Evidence for Multiple Glacial Advances and Ice Loading From a Buried Valley in Southern Manhattan

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INTRODUCTION

Our field and subsurface studies of glacial strata from construction sites and borings indicate that the glacial history of the New York City area is complex. The Ronkonkoma and Harbor Hill terminal moraines are evidence that the area has experienced more than one glacial advance. There is more to the story, however, than simply ice advance, retreat, repeat. Many locations in New York City display seemingly simple stratigraphy, such as thick layers of till over bedrock or 100' of outwash sands. Most sites aren't as obviously complex as one offering multiple tills intercalated with outwash and varved strata. When characteristics other than soil type are taken into consideration, however, stratigraphic differences sometimes appear. A change in color or mineralogy, for instance, might indicate ice coming from another direction. A change in engineering properties can also contribute to the art of unraveling glacial history.

A site in lower Manhattan near the Brooklyn Bridge occupies a bedrock valley filled with a variety of interlayered glacial drift. These varied strata mandate that multiple waves of ice have passed over the area. Changes in the compactness of the soil with depth, as measured by the Standard Penetration Test, provide additional evidence of ice loading. This paper will demonstrate that patterns in strata and SPT values can be used to determine which layers at a site have been ice loaded. Emerging from our study of recent excavations in southern Manhattan, stratigraphic and engineering studies indicate that the multi-glacier hypothesis of Sanders and Merguerian (1998) can be applied as a viable model for New York City and vicinity.

DRILLING PROCEDURE AND N-VALUE

When geotechnical borings are made, a standard procedure is commonly followed (ASTM D 1586-99). The borehole is drilled out to a chosen sample depth. A standard 2 inch outer diameter split-spoon sampler is attached to the drill rods and lowered to the bottom of the hole. A 140 pound hammer is dropped a height of 30 inches onto the rods/sampler assembly (Figure 1). The number of hammer blows needed to drive the sampler in 6 inch increments for a total of 18 or 24 inches is counted. The sampling technique is known as the Standard Penetration Test and the sum of the blows between the 6 inch and 18 inch interval is the Standard Penetration Resistance (N-value). The soil recovered in the sampler is described and retained for testing.

WHAT N-VALUES MEAN

The N-value can be used to estimate many different characteristics of the soil (Terzaghi, Peck, and Mesri, 1996). It predicts the relative density of cohesionless soils such as sand and reflects the consistency, and to some extent the strength, of cohesive soils such as clay. Low blow counts suggest that the soil is loose, or soft, or disturbed. Typical examples would be soft organic clays or poorly placed fill materials. High blow count values indicate that the soil is dense, stiff, or cemented. This would be the case with compacted fills or soils that previously have had heavy loads placed upon them. If the soil contains very coarse-grained sediments such as gravel or cobbles, the sampler may be too small to penetrate through the material, also resulting in high values (Figure 2). A change in the blow counts often indicates a change in the stratum. With correlations and calculations, N-values can be used to estimate values such as angle of internal friction, shear strength, and bearing capacity. The values are commonly analyzed to determine a soil's potential for liquefaction.
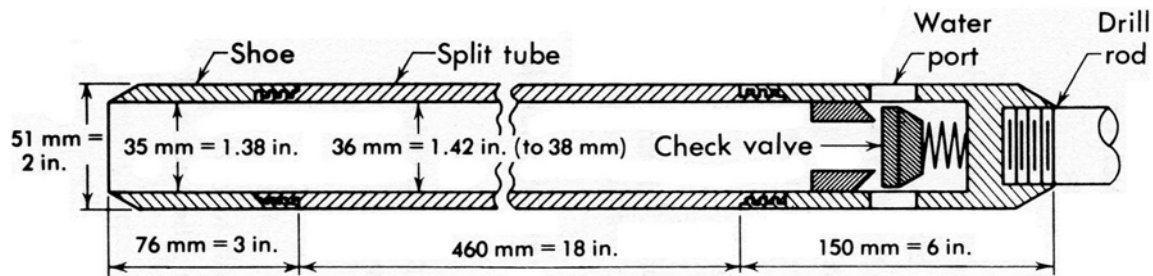
Figure 1. Diagram of a typical split-spoon sampler used for a standard penetration test (Sowers, 1979).

VARIABLES THAT CAN AFFECT N-VALUES

The SPT procedure has been standardized (ASTM D 1586-99), but there are many variables that can affect the N-values obtained during the drilling process. In the same soil, using different drilling equipment can produce dissimilar results. Variations in technique are used by different drillers and even used by the same driller at different times. A large chunk of gravel or a boulder blocking the opening of the sampler can give erroneously high blow counts. Improper drilling procedures can disturb the soil, resulting in abnormally low values. Despite these issues, N-values are relied upon as an indicator of the strength of subsurface soil horizons and, like other engineering tests such as consolidation tests (Moss and Merguerian, 2005), can provide an insight into the loading history of buried strata.

