

The Narrows Flood – Post-Woodfordian Meltwater Breach of the Narrows Channel, NYC

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Introduction

Subsurface information compiled from multiple sources indicates that two tills, outwash fans, and varved lake strata form a continuous blanket of regolith in the NY Harbor area and support a multi-glacier hypothesis for the region. Varved lake clays provide evidence that the Harbor Hill Moraine acted as a dam, impounding glacial lakes in the Hudson Valley. Investigations specific to the Narrows provide the tantalizing interpretation that an episodic breach took place through the Harbor Hill Moraine that drained the meltwater lakes and eroded the Narrows Channel. Such an event would have redirected the flow of the Hudson River across the Upper New York Bay into its modern course.

The Harbor Hill Moraine forms an impressive regional topographic element that extends from Long Island to Staten Island on westward into the New Jersey lowlands. Situated above the buried edge of the eroded Cretaceous coastal plain strata, the reddish-brown Harbor Hill is the younger of two major till units recognized in the NYC area. An older, brownish till, is presumed to be the Ronkonkoma Moraine but it may be entirely older. Regionally, the Harbor Hill Moraine is associated with extensive deposits of outwash and varved lake strata and truncates the older Ronkonkoma Moraine south of the Manhasset Peninsula near Roslyn Heights, Long Island (Figure 1). A decade of joint investigations of Pleistocene stratigraphic facies and superposed glacial flow indicators including the vergence of deformed drift, indicator stones, roche moutonnée structure, striae, and chattermarks (Sanders and Merguerian 1991a, b; 1992, 1994a, b; 1995, 1996, 1998; Sanders, Merguerian and Mills 1993; and Merguerian and Sanders, 1996) have concluded that the Harbor Hill was pre-Woodfordian in age, the result of regional glacial ice flow from the NNW to the SSE. These studies also suggested that the Ronkonkoma till overlies older glacial deposits from two contrasting flow directions.

Geology of the NY Harbor Area

New York Harbor sits at the convergence of numerous through-going geological provinces. The crystalline bedrock of NYC extends southward from New England and underlies the entire region. (See Figure 1.) Bedrock units include Proterozoic to Paleozoic gneiss, schist, amphibolite, marble, quartzite, pegmatite, and serpentinite. The bedrock sequence is overlain by tilted Mesozoic sedimentary and intercalated mafic igneous rocks of the Newark Supergroup in New Jersey and in smaller exposures in western Staten Island. The nonconformity near the base of the Palisades intrusive sheet is exposed in places but is largely buried at the base of the Hudson channel (Figure 2). The modern Hudson River follows this strike valley from Peekskill southward along its lower course but flowed far to the west in ancestral times.

Younger sediment cover in New York City consists of blankets of Cretaceous sand and clay and Quaternary strata. The Cretaceous was deposited above a planation surface (Fall Zone

Penneplain) that formed sometime after the mid-Jurassic and covered broad areas of NJ and southeastern NY including all of Long Island. Post-Cretaceous regional uplift, tilting, and erosion produced a cuesta of Cretaceous strata that eventually retreated southeastward toward the present shoreline (Figure 3). Cretaceous strata are found in central New Jersey, southwestern Staten Island, and in an arcuate subsurface belt through the Narrows into southwestern Brooklyn, northern Queens, and Long Island. Cretaceous strata are largely missing to the north of the Harbor Hill Moraine with the exception of displaced slabs of Cretaceous and Pleistocene in Port Washington (Mills and Wells, 1974) and southwestern Staten Island (Sanders, Merguerian, and Okulewicz, 1995).

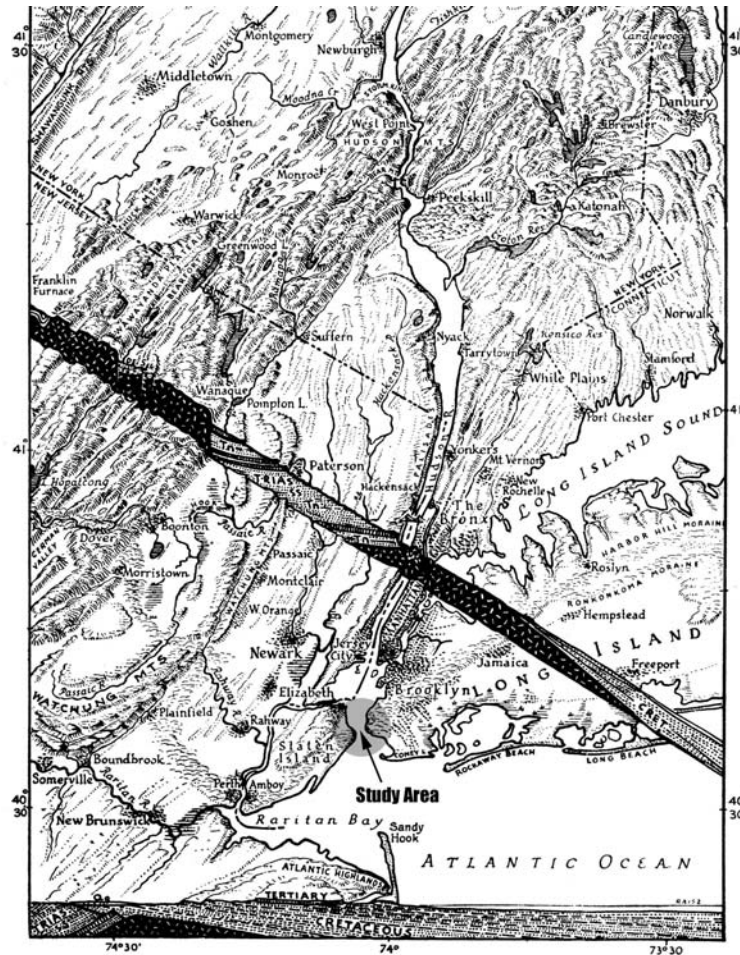


Figure 1 - Physiographic map of New York City and vicinity with two cut-away vertical slices to show the geologic structure. (E. Raisz.) Study area of the Narrows breach is shown with shaded circle.

