50 Ka Till-Filled Pleistocene Plunge Pools and Potholes Found Beneath the World Trade Center Site, New York, NY

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INTRODUCTION

During construction of the original World Trade Center Twin Towers in the 1970's an unusual feature was encountered. The southeast corner of the slurrywall cut through a bedrock valley filled with rounded and polished glacial boulders and cobbles. The geotechnical investigation in 2007 for Tower 4, under construction in the southeast corner of the WTC site, explored the feature further, identifying additional till filled depressions (Moss and Merguerian, 2008). During excavation for the foundation in 2008 the emerging plunge pools and potholes were studied in greater detail and wood found buried in the till was ^{14}C dated.
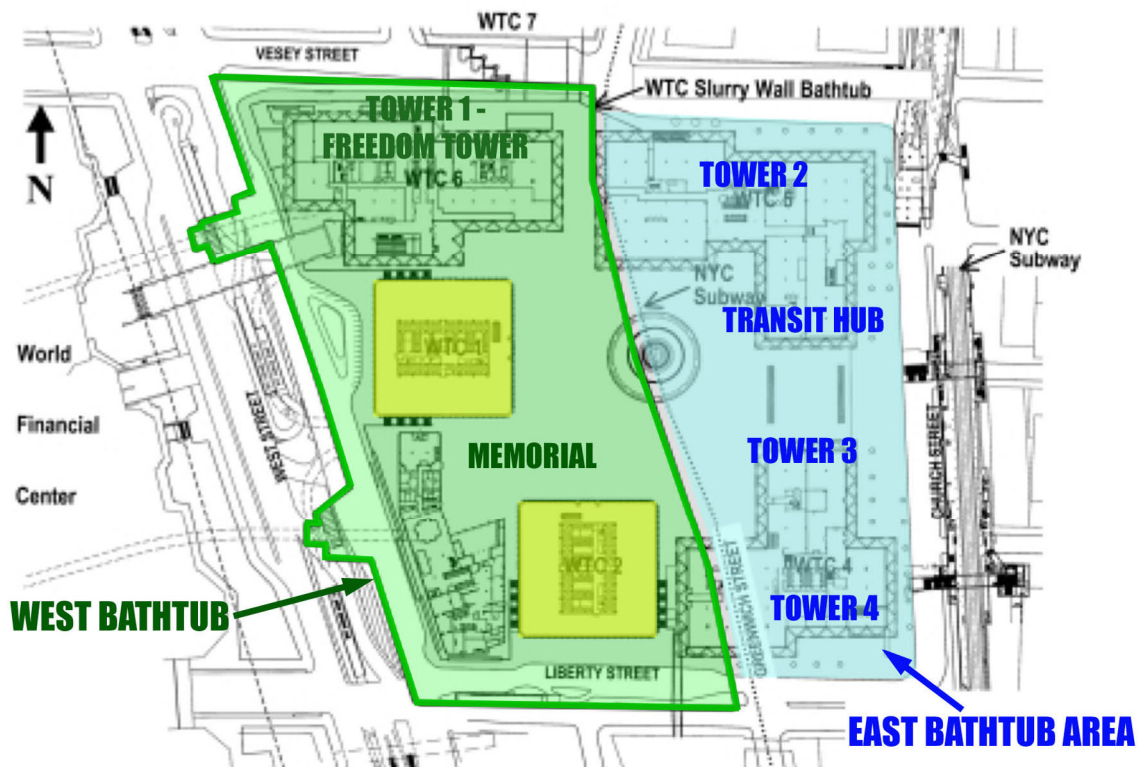

Figure 1 – World Trade Center site location. The site covers 12 city blocks bounded by Church, Vesey, West and Liberty Streets. The WTC Memorial and Tower 1-Freedom Tower are under construction in the original West bathtub. Towers 2, 3 and 4 and a Transportation Hub will be built in the recently constructed East bathtub.