NYC GLACIAL SUMMARY

The bedrock of New York City and vicinity has been greatly modified by the effects of glaciation in the form of glacial erosion (glacial polish, striae, grooves,

crescentic marks, and roche-moutonée structure) and the deposition of glacial deposits (till, outwash, varved strata, etc.). Based on over a decade of study five separate glacial episodes are now recognized (Table 1) based on superposition and cross-cutting relationships (Sanders and Merguerian, 1991, 1994a, 1994b, 1995, 1998; Sanders, Merguerian, and Okulewicz, 1995; and Merguerian and Sanders, 1996).
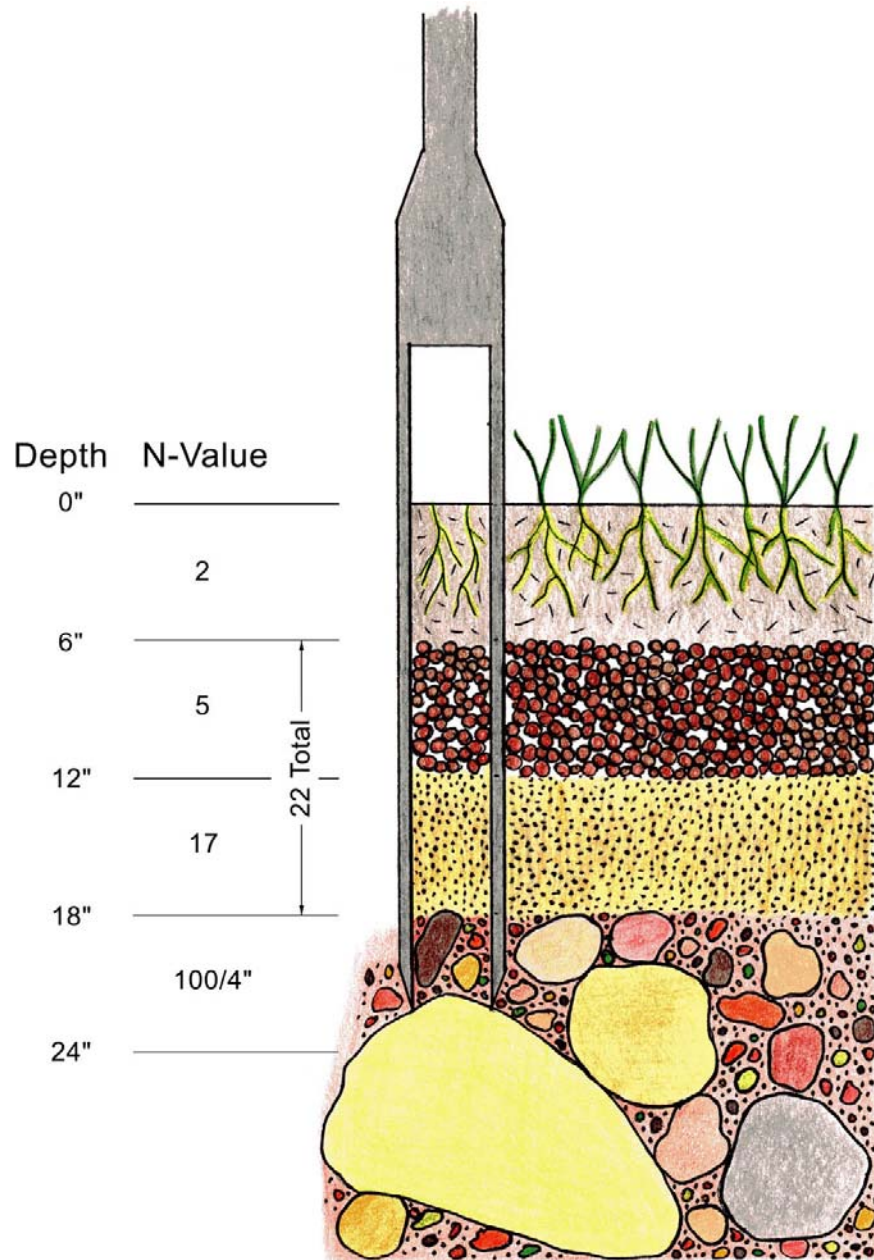

Figure 2. During sampling the blow counts can reflect the nature of the soil penetrated, and changes in N-values can indicate changes in strata. It took only 2 blows to drive the sampler 6 inches through soft organic topsoil, and 5 blows to penetrate loosely packed coarse sand. 17 blows were needed to advance the spoon another 6 inches through densely packed fine-grained soil. In a dense, gravelly till it took 100 blows to move the sampler only 4 inches before hitting refusal against a cobble. N-value = 22 for this test.

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

Table 1. Sanders and Merguerian (1998) lithostratigraphic classification of the Pleistocene deposits of New York City and vicinity.

Most workers accept the principle that flow from two ice centers occurred during New England Pleistocene glaciation. Known as the Keewatin and Labrador ice centers, periodic ice buildup resulted in flow from two contrasting directions – NNW to SSE and NNE to SSW. Not all workers are in full agreement over the total number of glaciations to affect the NYC region but we know that in New York City glacial sediments deposited by ice flowing from NNW to SSE (**across** the Hudson Valley) are characterized by their distinctive reddish-brown-color, the result of grinding over hematite-rich sedimentary rocks from the Newark Basin (Sanders and others, 1997). By contrast, sediments deposited by glaciers that flowed from the NNE to the SSW (**down** the Hudson Valley) are associated with yellow-brown- to brownish-gray tills, the result of glacial scour of non-hematite-bearing rocks underlying the "crystalline corridor" of metamorphic rocks exposed between the Newark- and Hartford basins (Sanders and Merguerian, 1994b). Each of the flow directions resulted in a system of crosscutting glacial features and diagnostic indicator stones, easily identifiable in the field.