Drainage History of NYC

Merrill (1891a, b; 1899), Kemp (1897), Merrill et al. (1902), Berkey (1906, 1910, 1911), Veatch (1906), and Fuller (1914), have shown the complexities of the Pleistocene and post-Cretaceous drainage patterns in NYC. Lovegreen (1974), Sanders (1974), and Binder (1975) revitalized the discussion of buried valleys in the NYC area. Today, the Narrows provides a

ready channel for the Hudson River to flow into the Atlantic Ocean but new subsurface data (this report) indicates that the Narrows Channel was blocked for long periods of time by glacial drift.

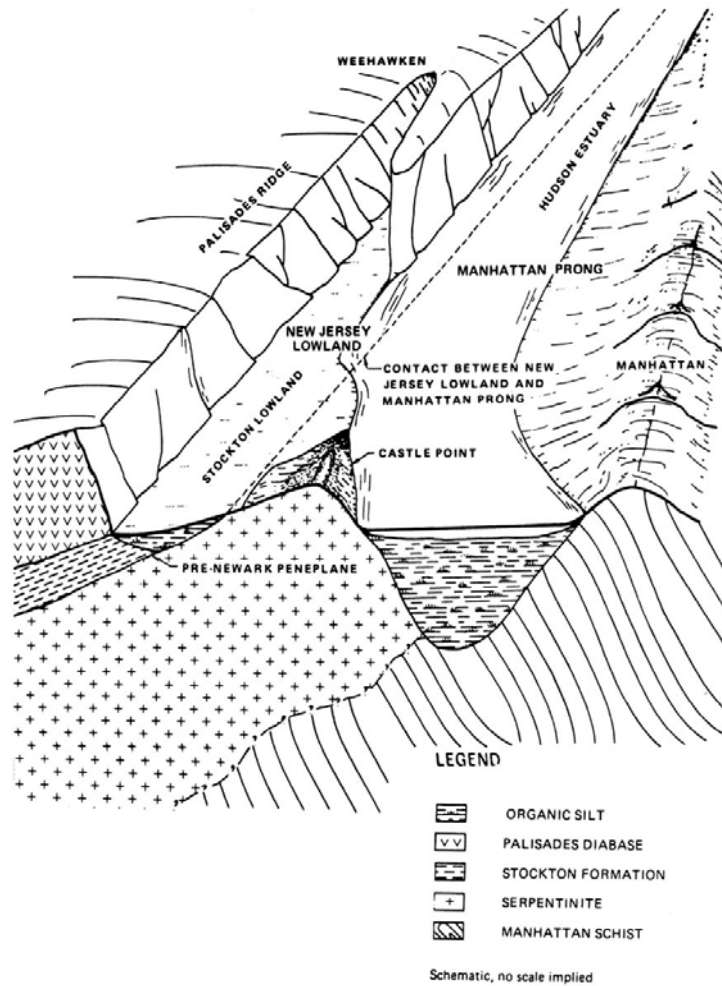


Figure 2 – Sketchmap showing the former stream-capture area of the lower Hudson River and the WSW “fossil” valley of the Hudson River. (From Lovegreen, 1974, Figure 3.)

The drainage history of the New York City region can be traced back roughly 200 Ma to a period when river systems drained from uplifted highland blocks and infilled the Newark Basin. Destruction of this ancient river system took place during mid-Jurassic tectonism. During the Early to Mid-Cretaceous a new river system was established that culminated in the production of the Fall Zone erosion surface. These rivers were buried during the Late Cretaceous when a high stand of sea level deposited Cretaceous sediment well inboard of the present shoreline. The lack of red-color in the Cretaceous sediment indicates that the Newark Basin strata were completely covered during this interval (Sanders, 1996). Indeed, Cretaceous coastal-plain strata covered much of what is now exposed land in southeastern New York. The Cretaceous shoreline may have paralleled the Ramapo Fault (the basin-marginal fault of the Newark Basin half-graben) or overstepped the beveled Proterozoic completely.

Marine conditions prevailed until Miocene times when domal uplift of the Appalachians pushed back the edge of the sea. During this interval the flow of the ancestral Hudson River was in the Hackensack Meadow of New Jersey (Figure 3). Confined by the coastal-plain cuesta as it flowed through the Sparkill Gap into the Triassic lowlands past the Millburn Gaps and through gaps in the Watchung basalt ridges, the Hudson then emptied to the south of Staten Island as the Raritan River (Johnson, 1931, 1933).

