present the basis for our multiple-glaciers interpretation.

Our discussion features evidence of effects of glacial erosion on bedrock from localities (only one being on Staten Island, at the Graniteville quarry) where we think the n value for Pleistocene glaciers must be >1. To this, we add local- and regional data from glacial sediments (provenance and long axes of drumlins) that support multiple-flow directions. Then follows a discussion of superposition of tills exposed at localities in Westchester County, in northern New Jersey, on Long Island, and on Staten Island. We close with a brief summary of the glacial geology of Staten Island interpreted using our proposed stratigarphic framework.

Age	Unit No.	Ice-flow Direction	Description; remarks
			Gray-brown till in W. Queens,
Late Wisconsinan	IV	NNE to SSW	Westchester Co.,
(Woodfordian)			Staten Is.; gray lake
			sediments at Croton Pt. Park
			Harbor Hill Terminal
Early	III	NW to SE	Moraine and associated
Wisconsinan (?)			outwash; Bellmore Fm. in
			Jones Beach subsurface;
			Wantagh Fm. of Jones
Sangamonian (?)			Beach subsurface;
			Ronkonkama Terminal
			Moraine and associated
Illinoian (?)	II	NW to SE	outwash (=Merrick Fm. of
			Jones Beach subsurface);
Yarmouthian			Gardiners Clay
			Manhasset Fm. of Fuller
			(including debris flows)
			deposited in Lake Long
Kansan (?)	I	NNE to SSW	Island dammed on S in
			part by pre-Ronkonkama
			terminal-moraine ridge;
			Gray till at Teller's
			Pt., Croton Pt. Park.
Aftonian			Not known to be present.
			Decayed-stone outwash
Nebraskan (?)			at AKR Excavating Co., SI

Table GG-2. Our stratigraphic classification of the Pleistocene deposits of New York City and vicinity.

DIRECTIONS OF GLACIAL FLOW BASED ON ERODED BEDROCK IN THE NEW YORK CITY REGION

We begin our presentation by summarizing the kinds of features glaciers erode on bedrock that can be used for inferring ice-flow direction(s). Then follows a presentation of results from study of local examples.

Kinds of Features Glaciers Erode on Bedrock That Can be Used For Inferring Ice-Flow Direction(s)

Features that a glacier erodes on the bedrock that can be used to infer ice-flow direction include striae and grooves, crescentic marks, long axes of roches moutonées and "roche-moutonée structures" and long axes of rock drumlins. We describe each of these and show their value in reconstructing ancient flow directions.

Striae and grooves

Glaciers are one of the few geologic agents known to create scratches and even large grooves on solid bedrock (Figure GG-16). The ice flowed along the trend of the linear elongate features.

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

Crescentic marks

In some places, 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 GG-17).

Orientations of long axes of roches moutonées and "roche- moutonée" structures

The distinctly asymmetric relief features sculpted by a glacier in the bedrock are known as roches moutonées. (See Figure GG-11.) 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].

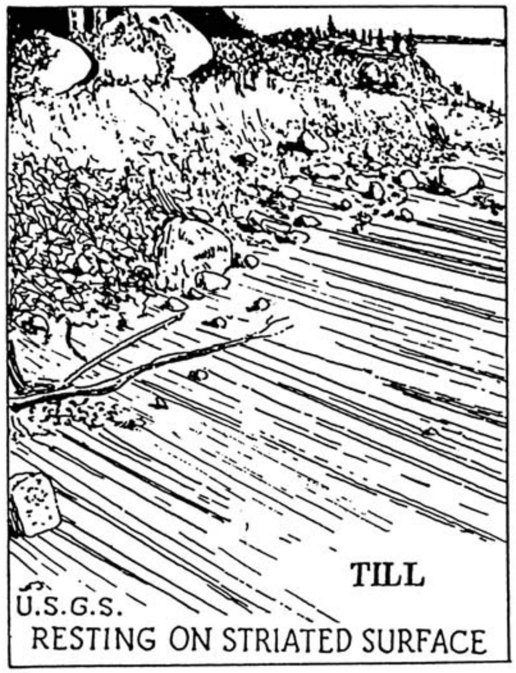

Figure GG-16. Sketch of a glaciated bedrock surface exposed by wave action; boulders resting on the linear striae have been eroded out of the bluff of till in the background. This sketch (locality not given) depicts what can be seen along the shore of Long Island Sound at South Twin Island, Pelham Bay Park, New York City. (A. K. Lobeck, 1939, upper right-hand sketch on p. 301, from U. S. Geological Survey.)

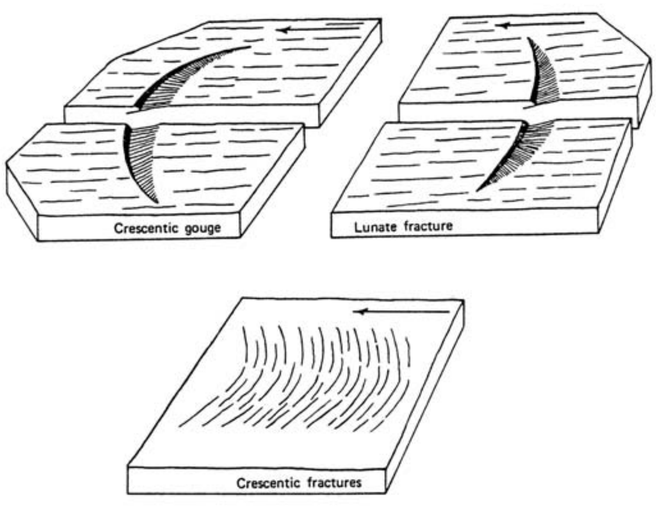

Figure GG-17. Sketches: glacial crescentic marks. (Flint, 1971.)

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

In our studies of ice-flow directions we have made use of the orientation of the median axis of the elongate, rounded up-ice side of a classic roche moutonée (Figure GG-18). We have been using the informal term "roche- moutonée structure" for these.

Orientations of long axes of rock drumlins

Drumlins are elongate streamlined hills shaped by the flow of a glacier; the long axis of a drumlin is parallel to the flow direction of the ice and the steeper side is toward the direction from which the ice came. 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 consistins of both till and of bedrock. Rock drumlins consist only of bedrock. (See Figure GG-10.) Because most drumlins consist of till, we discuss them in a following section devoted to glacial sediments. In this section, we include only rock drumlins. (We do not know why a glacier forms a rock drumlin instead of a roche moutonée or vice versa.)

Examples from Manhattan

Many examples of features eroded on bedrock by a glacier, notably striae and grooves, are known from nearly all parts of Manhattan where bedrock is exposed. Many are found in Central Park, in Riverside Park, in Fort Tryon Park, and in Inwood Hill Park. We present our results from all four of the parks mentioned. All of these parks are situated on the Central Park 7.5-minute topographic quadrangle map of the U. S. Geological Survey (Figure GG-19); the northern end of Inwood Hill Park lies on the southern edge of the Yonkers quadrangle.

Figure GG-18. Sketch showing a three-dimensional view of roche- moutonées. Arrow indicates direction of ice movement. (Lobeck, 1939, part of figure on p. 298.)

Central Park

In Central Park, glacial grooves trending NW-SE are present on virtually every rock knoll (Figure GG-20). Evidence for SE-directed glacial flow is obvious in the glacially sculpted exposure SE of the Zoo shed (UTM: 586.72E - 4513.18N). Large- and small grooves at the south end of the exposure are oriented N30°-35°W to S30°-35°E; on top of the knoll, they trend N40°W to S40°E. The steep, jagged slope on the E side of the exposure must be registered as a "fake" roche moutonée; the drill holes reveal it is the product of drilling and blasting during park construction.

All of the scattered outcrops E of the walkway just N of the 65th Street Transverse Road (UTM: 586.82E - 4513.42N) show the effects of glacial rounding and polish. Glacial grooves are oriented N47°W to S47°E; they resulted from ice flowing to the SE (Figure GG-20).

On the surface of the bedrock exposed E of the walkway where the walkways make an X pattern S of "The Dene" (UTM: 586.85E - 4513.49N), glacial grooves are oriented N25°W to N32°W; they are products of a glacier that flowed SE.

On the bedrock knoll W of "The Dene," (UTM: 586.7E - 4513.50N) numerous glacial grooves are oriented N35°W-S35°E, they indicate glacial flow toward the SE. At the NE end of the exposure, a subdued-roche moutonée structure with long axis oriented N37°E-S37°W has been cut by glacial grooves that trend N36°W-S36°E.

By "The Platform," the N end of the knoll E of "The Dene" and N of the playground (UTM: 586.90E - 4513.57N) has been shaped into broad roche- moutonée structure whose long axis trends N10°E-S10°S. Glacial grooves and -troughs nearby are oriented N32°W-S32°E, but we have not observed crosscutting relationships between the grooves and the roche- moutonée structure. We infer that the NW-SE-trending grooves are younger than the roche- moutonée structure.

At the U. S. Geological Survey benchmark S of The Pond (UTM: 586.92E - 4513.50N), glacial grooves oriented N32°W-S32°E indicate that glacial ice flowed over the Hartland Formation here in a SE direction.

The knoll W of The Pond, opposite the access to Central Park from the Avenue of the Americas (UTM: 586.35E - 4513.08N), prominent glacial grooves are oriented N28°W-S28°E. The long axis of a subdued roche moutonée structure is oriented N40°E-S40°W. As at "The Platform," we have not able to establish any cross-cutting relationships between the grooves and the roche-moutonée structure.

On the northward-sloping surface of the roche- moutonée structure at the knoll W of The Pond, opposite the access to Central Park from the Avenue of the Americas are SSW-oriented "chattermarks" (crescentic marks; products of Glacier IV?).

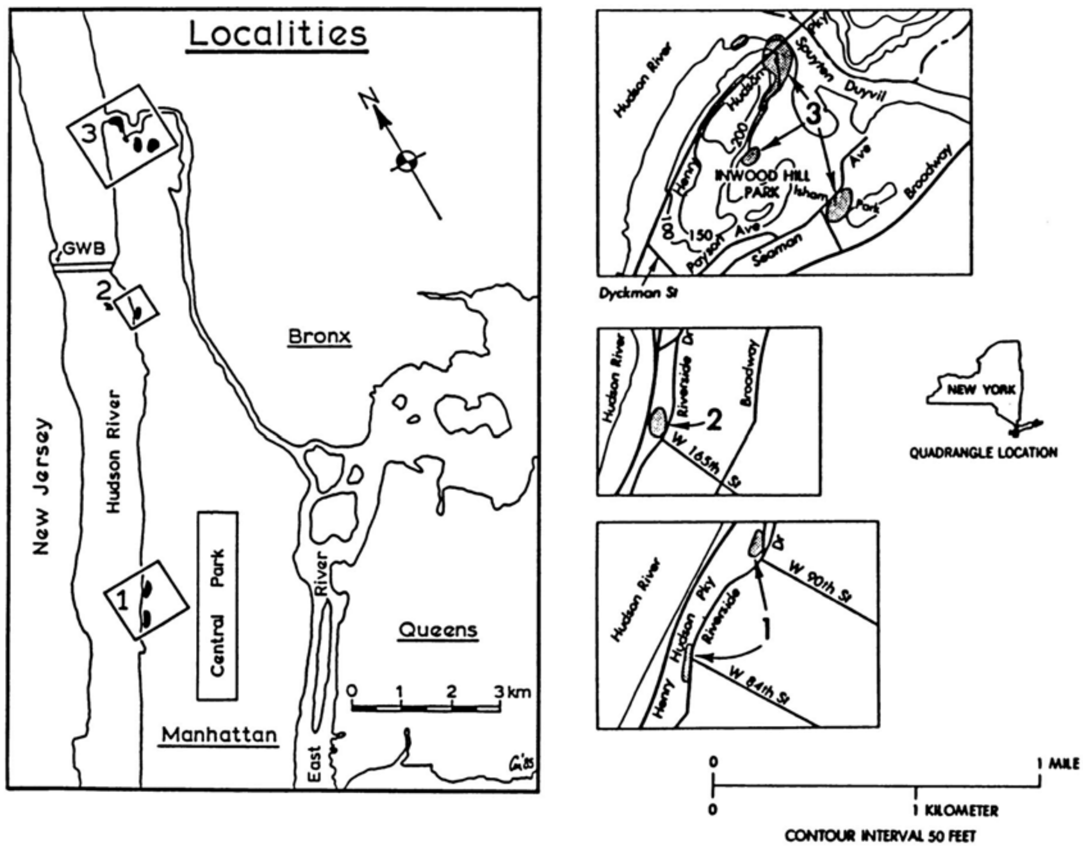

Figure GG-19. Index maps of three Manhattan park localities mentioned in text. 1) southern Riverside Park; 2) northern Riverside Park; 3) Inwood Hill Park. (Drawn by C. Merguerian.)

On the S side of West Drive, near the SW boundary of Central Park (UTM: 586.28E - 4513.10N), the effects of glacial rounding and -smoothing of the bedrock surface underlain by the Hartland Formation are conspicuous. The trend of the glacial grooves is N38°W-S38°E.

Umpire Rock (UTM: 586.25E - 4513.38N) is the most-spectacular natural exposure in the south part of Central Park (Figure GG-21). Here, rocks of the Hartland Formation show the effects of superposed folds, abundant syn- and post-tectonic pegmatite intrusives, brittle faults, and numerous glacial features. See Merguerian and Sanders (1993c) for details.

Perhaps the most-obvious geologic features here are of glacial origin. At the NW edge of the exposure, glacial meltwaters have modified spectacular glacial troughs oriented N28°W-S28°E parallel to the overall SE-directed roche- moutonée shape of the exposure that drops off settply toward the playground. Many glacial erratics can be found here. We have identified Palisades diabase and hornfelsic Lockatong Formation (from the Newark basin W of the Hudson River), Hartland Formation, granite, and diorite. Evidence of the youngest (Woodfordian) glacier that flowed from NNE to SSW is shown by a block of Hartland Formation that has been tipped upside down and now lies immediately south of its former "home" defined by steep joint faces. The fact the SE-flowing groove-making glacier did not displace this block of the Hartland Formation proves that the block was moved later on; therefore, the Woodfordian (i. e., youngest, our No. IV) glacier must have moved and tipped this block.

Figure GG-20. Index map of localities in southern Central Park. Arabic numerals show stop numbers from Merguerian and Sanders, 1993c, fig. 41, p. 143.

Around the steep, north-facing wall of the exposure, the glacial grooves are oriented N46°W-S46°E. On the eroded outcrops immediately north of the north-facing wall, groove orientation is N35°W-S35°E.

On the E side of the walk E of the Heckscher Playground (UTM: 586.38E - 4513.42N), a coarse pegmatite erratic, about 2 m high, displays megacrysts of K-feldspar. This erratic rests on rocks of the Hartland Formation that have been scored by glacial grooves trending N38°W-S38°E.

Farther N, near the 79th Street entrance to Central Park, opposite the main entrance of the American Museum of Natural History, a low bedrock knoll near the low wall separating the park from the sidewalk on Central Park West (UTM: 586.70E - 4514.75N) a low, rounded bedrock surface displays striae oriented NNE-SSW (more or less parallel to the wall, cut by our Glacier IV) that are younger than the larger, more-obvious grooves and striae trending NNW-SSE (products of our Glacier III and/or II). This is one locality in Central Park where the effects of Glacier IV and one or more of the earlier glaciers can be seen together.

Figure GG-21. Photograph of NW-SE-trending glacial grooves on glacially polished NW-facing slope of Umpire Rock. (Digital Image, C. Merguerian.)

Riverside Park

In Riverside Park from West 116th St. southward to West 75th St., bedrock knolls are numerous. Described here are exposures of the Hartland Formation near West 90th – 91st Streets and exposures from West 82nd – 85th Streets. (See Figure GG-19, No. 1.) The northernmost outcrops (UTM: 586.10E - 4515.96N) consist of gray-weathering, well-layered and slabby- to laminated, lustrous muscovitic schist containing interlayers of quartz-muscovite biotite granofels. Locally in the schist, l-cm-thick glassy quartzose layers and elliptical pods of recrystallized dark quartz are present.

Several glacial features of interest are present here. The overall shape of the surface of the bedrock defines several roche- moutonée structures. Not only have the rock surfaces been glacially rounded and -smoothed on a large scale, but glacier-cut grooves and -striae are present as well. The trends of these show that the ice flowed across the Hudson River, from NW to SE. Consistent with such a flow direction is the reddish-brown color of the till and the kinds of erratics present (including dolerite from the Palisades Sill and anthracite coal from northeastern Pennsylvania). (See Figure GG-13.)

The large knoll W of the intersection of Riverside Drive and West 165th St. (See Figure GG-19, No. 2; UTM: 589.1E - 4521.4N) displays evidence of both glacial erosion and -deposition. The overall shape of the surface of the knoll defines several roches moutonées. Many years ago, this particular knoll probably was a splendid exmple of a "natural" roche moutonée, it 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, as at the knoll SE of the Zoo shed in Central Park, has been blasted away to make way for the street and the sidewalk.

Not only has the rock surface been glacially rounded and -smoothed on a large scale, but glacial grooves and -striae are present as well. The trends of these show that the ice flowed from NW to SE, across the Hudson River. The reddish-brown color of the till and erratics of dolerite from the Palisades Sill and of Newark-age sandstone plus indicator "stones" of anthracite coal from northeastern Pennsylvania further demonstrate glacial flow from NNW to SSE.

Fort Tryon Park

At Fort Tryon Park (See Figure GG-10.), effects of glacial erosion are conspicuous. Only minor products of glacial deposition are present.

The enlarged contour map of Figure GG-10 shows that the whole park is situated on two aligned rock drumlins trending NNE-SSW. Along the sidewalk S of the deep cut for the access road from/to the northbound lanes of the Henry Hudson Parkway (UTM: 589.75E - 4523.75N) glacially rounded bedrock knolls and glacially-cut grooves trend N15°W-S15°E. Here is a well-defined example of a feature eroded by an older glacier (the more-southwesterly of the two aligned rock drumlins; we infer that it is a product of our Glacier I that flowed from NNE to SSW) which has been cut across by features eroded by a younger glacier (either our Glacier III or II that flowed from NNW to SSE).

Along the sidewalk at the SW corner of the Cloisters (UTM: 589.92E - 4524.00N), on the more-northeasterly and larger of the two aligned rock drumlins, prominent glacial striae trending N15°W-S15°E are present on a bedrock surface that was cleared during construction.

Inwood Hill Park

The area of Manhattan north of Dyckman Street, in the extreme northwest corner of Manhattan Island, is known as the Inwood section. Except for the "hill" in Inwood Hill Park, the region is underlain by a marble that Merrill (l890) named the Inwood Limestone. The "hill" is a synformal overthrust of allocthonous "Manhattan" Formation (Merguerian and Baskerville, 1987). Inwood Hill Park, is bordered by Dyckman Street on the S, by the Hudson River on the W, by Spuyten Duyvil (Harlem Ship Canal) on the N, and by Payson and Seaman Avenues on the E. (See Figure GG-19, No. 3.)

On the crest of the bedrock knoll at the NE end of Inwood Hill Park (UTM: 594.2E - 4525.9N) a broadly rounded roche- moutonée structure trending NNE-SSW, has been cut by grooves trending NNW-SSE, as at Fort Tryon Park.

Examples from The Bronx

Many bedrock knolls displaying the effects of glaciation are present in The Bronx. We describe those from only two localities: the New York Botanical Garden and Pelham Bay Park.

New York Botanical Garden

Published geological results of studies made in the New York Botanical Garden include origin of the Bronx River gorge (Kemp, 1897), discussion- and illustration of obvious glacial features such as erratics and prominent grooves, but with no measurements of groove orientations (Hollick, 1926), and investigations of the geologic structure (Langer, 1966; Bowes and Langer, 1969). Merguerian and Baskerville (1987) and Baskerville (1992) have independently mapped the rocks here as belonging predominantly to the Hartland Formation.

Glacial features noted in the Botanical Gardens include polished bedrock surfaces, roche-moutonée structure, and glacial grooves, indicating at least three major glacial episodes: (1) earliest movement from NNE to SSW (our Glacier I); (2) movement from the NNW to SSE (our Glaciers II and/or III), and (3) movement from NNE to SSW (our Glacier IV). These are in keeping with our results from studies of glaciation elsewhere in the region.

We have plotted localities in the New York Botanical Gardens on a trail- and garden map issued by the Botanical Gardens (Figure GG-22).

Along the road near the Rockefeller Rose Garden (UTM 594.87E - 4523.58N, a rounded bedrock knoll has been sculpted into a classic roche- moutonée structure with a gentle up-glacier side and a steep down-glacier side. As such, this asymmetrical erosional indicator indicates glacial flow from N15°E toward S15°W (Our Glacier I or IV in Table GG-2). The development of the steep, down-glacier side of the roche moutonée was undoubtedly facilitated by the subvertical A-C joints which formed perpendicular to the local F3 fold axes in the Hartland.

The evidence for glaciation here (UTM: 594.60E - 4523.62N) is in the form of a huge glacial erratic of the Fordham Gneiss perched upon the glacially polished outcrop surface of the Hartland Formation. Etched into the surface are prominent glacial grooves oriented from N26°W to S26°E (our Glacier II or III in Table GG-2). They are parallel to the overall asymmetry of the outcrop with smoothed, gentle NW slopes and jagged, steep SE ledges. The gentle, polished NE-facing slopes suggest that the outcrop may also have been sculpted in a direction parallel to the strike of the foliation (N21°E). The associated jagged SW edge of this suspected roche moutonée may have been strongly modified by the more-obvious effects of the younger, SE-directed glaciation.

The overall shape of this glacially sculpted, low-relief outcrop (UTM: 594.42E - 4523.61N) displays the erosional effects of two glaciations from different directions. The prominent N22°W to S22°E glacial grooves (Glacier II or III) here cut across an older roche-moutonée structure (Glacier I) oriented from N26°E to S26°W. Thus, when combined with evidence from localities previously discussed, further indicates glacial flow from two contrasting directions.