As described below, the glacial stratigraphy of the site indicates that at one point an older glacier (Glacier II in Table 1) flowed from the NW because the till it produced contains pebbles of serpentinite, presumably derived from massive serpentinite that crops out in Hoboken and southward in New Jersey (Figure 3). Overlying this basal till are additional glacial drift sheets that record the advance of a younger glacier or glaciers.
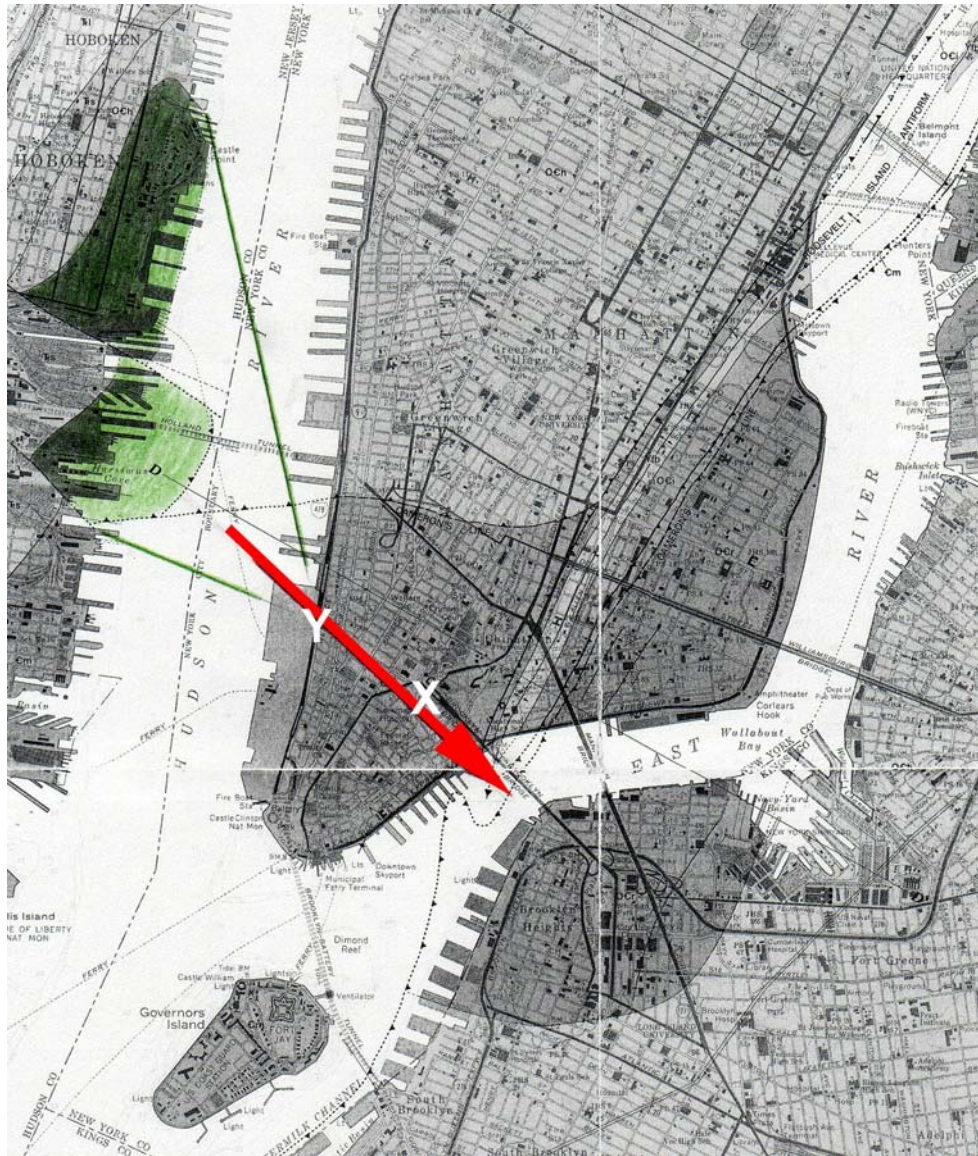
Figure 3. Geologic map of lower Manhattan with the main study area located at X. Y is another site mentioned in the text near West Street. The red arrow shows the location of a NW-SE trending valley in the bedrock and areas in green show local bodies of serpentinite found in New Jersey, the most likely source for the serpentinite gravel found in till in southern Manhattan. Base map from Baskerville (1994) with some subsurface information obtained from records of other MRCE jobs located in the vicinity.

GLACIAL STRATA FOUND AT THE SITE

The site (X in Figure 3 - exact location is proprietary client information) is located a few blocks south of the Brooklyn Bridge near Nassau and Beekman Streets in lower Manhattan. It lies above a NW–SE trending valley in the bedrock that deepens towards the SE suggesting the presence of a buried fracture or fault – certainly the orientation is parallel to a suite of NW-trending faults known to cut the region (Merguerian, 1996, 2002). Virtually no decomposed rock caps the bedrock, suggesting it was scoured clean