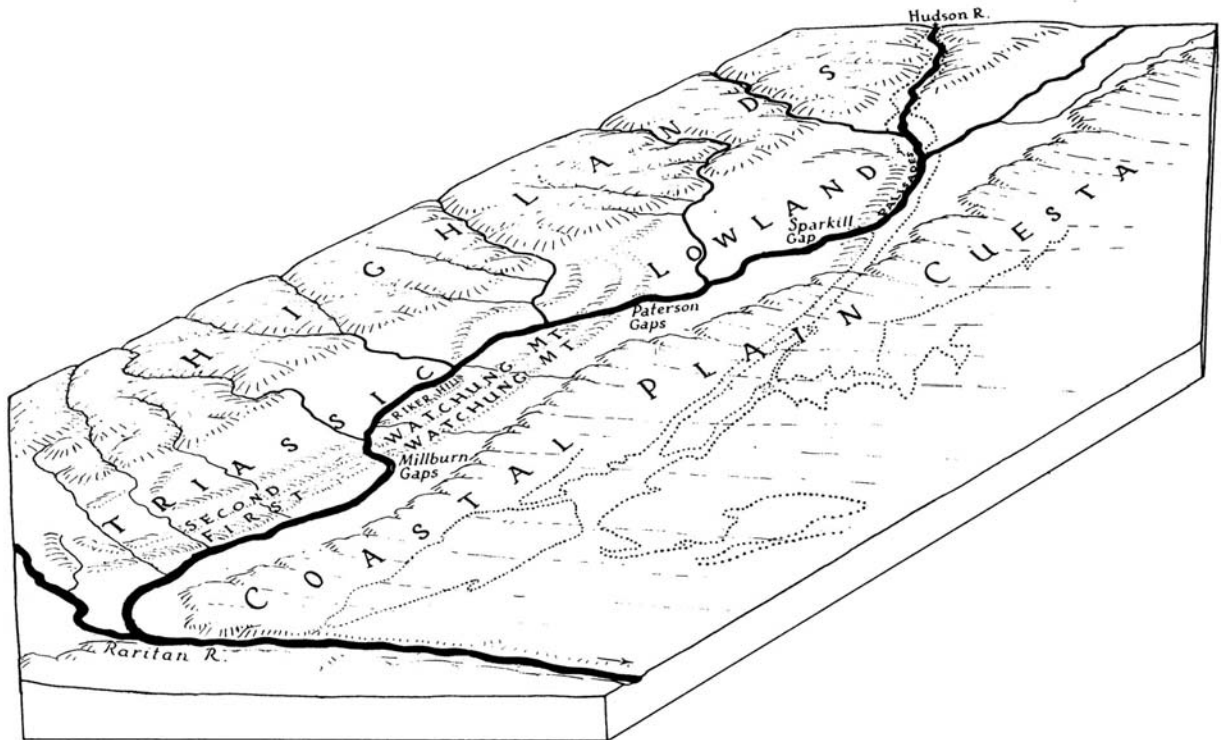


Figure 3 – Block diagram showing Johnson’s (1931) concept about the blockage of the ancestral Hudson River by the inner coastal-plain cuesta and its superposition across the Watchung basalt ridges. This scenario must have taken place during the Miocene or Pliocene, not the Cretaceous as Johnson had suggested.

A Pliocene episode of extensive and rapid uplift of New England and deep erosion of major river valleys (such as the Hudson and Sound rivers) sculpted the modern drainage pattern of the NYC area. Today, the Hudson River empties from a v-shaped gorge that follows the nonconformity at the base of the Newark Group and then crosses the Upper Bay to flow into the Atlantic Ocean through the Narrows. (See Figures 1 and 2.) In doing so, the river makes a sharp 15° bend from its ancient course (N15°E - S15°W) along a ready-made strike valley to a new N-S course. The N15°E - S15°W fossil valley continues to the SSW and eventually passes beneath the coastal-plain Cretaceous on Staten Island. Thus, the ancestry of the Hudson River strike-valley channel must be pre-Cretaceous (Lovegreen, 1974; Figure 19, p. 148). The course of the Hudson through the Narrows began in the Pliocene but was subsequently blocked by over 200’ of Pleistocene glacial drift.

Pleistocene History of NYC

During the Pleistocene Epoch, the NY Harbor area was the terminus for numerous episodes of Pleistocene continental glaciation. The Harbor Hill Moraine was the product of a pre-Woodfordian glacier (Glacier II in Table 1). Bennington (2003, this volume) offers convincing geomorphologic evidence that the Harbor Hill Moraine truncates the older Ronkonkoma Moraine (Glacier III) near Roslyn Heights, Long Island. The multitude of glaciations from the NNW and NNE flow directions (Table 1) and some degree of ice-front deformation, overthrusting, and imbrication of units (including the underlying Cretaceous) has created a Pleistocene sequence with complex internal stratigraphy and structure. The Harbor Hill moraine ridge should be considered a tectonostratigraphic unit in that it exhibits folding and imbrication of Pleistocene and Cretaceous units.

Three major soft-sediment units potentially constitute the regolith in the vicinity of the Narrows study area. From the top down these include a near continuous blanket of Holocene organic silt and anthropogenic fill followed by Pleistocene glacial strata and local Cretaceous coastal-plain strata. Local stratigraphic assemblages include glacial drift disconformably overlying older drift or Cretaceous coastal-plain strata. In some areas Pleistocene or Cretaceous are found to rest on weathered bedrock and in other places scoured “fresh” bedrock underlies these or younger deposits. In the Narrows channel, the typical stratigraphy (Pleistocene on Cretaceous) is absent. Instead, Holocene river silt rests on fresh, scoured bedrock.

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

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

Borings Across Upper New York Bay

Over the years, numerous construction efforts have provided abundant subsurface information in the NY Harbor area (Figure 4). Taken together, the sections indicate that the Upper New York Bay has been strongly modified by the combined actions of glacial ice and running water.