The most-obvious glacial feature at Elephant Rock (UTM: 594.43E - 4524.05N) is the enormous, split erratic boulder of Yonkers Gneiss on the NE part of the exposure near the entrance to the Rock Garden. The presence of the Yonkers here constrains ice-flow direction in that exposures of the Yonkers are limited to areas directly north and east of us. Accordingly, this boulder was NOT transported by ice flow from the NW; it must have been deposited by our Glacier IV from the NNE. (See Table GG-2.) Because subsequent glaciers tend not to leave pre-existing erratics in place, the mere presence of this Yonkers Gneiss boulder mandates the Glacier-IV interpretation.

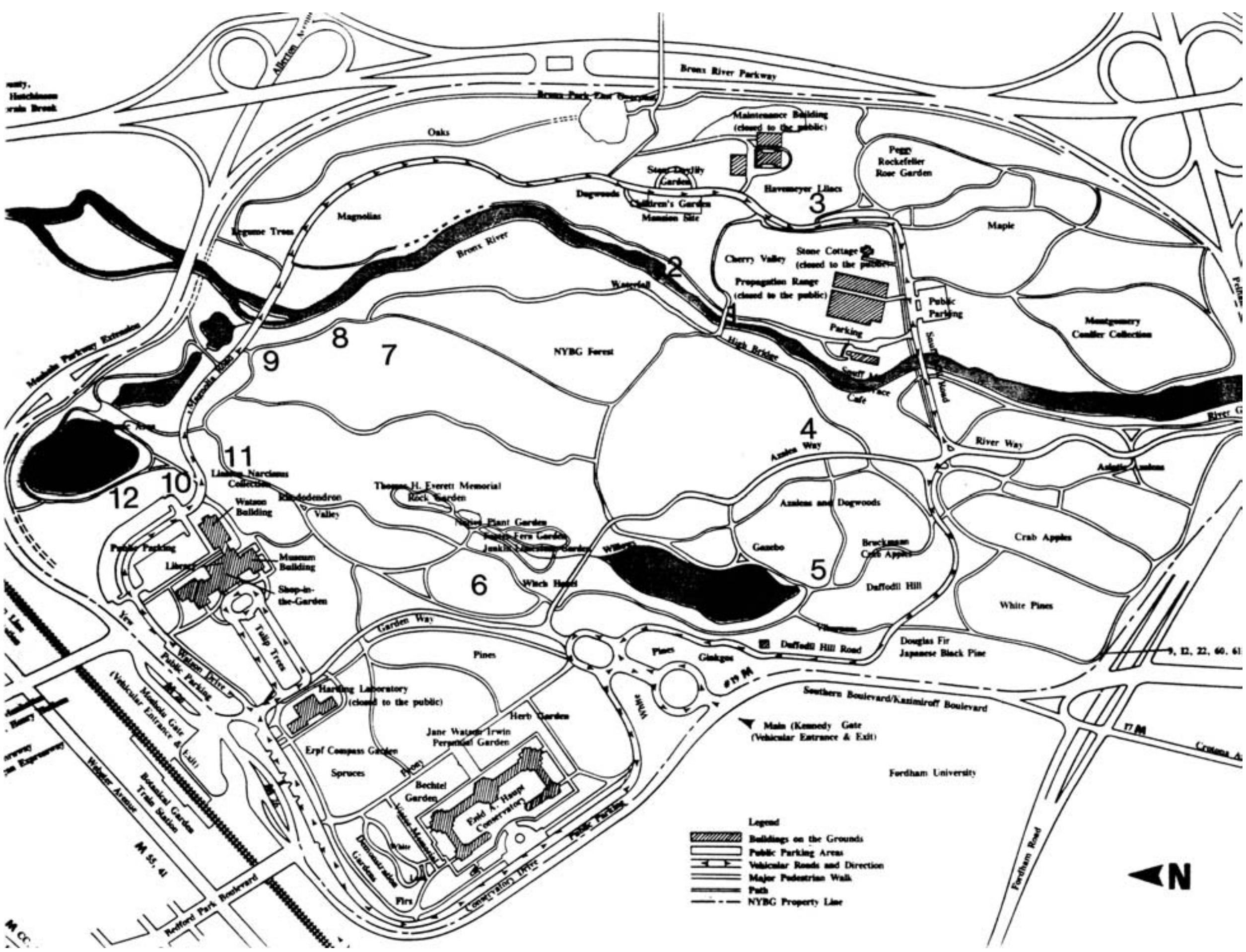

Figure GG-22. Trail map of the New York Botanical Gardens showing the locations of striae localities.

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

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

Lincoln Rock (UTM: 594.71E - 4524.14N) is the highest natural point in the New York Botanical Gardens and consists of highly glaciated rocks of the Hartland Formation in the form of a steep-walled rock drumlin. The older glacial feature (made by Glacier I) is the overall NNE- to SSW-oriented roche- moutonée structure of this large roche moutonée with its steep, well-polished NNE side and jagged, glacially plucked SSW side. Glacial striae eroded by Glacier I are oriented N13°E to S13°W. Superimposed on these features are glacial grooves oriented N32°W-S32°E, a divergence of 6° to 10° from our earlier measurements of the SE-directed flow of Glaciers II and/or III. This could be the result of a local westward divergence caused by the unusually steep-walled outcrop. Or, it may represent the basic difference in flow direction between Glaciers III and II.

In summary, glacial-erosion features on display in the New York Botanical Garden were cut by our Glacier I (flow from NNE to SSW), by our Glaciers II and/or III that flowed from NNW to SSE), and by our Glacier IV. Not many depositional features other than erratics (discussed in a following section) are present.

Pelham Bay Park

In this large park, we concentrate on the bedrock knolls at South Twin Island, near Orchard Beach (UTM: 602.4E - 4525.0N, Flushing 7.5 minute quadrangle).

The glacial features of South Twin Island are remarkable and take the form of glacial striae oriented N32°W-S32°E, glacial polish, and roche- moutonée structure (these features related to our Glacier II and/or III in Table GG-2). Two boulders of distinctive poikilitic ultramafic rock from the Cortlandt Complex in Peekskill, New York can be found at the southern end of the South Twin Island exposure near Orchard Beach. This discovery mandates glacial advance from the NNE (Glacier IV in Table GG-2). In addition to these features, a thin red-brown till, consisting of rounded boulders set in a reddish-brown matrix of poorly sorted sand, -silt, and -clay, was extensively exposed as a byproduct of the erosion of a wave-cut scarp during the higher-than-normal spring tides accompanying the perigee-syzygy Full Moon of Passover (06 April 1993). We do not know the exact date of the erosion, but can bracket it as being between 01 April 1993 when CM visited here with his class and 17 April when the Hofstra beginning-geology class trip stopped here. Judging from the newly visible features in the bedrock, we estimate that during the storm, the scarp retreated from 3 to 5 m.

Before the scarp was cut, a sod-covered slope extended down to the bedrock pavement. Beneath the red-brown till are clear NW-SE-trending glacial grooves on the bedrock surface. (Compare with Figure GG-16.) Here, then, is a second example of red-brown till resting on striated bedrock, as in the Queens localities described by Woodworth (1901). We have seen many examples of red-brown till and many other examples of striae oriented NW-SE, but this is the first example we have seen of these two features together.

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

Example from Long Island City, Queens

As previously mentioned, Woodworth (1901) recorded that in Long Island City (Queens), the red-brown materials forming the Harbor Hill moraine rest on striated bedrock with grooves oriented N25°W to S25°E. In his words:

> "One of the largest exposures of bed rock occupies a vacant lot adjoining the Queens county courthouse on the west. The ledge is heavily glaciated, forming a long low roche moutonée. The striae range in direction from 29° to 30° west (magnetic). A few striae run from n 15 w, and one set of scratches lies in a northwest direction. The strike of the foliation of the gneiss is n 25 e magnetic. Other outcrops occur to the northeast with striae running from the north northwest. A series of shallow oval depressions extends in a northwest and southeast direction across one outcrop..." (Woodworth, 1901, p. 652).

This is the same result we have described from Pelham Bay Park, but with the huge difference that the red-brown till at Pelham Bay Park is not part of a terminal moraine.

As we have mentioned in a preceding section, we interpret Woodworth's evidence on the relationship between flow directions and the reddish-brown color of the materials forming the Harbor HIll moraine to mean that the age of the Harbor Hill Moraine must be pre-Woodfordian. We assign the Harbor Hill Moraine to our Till III (Early Wisconsinan?). We regard as Woodfordian only the the 8 or 9 feet of gray till with "trap" boulders that overlies reddish-brown sands (outwash associated with our Till III?) that Woodworth described along the road from Corona to Astoria.

Examples from Staten Island

On the New Jersey Geological Association's Staten Island field trip, at Stop 1 we shall examine striae, grooves, and cresentic marks eroded on the Palisades Dolerite by our Glaciers III and/or II (indicating flow from NNW to SSE) and by No. IV (flow from NNE to SSW). For further particulars, consult the Stop descriptions.

Another example showing striae trending N15°W to S15°E ie present where the glacier eroded the Palisades Dolerite now exposed in the yard of PS 21, just SE of the tollgate plaza for the Bayonne Bridge (UTM: 572.40E - 4498.03N, Elizabeth, NJ-NY 7.5-minute quadrangle).

Examples from Bear Mountain and Stony Point, New York

Atop Bear Mountain at Perkins Observatory (UTM: 583.15E - 4573.5N, Popolopen Lake quadrangle), Proterozoic Y granitic gneiss exhibits crescentic glacial gouges. Here rounded knolls of Proterozoic gneiss have been sculpted by glaciers that flowed across the Hudson Highlands. The usual two directions are indicated: from NNE to SSW (Glacier I) and from NW to SE (Glacier II or III). The older glacier flowed from the NNE to SSW and shaped rock drumlins and roches moutonées. The younger glacier came from the NW and flowed SE. This glacier formed the many crescentic marks and smoothed any jagged southern ends of roches moutonées made by the earlier glacier.

Both glaciers flowed across the Highlands as if they were not a serious obstacle. This implies that these glaciers were very thick (perhaps, 8 to 10 km). By contrast, the most-recent Wisconsinan glacier (Woodfordian) did not leave many traces up here. For other reasons, we can infer that the thickness of the Woodfordian ice was much less than that of the earlier glaciers.

Within the grounds of the Stony Point Battlefield (UTM: 585.62E/4565.8N, Haverstraw quadrangle), intrusives forming the west edge of Cortlandt Complex crop out in glaciated knolls of diorite that show many cross-cutting fine-textured dike rocks. Here, glacial striae and roche moutonée are oriented N03°W.

We turn now to the features of glacial sediments from which glacial-flow direction can be inferred.

DIRECTIONS OF GLACIAL FLOW IN THE NEW YORK CITY REGION BASED ON GLACIAL SEDIMENTS: DIRECTIONS OF DISPLACEMENT OF ERRATICS AND INDICATOR STONES AND ORIENTATIONS OF LONG AXES OF DRUMLINS

The abundant evidence that glaciers eroded on the bedrock of New York City and vicinity does not provide much of any indication of age. As mentioned, in some cases, relative ages for three episodes of glacial erosion can be demonstrated. Other evidence comes from the glacial sediments. In this section, we include erratics and indicator stones and drumlins. In the following section, we take up stratigraphic aspects.

Definitions

An indicator stone is defined as an erratic whose parent area in the bedrock is known. Accordingly, a line between the indicator stone and its "home base" gives the direction of transport. As mentioned, a drumlin is an elongate but asymmetric streamlined hill shaped by the flow of a glacier (Figure GG-23). 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. The term used by itself usually implies a feature composed of till. A rock-cored drumlin is one that consists of both till and of bedrock. A rock drumlin consists only of bedrock.

Directions of Displacement of Indicator Stones

A prerequisite to understanding the significance of the indicator stones that were transported glacially during the Pleistocene is knowledge of the bedrock over which the glacier(s) flowed. In order to provide some background on the local bedrock, we include a brief summary of the geologic features in the bedrock of southeastern New York and vicinity.

Geologic features of the bedrock in southeastern NY and vicinity

In the following paragraphs, we review the distinctive features of the bedrock in southeastern New York and the state of Connecticut. Our objective is to help "soft-rockers" pinpoint distinctive kinds of bedrock so that certain erratics found in the till or along local bouldery beaches can serve as indicator stones.

The Newark and Hartford Basins. Extending southwestward from Stony Point, Rockland County, NY, on the Hudson River valley and into New Jersey, are Mesozoic igneous- and sedimentary rocks of the Newark basin (Figure GG-24). Distinctive in their reddish-brown color, the west-dipping sedimentary strata range in age from Late Triassic to Early Jurassic and are time- and lithostratigraphic equivalents of rocks of the Hartford basin of central Connecticut. The west-dipping Palisades intrusive sheet, which forms a prominent ridge on the west side of the Hudson River valley from the New York Bight to the vicinity of Stony Point, New York, is a medium- to coarse-textured diabase (dolerite) that was intruded into the Lockatong Formation to form a sill. Farther westward at at higher stratigraphic positions, sheets of extrusive basaltic rock underlying the Watchung mountains are intercalated within red-brown Jurassic sedimentary rocks. These constitute the fill of the Newark Basin, that extends SW from Rockland County, NY across central New Jersey and into Pennsylvania and beyond.

Near the Ramapo fault, the basin-marginal fault at the NW edge of the Newark Basin, distinctive clast-supported basin-marginal rudites are present that bear Paleozoic boulders eroded from above the Hudson-Reading Prong and from areas to the north- and northwest of the highlands, set in a red-brown matrix.

The Mesozoic sedimentary- and igneous rocks rocks filling the Hartford Basin underlie a north-south-trending lowland in the central part of Connecticut. This central lowland is one of three major geologic terranes in Connecticut. The central terrane intervenes between the western terrane and the eastern terrane (to be discussed in a following section). The central-Connecticut lowland continues northward into Massachusetts (Longwell, 1922, 1928, 1933, 1937). To the west, the basin-filling rocks adjoin the Paleozoic metamorphic rocks of the western crystalline terrane. In at least two localities, the unconformable contact between the younger Mesozoic sedimentary rocks and older Paleozoic metamorphic is visible. In most places, however, the boundary between the Mesozoic rocks and the Paleozoic rocks is a normal fault of probable Mid-Jurassic (or younger) age that has dropped the Mesozoic rocks. On the east, the basin-filling rocks end abruptly at the basin-marginal fault (Merguerian and Sanders, 1991e, 1994d). East of this fault are the rocks of the eastern crystalline terrane of Connecticut and Rhode Island. [In this discussion, we include the Mesozoic rocks found in an isolated half-graben known as the Pomeraug Basin within the western terrane. (See Figure GG-24.)]

Lithologically distinct, the strata filling the Mesozoic basins consist predominantly of east-dipping, red-colored sedimentary rocks and intercalated sheets of extrusive basalts with local intrusive mafic rocks (for example, the Buttress and West Rock dolerites). Correlative with the Upper Triassic to Lower Jurassic Newark Supergroup of New Jersey (Merguerian and Sanders, 1989b, 1991g, 1993c, 1993e), the rocks of the Hartford and Pomeraug Basins include the New Haven, Shuttle Meadow, East Berlin, and Portland formations consisting of red- to maroon-colored micaceous arkose and quartzose sandstone and -siltstone, shale, and local conglomerate and fanglomerate, together with subordinate black shale and local dolostone, and intercalated dark-colored mafic volcanic rocks of the Talcott, Holyoke, and Hampden basalts.

The strata filling both basins have been internally cut by a myriad of faults and, as discussed below, trend southward and project into Mesozoic grabens in the subsurface of Long Island and the New York Bight that have been identified by samples from drill holes and data from geophysical surveys (Klitgord and Hutchinson, 1985; Hutchinson, Klitgord, and Detrick, 1986; Hutchinson and Klitgord, 1988). The distinctive color- and lithology of these rocks make them ideally suited for use in analysis as indicator stones and as sources for the generation of red-colored tills but similarity with rocks of the Newark Basin complicates direct correlation. All is not lost however, as the presence of low-grade phyllites, -schist, and -metavolcanic rocks containing chlorite and epidote as erratics in concert with these distinctive Mesozoic lithologies would uniquely identify a Connecticut source. No such low-grade rocks of volcaniclastic parentage are present in the vicinity of the Newark Basin of New Jersey.

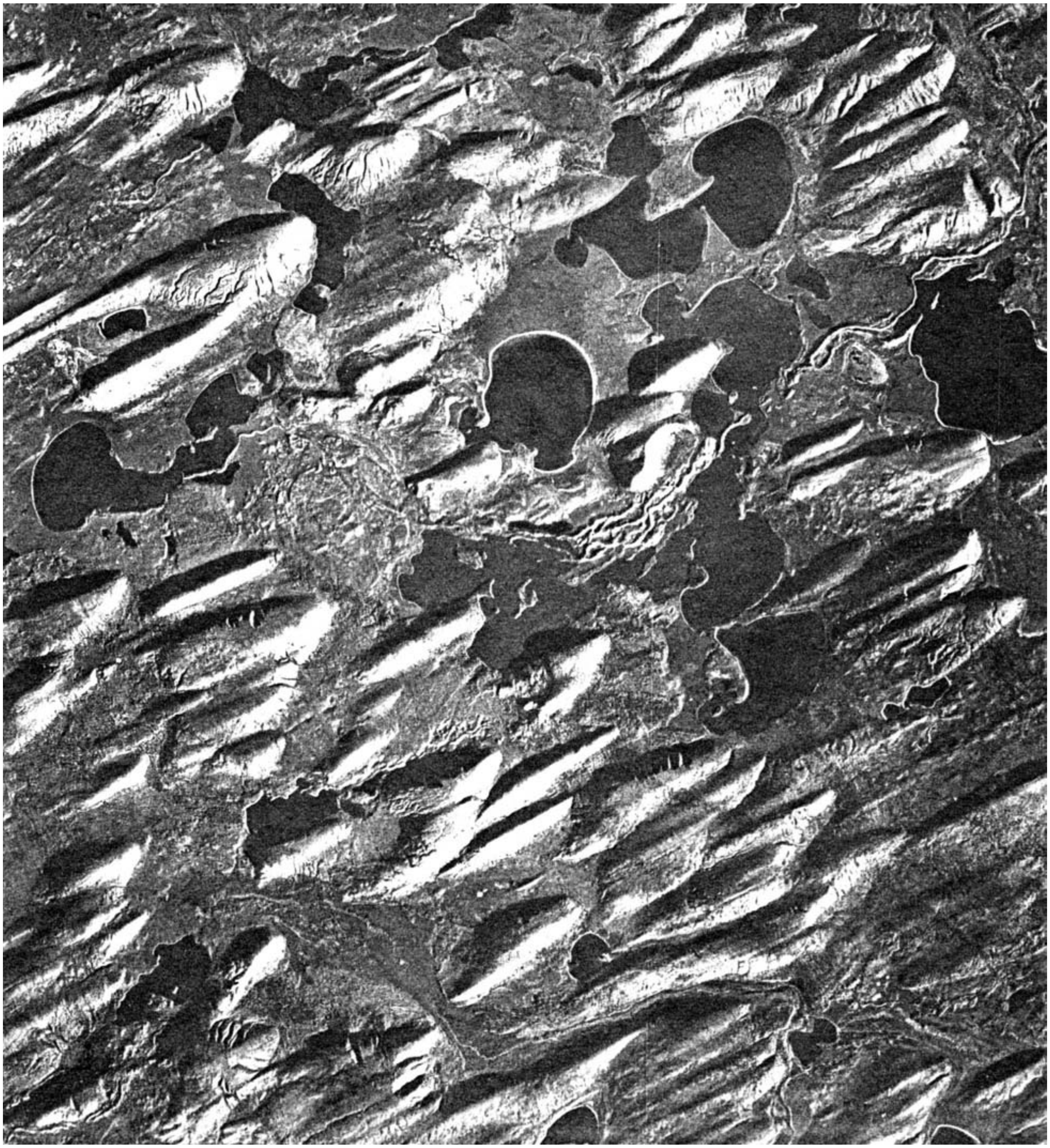

Figure GG-23. Swarm of drumlins viewed from vertically above in aerial photograph, northern Saskatchewan, Canada, created by a glacier that flowed from NE (upper right) to SW. The small circular lakes give the scale; their diameters are about 1 kilometer. The thin, curviliner light-toned features extending from the center of the view to the upper right margin are parts of an esker complex. (Geological Survey of Canada, Canadian Government Copyright; published in J. E. Sanders, 1981, fig. 13.24, p. 323.)

The "crystalline corridor of SE New York and western Connecticut. The bedrock of southeastern New York State is dominated by complexly deformed, metamorphosed rocks that underlie the Manhattan Prong (Figure GG-25). The ages of these rocks range from Proterozoic Y through Cambro-Ordovician. Most of them have been overthrust, but some more than others. Included are some distinctly allocthonous rocks that have been overthrust many km to the NW from their original depositional sites.