by glacial action. A relatively thin layer of gray-brown basal till with locally derived pebbles was then deposited across the area. The valley was subsequently filled in with approximately 100 feet of interlayered glacial sediments. The deposits vary, lensing across the site, but they follow a general sequence (Figures 4, 5).
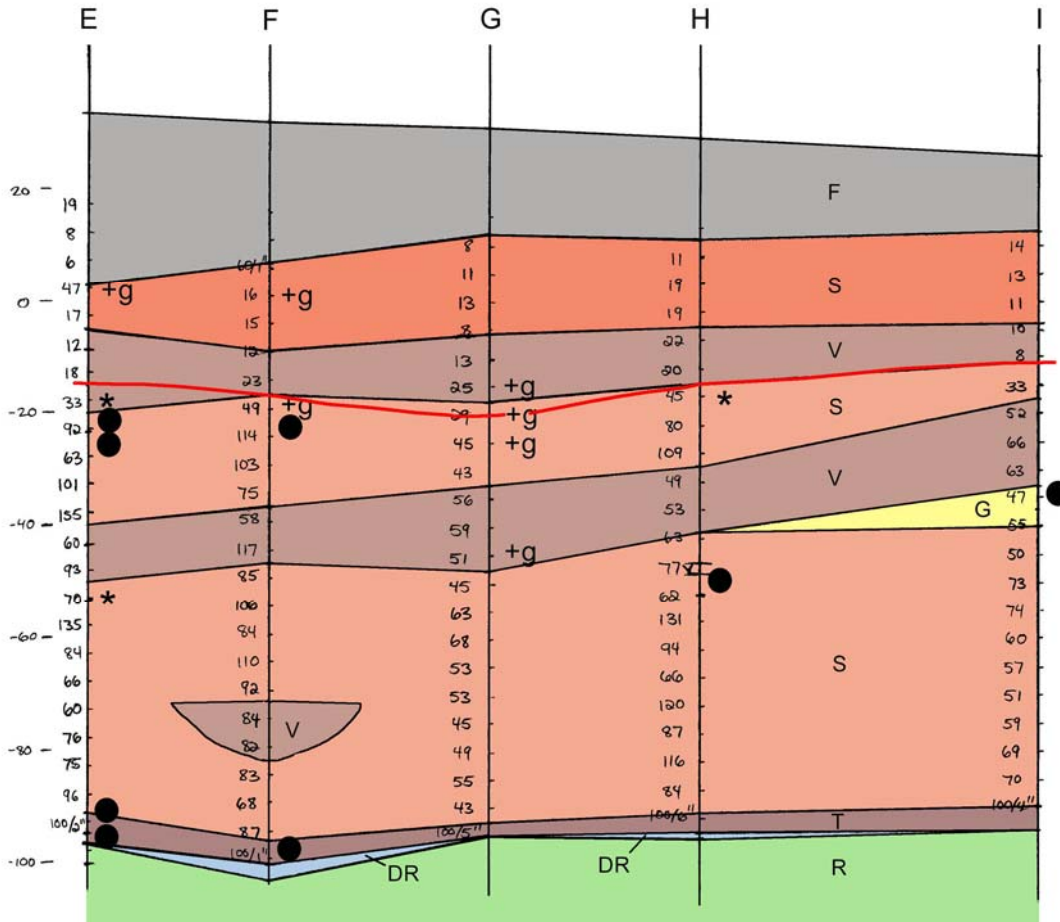

Figure 4. Cross-section of the study site along the south side (parallel to Beekman Street) based on borings lettered E, F, G, and H along top. The numbers are the SPT N-values taken at that elevation in the boring. The strata are F = fill, S = outwash sand, V = varved silt and clay, G = coarse sand with gravel, T = basal till, DR = decomposed rock, R = bedrock. The * indicates a distinct sample of till outside of the basal till stratum, **+g** indicates a sample of very fine grained soil containing gravel, ● indicates an area of rig chatter during drilling that generally means gravel, cobbles, and/or boulders are present at that elevation. Coarse-grained sediments, including till and gravel are found at the base of both varved layers. In all of the borings the N-values increase significantly below elevation –15 feet. In borings E and H the values increase below till at the base of the upper varved strata and in borings F and G it increases below soil containing very coarse sediments. The change from low to high N-values is shown by the thin red line. V.E. = 1.5X.
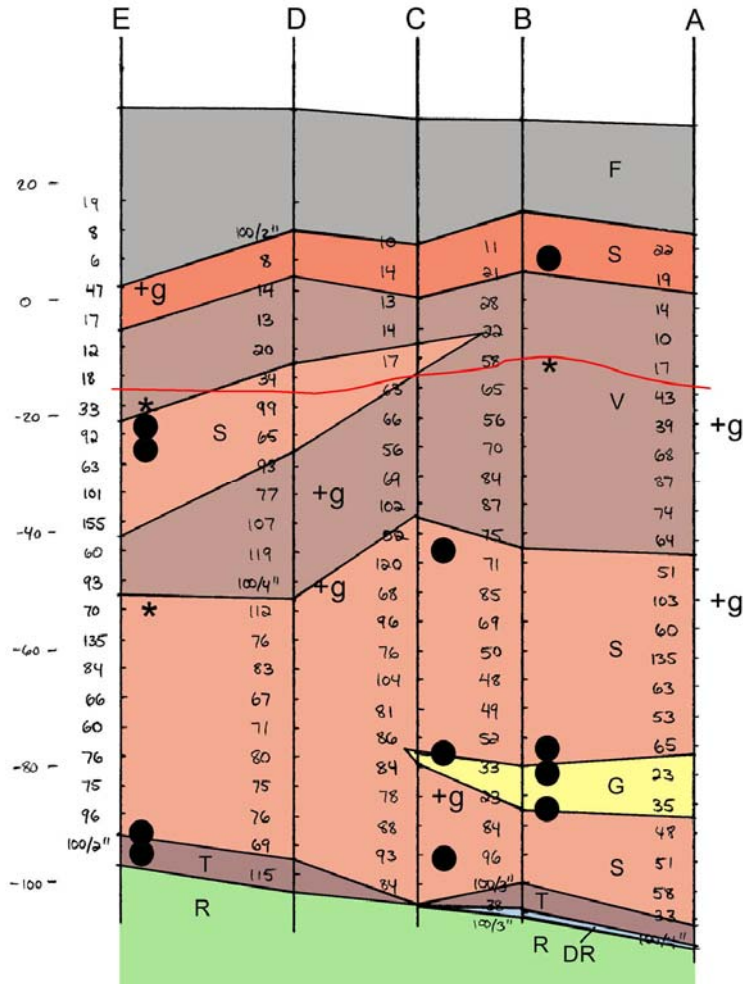
Figure 5. Cross-section of the study site along the west side (parallel to Nassau Street) based on borings lettered A, B, C, D, and E along top. The numbers are the SPT N-values taken at that elevation in the boring. The strata are F = fill, S = outwash sand, V = varved silt and clay, G = coarse sand with gravel, T = basal till, DR = decomposed rock, R = bedrock. An * indicates a distinct sample of till outside of the basal till stratum, **+g** indicates a sample of very fine grained soil containing gravel, ● indicates an area of rig chatter during drilling that generally means gravel, cobbles, and/or boulders are present at that elevation. Coarse-grained sediments, including till and gravel are found at the base of both varved layers. In all of the borings the N-values increase significantly below elevation –15 feet (red line). In borings B and E the values increase below till within the varved interval. V.E. = 1.5X.