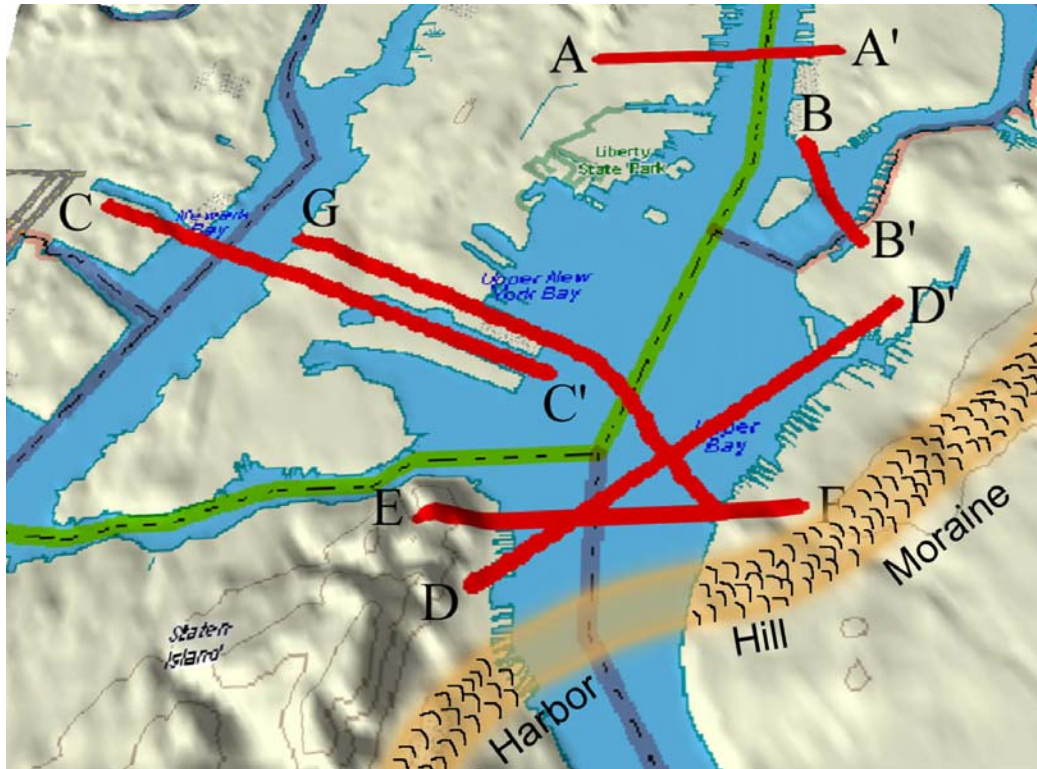


Figure 4 – Index map of Upper New York Bay showing the location of the Harbor Hill Moraine and positions of published and unpublished profile sections discussed below. A-A' and C-C' from Lovegreen (1974), B-B' from Berkey (1948), D-D' from Fluhr (1962), and E-F-G from proprietary sources.

Section A-A' (Figure 5) shows the truncation of Pleistocene lake strata (v) and outwash (o) by a thick sequence of Holocene organic silt and sand of the modern Hudson River. Deep incision of the Hudson channel here places Holocene organic silt above the nonconformity at the base of the Newark Supergroup. Although this strike channel predates the Pleistocene (See Figure 2.), truncation of glacial strata indicates rejuvenated downcutting after abandonment of the older Hudson channel to the west of Staten Island. This pre-Pleistocene fossil channel is seen in Section C-C' (Figure 6) where it is filled by a sequence of brown till (t), outwash (o), and varved lake strata (v). These units are all overlain by Holocene organic silt of the Hudson estuary.

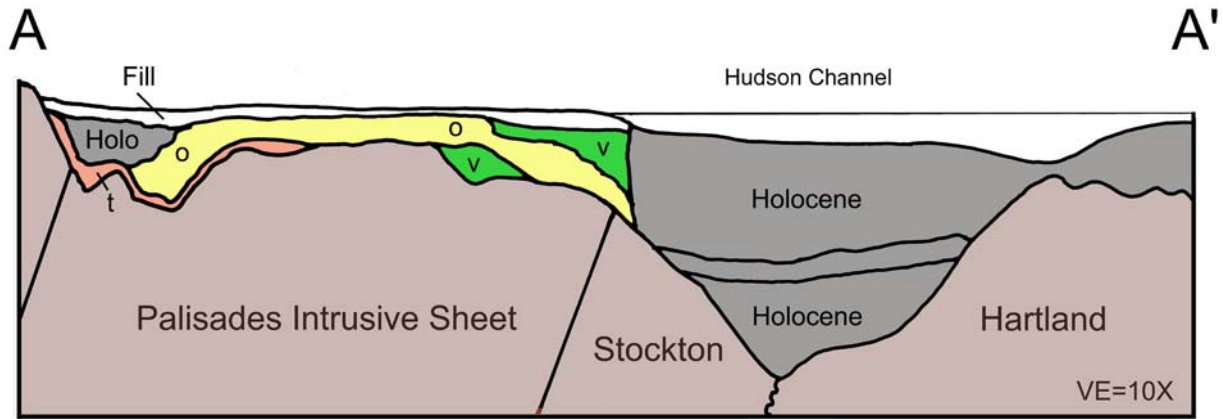


Figure 5 – Profile section across lower Hudson valley showing deep incision into bedrock above basal Newark unconformity and truncation of glacial till (t), outwash (o), and varved lake strata (v) by Holocene strata of the Hudson River. Modern fill (post-Holocene) is unshaded. Refer to Figure 4 for section location. (Adapted from Lovegreen, 1974, Figure 8, VE = 10X.)