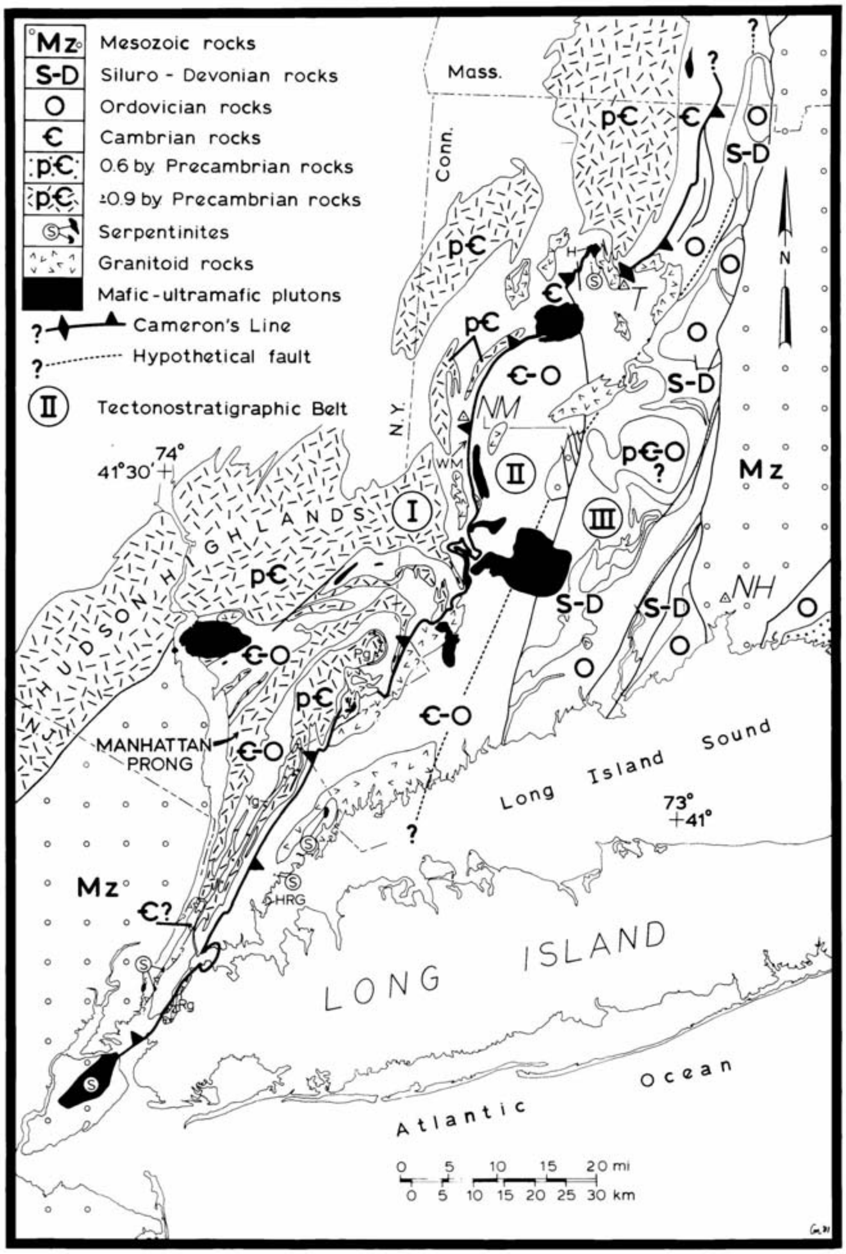

Figure GG-24. Geotectonic map of western Connecticut and southeastern New York. The location of our three field-trip stops and their geographic relationships to the crystalline "corridor" are shown. (Merguerian, 1983, fig. 1, p. 342.)

The **Manhattan Prong** is bounded on the northwest by Grenvillian Proterozoic Y rocks of the Hudson-Reading Prong. On the east is a ductile-fault contact (Cameron's Line) marked by a zone of syntectonically intercalated, mylonitic rocks. Cameron's Line, which skirts the New York-Connecticut state boundary, separates rocks of the Manhattan Prong to the west from coeval rocks to the east that were deposited in a dramatically different paleogeographic setting (continental rise and some rocks, on a former deep-sea floor). Rocks to the west of Cameron's Line include the metamorphic rocks of the Manhattan Prong whose Lower Paleozoic representatives [Lower Cambrian Lowerre (=Cheshire) Quartzite, the Cambrian-to-Ordovician Inwood (=Woodville, and Stockbridge) marbles, and overlying Middle Ordovician Manhattan Schist (Unit A) and correlative Annsville Phyllite] constitute a cover sequence that was deposited on the continental basement rocks of an ancient craton. These basement rocks include the Proterozoic Y Fordham Gneiss, the Proterozoic Z Yonkers and Poundridge gneisses and coeval rift-facies strata mapped as the Ned Mountain Formation (Brock, 1989, 1993 ms.). These basement-cover rocks are structurally overlain by allochthonous rocks of the Taconic sequence and their metamorphosed, dominantly massive southerly equivalents [the main body of the "Manhattan Schist" and related amphibolite (Units B and C), the Waramaug Formation, and locally, the Hartland Formation]. Farther north, beyond the Hudson-Reading Prong in New York State, less-metamorphosed lithostratigraphic equivalents of the Lower Paleozoic rocks are found including the Poughquag Quartzite, Wappinger carbonates, the Walloomsac slate and shale, the Normanskill graywackes and shale, and allochthonous rocks of the Taconic Sequence.

Many erratics from the varied lithologies found in southeastern New York and adjacent regions of New Jersey could have been transported to places where they are now found only by a glacier that flowed from NW to SE. For example, abundant rocks from the Palisades intrusive sheet (Mesozoic) are found as erratics on Manhattan Island.

The western terrane of Connecticut is underlain mostly by metamorphic rocks that form part of the central crystalline core of the Appalachians (Figure GG-26). The age range of these rocks is from Proterozoic Y through Early Paleozoic. Although volumetrically most of the metamorphic rocks are metasedimentary units, some distinctive igneous rocks (both intrusive and extrusive) are present as are some distinctive mylonites associated with a large-scale regional ductile shear zone known as Cameron's Line. (See Figures GG-24 and GG-26.)

We begin with the contrasting metasedimentary rocks found adjacent to Cameron's Line and then summarize some of the distinctive mylonitic rocks and igneous rocks. In westernmost Connecticut north of the "panhandle", rocks of the Manhattan Prong crop out. As they were described above we need not mention them again here.

East of Cameron's Line, the bedrock formations differ significantly from those of the Manhattan Prong to the west of this line. To the east, the Cambrian-to-Ordovician Hartland Formation dominates exposed surfaces of the crystalline highlands of western Connecticut. The Hartland Formation consists of a thick sequence of dominantly well-layered muscovite-rich schist, gneiss, amphibolite, and intercalated mafic- to felsic metavolcanic- and metavolcaniclastic rocks (Merguerian, 1983). Throughout the Hartland terrane of western Connecticut, local bodies of unique ferruginous- and manganiferous garnet-quartz granofels (coticules) are found as highly laminated rocks within the sequence (Merguerian, 1980, 1981). The Cambrian-to-Ordovician Hartland Formation is unconformably overlain by Siluro-Devonian metamorphic rocks of the Straits Schist.

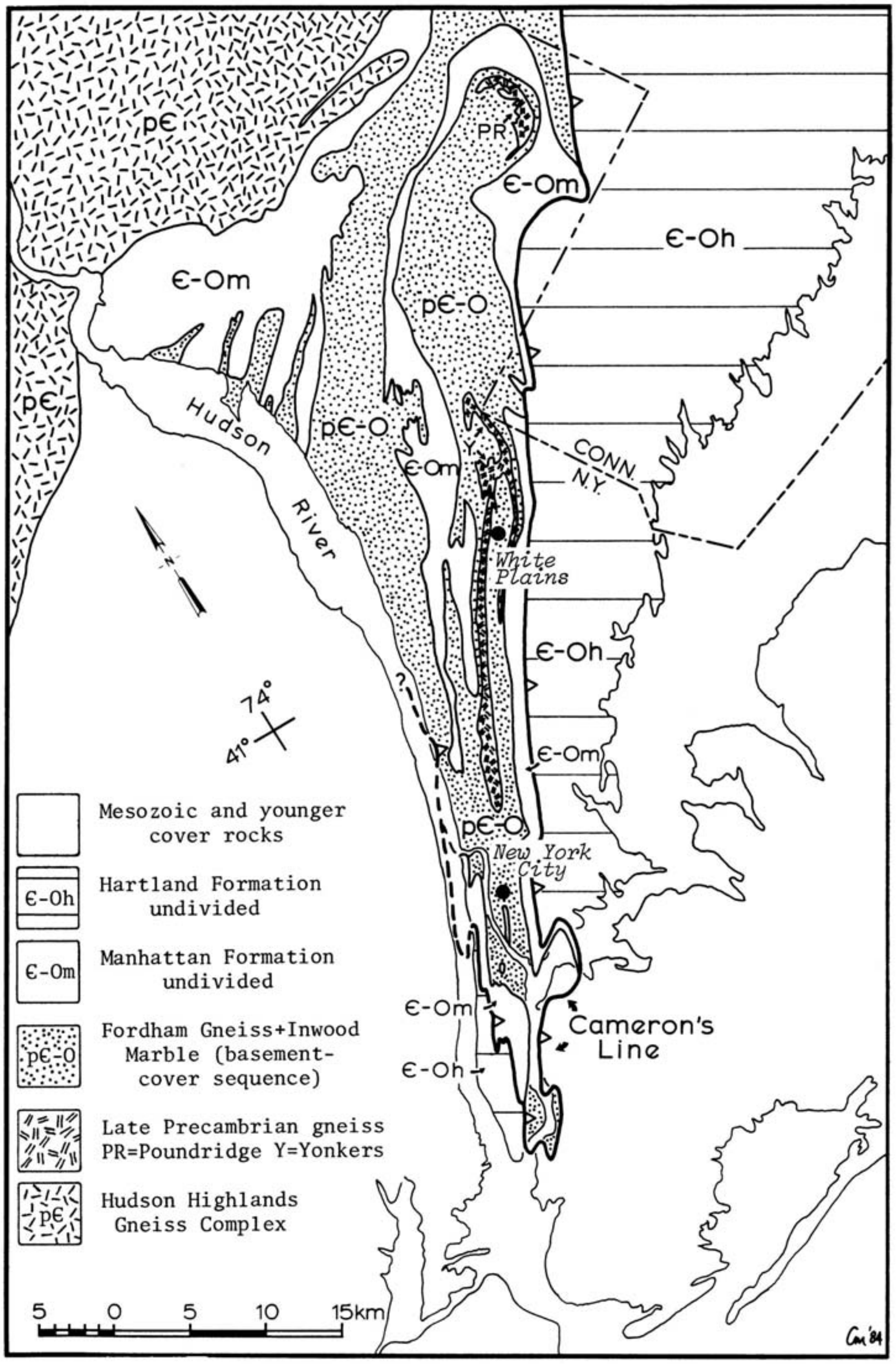

Figure GG-25. Simplified geologic map of Manhattan Prong showing the distribution of metamorphic rocks ranging in ages from Proterozoic to Early Paleozoic. Most intrusive rocks have been omitted. (Mose and Merguerian, 1985, fig. 1, p. 21).

To the east of the panhandle area of southwesternmost Connecticut, Silurian-to-Devonian metamorphic rocks are included in the Straits Schist to the south and north of the Cambrian (?) gneisses of the Waterbury Dome. (See Figure GG-26.) Farther east and cropping out in the vicinity of New Haven, in the extreme southeastern corner of the western terrane, are relatively low-grade (chlorite to garnet) schistose-, phyllitic-, and metavolcanic rocks of the Allingtown and Maltby Lake volcanics (Fritts 1962, 1963). These rocks are a part of the Middle Ordovician Bronson Hill-Ammonoosuc volcanic terrane which trends northeasterly through Connecticut, Massachusetts, and New Hampshire. Thus, as initially pointed out by Crowley (1968) and elaborated on by Merguerian (1983, 1985), in a transect extending from northwest to southeast across the western terrane, the interpreted protoliths of Paleozoic metamorphic rocks of the western terrane of southeastern New York and western Connecticut become less "continental" and more "oceanic"; at Cameron's Line, an abrupt lithologic change is present. (See Figures GG-24 and GG-26.)

CM interprets Cameron's Line as a thrust fault within a deep-seated subduction complex that formed during the Middle Ordovician Taconic orogeny adjacent to the Early Paleozoic shelf edge of eastern North America. This might explain the northwest- to-southeast imbrication of early Paleozoic shallow-water "continental" (Fordham-Lowerre-Inwood-Manhattan A plus correlative) lithologies with transitional slope- and rise- lithologies (Manhattan B and C, Waramaug, and parts of the Hartland Formation), from purely deep-water (including volcanic) rocks found west of the New Haven area. Thus, according to many workers, the juxtaposition of these largely coeval belts resulted from an arc-continent collision of the Taconic orogeny. The continental-margin sequence was telescoped and the volcanic arc and its fringing oceanic-basin deposits were overthrust upon it (Merguerian, 1983).

Along the Taconic suture (Cameron's Line) are displayed an impressive zone of mylonitic rocks that experienced abnormally high shear strain under deep burial during the Taconic arc-continent collision. Ductile-fault rocks bear unique metamorphic textures that can be easily identified: in the field, their highly laminated appearance can be seen megascopically; microscopic study of thin sections reveals distinctive mylonitic textures.

With respect to the Taconic orogeny, local plutons are both synorogenic and post-tectonic. The older group of synorogenic plutons cut across Cameron's Line in western Connecticut and southeastern New York. These include a series of mafic- to ultramafic plutons (now largely metamorphosed) that are similar in mineral composition and texture to the Cortlandt Complex of Peekskill, New York (Merguerian and Sanders, 1990a, 1990e). In the panhandle area of southeastern New York and southwestern Connecticut, high-grade Ordovician granitoid- and dioritic orthogneisses (including various phases of the Harrison Gneiss, Brookfield Diorite Gneiss, and Bedford Augen Gneiss) are in great abundance. Similar metaplutonic rocks including norite, hornblendite, and pyroxenite occur farther north near Litchfield and Torrington, Connecticut and are known as the Mount Prospect and Hodges Complexes and the Tyler Lake Granite (Cameron, 1951; Merguerian, 1977 ms., 1985).

Together, these orthogneisses represent late synorogenic plutons that were intruded into the developing suture zone during the waning stages of the Taconic orogeny (Merguerian, Mose, and Nagel, 1984). As such, these mineralogically- and texturally distinct metaplutonic rocks should serve as valuable indicator stones.

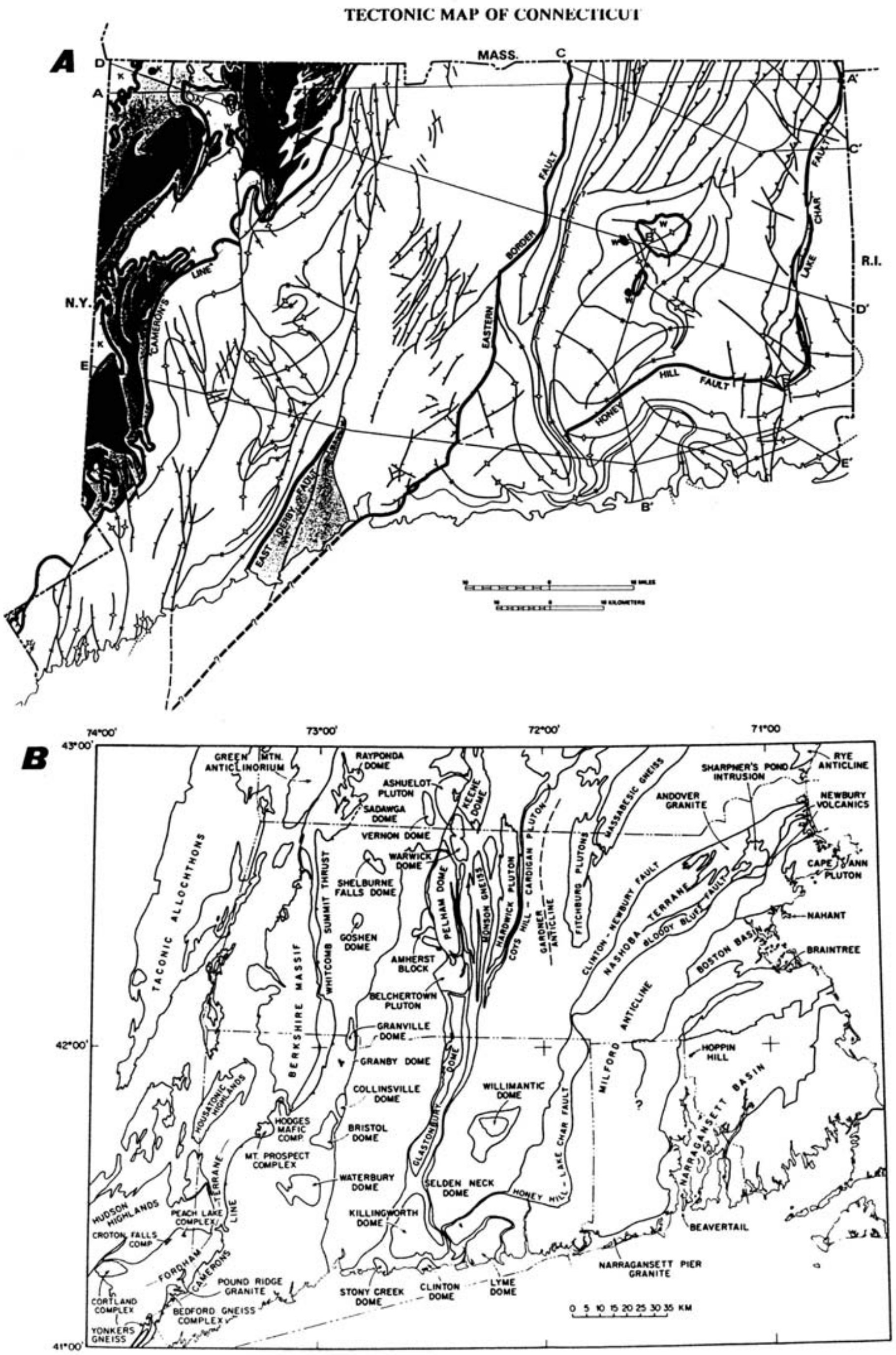

Figure GG-26. Maps of Connecticut and southern New England showing major tectonic features and rock bodies.

A. Tectonic map of Connecticut showing Cameron's Line and three major terranes. (John Rodgers, 1985.)
B. Tectonic sketch map of southern New England showing major domes, folds, and faults. (P. Robinson and L. Hall, 1980, fig. 3, p. 78.)

The younger post-orogenic intrusives include Devonian lamprophyre and potash feldspar-phyric Nonewaug Granite. Other plutonic rocks of still-younger ages include isolated bodies of Permian syenite, -adamellite, and -dacite porphyry. Of additional help, we are investigating the distribution of economic ore deposits in the crystalline terranes to the north- and northwest of Long Island in an effort to locate scarce, but highly useful indicator stones. During an On-The-Rocks field trip in November, 1990, Oliver Wayne found one such erratic, containing pyrrhotite- and chalcopyrite ore minerals, eroding out of the Montauk "till".

Eastern Connecticut and Rhode Island. The crystalline rocks to the east of the basin-marginal fault along the east side of the Hartford Basin underlie eastern Connecticut and Rhode Island. The bedrock formations here include exceedingly complex suites of metamorphic- and metaigneous rocks that range in age from Proterozoic through Permian. They have been cut by a regionally important ductile shear zone having the unlikely but nonetheless real name of Lake Chargoggagoggmanchauggagoggchaubunagungamaugg (sic)-Honey Hill Fault Zone [also known as the Lake Char - Honey Hill Fault Zone], which separates metavolcanic-, metaplutonic-, and metasedimentary rocks of the Bronson Hill-Ammonoosuc terrane to the north and west from Proterozoic Z gneisses and Permian intrusive rocks of the Avalonian terrane to the south and east. The Proterozoic Z rocks include the Plainfield Quartzite (a distinctive vitreous feldpathic +/- biotite quartzite), the Waterford Group, and the Sterling Plutonic Group. Within this sequence, many unusual porphyritic gneisses are present that should serve as excellent indicator stones.

The Ordovician rocks of the Bronson Hill-Ammonoosuc volcanic terrane include the Monson Gneiss and overlying Middletown and Brimfield formations as well as the Glastonbury Gneiss. These rocks are overlain by Silurian and Devonian metamorphic rocks of the Bolton Group and cut by the Devonian Maromas Granite Gneiss. To the east, correlatives include the Ordovician Quinebaug, Tatnic Hill, and Brimfield formations and overlying Siluro-Devonian units known as the Hebron Gneiss and equivalents.

Intrusive into these crystalline rocks are many plutons ranging in age from Ordovician to Permian. The distinctive rocks among this group on the Connecticut side of the Lake Char - Honey Hill Fault Zone include the Ordovician Preston Gabbro (+/- diorite), the Devonian Lebanon Gabbro (+/- diorite), and unnamed Devonian norite, diorite, and granitoid gneiss. In places where the mafic rocks are in close proximity to the Lake Char - Honey Hill Fault Zone, the rocks have been transformed into distinctive mafic mylonites. To the east of the Lake Char - Honey Hill Fault Zone are Permian intrusives known as the Narragansett Pier Granite (including a mafic phase) and the Westerly Granite, both distinctive lithologies. (See Foye, 1949; Dixon and Lundgren, 1968; Dixon, 1982; and Rodgers, 1985.)

From our brief summary, it should be obvious that chasing Pleistocene boulders is an exercise that best demonstrates the necessity of having a well-rounded knowledge of all fields in geology in order to arrive at a satisfactory conclusion.

Indicator stones in New York City and vicinity

In New York City and vicinity, recognition that indicator stones have been displaced both to the SSE and SSW from their parent areas started in 1828-29 with Dr. L. D. Gale. In Manhattan, Gale found indicator stones of anthophyllitic rock (a kind also made much of in Connecticut by J. G. Percival in 1842), and white marble that had been displaced to the SSW. (For the purposes of this discussion, we will include indicator stones from Queens and from Brooklyn under the heading of "New York City" rather than under "Long Island." As a glance at the map will indicate, however, Brooklyn and Queens are situated on Long Island.)

From the vicinity of Croton Point southward, red-brown color of till on the E side of the Hudson River serves as a kind of collective "indicator stone" of glacial transport across the Hudson River (i. e., by a glacier that flowed, at least locally, from NW to SE). The red-brown color comes from ground-up Newark sandstones and -siltstones.