SITE LOCATION

The World Trade Center site encompasses 12 city blocks in lower Manhattan (Figure 1). The original Twin Towers were built within the western 8 blocks that were encircled by a slurrywall socketed into bedrock – the famed bathtub – to allow their construction. The World Trade Center Memorial and Tower 1 – Freedom Tower are currently under construction in this section. In 2007 a second slurrywall was built around the eastern 4 blocks of the site to enable construction of Towers 2, 3 and 4, along with a Transportation Hub.
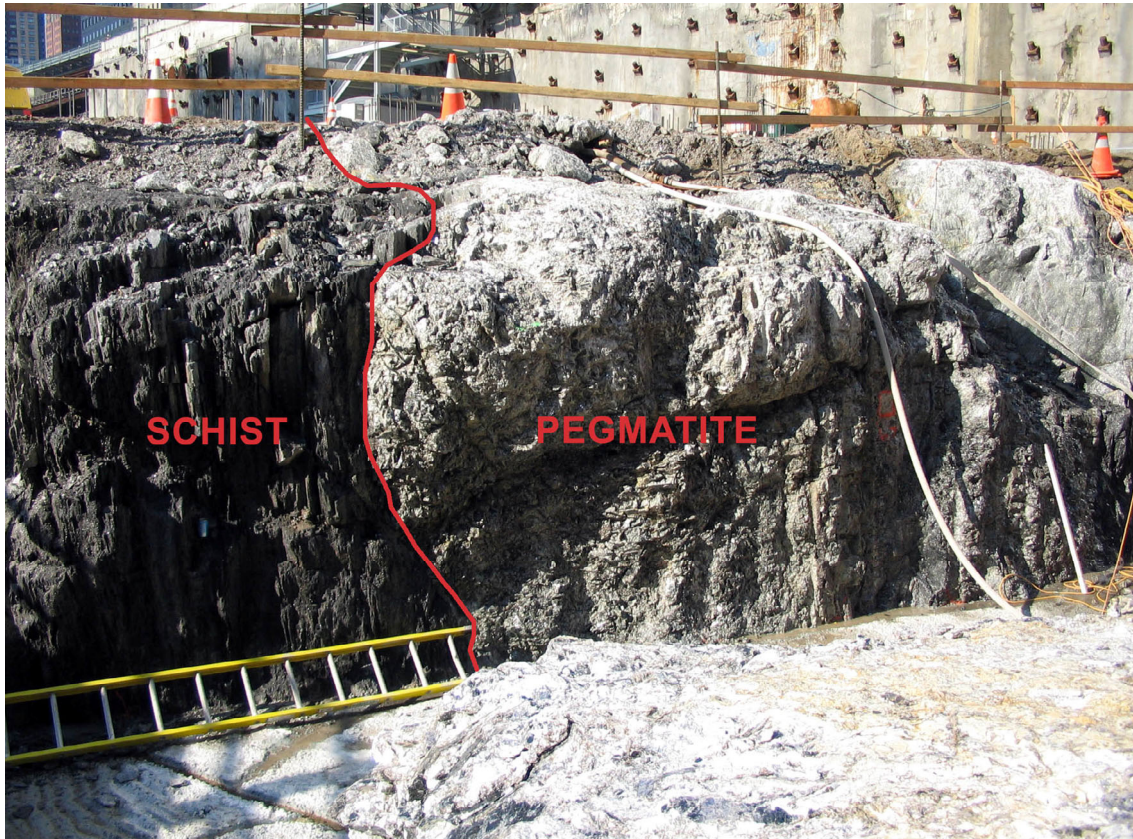

Figure 2 – The WTC site has predominantly schistose bedrock with near vertical foliation. Large distinctive intrusions of pegmatite are scattered across the site, with concentrations in the NW corner (Tower 1), seen above, and SE corner (Tower 4). (Digital image by C. J. Moss.)

SITE GEOLOGY

Similar to relationships established elsewhere in southern Manhattan, the bedrock across the site consists of complexly folded pyritic biotite schist and calc-silicate rock of the autochthonous mid-Ordovician Walloomsac formation together with schist, granofels and amphibolite of the allochthonous Cambro-Ordovician Hartland formation (Merguerian and Moss, 2006). The layers were thrust and folded together and turned on end in a subduction zone during the Taconic orogeny. Foliation is near vertical with a trend of roughly N30°E, varying somewhat due to the presence of tight symmetric- to asymmetric

vertical folds. Later (possible Devonian) intrusion of massive granitic pegmatite was concentrated primarily in the northwest (Tower 1 area) and southeast (Tower 4 area) corners of the site (Figure 2).