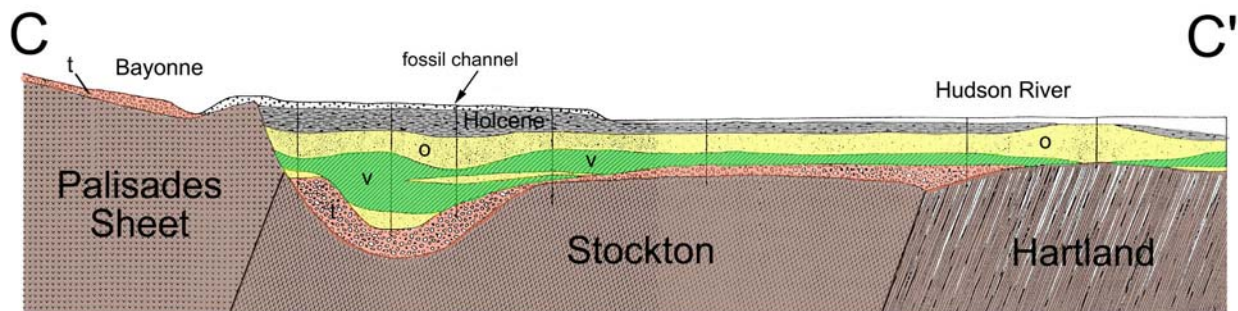


Figure 6 – Profile from borings from Bayonne New Jersey into the Hudson Estuary showing the fossil channel of the Hudson and overlying till (t), varved lake sediment (v), outwash (o), and Holocene silt. Refer to Figure 4 for location of section. (Adapted from Lovegreen, 1974, Figure 7, VE = 10X.)

Berkey's (1948) profiles utilized borings made for the east and west tunnel lines of the Brooklyn Battery Tunnel (Section B-B' in Figure 4). Portions of these are shown in Figure 7. Here bedrock of the Paleozoic Hartland Formation gives way to the Brooklyn Injection Gneiss (B.I.G.), a unit now correlated with the Proterozoic Queens Tunnel Complex or Fordham Gneiss (Brock, Brock, and Merguerian, 2001). The bedrock is overlain by the discontinuous Gardiners Clay (g), an interglacial marine unit of the *Yarmouthian* interval. (See Table 1.) On the Brooklyn side of the channel the Gardiners is overlain by over 150' of stratified glacial strata (o) and intervening varved lake sediment (v). The profile extends northwestward to Governor's Island and shows that the stratified drift and varved lake strata interfinger with and overlie a brown till (tl = Ronkonkoma). Also present is an upper reddish-brown till (tu = Harbor Hill) with intervening outwash. Berkey (1948) provides evidence for a pre-Ronkonkoma glaciation as he shows pre-Gardiners till in his extended profiles.

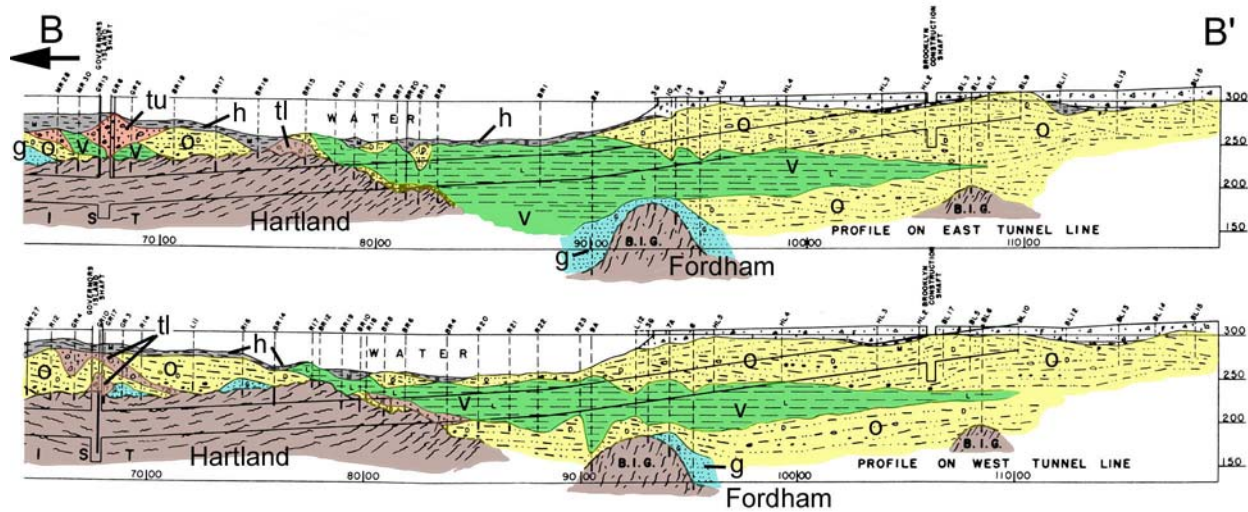


Figure 7 – Profile sections across the SE half of the Brooklyn Battery Tunnel showing stratified drift units (o) and an intervening lake sequence (v) resting above the pre-Ronkonkoma (Yarmouthian) Gardiners Clay unit (g). The Gardiners rests nonconformably above Brooklyn Injection Gneiss (B.I.G.) and the Hartland Formation. Two tills are shown above the Gardiners Clay – an upper till (tu = Harbor Hill Moraine) and a lower till (tl = Ronkonkoma Moraine). On the far right hand side of the upper section (east tunnel line) a pre-Ronkonkoma till occurs beneath the Gardiners Clay (Till IV or V in Table 1). See Figure 4 for section line. (Adapted from Berkey, 1948, Plate 2.)

Section D-D' (Figure 8) is from the Richmond Aqueduct Tunnel and shows the flat scoured bottom of the Hudson River and the Holocene sediment (soil) that rests above. Fluhr (1962) indicated that the Hudson River has a flat bottom in the Upper Bay, that he suggested was the result of a thin ice sheet and the inability of the ice to flow unencumbered in a southeastward direction.