Erratics of Palisades Dolerite are numerous on the E side of the Hudson River, as in the Ludlow section of Yonkers in the cut made at the Westchester County sewage-treatment plant, and in all the parks we have mentioned previously.

In Fort Tryon Park, a few distinctive erratics and indicator stones are present. North of the stone steps on the walkway leading away from the flagpole terrace (UTM: 589.80E - 4523.64 N), a large dolerite boulder from the Palisades rests on a glacially smoothed bedrock surface. In the dirt here are erratics of sandstone and black chert. Just south of the striae locality at the Cloisters, where the contact between the till and the glacially truncated bedrock surface is exposed, indicator stones of anthracite are present. At this locality, pieces of anthracite could have been brought to New York City on the Lehigh Valley Railroad to be used for fuel. The case for the erratic origin of the anthracite would scarcely be compelling based on specimens from Fort Tryon Park or Riverside Park. However, as we shall see at Stop 6 on today's GANJ field trip on Staten Island, pieces of anthracite in the till exposed in the eroding coastal cliffs demonstrate their erratic origin.

Proof of glacial transport of Carboniferous anthracite from northeastern Pennsylvania to the New York City region by a glacier that flowed from NW to SW (See Figure GG-13.) solves the problem faced by Zen and Mamay (1968) when they tried to interpret fossiliferous pieces of anthracite recovered from a roadcut in the Bronx.

We have found many other indicator stones from the Cortlandt Complex along the bouldery Hudson River "beach" where they have been washed out of one or both of the non-red tills at Croton Point Park, Westchester Co., NY. We have also seen three small examples of

Cortlandt-Complex indicator stones washed out of the Woodfordian till (not exposed in the low coastal bluff) at Twin Islands, near Orchard Beach, Pelham Bay Park, The Bronx.

Until one has become familiar with the distinctive ultramafic rocks from the Cortlandt Complex near Peekskill (See Figure GG-24.), it is possible to misidentify Contlandt stones as coase Palisades Dolerite. Other dark-colored rocks that might be identified as "trap rock" include Paleozoic amphibolites or Paleozoic mafic plutonic rocks from southeastern New York or western Connecticut and the Paleozoic metavolcanic rocks from SW of New Haven, CT.

In this connection, we raise the point that Woodworth's use of the words "trap boulders" for erratics in a gray till in Corona (Queens) would imply to most readers that this till had been derived from a glacier that had crossed the Palisades ridge. We suggest that the stones Woodworth referred to as "trap boulders" are probably not from the Palisades dolerite. If they are not from the Palisades, where could they have come from? Other possibilities include: (1) far-travelled (from the NE) trap rocks from the Hartford Basin; (2) mafic- or ultramafic rocks from the Cortlandt Complex; (3) Paleozoic amphibolites from SE New York; (4) Paleozoic mafic plutonic rocks from SE New York or western Connecticut; and (5) Paleozoic metavolcanic rocks from SW of New Haven, CT. The fact that the color of the till enclosing the "trap boulders" is gray implies to us that Woodford was describing our Till IV, the Woodfordian, which was deposited by glacial flow from the NNE. True "trap boulders" from the Palisades would be present only if the glacier had flowed from NW to SE, in which case its color would be reddish brown. By contrast, true trap boulders from the Hartford Basin would be present only if the glacier had flowed from NE to SW, in which case its color should also be reddish brown. Boulders from the Cortlandt Complex or the Paleozoic amphibolites and/or -mafic plutons would be possible only by glacial flow from NNE to SSW, in which case the color of the till would not be reddish brown.

In footnote 1 at bottom of p. 652 Woodworth wrote: "Boulders of trap and red sandstone were seen by Sir Charles Lyell in an excavation made in a boulder bed at the Brooklyn navy yard. See Lyell, Charles, Travels in North America. N. Y. 1845. 1: 189-90." Woodworth metioned Lyell's observations in this connection evidently because he thought Lyell was describing the same gray, "trap-rock"-bearing till that Woodworth had seen in Corona. As far as our experience goes, the co-existence in Brooklyn of trap boulders and red sandstone in the same till implies that the glacier had crossed the belt of outcrop of the Newark rocks on the W side of the Hudson River and thus to reach Brooklyn, must have flowed from NW to SE. In every exposure we have seen of till containing such erratic boulders the matrix color is a distinctive reddish brown. Although we have not as yet looked up the Lyell original to see if he mentioned the color of the till at the Brooklyn navy yard, we presume it would be reddish brown and thus we would assign this till in Brooklyn that Lyell mentioned to a glacial episode older than the Woodfordian (our Episode III or II). In New York City during the Woodfordian, only gray till was deposited by ice flow from the NNE to the SSW.

During the 1920's, when major landscaping was carried out at the Brooklyn Botanical Garden, many large erratics were encountered in the till. These were left as outdoor exhibits. Gager (1932), based on petrographic results by Robert Balk, showed that most of them had come from localities that are located to the NW of Brooklyn, rather than to the NNE.

Indicator stones implying flow from NW to SE have been found on Staten Island (Lower Silurian Green Pond Conglomerate from northwestern New Jersey; and Pennsylvanian anthracite from near Scranton, Pennsylvania. (See Figure GG-13.)

Gratacap (1890, p. 14) found an example of "ripple-marked Potsdam sandstone" in the drift at Tottenville. We suggest that Gratacamp's "Potsdam sandstone" may be the same as the "Lower Cambrian quartzite" boulders visible in the cliffs at GANJ field-trip Stop 4 (Conference House). The provenance significance of true "Potsdam" (outcrops confined to Adirondack borders) would differ considerably from that of the Lower Cambrian quartzite (widespread in the Appalachian fold-thrust belt extending across NW NJ and into SE NY).

Other studies of erratics on Staten Island have been carried out by Hollick (1908, 1915) and by Bourgeois (1972 ms.)

JES has found six notably large (diameters of 3 to 4 m) erratic indicator stones from the Cortlandt complex arranged in three clusters and partially exposed by erosion along the banks of the North Branch of Wicker's Creek in Dobbs Ferry (on the White Plains 7.5-minute quadrangle). Two of these boulder clusters are near the place where the old Croton Aqueduct crosses this branch of Wickers Creek (UTM: 594.90E - 4541.42N; and 594.86E - 4541.40N). A third is located on the N side of Wickers Creek W of the point where the two branches of this creek join (UTM: 594.70E - 4541.22N). These are contained in a grayish-brown till that overlies reddish-brown outwash.

Indicator stones on Long Island and Gardiners Island

Indicator stones from the beaches along the north shore of Long Island and on Gardiners Island have been eroded out of the material underlying the coastal cliffs. Much of this is "stratified drift," but some of it is till. We interpret the coarse stratified sediments as deposits made on Gilbert-type deltas that were built southward into Lake Long Island (Sanders, Merguerian, and Mills, 1993; Sanders and Merguerian, 1994). Whether they came from stratified drift or till, the boulders on the beaches form the basis for important provenance inferences. Some of the boulders have come from the NW and some from the NNE; the problem is to determine how these provenance directions are related to stratigraphic units.

If Long Island's two terminal-moraine ridges had been deposited by the Woodfordian glacier, as so many Pleistocene geologists believe, then we think that a well-defined zone of reddish-brown till and characteristic indicator stones from the Hartford Basin should be present in the glacial sediments in the central part of Long Island. The absence in central Long Island of reddish-brown till derived from the Hartford Basin and containing trap-rock boulders in a direction SSW of New Haven, CT is a very compelling argument against the concept that Long Island's famous terminal-moraine ridges were deposited by the Woodfordian glacier.

A common stone found on north-shore beaches is known popularly as "puddingstone." Such rocks are hematite-cemented "ironstone conglomerates" containing well-rounded quartz pebbles; they are from the Cretaceous and have been derived locally. This kind of rock might be confused with the Green Pond-Schunemunk metaconglomerates, but in the metaconglomerates, the rock breaks across the pebbles rather than around them as in the Cretaceous examples.

Target Rock is a locality where indicator stones from both the NNE and the NNW have been comingled on the beach. The abundant dark, mafic-looking "green" stones are altered volcanics from SW of New Haven, CT, that have been eroded from a gray till (our Till I), which underlies the deltaic outwash.

Indicator stones derived from the NW include rounded boulders of Inwood Marble. These are being eroded from a till (our No. III or No. II) that overlies the deltaic deposits.

Sirkin and Mills (1975) wrote about the erratics at Target Rock as follows:

> "Diabase and purple-red puddingstone conglomerate erratics, along with till fabrics and other rock compositions suggest a northwesterly source area for the till. The diabase may be derived from the Palisades and the puddingstone from lower or middle Paleozoic conglomerates such as the Green Pond Conglomerate found near the New York-New Jersey border northwest of the Palisades."

> "On the beach a number of predominantly dark colored (sic) erratics of mafic composition have been eroded from the till. Some of these rocks resemble the Harrison Gneiss found to the north and northwest in southern Westchester and Connecticut" (Sirkin and Mills, 1975, p. 320).

We think that Sirkin and Mills are correct in their remark that some of the "predominantly dark colored (sic) erratics of mafic composition" found on the beach that have been eroded from the till "resemble the Harrison Gneiss found to the north and northwest in southern Westchester and Connecticut." As with the indicator stones of Inwood Marble, these dark gneisses point to a till deposited by a glacier that flowed from NW to SE.

Our interpretation is that the upper till at Target Rock was deposited by a glacier that flowed from NW to SE, but this is not the till that contains the dark greenish Palisades look-alike rocks from the Ordovician Maltby Lakes metavolcanics from SW of New Haven, CT). Thus we infer that only some of the erratics upon which Sirkin and Mills (1975) invoked a NW provenance were correctly assigned. Other indicator stones which they thought came from the NW demonstrate quite the opposite--a NNE provenance.

The beach at Garvies Point Nature Preserve is littered with boulders of great variety and distinctive types include:

plagioclase-phyric gabbro with xenoliths,
amphibole-phyric lamprophyre,
potash feldspar phyric granitic gneiss,
mylonitic granitoid gneiss,
augen gneiss,
epidote amphibolite,
potash felspar pegmatite,
mica-rich red shale (Cretaceous),
hematite-cemented conglomerate (Cretaceous),
and many others.

As at Sands Point, no erratics of Triassic-Jurassic Newark-type basin fill rocks are present.

Unfortunately, we do not yet know the provenance of these boulders, some of which are very distinctive. The augen gneiss may be from the Bedford Gneiss of Westchester County and the epidote amphibolite is probably from the Orchard Beach area of Pelham Bay Park.

Along the beach on the NE side of Gardiners Island erratics of red sandstone and dark bluish-gray dolerite are abundant. The nearest place from which these can have been eroded is the Hartford Basin of central Connecticut and Massachusetts. A glacier traveling from NW to SE, such as deposited our Tills III and II, could have transported these erratics to Gardiners Island. The Fundy Basin in Nova Scotia, situated to the NE, also contains bedrock that could have provided these erratics. But, any glacier bringing Newark-type erratics to Gardiners Island would have transported erratics from the Hartford to central Long Island. Because central Long Island lacks such erratics, we prefer the interpretation that the erratics on Gardiners Island came from the Hartford Basin.

Orientations of long axes of drumlins

As mentioned in a preceding section, the long axes of drumlins are parallel to the direction of flow of a glacier and the steeper ends of the drumlins are on the up-flow side.

Well-developed fields of drumlins that we think were deposited by the Woodfordian glacier are present in Rockland County, NY, in the lowland S of the curving NW end of the Palisades ridge (Figure GG-27). Their axes trend N-S; some are several km long and their relief is many tens of meters. A single drumlin having this same N-S orientation is present at Enoch's Nose, Croton Point Park, Westchester County, NY (Figure GG-28).

A few examples of drumlins oriented NW-SE are present in Westchester County, NY, and adjacent parts of SW Connecticut. Localities include: (1) Yonkers, E of North Broadway at the former Boyce Thompson Institute (UTM: 594.6E - 4563.0N, Yonkers quadrangle; (2) in the the Westchester County airport, many drumlins are present astride the NY-CT border with long axes about parallel to the direction of this border (the center of one particularly large example is at UTM: 609.1E - 4547.6N on the Glenville, CT-NY quadrangle); and (3) on the golf course at

Pelham Bay Park, SE of Interchange 6 on I-95, near the boundary between New York City and Pelham Manor (UTM: 600.2E - 4526.0N on Mount Vernon quadrangle; Figure GG-29). The trends of these drumlins are about parallel to Magnetic North (local declination is 12°W).

DISCUSSION OF THE ICE-FLOW EVIDENCE IN THE NEW YORK CITY REGION

We conclude from the foregoing that the effects of at least three "generations" of ice flow can be recognized on bedrock surfaces in New York City and vicinity: (1) the oldest includes roches moutonée s and rock drumlins sculpted by glacial flow from NNE to SSW (N15°E to S15°W), a direction that closely parallels the Hudson River; (2) large grooves and various striae as well as roches moutonées cut by glacial ice that flowed from NW (N 25° to 45°W) to SE, a direction that is across the Hudson River; and (3) the youngest, from NNE to SSW, parallel to the oldest features and also parallel to the Hudson River.

So what about all these features? Our results support the remarkable work of Dr. L. D. Gale in the early 19th century, but we go him one better in finding evidence for three glacial-flow episodes not a single "diluvial current" with flow variations.

We have found convincing evidence that the ice flow from NW to SE was not merely local, as Salisbury and others have inferred, but must have been regional (Figure GG-30). The critical evidence includes erratics of anthracite from NE Pennsylvania and of Green Pond Conglomerate and the Schunemunk Conglomerate. (See Figure GG-13.)

Despite all these previous findings of two distinct ice-flow directions, nearly all geologists have interpreted them as products of a single glaciation.

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 (Figure GG-31). 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. (See Figure GG-5.)

STRATIGRAPHY OF SUPERPOSED TILLS AND PLEISTOCENE SEDIMENTS

Although, as mentioned, we have not found any sections in which tills and diagnostic nonglacial sediments are interstratified, we have found sections were two or more tills are superimposed. We mention two examples from Westchester County, NY (Croton Point and Yonkers), one example from northern New Jersey, five examples from Long Island, and one example from Staten Island.

Tills at Croton Point Park, Westchester County, NY

Along the west side of Croton Point Park, immediately across the Hudson River (about 2 km or 1.2 miles) from the Palisades Sill just south of Haverstraw, New York, waves generated by winds blowing across the wide part of the Hudson River (Tappan Zee and Haverstraw Bay) are eroding steep bluffs in the Pleistocene sediments. These bluffs expose one or more tills at Teller's Point on the south and at Enoch's Nose on the north. (See Figure GG-28.)

At Teller's Point two tills are present. A red-brown till caps the cliff; at a level of about 3 m above the water can be seen the top of a gray-brown till that persists down to water level. These two different tills harbor uniquely different suites of boulders, cobbles, and pebbles.

The red-brown till contains boulders- and pebbles of various facies of the Palisades trap rock, red-colored sedimentary rocks from the Newark Supergroup, the Green Pond Conglomerate, and chips of anthracitic coal. The dolerite stones show early stages of decomposition: concentric joints and breakdown of silicate minerals. Examples of most of the erratics can be seen in the cliff face and along the "beach," where they have been washed out of the till. Clearly, this red-brown till is a product of NW-SE glacial flow; the erratics have come from west of the Hudson.

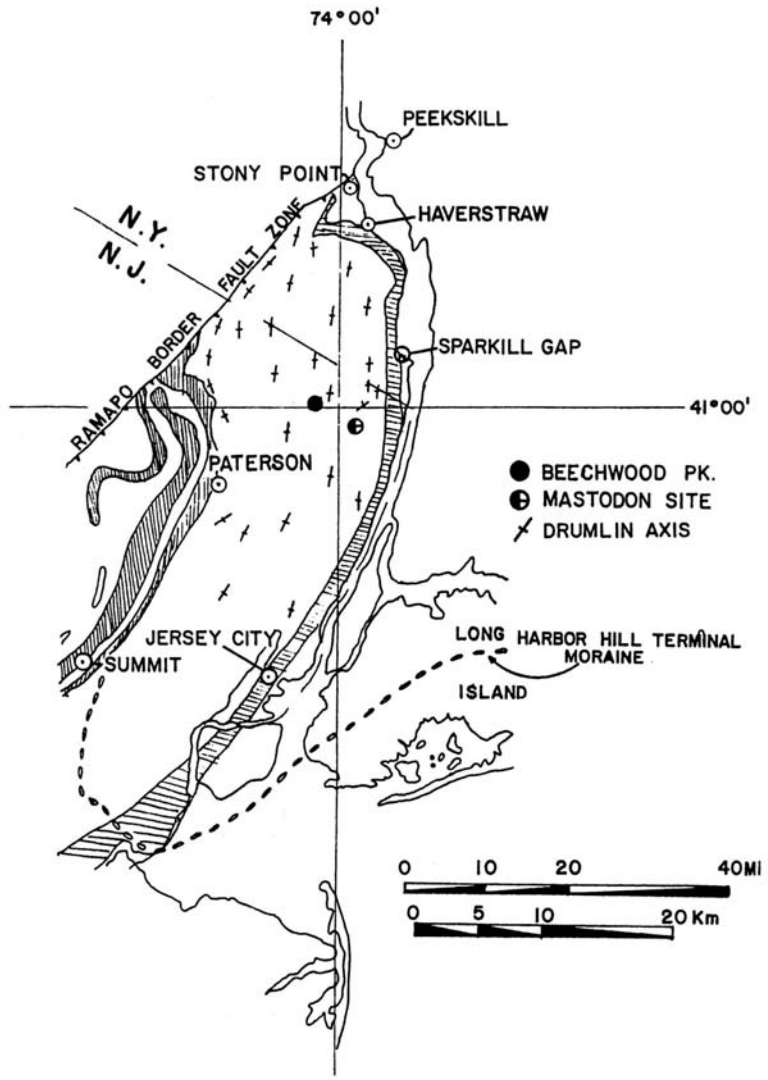

Figure GG-27. Axes of drumlins in the northeastern Newark Basin, Rockland Co., NY and adjacent northern New Jersey. The orientations of all drumlins shown are N-S or NNE-SSW. Closely spaced parallel lines mark prominent topographic ridges underlain by Mesozoic igneous rocks, not subdivided. (Averill, Pardi, Newman, and Dineen, 1980, fig. 1, p. 161.)

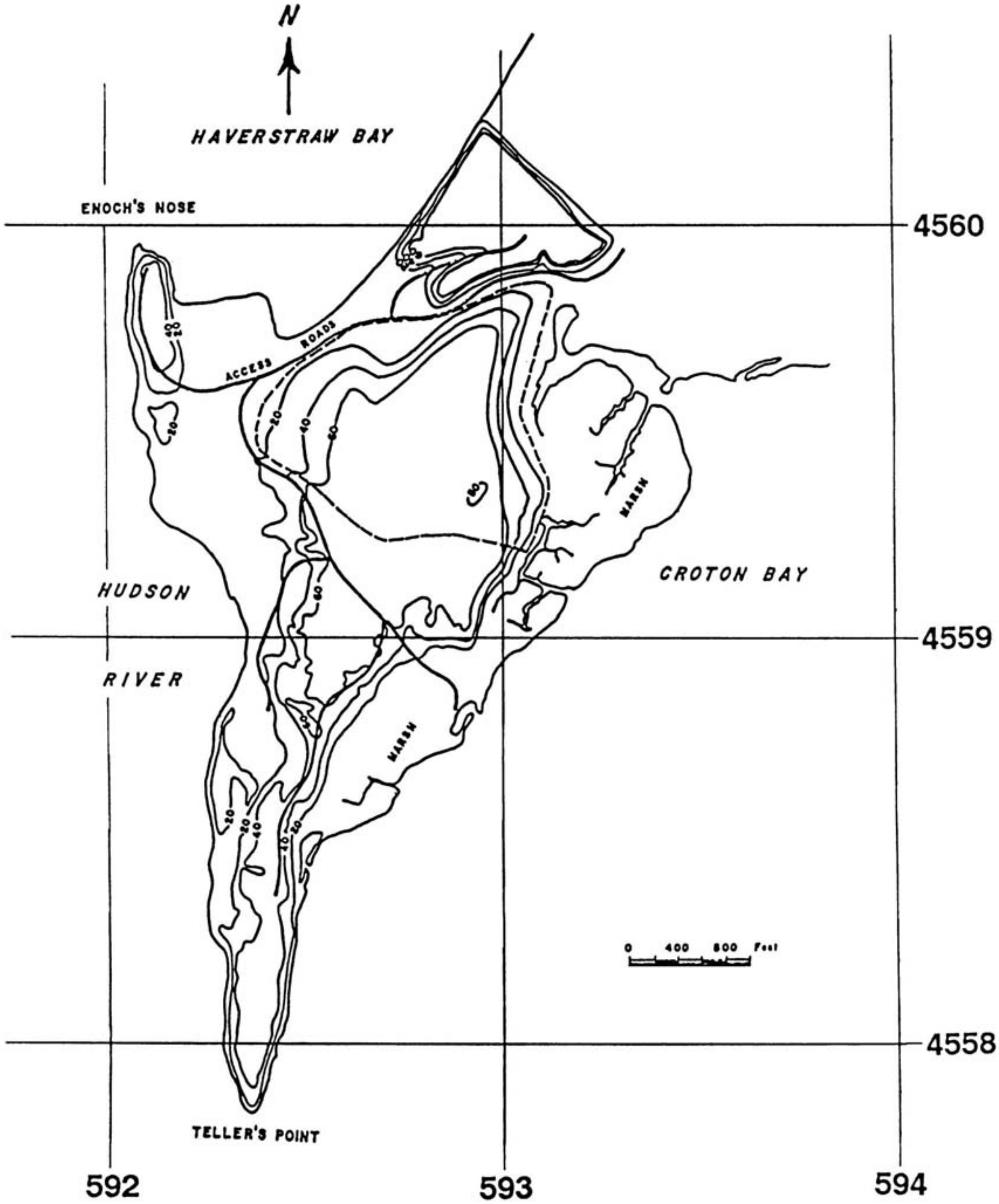

Figure GG-28. Topographic map (contour interval 20 ft) Croton Point Park, Westchester County, NY, in 1974 after the top of the landfill had reached an altitude of 60 feet. The elongate narrow hills trending N-S, at Enoch's Nose and Teller's Point are drumlins made by the most-recent glacier (our Glacier IV). UTM metric grid lines from Haverstraw 7.5-minute topographic quadrangle map of the U. S. Geological Survey added by JES. (Modified by JES from map in Geraghty and Miller, Inc., 1976 ms., fig. 11, p. 35.)