At least five different glaciations have affected the region, originating both from the northeast and, more significantly, the northwest. Little is known of the earlier glaciations. Most of the glacial features in the region are a result of the advances from the NW that produced the Ronkonkoma and, later, the Harbor Hill Moraines (Figure 3). The WTC bedrock is typically covered with a layer of basal till composed of clasts and sediment native to New Jersey, overlain by red-brown glacial lake silt and silty fine sand that shifts to outwash sand along the western edge of the site near West Street.
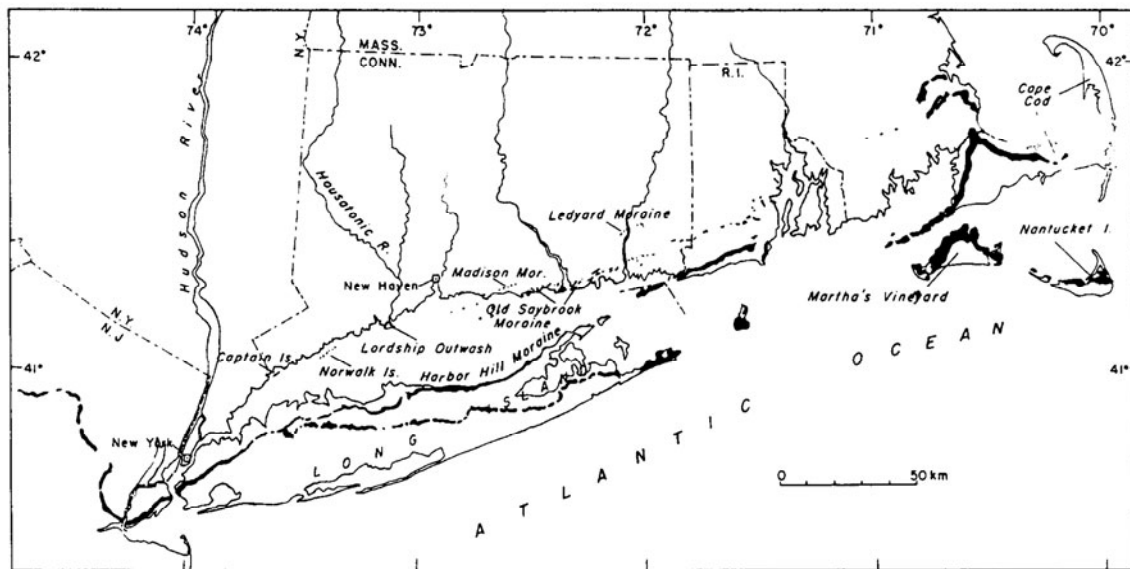

Figure 3 – Moraines across the region, shown in black. The older Ronkonkoma moraine forms the south fork of Long Island. The later Harbor Hill moraine, which forms Long Island's north fork, overran the Ronkonkoma in New York City. Although there were advances from the NNE, the dominant features were formed by the glaciations that flowed from the NW.

SITE INVESTIGATIONS

During construction of the original WTC Twin Towers in the 1970's, the western slurrywall unexpectedly cut through a ledge of schist and entered a bedrock valley filled with rounded boulders and cobbles before keying into bedrock below. This glacial valley cut through the SE corner of the slurrywall in 2 places (Figure 4). When it was time to rebuild after 9/11 initial information indicated the valley extended eastward into the future Tower 4 site. A more detailed geotechnical investigation was conducted in the Spring of 2007 to determine just what the feature was, where it was, why it was there, and how best to build a high-rise above it.