Red-brown to brown to gray-brown outwash sands, typically fine to medium-grained with trace to some silt were deposited over the basal till (Unit S in Figures 4 and 5). Along the northern and eastern sides of the site this is overlain by coarse to fine sand with gravel containing occasional cobbles and boulders. Above this lies more of the fine grained sand. The lower sand unit is completely overlain by varved silt and clay (Unit V in Figures 4 and 5). Along the southern side of the site this leads up into another layer of fine-grained sand before moving up into the upper portion of the varved unit. The top of the varved deposit is covered with a capping layer of the fine-grained outwash sand that

is darker in color and more micaceous than the lower sand units. Miscellaneous fill material (Unit F in Figures 4 and 5) covers the entire site.

One distinctive feature was present in many of the borings. Within the varved stratum often at or near the base of the layer, or immediately below it, occurs a thin layer of till containing clasts of serpentinite and local lithotypes (Figure 6). In a few of the borings the thin till samples were intact enough to identify the fabric and structure of the soil. The material was typical of the local densely packed basal till (Figures 7, 8). Samples from similar elevations in many of the other borings have coarse sand and/or gravel mixed in with the fine-grained sediments. (See symbol **+g** in Figures 4, 5.) Other borings encountered rough drilling conditions typical of gravel, cobbles, and boulders, also suggestive of till deposits at that level. (See symbol • in Figures 4, 5.)

Figure 6. Sample from Boring B of main study site at the base of the upper varved layer (asterisk in Figure 5 at elevation -15') of disturbed and dried out till containing gravel sized pieces of serpentinite. Ruler is graduated in tenths of feet.

Clasts of serpentinite were found in the till at the base of the upper varved layer. (See Figure 6.) One sample of till material at the base of the lower varved unit contained pieces of decomposed schist (Figure 9). The gravel encountered in other samples from around this elevation often included similar decomposed schistose rock. Based on these relationships we presume that the upper and lower varved units had different source areas, possibly different flow directions, and were the result of different glacial events.

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Figure 7. Sample of typical NYC area basal till taken in a split spoon sampler from lower Manhattan near the World Trade Center site. The distinctive structure and texture of the soil are typical of basal till found from many sites across the NYC area. Thin layers of till encountered in or near the base of the varved strata from the study site have the same soil structure as this sample.