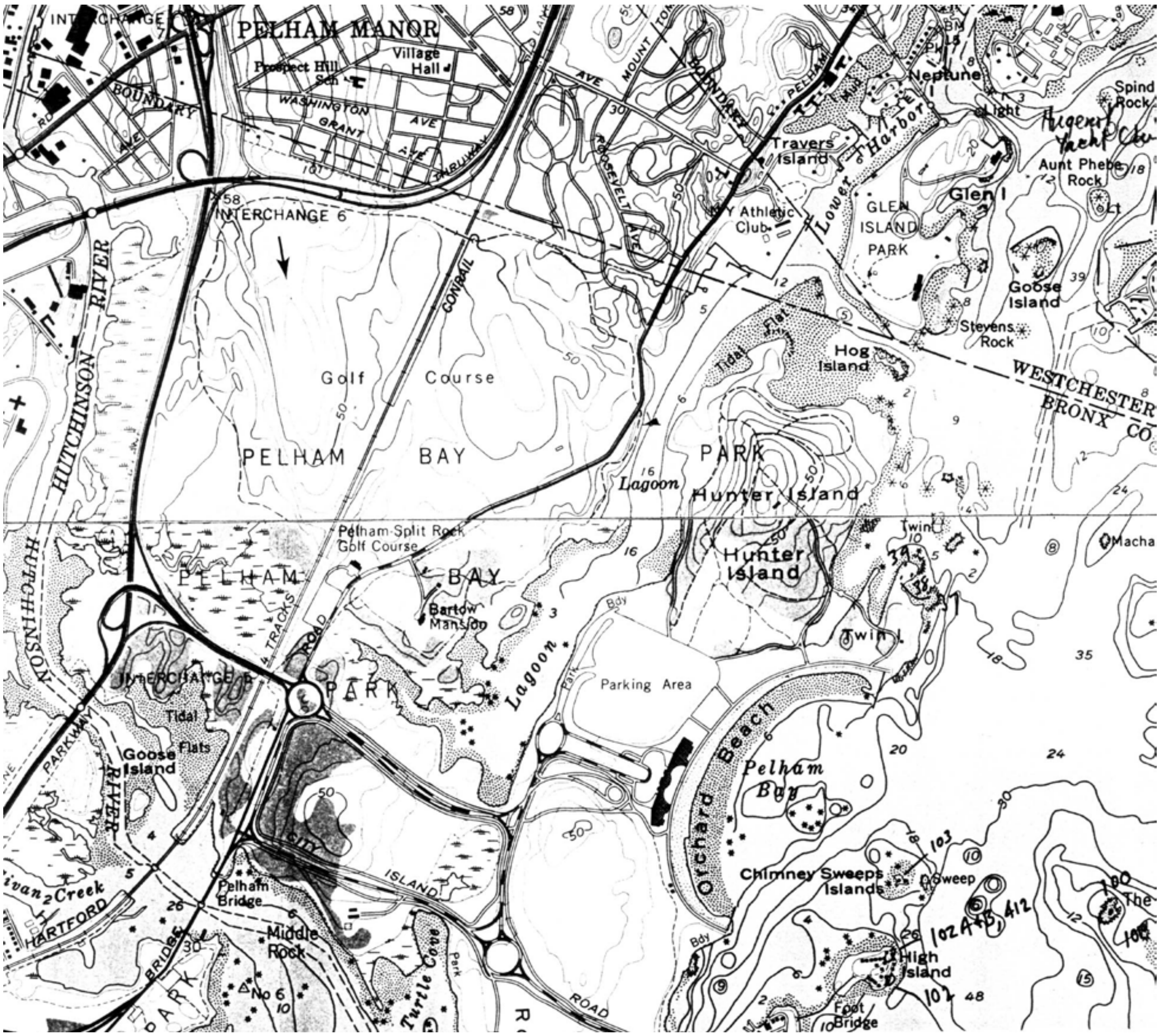

Figure GG-29. Topographic map (contour interval 10 feet) of Pelham Bay Park and vicinity, The Bronx, New York City, showing two small drumlins, with long axes oriented NNW-SSE on the golf course. Arrow (below label for Interchange 6) shows inferred direction of glacier flow, which is the same as the orientation of the dominant set of striae eroded on the bedrock surface that is being uncovered by wave erosion at Twin Island. (Copied from Mount Vernon and Flushing 7.5-minute topographic quadrangle maps of the U. S. Geological Survey; handwritten numbers on the Flushing quadrangle mark CM's field localities.)

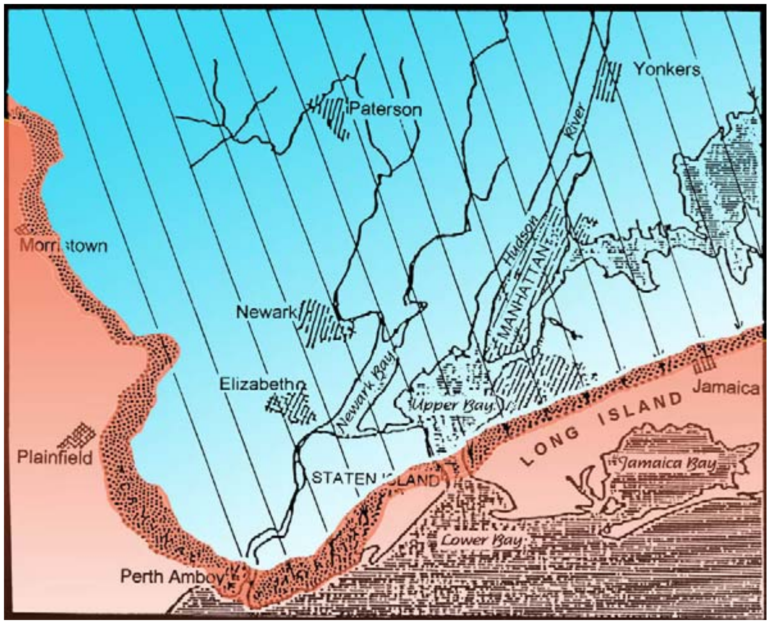

Figure GG-30. Rectilinear flow from NW to SE of inferred pre-Woodfordian glacier. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River.

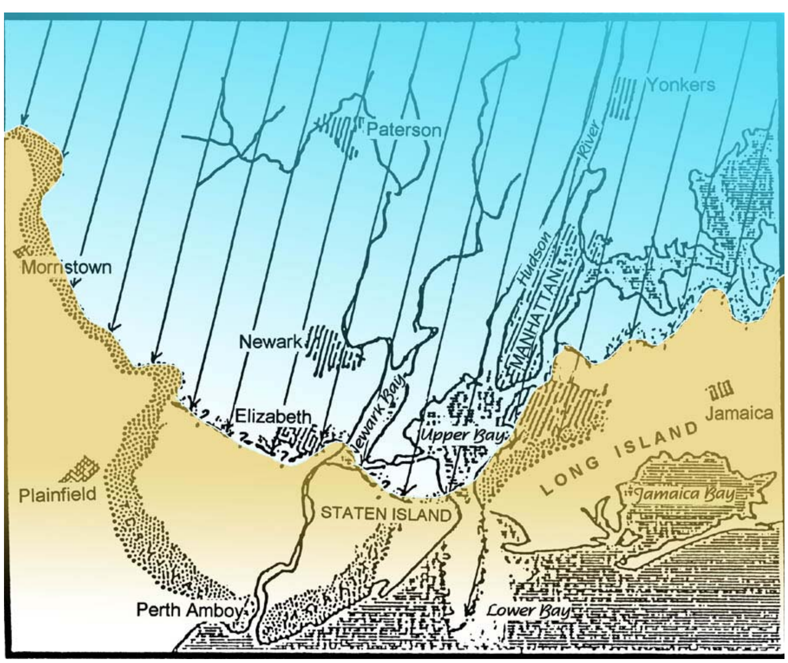

Figure GG-31. Inferred flow pattern of latest Wisconsinan (=Woodfordian) glacier, down the Hudson and Hackensack lowlands from NNE to SSW. On Long Island, this glacier affected only the westernmost parts; elsewhere, its terminal moraine was along the south coast of Connecticut.

The lower gray-tan till contains rocks not found west of the Hudson River. Rather, the distinctive rocks eroding out of the lower till consist of igneous- and metamorphic lithologies which crop out to the east of the Hudson, mostly from regions due north of us. The feldspars in the dark, smaller granitic stones in the lower part of the cliff face have totally decayed.

As mentioned in a previous section, these granitic rocks having such totally decayed feldspars are subject to several interpretations, only one of which implies long-time in-situ postdepositional weathering.

Whatever is eventually decided about the significance of the granitic stones having decayed feldspars, we are certain from the stratigraphic relationships here and the content of indicator stones from the Cortlandt Complex that the direction of flow of the oldest glacier at Croton Point was from N (or NNE) to S (or SSW; down the Hudson Valley) and not from NW to SE (across the Hudson Valley).

This locality provided us with the first stratigraphic evidence for an initial glaciation in the New York City area that antdates the accepted advance of glacial from NW to SE across the Hudson. What is more, it corroborates our observations at Inwood Hill Park, Central Park, and Fort Tryon Park in Manhattan and in the New Botanical Garden in The Bronx, where NW-SE-trending glacial grooves have been cut into an older NNE-SSW-trending roche- moutonée structure or rock drumlin. (See Figure GG-10.)

At the top of a low bluff at Squaw Cove beach, a few hundred meters N of Teller's Point, gray varved clay containing local dropstones is exposed. A dig in the bluff a few meters to the N of the place where the footpath ends shows that this same gray clay overlies the red-brown till. On the beach at Squaw Cove are many more reddish Newark sandstone boulders and mafic rocks of the Palisades Sill. Fewer boulders of the distinctive mafic- and ultramafic rocks from the Cortlandt complex are present here than at Teller's Point.

The top of the red-brown till undulates; the gray clay is limited to the low spots. Traced along the bluff toward the north, the whole face is higher and consists entirely of red-brown till (Figure GG-32).

Another 100 m or so to the north is a low bluff that exposes the top of the gray clay. The overlying unit is a brownish fluffy sand that strikes us as being comparable to coarse loess (windblown sandy silt).

We infer that the gray clay is same age as the deltaic sand/clays underlying the 70-foot terrace in the northeast part of the park. If so, then the clay represents a more-distal depositional site that was isolated from the influx of deltaic sand from the east. The N-S-trending ridge of till kept the deltaic sands from spreading this far west.

The elongate shape of the promontory at Enoch's Nose suggests that it is a drumlin, shaped by the advance of glacial ice from N to S. (See Figure GG-28.) The bluffs here consist of two red-brown tills with local reddish proglacial-lake type of outwash between two units of till. The bouldery "beach" is strewn with large erratics from the Cortlandt Complex and a few Newark sandstone boulders. The boulders of the Cortlandt Complex on the "beach" suggest that some gray till or other must have been eroded. Possibly the older such till is present but only at or below river level. Possibly these boulders came from the upper yellow-brown till that caps the hill. The Newark sandstone boulders came from the red-brown till.

The bluff at the NW end of the promontory and the large cliff at the north end of the drumlin both display the same red-brown till above and below with red-brown fine-sandy proglacial-lake type of outwash locally in between. The 40-ft terrace level (on which is an oyster midden) forms the boundary between the red-brown till(s) exposed in the eroding bluffs and the youngest yellow-brown till of which the drumlin is composed.

We interpret Kindle's (1949) Croton Point moraine at Enoch's Nose as a drumlin. As mentioned, the capping of this drumlin is composed of yellowish-brown till which is perched above red-brown till. The sequence is (from the base up): red-brown till, red-brown sandy proglacial-lake type of outwash and then red-brown till up to path level where the oyster middens are present. Higher up is the yellow-brown till, but such diggings as we have done to date have not yet exposed the contact between the yellow-brown till and the red-brown till.

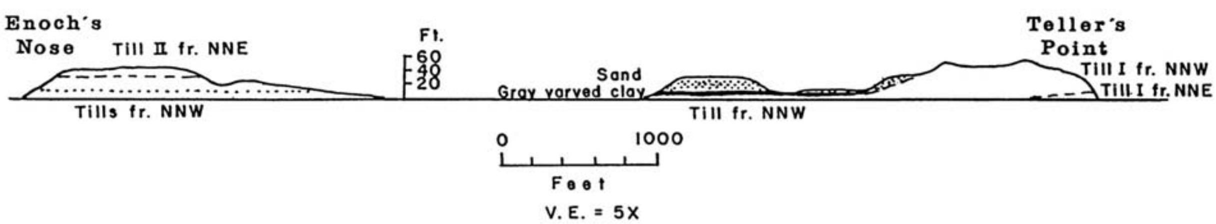

Figure GG-32. Profile-section of Pleistocene sediments along a N-S line from Enoch's Nose to Teller's Point, Croton Point Park, Westchester County, NY, drawn using Geraghty and Miller's June 1974 topographic map (Figure GG-28). The numbering system of the tills shown is by age and flow direction. In Table GG-2, Till II from the NNE is Till IV; the tills from the NNW are Tills III and II, respectively; and Till I from the NNE is Till 1. (J. E. Sanders, in Merguerian and Sanders, 1992e, fig. 42, p. 109.)

We correlate the red-brown till at Enoch's Nose with the red-brown till exposed at Teller's Point and Squaw Cove. Accordingly the entire Croton Point till sequence is (from oldest to youngest): gray-tan till with decayed granitic rocks and ultramafic indicator stones from the Cortlandt Complex, older red-brown till, proglacial-lake type of outwash deposits, newer red-brown till, and yellow-brown till. (See Table GG-2.)

To summarize the Pleistocene history of Croton Point, we offer the following sequence:

(1) Several tills starting with gray-tan, then red-brown, then, after red outwash was deposited, another red-brown till, followed by the yellow-brown till. The red-brown tills contain erratics from the west side of the Hudson River whereas the youngest and oldest tills contain only rocks found on the east side of the Hudson River.

(2) After the youngest of the tills had been deposited and the glacier responsible for it had melted away, the region was flooded. All the drainage from the Great Lakes flowed eastward through the Mohawk Valley and down the Hudson. Proglacial Lake Albany was backed up behind the natural dam of till at the Narrows. Deltaic sediments from the ancestral Croton River and possibly drainages to the north were deposited along the east shore of this lake. The water plane presumably stood at about elevation +70 feet (level of the flat terrace underlain by topset beds of the delta that coincide with the uppermost water level). To the west, the depth of water where the clay was deposited away from influence of the delta was 70 feet. The coarse browner clays probably represent the dark suspended load of the river(s). The light clays are winter deposits when river(s) experienced low- flow conditions and/or were shut down altogether because their waters froze solid.

Tills at Yonkers, Westchester County, NY

During construction at the Westchester County sewage-treatment plant in the Ludlow section of Yonkers near the Ludlow station on the Metro-North Railroad and at the former Otis Elevator plant just N of the Yonkers railroad station
red-brown till containing large dolerite erratics was exposed. At the sewage-treatment plant, the red-brown till is overlain by red-brown outwash that has been recumbently folded on a small scale. (See Figure 9-36, p. 266 in Friedman and Sanders, 1978.) Overlying this deformed red-brown outwash is brownish silt and sand, an inferred lake deposit. At the former Otis plant, the red-brown till is overlain by a gray till containing numerous large, rounded erratics of Inwood Marble.

Tills in Northern New Jersey

During the excavations made in 1974 to enlarge the Oradell reservoir on the Hackensack River, northern New Jersey (on the Yonkers 7.5-minute quadrangle), two tills having contrasting compositions were exposed. The color of the lower till was reddish brown. On the W side of the Hudson River, reddish-brown color is not diagnostic of flow direction; a glacier flowing from any direction here presumably could pick up reddish-brown Newark bedrock. By contrast, the color of the upper till was light yellow-brown to tan; it contained numerous boulders of Inwood Marble, found only on the E side of the Hudson River.

Averill, Pardi, Newman, and Dineen (1980, p. 168, caption for fig. 8) used the name Tappan Till for the upper till. Averill (in Averill, Pardi, Newman, and Dineen, 1980, p. 164) inferred that "the two tills in the Hackensack valley represent two late Wisconsin stades separated by a significant interstade." By contrast we assign the upper till to our Till IV and the one beneath it, to Till III. We consider the age of Till IV to be Late Wisconsinan but that of Till III to be Early Wisconsinan.

Pleistocene Sediments on Long Island, NY

The Pleistocene sediments on Long Island are dominated by outwash, a situation that was noticed long ago and has been mentioned by many investigators. We describe our observations at five localities (from W to E): Sands Point, Garvies Point, Caumsett State Park, Target Rock, and Montauk Point. In a previous section, we discussed the subsurface stratigraphic relationships at Jones Beach.

Sands Point

Except for a thin (1 m or so) till and overlying loess at the crest, the body of the cliffs E of the place where the trail ends at a wooden stairway to the beach at Sands Point is composed of outwash (the Manhasset Formation of Fuller). The top third consists of pebbly, trough-cross-stratified typical coarse outwash, with flow indicated toward the S or SW.

At the E end of the first stretch of beach E of the trail, strata of sands dip steeply (ca. 45°) into the cliff. At first sight from a distance, this dip appears to be the kind of thing that results from rotational tilting on a slumped block. The proof that these are true Gilbert-type delta foresets is that horizontal sets of coarse, trough-cross-stratified pebbly outwash overlie the inclined foresets and truncate them along a horizontal surface. Moreover, the composition of the foresets differs from that of the topsets; the foresets are finer and regularly bedded.

Just to the W of where the stairway leads to the beach,is exposed a red-brown till filling a U-shaped valley carved into the delta deposits. We infer that this means the delta cannot possibly be of Wisconsinan age, but must be older than one of the red-brown tills deposited by a glacier that flowed from NW to SE (our Till III or possibly II). If this red-brown till is our Till III and our age assignment of Early Wisconsinan is correct, then at least some N-flowing fluvial valleys were already in existence. Bear in mind that according to Fuller's interpretation, the largest set of valleys opening to the north was eroded during a prolonged interval of low base level (Fuller's Vineyard erosion interval that he correlated with the Sangamon interglacial stage).

In an exposure E of where the road leads down to the seawall in distress, a small, shallow boulder-lined U-shaped trough had been cut into the delta topsets and backfilled with till, now totally reworked by outwash streams. (An exactly comparable relationship is shown in Mather's sketch of Figure GG-2; and a closely analogous but larger, boulder-lined channel formerly was visible cutting into the lake sediments at Montauk Point that form the bulk of the eroding cliff S of the lighthouse.) By digging, we uncovered the truncated layers in the topset sands and the fact that any boulders containing biotite have decayed considerably.

Garvies Point

For permission to visit the section we describe at Garvies Point, contact Ms. Kathryne Natale [Chief; tel. (516) 671-0300 or Mr. Douglas Winkler (Asst. Curator) (same #)]. Garvies Point Museum and Preserve, Barry Drive, Glen Cove, N.Y. 11542. (UTM: 613.5E - 4523.7N, Sea Cliff 7-1/2 minute quadrangle).

Two chief features exposed in the slumped- and eroding bluffs south of the stairs here are: (1) the Cretaceous strata; and (2) the Lower Pleistocene till containing decayed granite clasts (the Manetto of Fuller). In addition, the boulders on the beach contain a large variety of erratics.

The exposed Cretaceous consists of varigated clays and -sands with lignite seams and layers of charcoal (products of Cretaceous forest fires). Stratigraphy as found in slump block to south of wooden stairs is:

Yellow-brown sand with local cross strata, underlain by
Whitish clay,
Red-purple clay with local lignite at base, and
Gray clay.

The Cretaceous is overlain by a reddish till consisting of deeply weathered granitic boulders, Cretaceous ironstones, and manganiferous residue at contact with underlying outwash. At the right side of the face that a storm cleaned off for study is a large groove in the underlying Cretaceous. Of significant importance, the orientation of this groove indicates ice flow from the NW or even WNW.

Caumsett State Park

The relationships found at Sands Point generally prevail also at Caumsett State Park. At Caumsett, however, inclined pebbly beds predominate in the foresets. Among the pebbles are numerous decomposed mafic metamorphic rocks. We take these decomposed rocks as evidence that the age of this deltaic deposit is pre-Wisconsinan.

Target Rock

The cliff exposures at the Target Rock National Wildlife Preserve (UTM: 632.0E - 4531.8N, Lloyd Harbor 7.5 minute quadrangle) were described in a field-trip guidebook prepared in 1975 by Sirkin and Mills. We have examined this cliff both before and after it was eroded by a severe storm.

At Target rock, the lower half of the cliff consists of gray till containing the green erratics from the Maltby volcanics W of New Haven, CT, indicating the ice flowed from NNE to SSW.