Later in 2007 the southern half of the newly built eastern bathtub was prepared for construction by removing remnants of previous foundations, along with the excavation of glacial lake silt, basal till and bedrock above elevation -60 feet. In early 2008 excavation began on the foundation for Tower 4. As the till filling the glacial depressions was gradually removed the true extent and nature of the features became apparent. The conclusions of the prior geotechnical investigation were confirmed and new questions that had arisen resolved, however it was unexpected how extensive and dramatic the emerging basins would be.
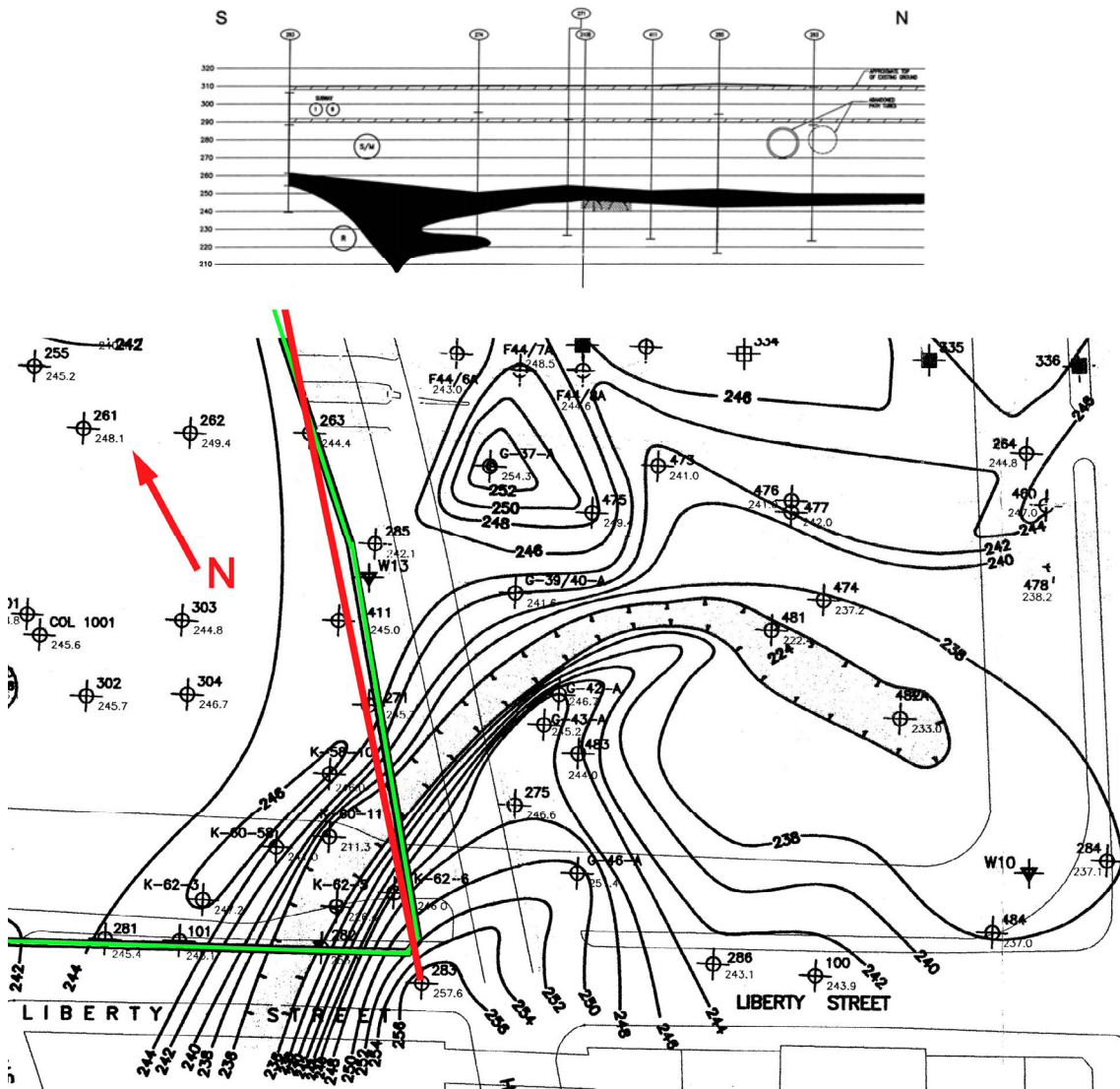

Figure 4 – Top of bedrock contours in the SE corner of the WTC site. During construction of the original Twin Towers the SE corner of the west slurrywall (green line) cut through a ledge over a boulder till-filled valley. The x-section, shown above, runs along the red line. Data obtained prior to the geotechnical investigation for Tower 4 indicated that the feature, presumed to be a valley, extended eastward into the Tower 4 site. Elevation 300' is equal to El +2.653' on USGS Mean Sea Level Datum at Sandy Hook, NJ (1929 NGVD).