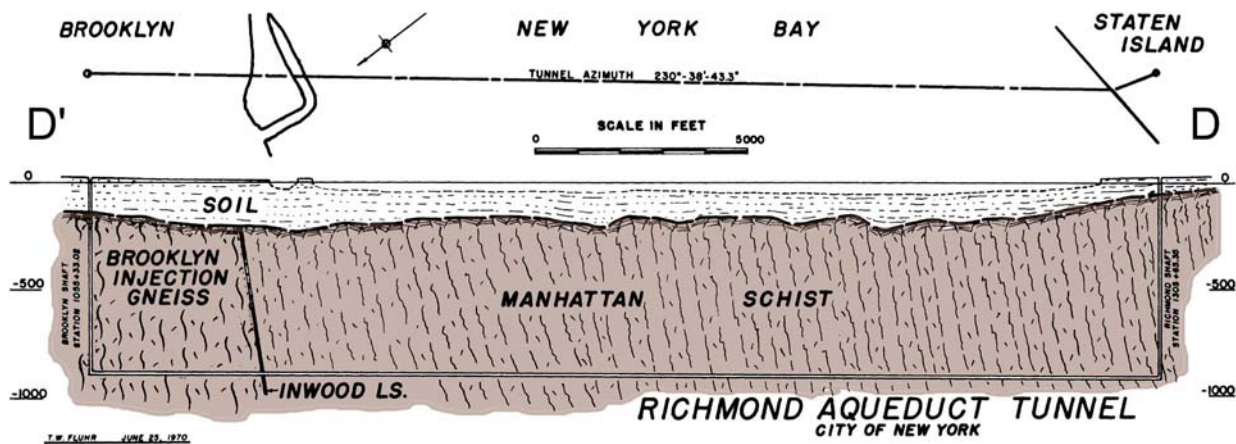


Figure 8 - The bedrock surface of the Upper New York Bay is shallow and quite flat according to Fluhr (1962), varying from 132' to 203' below the water surface.

Recent borings from Brooklyn across the Upper New York Bay to Staten Island and New Jersey have been interpreted by the geotechnical staff of Mueser Rutledge Consulting Engineers. I have redrafted their work as a fence diagram in Figure 9 (Section E-F-G). Both sections show clearly that two tills (tl = Ronkonkoma and tu = Harbor Hill) and intervening outwash (o) and lake strata (v) extend onto either side of the Hudson channel. Thus, behind the Harbor Hill Moraine (See Figure 4) a continuous blanket of Pleistocene drift once covered the NY Harbor area. The difference in bottom morphology (compare Sections D-D' and F-G to E-F) is striking. Deep incision of the Narrows channel adjacent to Staten Island is indicated, by comparison to the flatter rock floor of the Upper New York Bay.