Figure 8. Sample of till from Boring E (asterisk in Figures 4 and 5 at elevation -19') from the base of the upper varved layer. Most of the soil structure was disturbed during the reclassification process and storage. Note the presence of coarse gravel and a few serpentinite pebbles in a red-brown silty matrix. The soil mass shows the mix of fine to coarse-grained sand tightly packed together with red-brown silt. Width of view is roughly 3 inches.
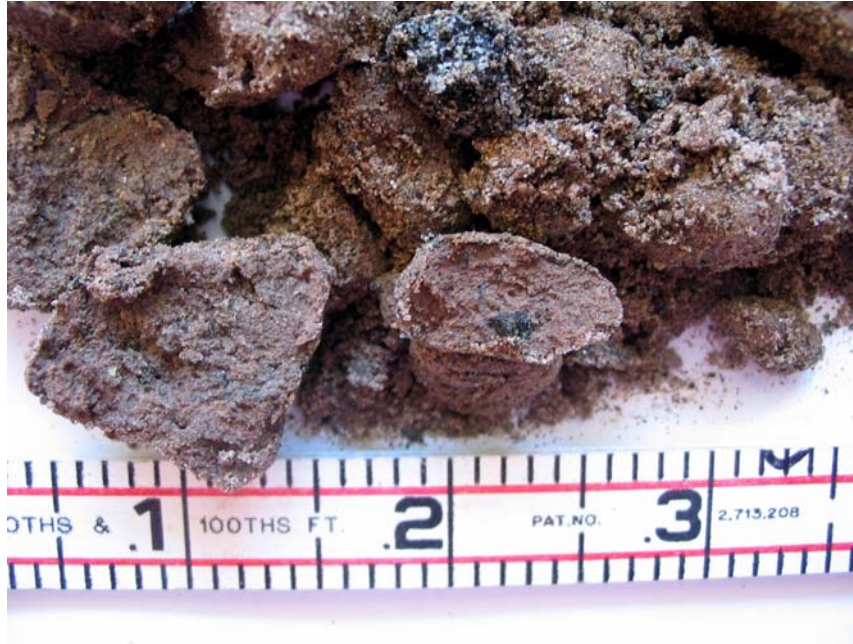
Figure 9. Sample of till from Boring E from below the base of the lower varved layer (asterisk in Figures 4 and 5 at elevation -55'). Most of the soil structure was disturbed during the reclassification process and storage. However, a few small pieces remain that show the mix of fine to coarse-grained sand and gravel tightly packed together with silt. Note the presence of coarse sand/gravel sized decomposed schist at the top center of the image.

DIFFERENT N-VALUES ACROSS SITE

Logically, one would expect the N-values to vary with the different strata, and be reasonably consistent within each layer. Within a stratum, the blows might increase gradually with depth, reflecting the increasing overburden load. That was not the case, however, with this site. The N-values in the uppermost outwash sand averaged 17 blows per foot (bpf). The outwash layers found below the varved stratum averaged 68 bpf. Where there was only one layer of varved sediments present, its N-value averaged 39 bpf. In the borings where there was a second, stratigraphically lower varved layer the average was 76 bpf.

Interestingly, the blow counts increase significantly at or immediately below the thin till layers found at the base of the varved layer intervals. This trend is remarkably more pronounced for the upper varved layer. Here the till is generally found at approximately elevation -15 feet. Even in borings that do not have the thin till layers present, the blows tend to increase immediately below elevation -15 feet. (See red line in Figures 4 and 5.) The presence of basal till indicates that any soils below were loaded by glacial ice. The rise in blow counts below the till, reflecting a densification of the soil, is almost certainly the result of ice loading. Some borings across the site showed an additional rise in N-values below the lower varve/till unit, allowing for the interpretation that the soil may have been loaded twice.

The site investigation took place over 2 different time periods, using different drill rigs, drillers, and inspectors. The pattern of N-values was consistent throughout and could not be correlated with any of these variables. Borings made for Mueser Rutledge Consulting Engineers in 1962 in areas immediately surrounding the site area also exhibited the same rapid increase in blow counts below elevation -15 feet.

DEPOSITS ASSOCIATED WITH ICE ADVANCE

The lack of till or other signs of ice loading, other than the increased blow counts, in many of the borings can readily be explained. The New York City area was located at the southern margin of the ice advance where the regional climate was probably more temperate. Temperate zone glaciers tend to carry less sediment at the base of the ice that would contribute to the deposition of basal till (Boulton, 1970). They are also more likely to be a wet-based glacier. Unlike dry-based glaciers that tend to be frozen to the substrate, wet-based glaciers generally have a layer of water separating the ice from the soil below, allowing it to flow more freely. Conditions that increase the amount of friction between the base of the glacier and the bed below tend to increase the amount of basal till deposited and/or increase the amount of deformation in the substrate. Increased friction can result from factors such as a steeper slope in the substrate, a rougher surface of the glacial bed, a thicker (heavier) layer of glacial ice, and well drained subsurface soils that reduce the "lubricating" effects of water between the ice and the bed.

The weight of thicker ice can strengthen the soil below, decreasing the amount of deformation, especially if the angle of internal friction in the soil is high (as in coarse-grained soils). This effect can be counteracted if the soil is poorly drained. The pore water pressure in the fully saturated sediment below helps to support the overburden of the ice, reducing the degree the soil is strengthened, allowing it to be deformed more readily (Edwards, 1978).

In the New York City area bedrock and basal till are overlain with layers of outwash sands and varved silts and clays. These sediments are generally relatively fine-grained, creating a smooth bed with most likely a gentle slope. While the outwash sands can drain freely if the water table is low, if meltwater is dammed behind the terminal moraine the water table may be high. These conditions do not favor the deposition of basal till, especially if the layer of advancing ice is not very thick. It is also possible that sediments that were initially deposited and/or deformed were later eroded away. Soil below the glacier can become frozen to the base and incorporated into the glacial ice, where it is transported farther downflow before being re-deposited. This process is most likely to occur in the marginal zone of a glacier (Boulton, 1972, 1975). Consequently, the traditional basal sediments may have never been deposited, and the expected pro-glacial and sub-glacial deposits may have been eroded away by the over-riding ice. Ironically, the only sedimentary evidence of the glacial advance may be the deposits left behind as the ice retreats.