REVEALED BY INVESTIGATION AND EXCAVATION

ROCK

The investigation and subsequent excavation revealed that the Tower 4 location, which covers the southern quarter of the east bathtub, has two very large and deep depressions in the center of the site (Figure 5). The valley through the corner of the western slurrywall continues eastward into the Tower 4 area, approaching the western depression. This basin has no real outlet and extends as much as 50' deep into the bedrock, bottoming out at El. -100'. The adjacent eastern depression, which was never fully excavated, appears to lead to another valley in the rock that runs below the eastern side of the east slurrywall, heading toward and beneath Church Street.

Figure 5 – Two large depressions beneath the Tower 4 site. The western basin (seen at top, facing west) had no outlet. Across the site, bedrock was initially excavated down to El. -60' and the basin bottomed out, under the green pond, at El. -100'. The pond fills a circular whirlpool and plunge pool below a near vertical cliff. During the geotechnical investigation a boring located just behind the cliff face penetrated 11' of pegmatite before entering 32' of till below. A boring on the opposite, eastern side of the basin also penetrated a small ledge of bedrock above till. The eastern depression, lower right corner, was never fully excavated so its true extent is not known. A temporary secant wall keyed into the original top of bedrock is seen along the top of the photo. (Digital image by C. J. Moss.)

When top of bedrock contours were initially drawn it appeared that the two large basins were roughly circular, but excavation confirmed suspicions that there were more ledges over till (Figure 6). The depressions turned out to be a mix of potholes, plunge pools, basins and "waterslides" that were scoured out and then filled with a very dense mix of silt and clay to rounded boulder till with occasional slabs of native bedrock (Figure 7).

Figure 6 – Northeastern face of the western depression. The view shows an upper "cave" carved out by a whirlpool. A boring made during the geotechnical investigation cut through the upper ledge of bedrock before penetrating the till which filled the structure. A mid-level whirlpool is seen being cleared of till. Till filled potholes are visible in the upper left corner. The till was so densely compacted that sediments in the near vertical exposures remain in place. (Digital image by C. J. Moss.)

Going into the investigation, three different origins were considered for the formation of the presumed valley (Moss and Merguerian, 2008). We thought, the feature could follow the trend of a pre-existing fault, as is the case for some other glacial filled valleys in Manhattan, or that it could have formed along a solution cavity in calc-silicate rock of the Walloomsac formation, known to be present in the west bathtub (Merguerian and Moss, 2006). Differential erosion along the contact of contrasting rock types was also considered and proposed.

The higher bedrock surface along the western and southern edges of the Tower 4 site, along with the southeast corner of the west slurrywall, is underlain by a massive body of

granitic pegmatite (Figure 8). To the north and east the rock is predominantly gneissic schist to schistose gneiss. It was apparent from the investigation and confirmed by excavation that, as a result of differential erosion, the depressions were carved out of the softer schistose rock. The harder pegmatite resisted erosion and was left to form higher ground. There was no indication that faulting or solution of calcareous rock played a significant role.

Figure 7 – Northwestern face of the west depression. At top, temporary secant wall sits above the original top of bedrock surface. Densely packed, bouldery till is seen in the center, filling a large void under the cliff face that was scoured by a plunge pool. Center right is a large, flat slab of polished, native bedrock that was originally thought to be a rock ledge until the underlying till was removed. Potholes, some still filled with till, are scattered along the sides. Green pond fills the lowest level whirlpool. Yellow arrow points to boring that cut through the upper ledge. (Digital image by C. J. Moss.)

Differential erosion was also a key player in the formation of the smaller scale features. The schistose bedrock consists of alternating vertical layers of schist and gneiss. The softer, more micaceous, schistose layers were preferentially eroded, generally forming the deeper grooves and gouges. The harder gneissic layers formed ridges. Rock type so dominated the patterns of erosion that it cannot be determined with certainty what direction the eroding water and/or ice flowed from. There are no linear features that cut across the foliation.