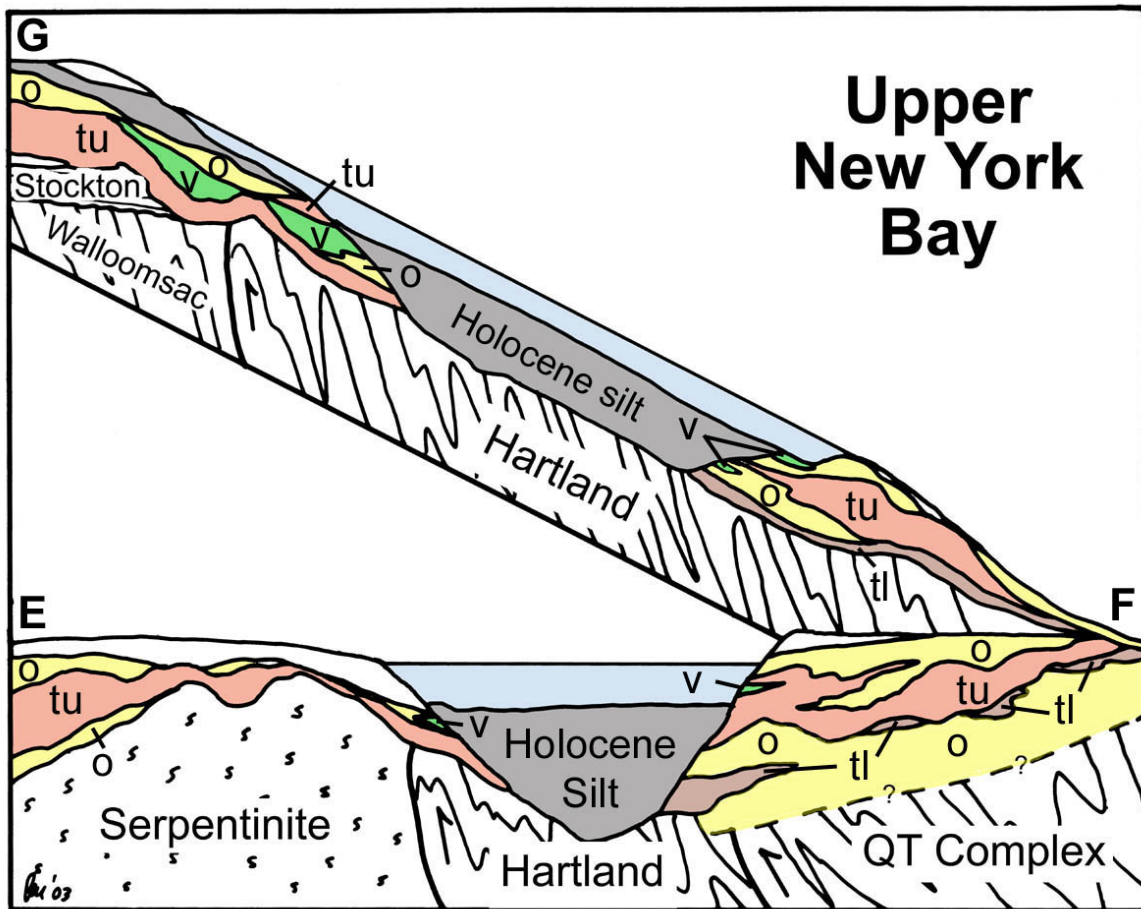


Figure 9 – Diagrammatic fence diagram of Upper New York Bay compiled from subsurface data showing truncation of two tills [tu = Harbor Hill Moraine; tl = Ronkonkoma Moraine] on either side of the Hudson Channel. The patchy, discontinuous nature of the Ronkonkoma suggests that Harbor Hill ice eroded and modified the area. Note the flatter bottom profile in comparing section F-G to E-F, where nearly 200' of interlayered Pleistocene strata are truncated against the valley walls by Holocene silt. They have been replaced by 160' of Holocene organic silt and sand. Of additional interest to card-carrying structural geologists, a tectonic contact between the Hartland and Wallomsac formations is indicated by study of the hard rock borings near the section end at G. (Adapted from proprietary data sources, courtesy Mueser Rutledge Consulting Engineers.)

The subsurface borings across to Staten Island (Section E-F) provide evidence that nearly 200' of interlayered glacial drift have been cut from the Narrows channel in latest Pleistocene time. Over 120' of modern organic river silt and interbedded sand now rests directly on both weathered and fresh Paleozoic bedrock of the Hartland and Walloomsac Formations in the Narrows channel. (Based on January 2003 examination of borings into bedrock.) The truncation of Pleistocene strata on the sides of the Narrows channel between Brooklyn and Staten Island and the removal of intervening Pleistocene strata (including the Harbor Hill and remnant Ronkonkoma moraines and surrounding Pleistocene strata) points to a possible catastrophic cause. The possibility that the gorge was produced by a Woodfordian ice surge is not in keeping with the facts as no Woodfordian deposits are found to overlie the Harbor Hill sequence of till, outwash, and varved lake strata.

A Tale of Two Tills and Other Implications

The compilation of subsurface borings across the Upper New York Bay indicate the presence of two major till units (Harbor Hill and older Ronkonkoma) and intervening Pleistocene drift strata. Thus, the Pleistocene stratigraphy displayed in the subsurface borings supports a multi-glacier hypothesis and offers some new insights into the Pleistocene and Holocene history of the region. Laterally extensive varved lacustrine strata interfinger with and locally overlie the Harbor Hill Moraine, indicating that extensive lakes covered the region during periods of glacial meltback. (See Figures 5, 6, 7, and 9.) Lacking in the profiles is drift from the Woodfordian glacier (Glacier I in Table 1). In the view of Sanders and Merguerian (1995, 1998) Woodfordian glaciation was a non-event in the NYC area. Not much in the way of post-Harbor Hill (Glacier II in Table 1) strata are found with the exception of local thin till and loess on the exposed cliffs of Nassau County, Long Island. The Woodfordian glacier may have never descended south of the Connecticut shore (Hamden Till) with the exception of localized valley glaciation (e.g. – Hudson valley and Hackensack Meadow). Younger, Woodfordian glacial meltback may have refilled the pre-Woodfordian lakes with the existing Harbor Hill Moraine still acting as a topographic barrier. Thus, the Harbor Hill Moraine may have twice acted as a dam for the buildup of glacial meltwater lakes.

The Harbor Hill moraine evidently dammed the ancient Hudson River in the Late Pleistocene and ultimately led to the development of Glacial Lake Albany. Episodic downcutting of the Narrows may have occurred during a raging torrent of water that drained Glacial Lake Albany through the Narrows less than 12,000 to 13,000 years ago. The drainage of Glacial Lake Albany through the Narrows would have torn through the stacked Pleistocene strata (including the Harbor Hill and remnant Ronkonkoma moraines) and scoured the channel to fresh bedrock. Running water may have created the Hudson submarine canyon on what was then an exposed continental margin platform. After the drainage, rising water of the modern ocean submerged low-lying areas and has created the Hudson estuary. The constriction of flood water through the Narrows resulted in major downcutting and the formation of a steep gorge in that area by comparison to profiles in the wider areas of New York Bay to the north (Sections D-D' and F-G) and across the Verrazano-Narrows Bridge alignment to the south (Fluhr, 1969).

Of additional interest, the position of the Cretaceous coastal plain cuesta may have figured into the Pleistocene history of the region. Subsurface data of Suter et al. (1949) and engineering drawings for the Whitestone and Throgs Neck bridges (Fluhr, 1969) and for the Brooklyn and Queens Tunnel segments of City Water Tunnel #3 (Fluhr and Terenzio, 1984) accurately identify the buried edge of the Cretaceous. The edge of the Cretaceous coincides exactly with the position of the Harbor Hill Moraine. Thus, it would appear that the former cuesta of the Cretaceous had a controlling influence on the terminal position of the Harbor Hill Moraine. The juxtaposition of the ice front caused imbrication of Pleistocene and Cretaceous strata within the Harbor Hill Moraine.

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REFERENCES CITED

Berkey, C. P., 1906, Notes on the preglacial channels of the lower Hudson Valley as revealed by recent borings (abs.): Science, new series, v. 24, p. 691.