We correlate this till with the oldest till at Croton Point Park (the gray till containing decayed granite stones; Merguerian and Sanders, 1990a; 1992c). Above this till is 1 cm or so of fine gray clay, and then come ripple-laminated silts/fine sands, with splendid examples of climbing ripples (as illustrated by Sirkin and Mills, 1975, description of Stop 3A). These rippled strata display lateral particle-size changes along the ripple profiles from coarser to finer, with superposition of these yielding "pseudo-bedding." Some of the ripple laminae have been oversteepend. We think they are not "small folds that are overturned to the southeast, and represent additional evidence of minor glacial deformation due to overriding by the ice," as interpreted by Sirkin and Mills (1975), but rather examples of the effects of current drag on a bottom where the sediment falling out from suspension becomes cohesive and responds to shearing by the current by deforming (Friedman, Sanders, and Kopaska-Merkel, 1992, p. 252-253). We agree with Sirkin and Mills (p. 320) that "this unit probably represents sedimentation in a proglacial lake that formed between the ice just to the north and the upland to the south."

We infer that these sediments with climbing-ripple laminae and the clay are the bottomset beds, if you will, of the delta foresets exposed at Caumset State Park. Another thin till at the top of the cliff at Target Rock must have come from the NNW; it would have been deposited by a glacier that flowed from NW to SE, to bring the erratics of Inwood Marble and Cortlandt Complex (Sanders and Merguerian, 1991b). Sirkin and Mills (1975) also recognized that two tills are present here.

If our analysis of these tills is correct, then the age of the newly discovered delta deposits must be no younger than mid-Pleistocene (younger than old gray till from NNE and older than a till deposited by a glacier that flowed from the NW).

Montauk Point

The significant relationship about the lake deposits at Mantauk is that they are being eroded in a cliff that faces the open Atlantic Ocean. Given the requirement that a terminal moraine is required to serve as a dam along the southern margin of any proglacial lake that now faces the open ocean of extreme eastern Long Island, then the lake sediments near the Montauk lighthouse require us to infer that a terminal moraine, older than and lying south of the Ronkonkama Moraine, formerly existed seaward of the present S shore of eastern Long Island and has been eroded and submerged (Figure GG-33).

Based on the increase in gravel in the delta foresets eastward from Sands Point to Caumsett State Park, we think that the vaguely stratified diamictites having displaying prominent dips do not represent deformed till as Fuller (1914) and others have supposed but rather are deltaic deposits, products of sublacustrine debris flows.

The abundance of sandy outwash deposited between the terminus of a glacier and its terminal moraine points up the need to distinguish between outwash deposited in fans beyond the terminal moraine from "outwash" deposited in proglacial lakes held in between the ice front on the N and high ground of Long Island or a terminal moraine on the S. [This point is emphasized by Cadwell (1989), who mapped as "lake deposits" some of the "outwash" of Soren (1988).]

The delta-foreset +/- topset outwashes are critical for the correct age assignment of the Manhasset Formation (at Sands Point, they are older than a red-brown till that fills valleys; at Caumsett, they contain decayed pebbles; and at Target Rock, they are younger than a gray till with stones from NNE).

By contrast outwash spread southward from a glacier that was standing at its terminal moraine fans out onto the coastal plain. Such outwash would be one of the first glacial deposits submerged by a rising sea. Hence, bay sediments could overlie such outwash as it evidently did in the Jones Beach subsurface.

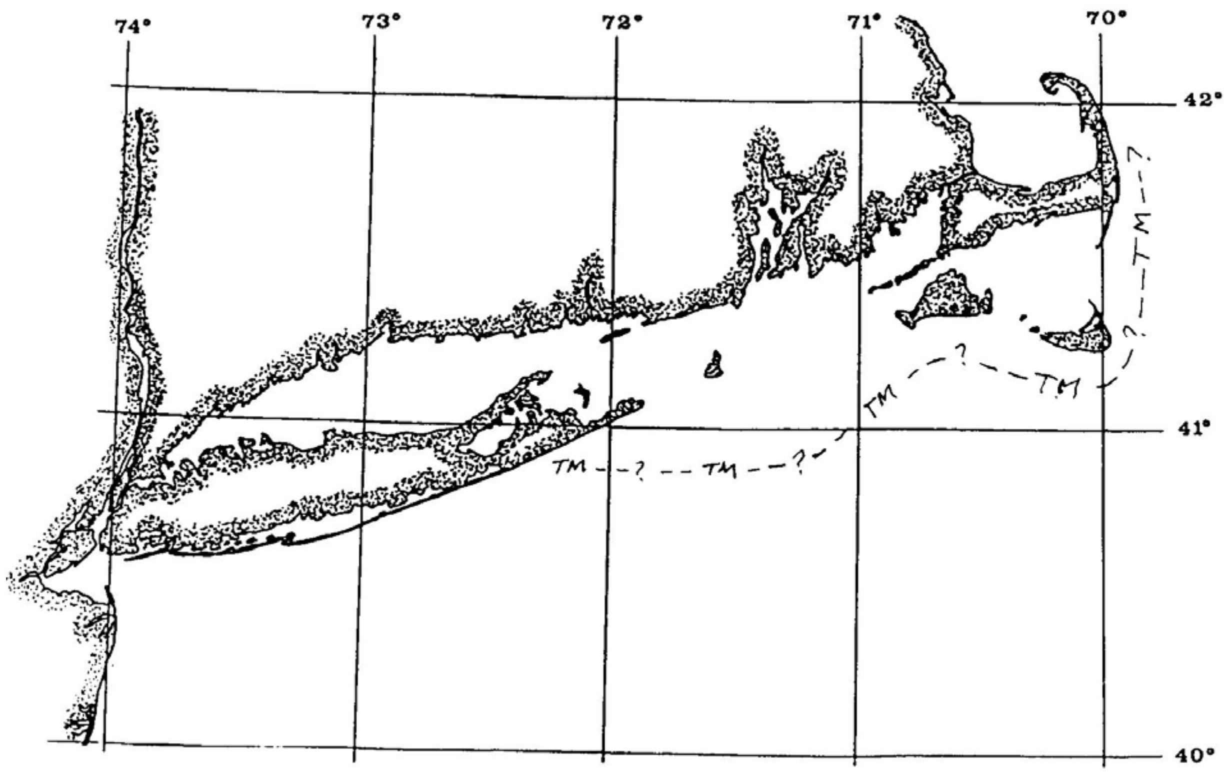

Figure GG-33. Outline map of southern New England and Long Island showing speculative position of a now-vanished terminal moraine marked by TM - - ? - - TM - - ? that we infer must have existed to serve as a dam for the lake in which the lacustrine strata in the coastal cliff at Montauk Point were deposited. (Sanders and Merguerian, 1994, fig. 2, p. 104.)

Tills on Staten Island, NY

On today's field trip, we shall examine two localities where degree of decomposition of tills can be compared (one of which displays a till capped by a well-developed paleosol); a coastal cliff exposing both tills and outwash within which is a giant displaced sheet of Cretaceous sediments; and the glacially eroded bedrock at the Graniteville quarry, part of which is overlain by till that we assign to the Woodfordian.

SUMMARY OF GLACIAL GEOLOGY OF STATEN ISLAND

Students of the glacial geology of New York City and vicinity unanimously agree that all of Staten Island has been glaciated. In contrast with Long Island, where outwash predominates, Staten Island's glacial record features widespread till; outwash is exposed only locally near Great Kills and in coastal cliffs at Princess Bay (Figures GG-34 and GG-35). Other bodies of outwash, however, are known from the subsurface, from water wells in the northwestern part of the island (Perlmutter and Arnow, 1953; in the fill of the buried basal-Newark strike valley studied by Lovegreen, 1974 ms.) and from the borings- and excavations made in the construction of the sewer line under Hylan Boulevard (Mueser Rutledge Consulting Engineers, 1990). Moreover, a prominent terminal-moraine ridge extends from the Narrows along the coast of Staten Island (Salisbury, in Merrill and others, 1902; Perlmutter and Arnow, 1953; Soren, 1988; Cadwell, 1989; also Figures GG-34 and GG-35).

On the subject of how many glacial episodes have affected Staten Island, most glacial geologists vote one--the most recent, or Woodfordian substage of the Wisconsinan stage. In the absence of any compelling evidence of multiple glaciations, such as interstratified glacial- and nonglacial deposits exposed in a single section, the one-glacier-did-it-all school has ruled supreme. Evidence that might be associated with multiple glacial advances, such as striated bedrock displaying striae having contrasting orientations, has been interpreted in terms of ice domes at the margin of the ice sheet or of the behavior of a lobate ice margin. Within each lobe, the ice from a single glacier may flow in different directions.

CONCLUSIONS

As a result of studying the erosive effects on bedrock that enable the directions of flow of an ancient glacier to be inferred, we have arrived at conclusions that differ significantly from those that are generally accepted among specialists in Pleistocene geology. We argue that the youngest glacier that came to New York City and vicinity (our Glacier IV; the Woodfordian of standard classification) flowed along a direction that is parallel to the Hudson Valley (from about N10°E to S10°W). In those parts of the New York City area lying E of the Hudson River, the color of the till deposited by this glacier is gray or yellowish brown. Because erratics from the Hartford Basin are not found in the Pleistocene sediments on Long Island that are situated in a downflow direction from New Haven, CT, we infer that the Woodfordian glacier did not reach most of Long Island, but rather stopped along the coast of Connecticut. It did reach Queens, where it deposited the non-red Roslyn Till.

The next-older till flowed from a direction that is across the lower Hudson Valley (direction from N15°W to S15°E). In his study of the Pleistocene deposits of Queens, J. B. Woodworth (1901) showed that the Harbor Hill moraine is associated with a reddish-brown till that rests on striated bedrock with striae oriented N25°W-S25°E (magnetic). In our scheme of things, we take this as further, and conclusive, evidence that the Harbor Hill moraine cannot possibly be of Late Wisconsinan age (i. e., Woodfordian, as most workers believe), but must be at least one glacier older. We assign it to the Early Wisconsinan.

At Orchard Beach in The Bronx, long axes of drumlins on the golf course trend N15°W-S15°E. Along the water's edge of Long Island Sound, on South Twin Island, we have found a reddish-brown till (our Till III) resting on a striated glacial pavement with the striae oriented N15°W-S15°E, as Woodworth found in Long Island City. The till at Orchard Beach is not associated with any moraine that we know of. Despite the lack of any morainal association, we think that the relationships at Orchard Beach demonstrate two points of great significance: (1) the striae oriented N15°W-S15°E cut at least one older roche- moutonée structure eroded by a glacier that flowed from about N10°E to S10°W, and (2) the numerous large erratics that have been washed out of the till(s) include several indicator stones from the Cortlandt Complex near Peekskill. We infer that these indicator stones must have been washed out of the Woodfordian till, which is not exposed in the low bluff at the water's edge.

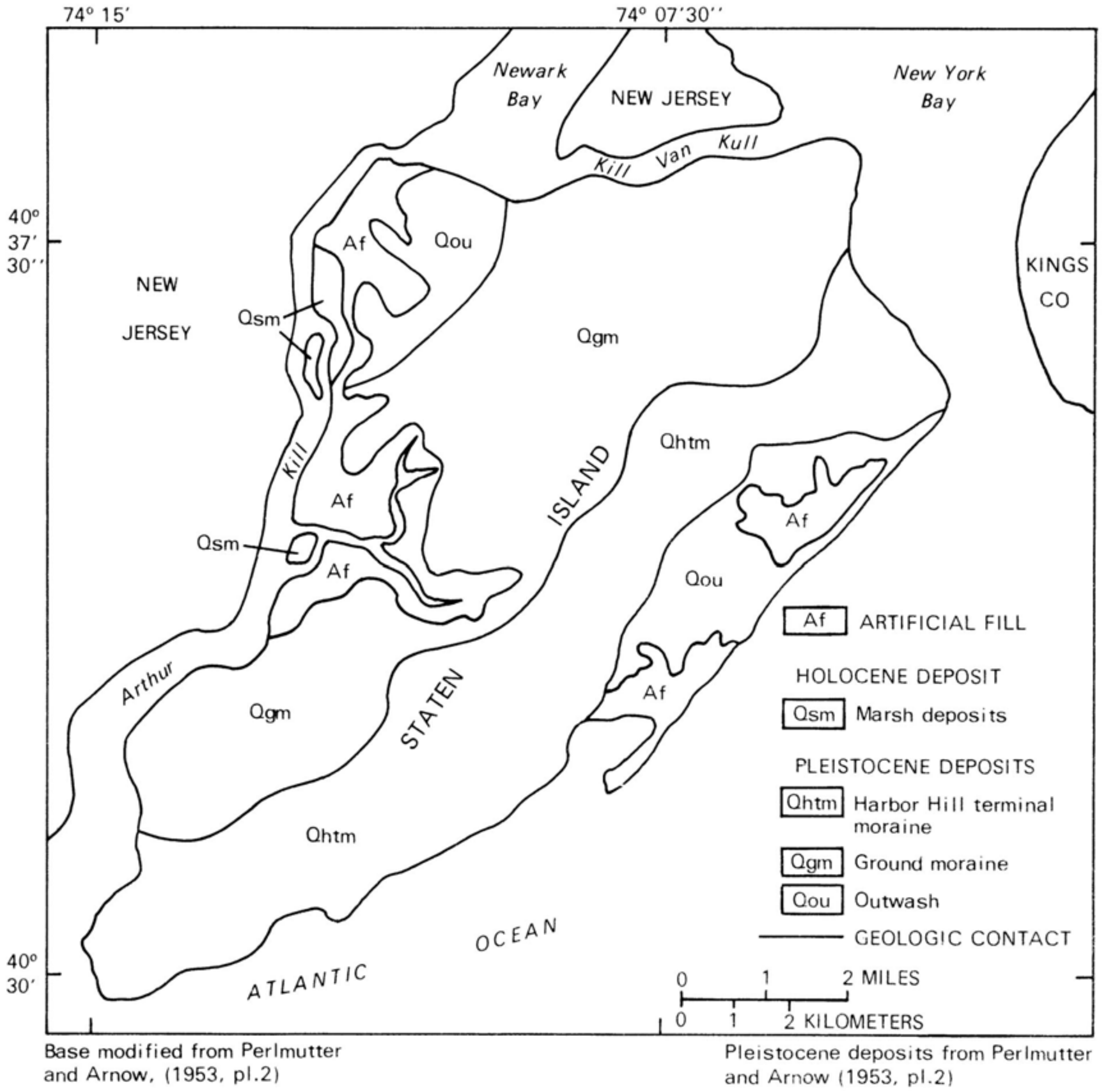

Figure GG-34. Map of surficial deposits on Staten Island, New York. (Soren, 1988.)

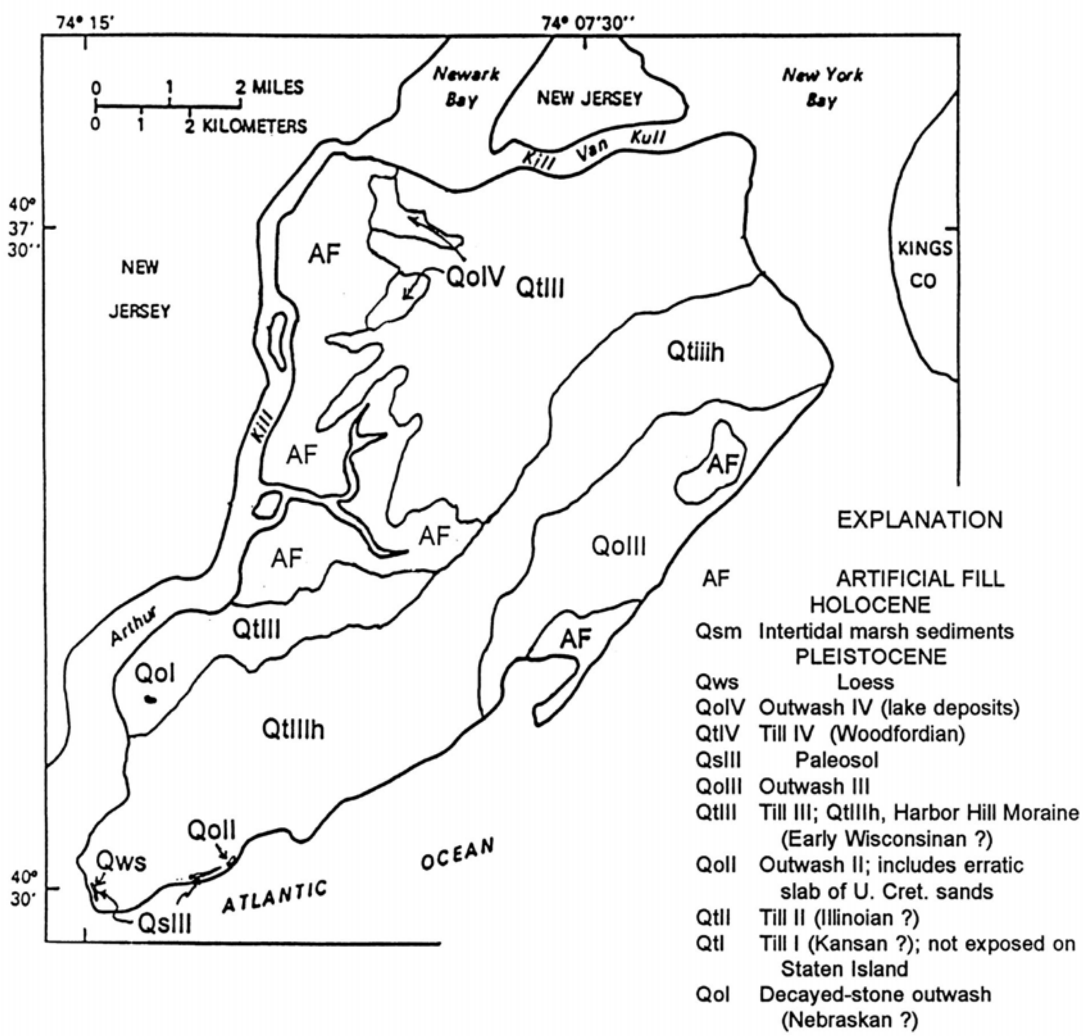

Figure GG-35. Map of surficial deposits on Staten Island made by JES using the outline of Soren's map and most of the contacts from Cadwell's (1989) map, but with additions to show units in our classification.

At present, the best hope for settling our chronological impasse is amino-acid racemization analysis of shells from the Wantagh Formation. Our inference is that the Wantagh is Sangamonian, but as noted above, it could be mid-Wisconsinan or even Yarmouthian.

In many respects, our work re-establishes the validity of Fuller's (1914) interpretation of the glacial geology of Long Island (See Table GG-1.), which has been out of favor since the mid-1930s. Although we support Fuller in most respects, we differ from the universally accepted post-Fuller position in assigning a pre-Woodfordian age to Long Island's prominent terminal moraines. We think it is possible that Fuller was correct in his assignment of the Harbor Hill Moraine to the Early Wisconsinan, but we think he was not correct in assigning an Early Wisconsinan age to the older Ronkonkama moraine. We think that the correct resolution of the ages of these two moraines depends on the age of the Wantagh Formation. We correlate the Harbor Hill Moraine with the Bellmore Formation, which overlies the Wantagh Formation. If the Wantagh proves to be Sangamonian, then the position of Bellmore Formation (and the Harbor Hill Moraine, which we associate with our Till III) becomes Early Wisconsinan, where Fuller assigned the Harbor Hill Moraine. The Sangamonian age assignment for the Wantagh Formation places the Ronkonkama Moraine in the Illinoian. We interpret the Manhasset Formation as extensive deltaic sediments deposited in Lake Long Island that we infer was dammed on the S in part by the Ronkonkama- or a still-older terminal moraine (See Figure GG-33.), so its age assignment is tied to that of whatever terminal moraine held it in on the south. If the Long Island Lake were dammed on the S in part by a terminal moraine older than the Ronkonkama, then that feature has been reduced by erosion and submerged by the sea so that its remnants now exist only as bouldery shoals.

ACKNOWLEDGEMENTS

Our study of the Pleistocene history of New York City was aided by the assistance of many individuals and organizations. We have learned a great deal from our colleagues in the field, from their field-trip guidebooks, and from their publications. Aside from those quoted in the text we here acknowledge information shared on two field trips run by Dr. Les Sirkin, of Adelphi University, that were instrumental in galvanizing our views on the glacial geology of Long Island. Dr. Herbert C. Mills, Curator of Geology, Sand's Point Preserve, Port Washington, New York, spent two days in the field with us, sharing ideas and testing our resolve, and Dr. Alan I. Benimoff, College of Staten Island, for spending a few days in the field and inviting us to publish our results in this field-trip guidebook. In this connection we also thank Dr. Gilbert N. Hanson, of SUNY, Stony Brook, who invited us to present our work in June 1991 on a field trip for the Long Island Geologists and to present our ideas at a conference at Stony Brook University earlier this year. The logistical support for our field endeavors from the Geology Department of Hofstra University is gratefully acknowledged. We also than Matthew Katz and Marcie Brenner of the New York Academy of Sciences for their continual support of our On-The-Rocks field-trip program, in which many of our ideas were spawned and/or amplified upon. We also thank our many On-The-Rocks participants, particularly James P. Gould, for their interest in our work, stimulating questions, and penetrating observations.

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We dedicate our paper to the use of JES' G.I. trenching tool and his rusty old machete, two indispensible pieces of field equipment that accompanied us (and were used) on all of our research trips.

REFERENCES CITED

Averill, S. P., Pardi, R. R., Newman, W. S., and Dineen, R. J., 1980, Late Wisconsin-Holocene history of the lower Hudson region: new evidence from the Hackensack and Hudson River valleys, p. 160-186 in Manspeizer, Warren, ed., Field studies of New Jersey geology and guide to field trips: New York State Geological Association Annual Meeting, 52nd, Newark, New Jersey, 10-12 October 1980: Newark, NJ, Rutgers University Newark College of Arts and Sciences Geology Department, 398 p.

Baskerville, C. A., 1987, Bedrock (sic) and engineering geologic (sic) maps of Bronx County and parts of New York and Queens Counties, New York: United States Geological Survey Open-File Report 87-360, scale 1:24,000, 3 sheets.