Figure 8 – The plan view at bottom shows the updated top of bedrock contours obtained from the Tower 4 geotechnical investigation. Borings in pink are pegmatite, blue indicates schist and gneiss, purple indicates that a mixture of pegmatite and schist/gneiss is found in the boring. Construction of the original west bathtub revealed a mass of pegmatite (circled) at the SE corner, on the SE side of the glacial valley. The valley and the rest of the slurry wall were in schistose rock. The black line shows the location of the cross-section shown at the top. Pink shading on the cross-section shows the original interpretation of the bedrock, with a possible ledge in question. The additions in red show the approximate bedrock profile, including 2 ledges, revealed by the excavation. Elevation 300' is equal to El +2.653' on USGS Mean Sea Level Datum at Sandy Hook, NJ (1929 NGVD).

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TILL

The till found across the site is composed of rounded, polished boulders, cobbles and gravel, with sand, silt and clay. The sediment is clearly derived from rock native to the northwest in New Jersey. Cobbles of diabase from the Palisades, serpentinite from Hoboken/Jersey City and reddish sandstone and siltstone from the Newark Basin and gneiss and quartzite from the Hudson Highlands make up the bulk of the till cobbles (Figure 9). The presence of cobbles of the distinctive Green Pond sandy facies, which only outcrops in northern New Jersey, further helps to narrow the range of the source area. This clearly indicates that the glacier that deposited the till advanced from the northwest, presumably one that deposited the Harbor Hill or earlier Ronkonkoma moraines.

Figure 9 – Dense mix of silt and clay to boulder till packed under a plunge pool overhang. Reddish-brown boulders to the right are from Newark Basin redbeds, as is the reddish-brown silt-clay matrix holding it all together. (Digital image by C. J. Moss.)

The till was so coarse-grained and dense that the borings made for the geotechnical investigation had to core through the till to get recovery. Occasionally "local" rock was recovered in addition to the cobbles that originated in New Jersey. A major question that arose from the borings was whether some of the rock that was cored was part of a

bedrock ledge or from slabs of native rock mixed into the till. Across the site the schistose rock has a micaceous foliation that is nearly vertical except where it sometimes wraps around an intrusive body. Thick pieces of schist with gently dipping foliation turned out to be slabs plucked from the sides of the depressions and dropped into the till (Figure 10). However, an 11 foot thick layer of massive pegmatite above 32 feet of till was revealed to be a ledge (Figures 7 and 8) of pegmatite only feet from the edge of a 43 foot high, near vertical face of rock that formed the western side of the west depression. A smaller ledge of schistose bedrock was also encountered in the neighboring boring on the east side of the depression (Figures 6 and 8).

Figure 10 – Bedrock to the left shows the natural subvertical foliation. Till is to the center and right. Seen in the midst of the bouldery till is a slab of schistose bedrock that had broken loose and tipped to the side as it was incorporated into the mix. (Digital image by C. J. Moss.)

INTERPRETATION OF FEATURES

Potholes and plunge pools commonly form in rapidly flowing rivers. When associated with glaciers, it was originally thought that potholes formed at the base of moulins, streams of meltwater flowing through the glacial ice. This theory has long been discredited. Instead, rapidly moving, pressurized meltwater flowing under glacial ice is often considered to be responsible for the features (Kehew and others, 2007). This is particularly the case for potholes that are found on top of a ridge crest or high up the side

of a valley wall. In these cases, water filling an adjacent river would not be deep enough to flow at the feature's higher elevation and would require a confining layer of ice to keep water running along the bedrock. The meltwater could flow continuously or in occasional outburst floods (Shaw, 2002). Jökulhlaups have also been associated with these carved bedrock features. Pro-glacial meltwater streams from an advancing and/or retreating glacier may also play a part. It is not yet clear which of these processes were involved in the formation of the erosional structures found at the WTC site.

Figure 11 – Pothole filled with dense till. Spiral grooving can be seen in the bedrock. (Digital image by C. J. Moss.)

It has also been suggested that glacial potholes can be carved out by glacial ice or slushy till (Benn and Evans, 1998). The bedrock features at the WTC site, however, appear to have been scoured out by sediment-laden water. The harder, less micaceous rock and boulders present in the potholes, basins, plunge pools and waterslides are-smooth and polished, not striated. The basins are quite circular and potholes along the sides of the depressions exhibit spiral grooving (Figure 11). When cobbles were "bowled" down the existing waterslides, upon hitting the first pothole the cobble would launch into the air only to land directly into the next pothole downhill, repeating the cycle until the cobble hit bottom. Sediments embedded in ice would not cause erosion in this pattern. Differential erosion between the N30ºE-trending vertical schistose and gneissic layers is the primary controlling factor on the linear features produced at the site. However, a "cave" cut into the eastern side of the western depression (Figure 12) takes the form produced when a jet of water enters the top of a column of water at a shallow angle

(Alexander, 1932). If rock type is not the exclusive controlling factor, then this feature suggests that the water flow came from the north.