Berkey, C. P., 1910, Areal 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., 1911, Geology of the New York City (Catskill) aqueduct: New York State Museum Bulletin 146, 283 p.

Berkey, C. P., 1948, Engineering geology in New York City, Excursion No. 4, p. 51-66 in Creagh, Agnes, *ed.*, Guidebook of Excursions: Geological Society of America Annual Meeting, 61st, New York City, 135 p.

Binder, Louis, 1975, New York City, a buried channeled scabland area: The Municipal Engineers Journal, p. 151-157.

Brock, Pamela Chase; Brock, Patrick W. G.; and Merguerian, Charles, 2001, The Queens Tunnel Complex: a newly discovered granulite facies Fordham orthogneiss complex that dominates the subsurface of western Queens: p. 1-8 in Hanson, G. N., *chm.*, Eighth Annual Conference on Geology of Long Island and metropolitan New York, 21 April 2001, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 128 p.

Fluhr, T. W., 1962, New York Bay-bedrock profile: Geological Society of America Bulletin, v. 73, p. 261-262.

- Fluhr, T. W., 1969, Recent engineering data on the New York City Group of formations, p. 1-11 *in* Alexandrov, E. A., *ed.*, 1969, Symposium on the New York City Group of Formations: New York State Geological Association Annual Meeting, 40th, Flushing, New York: Flushing, NY, Queens College Department of Geology Geological Bulletin 3, Queens College Press, 83 p.
- Fluhr, T. W., and Terenzio, C. G., 1984, Engineering geology of the New York City water supply system: Albany, NY, New York State Museum and Science Service Geological Survey Open-File Report 05.08.001, 183 p.
- Johnson, D. W., 1931, A theory of Appalachian geomorphic evolution: *Journal of Geology*, v. 39, no. 16, p. 497-508.
- Johnson, D. W., 1933, Geomorphology of the central Appalachians: International Geological Congress, 16th, United States, Guidebook 7, Excursion 7A, 50 p.
- Lovegreen, J. R., 1974, Paleodrainage history of the Hudson Estuary: New York, NY, Columbia University Department of Geological Sciences Master's Thesis, 151 p., 8 pl.
- Merguerian, Charles; and Sanders, J. E., 1996, Glacial geology of Long Island: Guidebook for On-The-Rocks 1996 Fieldtrip Series, Trip 39, 01 + 02 June 1996, Section of Geological Sciences, New York Academy of Sciences, 130 p.
- Merrill, F. J. H., 1891a, Quaternary geology of the Hudson Valley: *New York State Geologist Annual Report*, v. 10, p. 103-109.
- Merrill, F. J. H., 1891b, On the postglacial history of the Hudson River valley: *American Journal of Science*, 3rd series, v. 41, p. 460-466.
- Merrill, F. J. H., 1899, Origin of the white (*sic*) and variegated clays of the north shore of Long Island: *New York Academy of Sciences Annals*, v. 12, p. 113-116.
- 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 1:62,500).
- 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.
- 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., 1996, Drainage history of the New York City region, p. 147-158 *in* Hanson, G. H., *ed.*, *Geology of Long Island and Metropolitan New York Program with Abstracts*: Stony Brook, NY, Long Island Geologists, 177 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 SSW and NW to SE): *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: *Geological Society of America Abstracts with Programs*, v. 24, no. 1, p. 72.

Sanders, J. E.; and Merguerian, Charles, 1994a, Fitting newly discovered north-shore Gilbert-type lacustrine deltas into a revised Pleistocene chronology of Long Island, 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.; and Merguerian, Charles, 1994b, Glacial geology of the New York City region, p. 93-200 *in* Benimoff, A. I., *ed.*, The geology of Staten Island, New York: Geological Association of New Jersey Annual Meeting, 11th, Somerset, NJ, 14-15 October 1994, Field guide and proceedings, 296 p.

Sanders, J. E. and Merguerian, Charles, 1995, Evidence for pre-Woodfordian ages of Long Island's terminal moraines, p. 91-106 *in* Hanson, G. N., *chm.*, Geology of Long Island and metropolitan New York, 22 April 1995, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 135 p.

Sanders, J. E.; and Merguerian, Charles, 1996, Trip 39: Glacial geology of Long Island, 01-02 June 1996 (revision of Trip 15, 17-18 November 1990): New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 129 p.

Sanders, John E., and Merguerian, Charles, 1998, Classification of Pleistocene deposits, New York City and vicinity – Fuller (1914) revived and revised: p. 130-143 *in* Hanson, G. N., *chm.*, Geology of Long Island and Metropolitan New York, 18 April 1998, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 161 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: Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A-308.

Sanders, J. E.; Merguerian, Charles; and Okulewicz, S. C., 1995, Recumbent fold in displaced slab of Upper Cretaceous sediments, Princes Bay, Staten Island, New York: Further evidence that ice flowing southeastward deposited the Harbor Hill Moraine, p. 107-117 *in* Hanson, G. N., *chm.*, Geology of Long Island and metropolitan New York, 22 April 1995, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 135 p.

Suter, Russell; de Laguna, W.; and Perlmutter, N. M., 1949, Mapping of geologic formations and aquifers of Long Island, New York: New York State Department of Conservation Water Power and Control Commission Bulletin GW-18, 212 p.

Veatch, A. C., 1906, Outlines of the geology of Long Island, Chapter 1, p. 15-85 *in* Veatch, A. C.; Schlichter, C. A., Bowman, Isiah, Crosby, W. O.; and Horton, R. E., 1906, Underground water (*sic*) resources of Long Island, New York: United States Geological Survey Professional Paper 44, 394 p.