Baskerville, C. A., 1989b, New York City: juxtaposition of Cambrian and Ordovician miogeoclinal (sic) and eugeoclinal rocks: p. T361:39-T361:48 in Baskerville, C. A. ed., Geology and engineering geology of the New York Metropolitan area, International Geological Congress, 28th, Washington, D. C., Guidebook to Field Trip T361, 59 p.

Baskerville, C. A., 1992, Bedrock (sic) and engineering geologic (sic) maps of Bronx County and parts of New York and Queens counties, New York: U. S. Geological Survey Miscellaneous Investigations Series Map I-2003 (scale 1:24,000).

Baskerville, C. A.; and Merguerian, C., 1983, Stratigraphic differentiation in the Manhattan Schist, New York City (abstract): Geological Society of America Abstracts with Programs, v. 15, p. 169 (only).

Belknap, D. F., 1979 ms., Application of amino acid (sic) geochronology to stratigraphy of late Cenozoic marine units of the Atlantic Coastal Plain: Newark, DE, University of Delaware Ph. D. dissertation.

Berkey, C. P., 1910a, Areal (sic) and structural geology of southern Manhattan Island: New York Academy of Sciences Annals, v. 19, no. 11, part 2, p. 247-282.

Berkey, C. P., 1910b, Observations on rate of sea-cliff erosion (abstract): Geological Society of America Bulletin, v. 21, p. 778 (only).

Berkey, C. P., 1911, Geology of the New York City (Catskill) aqueduct: New York State Museum Bulletin 146, 283 p.

Berkey, C. P., 1913, Is there fault control of the Hudson River course? (abstract): New York Academy of Sciences Annals, v. 22, p. 351 (only).

Berkey, C. P., 1930, The water supply of a great city: Natural History, v. 20, p. 406-421.

Berkey, C. P., ed., 1933, New York City and vicinity: International Geological Congress, 16th, United States, Guidebook 9, New York excursions: Washington, D. C., U. S. Government rinting Office, 151 p.

Berkey, C. P., 1933, Engineering geology of the City of New York, p. 77-123 in Berkey, C. P., ed., Guidebook 9, New York Excursions, New York City and vicinity: International Geological Congress, 16th, United States, 1933, Washington, D. C., United States Government Printing Office, 151 p.

Berkey, C. P., 1948, Engineering geology in and around New York, p. 51-66 in Creagh, Agnes, ed., Guidebook of Excursions: Geological Society of America Annual Meeting, 61st, New York City, 135 p.

Berkey, C. P., and Colony, C. P., 1933, Structural geology between New York and Schunemunk Mountain, p. 40-41 in Berkey, C. 1P., ed., Guidebook 9, New York Excursions, New York City and vicinity: 16th International Geological Congress, United States, 1933, Washington, D. C., United States Government Printing Office, 151 p.

Berkey, C. P.; and Fluhr, T., 1948, Engineering geology of New York City water supply, p. 121-135 in Creagh, Agnes, ed., Geological Society of America Annual Meeting, 61st, New York City, Guidebook of Excursions, 135 p.

Berkey, C. P. and Healy, J. R., 1912, The geology of New York City and its relations (sic) to engineering problems (with discussion): Municipal Engineers of the City of New York Proceedings for 1911, p. 5-39.

Berkey, C. P.; and Rice, Marion, 1919, Geology of the West Point quadrangle, New York: New York State Museum Bulletin 225-226, 179 p.

Bier, J. A., 1964, Landforms of New York: Alpine Geographical Press, Illinois, Scale 1:1,000,000

Blank, H. R., 1978, Fossil laterite on bedrock in Brooklyn, New York: Geology, v. 6, p. 21-24.

Bourgeois, Joanne, 1972 ms., The study of glacial boulders: New York, NY, Barnard College Columbia University Department of Geology Senior Thesis, 64 p.

Bowes, D.; and Langer, A., 1969, Polyphase deformation in the schists of the Bronx, New York City, p. 17-31 in Alexandrov, E. A., ed., Symposium on the New York City Group of Formations: Flushing, NY, Queens College Press Geological Bulletin 3, 83 p.

Brock, P. W. G., 1989, Stratigraphy of the northeastern Manhattan Prong, Peach Lake quadrangle, New York-Connecticut, p. 1-27 in Weiss, Dennis, ed., New York State Geological Association Annual Meeting, 61st, Field trip guidebook: Middletown, NY, Orange County Community College, Department of Science and Engineering, 302 p.

Brock, P. J. C., 1993 ms, Geology of parts of the Peach Lake and Brewster quadrangle, southeastern New York and adjacent Connecticut, and basement blocks of the north-central Appalachians: New York, NY, City University of New York Graduate Faculty in Earth and Environmental Sciences, Ph. D. Dissertation, 494 p., 6 plates.

Cadwell, D. H., ed., 1986, The Wisconsinan Stage of the First Geological District, eastern New York: New York State Museum Bulletin 455, 191 p.

Cadwell, D. H., 1989, Surficial geology map of New York, Lower Hudson sheet: New York State Museum Map and Chart Series 40, scale 1:250,000.

Cameron, E. N., 1951, Preliminary report on the geology of the Mount Prospect Complex: Connecticut Geology and Natural History Survey Bulletin 76, 44 p.

Chamberlin, T. C., 1883, Preliminary paper on the terminal moraine of the second glacial epoch, 291-402 in United States Geological Survey Annual Report, 3rd (1881-1882), 564 p.

Chamberlin, T. C., 1888, The rock scorings of the great ice age: United States Geological Survey Annual Report, 7th (1885-1886), p. 147-248.

Chamberlin, T. C., 1895a, Glacial phenomena of North America, p. 724-775 in Geikie, James, The great ice age: New York, D. Appleton and Company, 545 p.

Chamberlin, T. C., 1895b, The classification of American glacial deposits: Journal of Geology, v. 3, p. 270-277.

Cook, G. H., 1979, Report on the clay deposits of Woodbridge, South Amboy and other places in New Jersey, together with their uses for fire brick, potting, &c: Trenton, Naar, Day and Naar Printers, 381 p.

Crowley, W. P., 1968, The bedrock geology of the Long Hill and Bridgeport quadrangles, Connecticut: Connecticut Geological and Natural History Survey Quadrangle Report 24, 81 p. plus maps (scale 1:24,000).

deLaguna, Wallace, 1963, Geology of Brookhaven National Laboratory and vicinity, Suffolk County, New York: United States Geological Survey Bulletin 1156-A, 35 p.

Dixon, H. R., 1982, Multistage deformation of the Preston gabbro, eastern Connecticut, p. 453-465 in Joesten, R.; and Quarrier, S. S., eds., Guidebook for field trips in Connecticut and south-central Massachusetts: Connecticut Geological and Natural History Survey Guidebook No. 5, 482 p.

Dixon, H. R.; and Lundgren, L. W. Jr., 1968, Structure of eastern Connecticut, p. 219-229 in Zen, E-An; White, W. S.; Hadley, J. B., Jr.; and Thompson, J. B. Jr., eds., Studies of Appalachian geology: northern and maritime: New York, NY, Wiley-Interscience, 475 p.

Doriski, T. P.; and Wilde-Katz, Franceska, 1983, Geology of the "20-foot" clay and Gardiners Clay in southern Nassau and southwestern Suffolk counties, Long Island, New York: Syosset, NY, U. S. Geological Survey Water-Resources Investigations Report 82-4056 (Prepared in cooperation with the Nassau County Department of Public Works and the Suffolk County Department of Health Services), 17 p.

Fleming, W. L. S., 1935, Glacial geology of central Long Island: American Journal of Science, 5th series, v. 30, p. 216-238.

Flint, R. F., 1943, Growth of North American ice sheet during the Wisconsin Age: Geological Society of America Bulletin, v. 54, no. 3, p. 325-362.

Flint, R. F., 1945, Glacial map of North America: Geological Society of America Special Papers No. 60, 37 p.

Flint, R. F., 1961, Two tills in southern Connecticut: Geological Society of America Bulletin, v. 72, no. 11, p. 1687-1691.

Flint, R. F., 1971, Glacial (sic) and Quaternary geology: New York-London-Sydney-Toronto, John Wiley and Sons, Inc., 892 p.

Flint, R. F., and Gebert, J. A., 1974, End moraines on and off the Connecticut shore (abstract): Geological Society of America Abstracts with Programs, v. 6, no. 7, p. 738-739.

Flint, R. F., and Gebert, J. A., 1976, Latest Laurentide ice sheet: new evidence from southern New England: Geological Society of America Bulletin, v. 87, p. 182-188.

Flint, R. F.; Sanders, J. E.; and Rodgers, John, 1960a, Symmictite: a name for nonsorted terrigenous sedimentary rocks that contain a wide range of particle sizes: Geological Society of America Bulletin, v. 71, no. 4, p. 507-510.

Flint, R. F.; Sanders, J. E.; and Rodgers, John, 1960b, Diamictite, a substitute term for symmictite: Geological Society of America Bulletin, v. 71, no. 12, p. 1809.

Foye, W. G., 1949, The geology of eastern Connecticut: Connecticut Geological and Natural History Survey Bulletin 74, 95 p.

Friedman, G. M., and Sanders, J. E., 1978, Principles of sedimentology: New York-Chichester-Brisbane-Toronto, John Wiley and Sons, 792 p.

Friedman, G. M., Sanders, J. E., and Kopaska-Merkel, D. C., 1992, Principles of sedimentary deposits. Stratigraphy and sedimentology: New York, NY, Macmillan Publishing Company, 717 p.

Fritts, C., 1962, Age (sic) and sequence of metasedimentary and metavolcanic formations northwest of New Haven Connecticut: United States Geological Survey Professional Paper 450-D, p. D32-D36.

Fritts, C., 1963, Bedrock geology of the Southington quadrangle, Connecticut: United States Geological Survey Quadrangle Map GQ-200, scale 1:24,000.

Fuller, M. L., 1914, The geology of Long Island, New York: United States Geological Survey Professional Paper 82, 231 p.

Fuller, M. L., 1937, Comment on: "Correlation of Late (sic) Pleistocene marine (sic) and glacial deposits of New Jersey and New York:" Geological Society of America Bulletin, v. 47, p. 1982-1994.

Fullerton, D. S., 1986, Stratigraphy (sic) and correlation of glacial deposits from Indiana to New York and New Jersey: Quaternary Science Reviews, v. 5, p. 23-37.

Fullerton, D. S., and Richmond, G. M., 1986, Comparison of the marine oxygen isotope (sic) record, the eustatic sea level (sic) record and the chronology of glaciation in the United States of America: Quaternary Science Reviews, v. 5, p. 197-200.

Gager, C. S., 1932, The story of our boulders: Brooklyn Botanical Garden, Record, v. 21, no. 8, p. 165-207.

Gale, L. D., 1839, Report on the geology of New York County, p. 177-199 in New York (State) Geological Survey, Annual Report, 3rd: Albany, New York, 339 p.

Gale, L. D., 1843, Diary of a geological survey of the Island of New York, p. 581-604 in Mather, W. W., The geology of New York, Part I. Comprising (sic) the geology of the First Geological District: Albany, Carroll & Cook, Printers to the Assembly, 653 p., 46 pl.

Geraghty and Miller, Inc., 1976 ms., Ground-water investigation at the Croton Point Landfill: Port Washington, NY. Summary Report to Westchester County, NY, 47 p.

Gilbert, G. K., 1885, The topographic features of lake shores, p. 69-123 in U. S. Geological Survey, Annual Report, 5th (1883-1884), 469 p.

Gilbert, G. K., 1890, Lake Bonneville: U. S. Geological Survey, Monograph 1, 438 p.

Gilbert, G. K., 1906, Crescentic gouges on glaciated surfaces: Geological Society of America Bulletin, v. 17, p. 303-306.

Gratacap, L. P., 1887, [Serpentine rock of Staten Island, N. Y.]: Staten Island Natural Science Association Proceedings, v. 1, p. 55 (only).

Gratacap, L. P., 1890, On ripple-marked Potsdam sandstone from drift at Tottenville, Staten Island, New York: Science, v. 16, p. 14.

Gratacap, L. P., 1901, Geology of the City of New York (greater New York). For use in schools, institutes and classes: New York, NY, privately published, 82 p.

Gratacap, L. P., 1909, Geology of the City of New York (2nd ed.): New York, NY, Henry Holt Publishing Company, 232 p.

Gustavson, T. C., 1976, Paleotemperature analysis of the marine Pleistocene of Long Island, New York, and Nantucket Island, Massachusetts: Geological Society of America Bulletin, v. 87, no. 1, p. 1-8.

Hanley, Thomas; and Graff, M. M., 1976, Rock trails in Central Park: New York, The Greensward Foundation, Inc., 94 p.

Harris, S. E., 1943, Friction cracks and the direction of glacial movement: Journal of Geology, v. 51, p. 244-258.

Hollick, C. A., 1894, Dislocations of certain portions of the Atlantic plain (sic) strata and their probable causes: New York Academy of Sciences Transactions, v. 14, p. 8-20.

Hollick, C. A., 1906, A fossil forest fire [charred wood at Kreischerville, Staten Island, New York] Staten Island Association Proceedings, v. 1, p. 21-23.

Hollick, C. A., 1908, Drift boulders from the shore at Tottenville: Staten Island Association Proceedings, v. 2, p. 9.

Hollick, C. A., 1915, A conspicuous Staten Island Boulder trail: Staten Island Association Proceedings, v. 5, p. 8-9.

Hollick, C. A., 1926, Records of glaciation in the New York Botanical Garden: New York Botanical Garden Journal, v. 27, p. 269-278.

Hutchinson, D. R., and Klitgord, K. D., 1988, Deep structure of rift basins from the continental margin around New England, p. 211-219 in Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of the early Mesozoic basins of the eastern United States: United States Geological Survey Bulletin 1776, 423 p.

Hutchinson, D. R., Klitgord, K. D., and Detrick, R. S., 1986, Rift basins of the Long Island platform: Geological Society of America Bulletin, v. 97, p. 688-702.

Johnson, M. E., 1961, Thirty-one selected deep wells. Logs and maps: New Jersey Geological Survey Report Series No. 2, 110 p.

Kaye, C. A., 1964a, Boulder train of silicified Paleozoic wood, southeastern Massachusetts: Geological Society of America Bulletin, v. 75, no. 3, p. 233-236.

Kaye, C. A., 1964b, Outline of Pleistocene geology of Martha's Vineyard, Massachusetts: United States Geological Survey Professional Paper 501-C, p. C134-C139.

Kaye, C. A., 1964c, Illinoisan and early Wisconsin moraines of Martha's Vineyard, Massachusetts: United States Geological Survey Professional Paper 501-C, p. C140-C143.

Kaye, C. A., 1967, Erosion of a sea cliff, Boston Harbor, Massachusetts, p. 521-528 in Farquhar, O. C., ed., Economic geology in Massachusetts: Amherst, MA., University of Massachusetts Graduate School Publications, 568 p.

Kaye, C. A., 1982, Bedrock (sic) and Quaternary geology of the Boston area, Massachusetts, p. 25-40 in Legget, R. F., ed., Geology under cities: Boulder, Colorado, The Geological Society of America, Reviews in Engineering Geology, v. 5, 131 p.

Kemp, J. F., 1897, The glacial (sic) or postglacial diversion of the Bronx River from its old channel: New York Academy of Sciences Transactions, v. 16, p. 18-24 (map).

Klitgord, K. D., and Hutchinson, D. R., 1985, Distribution and geophysical signatures of early Mesozoic rift basins beneath the U. S. Atlantic continental margin, p. 45-61 in Robinson, G. R., and Froelich, A. J., eds., U. S. Geological Survey workshop on the Early Mesozoic basins of the eastern United States, Second, Proceedings: United States Geological Survey Circular 946, 147 p.

Kuenen, Ph. H., and Sanders, J. E., 1956, Sedimentation phenomena in Kulm and Fl”zleeres graywackes, Sauerland and Oberharz, Germany: American Journal of Science, v. 254, p. 649-67l.

Kümmel, H. B., 1933, Glacial history of the Passaic Valley and related geologic features, p. 64-77 in Berkey, C. P., ed., International Geological Congress, 16th, United States, Guidebook 9: New York Excursions, New York and Vicinity, 151 p.

Langer, A. M., and Bowes, D., 1969, Polyphase deformation in the Manhattan Formation, Manhattan Island, New York City, p. 361-377 in Larsen, L. H.; Prinz, M.; and Manson, V., eds., Igneous (sic) and metamorphic geology: Boulder, CO, Geological Society of America Memoir 115, 000 p.

Leet, L. D., and Judson, Sheldon, 1965, Physical geology (3rd ed.): Englewood Cliffs, NJ, Prentice-Hall, Inc., 406 p.

Leverett, Frank; and Taylor, F. B., 1915, The Pleistocene of Indiana and Michigan and the history of the Great Lakes: U. S. Geological Survey Monograph 53, 529 p.

Lobeck, A. K., 1939, Geomorphology. An introduction to the study of landscapes: New York and London, McGraw-Hill Book Company, Inc., 731 p.

Longwell, C. R., 1922, Notes on the structure of the Triassic rocks in southern Connecticut: American Journal of Science, 5th series, v. 4, p. 233-236.

Longwell, C. R., 1928, The Triassic of Connecticut: American Journal of Science, 5th series, v. 16, p. 259-263.

Longwell, C. R., 1933, The Triassic belt of Massachusetts and Connecticut, p. 93-118 in Longwell, C. R. ed., Eastern New York and western New England: International Geological Congress, 16th, United States 1933, Guidebook 1, Excursion A-1: Washington, D. C., U. S. Government Printing Office, 118 p.

Longwell, C. R., 1937, Sedimentation in relation to faulting: Geological Society of America Bulletin, v. 48, p. 433-442.

Longwell, C. R., Flint, R. F., and Sanders, J. E., 1969, Physical geology: New York, NY, John Wiley and Sons, 685 p.

Lovegreen, J. R., 1974 ms., Paleodrainage history of the Hudson Estuary: New York, NY, Columbia University Department of Geological Sciences Master's Thesis, 151 p., 8 pl.

Lyell, Charles, 1845, Travels in North America. New York, NY. 1: 189-190 (excavation in boulder bed at Brooklyn Navy Yard; erratics of trap and Mesozoic red sandstone). (Woodworth 1901)

Lyttle, P. T., and Epstein, J. B., 1987, Geologic map of the Newark 1° by 2° quadrangle, New Jersey, Pennsylvania, and New York: United States Geological Survey Miscellaneous Investigations Series Maps, Map I-1715 (2 sheets; scale 1:250,000).

MacClintock, Paul, 1953, Crescentic crack, crescentic gouge, friction crack, and glacier movement: Journal of Geology, v. 61, p. 186.

MacClintock, Paul, 1954, Leaching of Wisconsinan glacial gravels in eastern North America: Geological Society of America Bulletin, v. 65, p. 369-384.

MacClintock, Paul; and Richards, H. G., 1936, Correlation of the late (sic) Pleistocene marine (sic) and glacial deposits of New Jersey and New York: Geological Society of America Bulletin, v. 47, no. 3, p. 289-338.

MacClintock, Paul; and Richards, H. G., 1937, Correlation of the late (sic) Pleistocene marine (sic) and glacial deposits of New Jersey and New York: Geological Society of America Bulletin, v. 47, no. 3, p. 289-338.

Mather, W. W., 1843, Geology of New York. Part I. Comprising (sic) the geology of the First Geological District: Albany, Carroll & Cook, Printers to the Assembly, 653 p., 46 pl. (Includes report of Dr. L. D. Gale on New York Island based on survey of 1828 and 1829.)

Merguerian, Charles, 1977 ms., Contact metamorphism and intrusive relations of the Hodges Complex along Cameron's Line, West Torrington, Connecticut: New York, N.Y., M.A. thesis, The City College of New York, Department of Earth and Planetary Sciences, M.A. thesis, 89 p.

Merguerian, Charles, 1980, Metamorphosed manganiferous sediments (coticules) in the Ordovician of southern New England (abstract): Geological Society of America Abstracts with Programs, v. 12, p. 73 (only).

Merguerian, Charles, 1981, Coticules in New England - Ancient examples of metalliferous sediments (abstract): Transactions of the American Geophysical Union, v. 62, p. 310 (only).

Merguerian, Charles, 1983a, The structural geology of Manhattan Island, New York City (NYC), New York (abstract): Geological Society of America Abstracts with Programs, v. 15, p. 169 (only).

Merguerian, Charles, 1983b, Tectonic significance of Cameron's Line in the vicinity of the Hodges Complex - an imbricate thrust model for Western Connecticut: American Journal of Science, v. 283, p. 341-368.

Merguerian, Charles, 1985, Geology in the vicinity of the Hodges Complex and the Tyler Lake granite, West Torrington, Connecticut, p. 411-442 in R. J. Tracy, ed., New England Intercollegiate Geological Conference, 77th, New Haven, Connecticut: Connecticut Geological and Natural History Survey Guidebook No. 6, 590 p.

Merguerian, Charles, 1986a, Tunnel vision - A deep view of the bedrock geology of New York City (NYC) (abstract): Geological Society of America Abstracts with Programs, v. 18, p. 54-55.

Merguerian, Charles, 1986b, The bedrock geology of New York City (NYC) (abstract): Hempstead, New York, Hofstra University, Symposium on the Geology of Southern New York, Abstracts with Programs, p. 8 (only).

Merguerian, Charles, 1994, Stratigraphy, structural geology, and ductile- and brittle faults of the New York City area (extended abstract), p. 49-56 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994: Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Merguerian, Charles; and Baskerville, C. A., 1987, The geology of Manhattan Island and the Bronx, New York City, New York, p. 137-140 in Roy, D. C., ed., Northeastern Section of the Geological Society of America, Centennial Fieldguide, v. 5, 481 p.

Merguerian, Charles; Baskerville, C. A.; and Okulewicz, S., 1982, Cameron's Line in the vicinity of New York City (abstract): Geological Society of America Abstracts with Programs, v. 14, p. 65 (only).