SERPENTINITE IN TILL INDICATES A NEW JERSEY ORIGIN

Much of the glacial soils at the site are red-brown to brown in color, typical of hematite-rich tinted soils originating in New Jersey. The presence of serpentinite in the upper till layers indicates that the ice that deposited it clearly came from the NW. (See Figure 3.) The only other known surface exposures of serpentinite in the region are in Staten Island to the southwest and in a relatively small area on the west side of Manhattan near 59th street (Cozzens, 1843; Gratacap, 1887). No evidence exists to suggest the glaciers ever flowed from the southwest and the serpentinite found in Manhattan typically has a distinctly darker color than the light green serpentinite found in New Jersey. The alignment of the site with the serpentinite exposures in New Jersey also coincides with the trend of the underlying bedrock valley. (See Figure 2.)

SIMILAR PATTERN AT A SITE ON THE LOWER WEST SIDE

The pattern of comparatively loose outwash over soil containing till over denser outwash soil is not unique to one area in lower Manhattan. Another MRCE site near West Street in lower Manhattan (Y in Figure 3), that happens to lie in the New Jersey – New York alignment exhibits the same pattern. The location has mostly outwash sands with only a few scattered layers of varved silts. However, within the sand there are occasional thin pockets of till containing light green serpentinite above suddenly higher N-values. At the western edge of the site blow counts increase below elevation -65 feet. As you approach the eastern side of the site the blow counts increase below elevation -45 feet. Data from previous MRCE jobs in surrounding locations also have the same N-value trends. A site directly to the north has blow counts that also increase at elevation -65 feet. Sites immediately to the south and east indicate that the N-values increase below elevations between -40 feet and -20 feet.

IMPLICATIONS OF CROSSHOLE SEISMIC TEST RESULTS

During the course of the boring investigation at the site, a cross hole seismic test was successfully conducted between two borings. Shear wave velocities were as expected in the bedrock and in the upper glacial soils. The outwash sand below the lower varve/till sequence, however, had velocities that were much higher than the soil above and dramatically higher than what correlations would predict. The values were more typical of very stiff soil or soft rock. Determining the exact reason for the high values was beyond the scope of the investigation but it was speculated that the soil grains had become weakly cemented together. If this is indeed the case, then the soil below the lower varved layer is old enough to allow cementation to take place. Since the soils above the lower outwash have typical shear wave velocities, they were probably deposited during a separate glacial episode.

CONCLUSION - POSSIBLE SEQUENCE OF GLACIAL EVENTS

As a result of its former position at the ice margin during the Pleistocene, New York City can be expected to record a complex glacial history. Based on the interpretation of data from this study, the glacial strata of southern NYC provides evidence for most phases of the multi-glacier hypothesis of Sanders and Merguerian (1998). The oldest glacial ice to flow through the valley scoured the bedrock and removed most of the decomposed rock that was present (NW to SE flowing Glacier V in Table 1). The gray-brown basal till (T in Figures 4, 5) is quite different in color from the overlying reddish-brown sediments and appears to be derived from local rock types. (See Figure 7.) The thin till may be the result of Glacier V or be the result of Glacier IV from the NNE since it does not possess the typical reddish color indicative of NW to SE flow.

A thick sequence (~50') of brown to gray-brown outwash rests above the basal till but we do not know if the outwash was left by a retreating glacier (Glacier IV) or by the advance of the next "Ronkonkoma Phase" wave of ice (III), or a combination of both. It is likely though, that the stratum was the product of glacial episodes IIIC and IIIB. Thus, the seemingly uniform layer is correlative with the Manhassett Formation. The lower layer of sand was then overrun by new ice (Ronkonkoma Phase - Glacier IIIA) which in spots deposited a thin layer of till containing schist. A period of weathering may have preceded this advance and cemented the lower outwash sand layer, a plausible explanation for seismic data indicating denser material beneath elevation -55'. The schist-bearing till unit and above do not show signs of possible cementation. Ultimate retreat of the Glacier IIIA ice sheet left behind a layer of varved sediments (lower layer V in Figure 4) and produced the Ronkonkoma moraine, an effective dam for the varved strata.

Pro-glacial outwash may have preceded the next major advance (middle layer S in Figure 4), which was later overrun and loaded by NNW to SSE flowing ice (Harbor Hill Phase - Glacier II). The red line shown in Figures 4 and 5 may be a loading record of this event. This new ice wave scoured the outwash layer and deposited pockets of serpentinite-bearing till derived from the NW in New Jersey and ultimately formed the regionally extensive Harbor Hill moraine. The Harbor Hill moraine truncates the Ronkonkoma moraine in Long Island and extends across Queens, Brooklyn and Staten Island. Retreat of the Harbor Hill ice left behind the "upper" layer of varved silts and clays.

The difference between the mineralogy of the upper varve/till and lower varve/till sequences (serpentinite clasts versus schist clasts) indicates that the two events may have had different source areas or paleoflow azimuths. In each sequence some of the schist and serpentinite gravel has decomposed in place. The absolute ages of the advances are unknown but clearly the deposits are old enough to have undergone some degree of chemical weathering. For this reason we assign them to pre-Woodfordian glacial intervals II and III.