Merguerian, Charles; Mose, D.; and Nagel, S., 1984, Late syn-orogenic Taconian plutonism along Cameron's Line, West Torrington, Connecticut (abstract): Geological Society of America Abstracts with Programs, v. 16, p. 50 (only).

Merguerian, Charles; and Sanders, J. E., 1988, Trip 03: Geology of Manhattan and the Bronx, 20 November 1988: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 29 p.

Merguerian, Charles; and Sanders, J. E., 1989a, Trip 04: Geology of Staten Island and vicinity, 15 April 1989: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 49 p.

Merguerian, Charles; and Sanders, J. E., 1989b, Trip 05: Geology of the Palisades and the Newark basin, 21 May 1989: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 65 p.

Merguerian, Charles; and Sanders, J. E., 1989c, Trip 06: Geology of Western Connecticut Mines and Mineral Deposits, 03 June 1989: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 52 p.

Merguerian, Charles; and Sanders, J. E., 1989d, Trip 07: Geology of Robert Moses State Park, 17 September 1989: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 121 p.

Merguerian, Charles; and Sanders, J. E., 1989e, Trip 08: Geology of the Taconic range of eastern New York, 21-22 October 1989: New York Academy of Sciences Section of Geological Sciences 1989-90 Trips on the Rocks Guidebook, 98 p.

Merguerian, Charles; and Sanders, J. E., 1989f, Trip 09, Geology of the Shawangunks and Bellvale Mountain, 11 November 1989: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 56 p.

Merguerian, Charles; and Sanders, J. E., 1990a, Trip 10: Croton Point and Peekskill Hollow, 12 May 1990: New York Academy of Sciences Section of Geological Sciences 1989-90 Trips on the Rocks Guidebook, 74 p.

Merguerian, Charles; and Sanders, J. E., 1990b, Trip 11: Geology of the Little Appalachians and the Catskills, 26-27 May 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 90 p.

Merguerian, Charles; and Sanders, J. E., 1990c, Trip 12: Geology of Franklin Furnace, New Jersey, 17 June 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 83 p.

Merguerian, Charles; and Sanders, J. E., 1990d, Trip 13: Geology of Cameron's LIne and the Hodges Complex, West Torrington, Connecticut, 23 September 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 72 p.

Merguerian, Charles; and Sanders, J. E., 1990e, Trip 14: Geology and history of the Hudson River valley, 28 October 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 106 p.

Merguerian, Charles; and Sanders, J. E., 1990f, Trip 15: Glacial geology of Long Island, 17-18 November 1990: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 96 p.

Merguerian, Charles; and Sanders, J. E., 1991a, Trip 16: Geology of Manhattan and the Bronx, 21 April 1991: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 141 p.

Merguerian, Charles; and Sanders, J. E., 1991b, Trip 17: Geology of Stokes State Forest, New Jersey, 19 May 1991: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 88 p.

Merguerian, Charles; and Sanders, J. E., 1991c, Trip 18: Connecticut mines and dinosaurs, 16 June 1991: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 91 p.

Merguerian, Charles; and Sanders, J. E., 1991d, Trip 19: Geology of Staten Island and vicinity, 29 September 1991 (revision of 1989 Trip 04, 15 April 1989): New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 78 p.

Merguerian, Charles; and Sanders, J. E., 1991e, Trip 20: Palisades and the Newark basin, 26 October 1991 (revision of Trip 05, 21 May 1989): New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 83 p.

Merguerian, Charles; and Sanders, J. E., 1991f, Trip 21: Cameron's Line and the Bronx parks, 24 November 1991: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks, Guidebook, 141 p.

Merguerian, Charles; and Sanders, J. E., 1992a, Xenoliths as indicators of paleoflow and paleoenvironmental conditions in the Palisades sheet, New York and New Jersey (abstract): Geological Society of America, Abstracts with Programs, v. 24, no. 3, p. 62-63.

Merguerian, Charles; and Sanders, J. E., 1992b, Trip 22: Geology of the Taconic Range of Eastern New York and Massachusetts, 10-11 May 1992: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks, Guidebook, 107 p.

Merguerian, Charles; and Sanders, J. E., 1992c, Trip 23, Geology of the Delaware Water Gap and vicinity, 28 June 1992, (revision of Trip 10, May 1990): New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 109 p.

Merguerian, Charles; and Sanders, J. E., 1992d, Trip 24, Beach at Robert Moses State Park, 26 September 1992: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 103 p.

Merguerian, Charles; and Sanders, J. E., 1992e, Trip 25, Geology of Croton Point and Peekskill Hollow, 21 November 1992, (revision of Trip 10, May 1990): New York Academy of Sciences Section of Geological Sciences 1992 Trips on the Rocks Guidebook, 107 p. [109 p.?]

Merguerian, Charles; and Sanders, J. E., 1993a, Trip 26, Cameron's Line and The Bronx parks, 08 May 1993 (revision of Trip 21, 24 November 1991): New York Academy of Sciences Section of Geological Sciences 1993 Trips on the Rocks Guidebook, 126 p.

Merguerian, Charles; and Sanders, J. E., 1993b, Trip 27, Geology of the Newark basin in the Delaware Valley, 19 June 1993: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 90 p.

Merguerian, Charles; and Sanders, J. E., 1993c, Trip 28, Geology of southern Central Park, New York City, 26 September 1993: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 143 p.

Merguerian, Charles; and Sanders, J. E., 1993d, Trip 29, Geology of the northeastern Newark basin, 14 November 1993: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 93 p.

Merguerian, Charles; and Sanders, J. E., 1994a, Trip 30: Geology of the Hudson Highlands and Bear Mountain, 21 May 1994: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 112 p.

Merguerian, Charles; and Sanders, J. E., 1994b, Trip 31: Connecticut mines and dinosaurs, 18 June 1994: New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 111 p.

Merrill, F. J. H., 1890, On the metamorphic strata of southeastern New York: American Journal of Science, 3rd series, v. 39, p. 383-392.

Merrill, F. J. H.; Darton, N. H.; Hollick, Arthur; Salisbury, R. D.; Dodge, R. E.; Willis, Bailey; and Pressey, H. A., 1902, Description of the New York City district: United States Geological Survey Geologic Atlas of the United States, New York City Folio, No. 83, 19 p. (Includes colored geologic map on a scale of l:62,500).

Mills, H. C., and Wells, P. D., 1974, Ice-shove deformation and glacial stratigraphy of Port Washington, Long Island, New York: Geological Society of America Bulletin, v. 85, no. 3, p. 357-364.

Mose, D. G.; and Merguerian, Charles, 1985, Rb-Sr whole-rock age determination on parts of the Manhattan Schist and its bearing on allochthony in the Manhattan Prong, southeastern New York: Northeastern Geology, v. 7, no. 1, p. 20-27.

Mueser Rutledge Consulting Engineers, 1990, Ground conditions encountered Oakwood Beach Water Pollution Control (sic) Project Contract 6B-3, East Heading, Staten Island, New York: Report submitted to New York City Department of Environmental Protection for Moretrench American Corporation, not paginated.

Muller, E. H., and Calkin, P. E., 1993, Timing of Pleistocene glacial events in New York State: Canadian Journal of Earth Sciences, v. 30, p. 1829-1845.

Muller, E. H.; Sirkin, Les; and Craft, J. L., 1993, Stratigraphic evidence of a pre-Wisconsinan interglaciation in the Adirondack Mountains, New York: Quaternary Research, v. 40, p. 163-138.

Oldale, R. N., 1982, Pleistocene stratigraphy of Nantucket, Martha's Vineyard, the Elizabeth Islands, and Cape Cod, Massachusetts, p. 1-34 in Larson, G. L., and Stone, B. D., eds., Late Wisconsinan glaciation of New England. A symposium: Dubuque, IA, Kendall/Hunt Publishing Company, 242 p. (Symposium held at Northeastern section, Geological Society of America, 13 March 1980, Philadelphia, PA.)

Oldale, R. N., and Colman, S. M., 1992, On the age of the penultimate full glaciation of New England, p. 163-170 in Clark, P. U., and Lea, P. D., eds., The last Interglacial-Glacial transition in North America: Boulder, CO, Geological Society of America Special Paper 270, 317 p.

Oldale, R. N., and Eskenasy, D. M., 1983, Regional significance of pre-Wisconsin till from Nantucket Island, Massachusetts: Quaternary Research, v. 19, p. 302-311.

Oldale, R. N., Valentine, P. C., Cronin, T. M., Spiker, E. C., Blackwelder, B. W., Belknap, D. F., Wehmiller, J. F., and Szabo, B. J., 1982, Stratigraphy (sic), structure (sic), absolute age (sic), and paleontology of the upper Pleistocene deposits at Sankaty Head, Nantucket Island, Massachusetts: Geology, v. 10, no. 5, p. 246-252.

Peet, C. E., 1904, Glacial (sic) and post-glacial history of the Hudson and Champlain valleys: Journal of Geology, v. 12, p. 415-469, 617-660.

Perlmutter, N .M.; and Arnow, Theodore, 1953, Ground water in Bronx, New York, and Richmond counties with summary data on Kings and Queens counties, New York City, New York: New York State Water Power and Control Commission Bulletin GW-32, 86 p.

Perlmutter, N. M., and Geraghty, J. J., 1963, Geology (sic) and ground-water conditions in southern Nassau and southeastern Queens counties, Long Island, New York: U. S. Geological Survey Water-Supply Paper 1613-A, 205 p.

Perlmutter, N. M.; Geraghty, J. J.; and Upson, J. E., 1959, The relation (sic) between fresh (sic) and salty ground water in southern Nassau and southeastern Queens counties, Long Island, New York: Economic Geology, v. 54, no. 3, p. 416-435.

Percival, J. G., 1842, Report on the geology of the state of Connecticut: New Haven, Connecticut, Osborn and Baldwin, 495 p.

Rampino, M. R., 1978 ms., Quaternary history of south-central Long Island, New York: New York, New York, Columbia University, Department of Geological Sciences, Ph. D. Dissertation, 742 p.

Rampino, M. R., and Sanders, J. E., 1976, New stratigraphic evidence for major mid-Wisconsinan climatic oscillation and sea-level rise: "Interstadial" or "Interglacial"? (abstract): Geological Society of America Abstracts with Programs, v. 8, p. 1059-1060.

Rampino, M. R., and Sanders, J. E., 1980, Holocene transgression in south-central Long Island, New York: Journal of Sedimentary Petrology, v. 50, no. 4, p. 1063-1080.

Rampino, M. R., and Sanders, J. E., 1981, Episodic growth of Holocene tidal marshes in the northeastern United States: a possible indicator of eustatic sea-level fluctuations: Geology, v. 9, no. 2, p. 63-67.

Rampino, M. R., and Sanders, J. E., 1981a, Evolution of the barrier islands of southern Long Island, New York: Sedimentology, v. 28, no. 1, p. 37-47.

Rampino, M. R., and Sanders, J. E., 1981b, Upper Quaternary stratigraphy of southern Long Island, New York: Northeastern Geology, v. 3, no. 2, p. 116-128.

Ricketts, H. C., 1986, Examination in boreholes of the subsurface Gardiners Clay (Pleistocene), in the context of the Cretaceous-Quaternary section of Great Neck, Long Island, New York: Northeastern Geology, v. 8, nos. 1/2, p. 13-22.

Robinson, Peter; and Hall, L. M., 1980, Tectonic synthesis of southern New England, p. 73-82 in Wones, D. R., ed., International Geological Correlation Project, Proceedings, Project 27: The Caledonides in the U. S. A.: Blacksburg, Virginia, Virginia Polytechnic Institute and State University, Department of Geological Sciences, Memoir 2, 329 p.

Rodgers, John, 1985, Bedrock geological map of Connecticut: Hartford, Connecticut, Connecticut Geological and Natural History Survey, Connecticut Natural Resources Atlas Series, scale 1:250,000.

Salisbury, R. D., 1892, A preliminary paper on drift or Pleistocene formations in New Jersey, p. 35-108 (+ maps) in New Jersey Geological Survey Annual Report of the State Geologist for 1891,

Salisbury, R. D., 1893a, Surface geology--report of progress , p. 37- 61 (+map) in New Jersey Geological Survey Annual Report of the State Geologist for 1892

Salisbury, R. D., 1893b, Distinct glacial epochs and the criteria for their recognition: Journal of Geology, v. 1, p. 61-84.

Salisbury, R. D., 1894, The drift, its characteristics and relationships: Journal of Geology, v. 2, p. 708-724; 837-851.

Salisbury, R. D., 1895, Surface geology; report of progress, p. 1-149 (+ map) in New Jersey Geological Survey Annual Report of the State Geologist for 1894

Salisbury, R. D., 1896, Surface geology; report of progress, p. 1-16 (+ map) in New Jersey Geological Survey Annual Report of the State Geologist for 1895

Salisbury, R. D., 1898a, Surface geology; report of progress, p. 1-22 (+ map) in New Jersey Geological Survey Annual Report of the State Geologist for 1897

Salisbury, R. D., 1898b, The physical geography of New Jersey: New Jersey Geological Survey Final Report, v. 4, p. 1-176 (+maps).

Salisbury, R. D., 1900, The local origin of glacial drift: Journal of Geology, v. 8, p. 426-432.

Salisbury, R. D., 1902, Pleistocene formations, p. 11-17 in Merrill, F. J. H., Darton, N. H., Hollick, Arthur, Salisbury, R. D., Dodge, R. E., Willis, Bailey,, and Pressey, H. A., Description of the New York City district: United States Geological Survey Geologic Atlas of the United States New York City Folio, No. 83, 19 p.

Salisbury, R. D., 1908a, The Quaternary System, p. 13-18 in Description of the Franklin Furnace quadrangle, New Jersey: U. S. Geological Survey Geologic Atlas of the United States Franklin Furnace Folio No. 161, 27 p.

Salisbury, R. D., 1908b, The Quaternary system, in Description of the Passaic quadrangle, New Jersey-New York: U. S. Geological Survey Geologic Atlas of the United States Passaic Folio No. 157, 27 p.

Salisbury, R. D., and Knapp, G. N., 1897, Surface geology; report of progress, p. 1-23 (+ maps) in New Jersey Geological Survey Annual Report of the State Geologist for 1896

Salisbury, R. D., and Kümmel, H. B., 1895, Lake Passaic, an extinct glacial lake: Journal of Geology, v. 3, p. 533-560.

Salisbury, R. D., assisted by H. B. Kümmel, C. E. Peet, and G. N. Knapp, 1902, The glacial geology of New Jersey: Geological Survey of New Jersey, Final Report of the State Geologist, v. 5: Trenton, New Jersey, MacCrellish and Quigley, Book and Job Printers, 802 p.

Salisbury, R. D., and others, 1894, Surface geology--report of progress, p. 33-328 (+ maps) in New Jersey Geological Survey Annual Report of the State Geologist for 1893: Trenton, NJ, The John L. Murphy Publishing Company Printers, 457 p.

Salisbury, R. D., and Peet, C. E., 1894, Section V. Drift phenomena of the Palisade ridge, p. 157-224 in New Jersey State Geologist Annual Report for 1893: Trenton, NJ, The John L. Murphy Publishing Company Printers, 457 p.

Sanders, J. E., 1974, Geomorphology of the Hudson Estuary, p. 5-38 in Roels, Oswald, ed., Hudson River Colloquium: New York Academy of Sciences Annals, v. 250, 185 p.

Sanders, J. E., 1981, Principles of physical geology: New York, NY, John Wiley and Sons, 624 p.

Sanders, J. E., and Merguerian, Charles, 1991a, Pleistocene tills in the New York City region: New evidence confirms multiple (three and possibly four) glaciations from two directions (NNE to SSE (sic) and NW to SE) (abstract): Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 123.

Sanders, J. E.; and Merguerian, Charles, 1991b, Pleistocene geology of Long Island's north shore: Sands Point and Garvies Point to Target Rock: Long Island Geologists' Association Field Trip 29 June 1991 Guidebook: Hempstead, NY, Hofstra University Department of Geology, 40 p.

Sanders, J. E.; and Merguerian, Charles, 1992, Directional history of Pleistocene glaciers inferred from features eroded on bedrock, New York metropolitan area, SE NY (abstract): Geological Society of America Abstracts with Programs, v. 24, no. 1, p. 72 (only).

Sanders, J. E.; Merguerian, Charles; and Mills, H. C., 1993, "Port Washington Deltas" of Woodworth (1901) revisited: pre-Woodfordian Gilbert-type delta revealed in storm-eroded coastal bluff, Sands Point, New York (abstract): Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A-308 (only).

Sanders, J. E.; and Merguerian, Charles, 1994, Fitting newly discovered north-shore Gilbert-type lacustrine deltas into a revised Pleistocene chronology of Long Island (extended abstract), p. 103-113 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Sanders, J. E.; Merguerian, Charles; and Mills, H. C., 1993, "Port Washington deltas" of Woodworth (1901) revisited: pre-Woodfordian Gilbert-type deltas revealed in storm-eroded coastal bluff, Sands Point, New York (abstract): Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A-308 (only).

Sanders, J. E., and Rampino, M. R., 1978, Wisconsinan stratigraphy, New York metropolitan area: interpretation of newly recognized units does not support modern concepts of the "Laurentide" ice sheet (abstract): Geological Society of America Abstracts with Programs, v. 10, no. 2, p. 84 (only).

Schuberth, C. J., 1968, The geology of New York City and environs: Garden City, NY, Natural History Press, 304 p.

Sirkin, L. A., 1968, Geology (sic), geomorphology (sic) and late glacial (sic) environments of western Long Island, New York, p. 233-253 in Finks, R. M., ed., New York State Geological Association Annual Meeting, 40th, Queens College, Guidebook to field trips: Flushing, NY, Queens College of City University of New York Department of Geology, 253 p.

Sirkin, L. A., 1971, Surficial geology (sic) deposits and postglacial pollen stratigraphy in central Long Island, New York: Pollen et Spores, v. 23, p. 93-100.

Sirkin, L. A., 1977, Late Pleistocene vegetation and environments (sic) in the middle Atlantic region: New York Academy of Sciences Annals, v. 288, p. 206-217.

Sirkin, L. A., 1982, Wisconsinan glaciation of Long Island, New York to Block Island, Rhode Island, p. 35-59 in Larson, G. J., and Stone, B. D., eds., Late Wisconsinan glaciation of New England. A symposium: Dubuque, Iowa, Kendall/Hunt Publishing Company, 242 p. (Symposium held at Northeastern section of Geological Society of America, 13 March 1980, Philadelphia, Pennsylvania.)

Sirkin, L. A., 1986, Pleistocene stratigraphy of Long Island, New York, p. 6-21 in Cadwell, D. H., ed., The Wisconsinan Stage of the First Geological District, eastern New York: New York State Museum Bulletin 455, 191 p.

Sirkin, L. A., 1991, Stratigraphy of the Long Island platform, p. 217-227 in Gayes, P., Lewis, R. S., and Bokuniewicz, H. J., eds., Quaternary geology of Long Island Sound: Journal of Coastal Research, Walter Newman Memorial volume, Special Issue No. 11, 215 p.

Sirkin, L. A., 1994, Geology of the Long Island platform (extended abstract), p. 137-139 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Sirkin, L. A., and Mills, H. C., 1975, Wisconsinan glacial stratigraphy and structure of northwestern Long Island, Trip B5, p. 299-327 in Wolff, M. P., ed., Guidebook to Field Excursions: New York State Geological Association, Annual Meeting, 47th, Hofstra University, Hempstead, New York: Hempstead, N.Y., Hofstra University, Department of Geology, 327 p.

Sirkin, L. A.; and Stuckenrath, R., 1980, The Portwashingtonian warm interval in the northern Atlantic coastal plain: Geological Society of America Bulletin, v. 91, p. 332-336.

Soren, Julian, 1988, Geologic (sic) and geohydrologic reconnaissance of Staten Island, New York: United States Geological Survey Water Resources Investigations Report 87-4048, 22 p.

Stone, B. D.; and Borns, H. W., Jr., 1986, Pleistocene glacial (sic) and interglaical stratigraphy of New England, Long Island and adjacent Georges Bank and Gulf of Maine: Quaternary Science Reviews, v. 5, p. 39-52.

Upham, Warren, 1879, Terminal moraines of the North American ice sheet: American Journal of Science, 3rd series, v. 18, p. 81-92, 179-209.

Upson, J. E., 1968, Is the Gardiners Clay the Gardiners Clay? Notes on the Gardiners Clay in a portion of eastern Long Island, New York (abstract): Geological Society of America Special Paper 101, p. 281 (only).

Upson, J. E., 1970, The Gardiners Clay of Long Island, New York--a reexamination: United States Geological Survey Professional Paper 700-B, p. B157-B160.

Wehmiller, J. F., Belknap, D. F., Boutin, B. S., Mirecki, J. E., Rahaim, S. D., and York, L. L., 1988, A review of aminostratigraphy of Quaternary mollusks from United States Atlantic Coastal Plain sites, p. 82-84 in Geological Society of America Special Paper 227.

Widmer, Kemble, 1964, The geology (sic) and geography of New Jersey: The New Jersey Historical Series, v. 19: Princeton-New York-Toronto-London, D. Van Nostrand Company, Inc., 193 p.

Wolff, M. P., Sichko, M. J., and Liebling, R. S., 1987, Concepts of physical geology. An illustrated overview: Dubuque, IA, Kendall/Hunt Publishing Company, 134 p.

Woodworth, J. B., 1897, Unconformities on Marthas Vineyard and Block Island: Geological Society of America Bulletin, v. 8, p. 204-211.

Woodworth, J. B., 1901, Pleistocene geology of portions of Nassau County and Borough of Queens (N.Y.): New York State Museum Bulletin 48, p. 618-670. (Includes colored geologic map on scale of 1:62,500.)

Zen, E-An; and Mamay, S. H., 1968, Middle Pennsylvanian plant fossils: problematic occurrence in the Bronx: Science, v. 161, p. 157-158.