The upper outwash layer (uppermost red-brown glacial layer S in Figure 4) is very similar to the deeper outwash sands but it is deeper in color and contains noticeably more mica suggesting it came from a clearly separate event. This outwash deposit and the immediately underlying upper varved stratum do not have N-values indicative of ice loading, so presumably no younger mass of ice reached the site. The youngest glacial event is assigned to the Woodfordian ice advance (Glacier I in Table 1) that, based on regional loading data presented in a previous report (Moss and Merguerian, 2005), did not reach southern Manhattan and left no deposits. Rather, the Woodfordian ice margin stalled to the north of the study area and liberated great volumes of melt water that locally produced a proglacial outwash sheet. Continued melting of ice ponded water behind the Harbor Hill moraine and produced a glacial lake whose rising levels eventually breached the Narrows in a cataclysmic flood (Merguerian, 2003).

Many locations around town have sediments with a pattern of low blow counts above dramatically higher values, without any obvious change in strata to account for the difference. Our evidence from the southern Manhattan site indicates that ice loading can be responsible for these observed differences. The absence of tell tale signs of glaciation do not exclude it as an option. Particularly in the marginal zone of a glacier, expected pro-glacial and sub-glacial sediments can be removed by ice action and basal till may not be deposited at all. Compacted soil overlain by loose material left in the wake of the retreating ice may be the only sign of a particular glacial event. Both standard stratigraphic principles and engineering properties can be employed in analyzing areas that contain interlayered glacial drift. Where geologic evidence is lacking, engineering properties may be significant help in interpreting the glacial history.

ACKNOWLEDGEMENTS

REFERENCES CITED

ASTM D 1586 – 99, "Standard Test Method for Penetration Test and Split-Barrel Sampling of Soils," ASTM International.

Baskerville, C. A., 1994, Bedrock and engineering geology maps of New York County and parts of Kings and Queens counties, New York and parts of Bergen and Hudson counties, New Jersey: U. S. Geological Survey Miscellaneous Investigations Series Map I-2306 (2 sheets; colored maps on scale of 1/24,000).

Boulton, G. S., 1970, On the origin and transport of englacial debris in Svalbard glaciers: Journal of Glaciology, Vol. 9, No. 56, p. 213 – 229.

Boulton, G. S., 1972, The role of thermal regime in glacial sedimentation: Polar Geomorphology, R. J. Price and D. E. Sugden, editors, Institute of British Geographers Special Publication 4, p. 1 – 19.

Boulton, G. S., 1975, Processes and patterns of subglacial sedimentation: a theoretical approach: in Ice Ages: Ancient and Modern, A. E. Wright and F. Moseley, editors, Geological Journal Special Issue No. 6, p. 7 – 42.

Cozzens, Issachar, 1843, A geological history of Manhattan or New York Island: New York, NY, 114 p. (includes map).

Edwards, M. B., 1978, Glacial Environments: in Sedimentary Environments and Facies, H. G. Reading, editor, Elsevier, New York, p. 416 – 438.

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

Lutenegger, A. J., Kemmis, T. J., and Hallberg, G. R, 1983, Origin and properties of glacial till and diamictons: Geological Environmental and Soil Properties: Special Publication, ASCE geotechnical Engineering Division, Houston Texas, October 17 – 21, 1983, p. 310 – 331.

Merguerian, Charles, 1996, Stratigraphy, structural geology, and ductile- and brittle faults of New York City, p. 53-77 in Benimoff, A. I. and Ohan A. A., chm., The Geology of New York City and Vicinity, Field guide and Proceedings, New York State Geological Association, 68th Annual Meeting, Staten Island, NY, 178 p.

Merguerian, Charles, 2002, Brittle faults of the Queens Tunnel Complex, NYC Water Tunnel #3: p. 63-73 in Hanson, G. N., chm., Ninth Annual Conference on Geology of Long Island and metropolitan New York, 20 April 2002, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 116 p.

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.

Merguerian, Charles, 2003, The Narrows flood – Post-Woodfordian meltwater breach of the Narrows channel, NYC: in Hanson, G. N., chm., Tenth Annual Conference on Geology of Long Island and Metropolitan New York, 12 April 2003, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts, 13 p.
http://www.geo.sunysb.edu/lig/Conferences/abstracts-03/merguerian/merguerian.htm.

Moss, C. J., and Merguerian, Charles, 2005, Loading patterns in varved Pleistocene sediment in the NYC area: in Hanson, G. N., chm., Twelfth Annual Conference on Geology of Long Island and Metropolitan New York, 16 April 2005, State University of New York at Stony Brook, NY, Long Island Geologists Program with Abstracts.
http://www.geo.sunysb.edu/lig/Conferences/abstracts-05/ moss-merguerian.htm

Sanders, J. E.; and Merguerian, Charles, 1991, 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, 1994a, 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.; 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 (extended abstract), 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, 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; Levine, Jessica; and Carter, P. M., 1997, Pleistocene multi-glacier hypothesis supported by newly exposed glacial sediments, South Twin Island, The Bronx, New York, p. 111-122 *in* Hanson, G. N., *chm*., Geology of Long Island and metropolitan New York, 19 April 1997, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 128 p.

Sanders, J. E.; Merguerian, Charles; and Okulewicz, S. C., 1995, Recembent 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.

Sowers, George, 1979, Introductory Soil Mechanics and Foundations: Geotechnical Engineering: Macmillan Publishing Co., Inc., New York, 621 p.

Terzaghi, K., Peck, R. B., and Mesri, G., 1996, in Soil Mechanics in Engineering Practice, Third Edition: John Wiley and Sons, New York, 549 p.