Figure 12 – "Waterslides" run down the north face of the west depression into the basins below. The more gneissic layers (white) resisted erosion and form ridges. The more micaceous schistose layers (gray) were more easily eroded and form channels. Erosion follows along the foliation. The only features that cut across the linear foliation are the round whirlpools. Overhangs create a "cave" like structure around the upper basin, which has higher ground in the center as swirling sediment scoured down the edges. A mid-level basin is in the center, and the lower basin that bottomed out at El. -100' is center right with a slab of mass fill concrete already poured. (Digital image by C. J. Moss.)

It is unknown to what extent previous glaciations contributed to the formation of the WTC glacial features. The sides and bottoms of the depressions were primarily sculpted and polished by water erosion. The depressions were filled with an extremely dense New Jersey based till. However, mixed in were slabs of native bedrock mostly lying on their sides, at least some clearly scoured and polished like the surrounding rock (Figure 13).

If the till only contained rock from New Jersey, then it's possible that the features were carved out in an unidentified event and filled in much later with till that was subsequently overrun and loaded by glacial ice. The presence of native rock complicates the scenario. There is no likely alternate source of local rock nearby. The bedrock surface across the site is generally gently undulating with small, shallow potholes leading up to the

depressions. There don't appear to be any places where large vertical slabs could have been plucked out, polished over a short distance of travel and then dropped into the depressions.

Figure 13 – A polished slab of bedrock mixed into the till. The rock, which was over 14' thick, was originally thought to be a ledge until the till was excavated out from beneath. Actual polished rock is in the lower right corner. (Digital image by C. J. Moss.)

To carve so much so deeply, substantial segments had to have been eroded out before the coarsest sediments started to fill in. The presence of the occasional slabs of native bedrock lying on their sides indicates that the depressions started to fill with till before all the overhangs and/or pothole perforated edges had broken loose. These slabs were more likely polished before they fell into the till below rather than scoured by new water flow after deposition. The turbulent water flow needed to polish the rock would have removed the fine-grained sediment from the mix, leaving behind a lag deposit. This does not appear to be the case anywhere, unless subsequent time and glacial loading from above somehow allowed the finer grained sand and silt to be "injected" into the voids between the gravel and cobbles.

Although the fairly uniform, mostly unstratified nature of the till suggests continuous deposition, mainly by ice rather than by water, this was not exclusively the case, with activity possibly taking place in waves. In a couple of places a finer grained, more uniform till mix was found at the bottom of a small ravine and under a rock slab, with the coarser, more typical till mix above. Of particular interest, there was one section of the

western depression, about 15' below the top of rock, where a lens of silt formed above the till under the shelter of an inclined slab of fallen bedrock (Figure 14). Imbedded between the till and the silt was a small tree branch. More till was above all this, and the whole mass was so densely compacted that it had to have been ice loaded by an over-riding glacier on at least one occasion.

Figure 14 – Layer of silt deposited under an inclined slab of bedrock in the west depression, surrounded by till. A small tree branch was found lying on top of the till under the silt. (Digital image courtesy of D. Chen and R. Nunez.)

The till above the silt lens appears to be the same as the till surrounding and below – no change in color, composition, texture, or weathering. There is no indication that there were widely spaced episodes of deposition, and it is likely that the depressions were filled in during one glacial event rather than several. Given the time needed to carve and/or clean out the basins, fill them 2/3 full of till, trap a tree branch, fill the remaining 1/3 to the top, and then overrun with ice to compact the mix, the branch was probably deposited towards the mid to latter half of the glaciation. The big question is which glaciation?

^{14}C DATE OF WOOD SAMPLE AND HISTORIC CONTEXT

Glacial deposits mapped in the American midwest indicated that there were 4 major glaciations. Over time, it became apparent that some of the events actually had multiple advances, and subsequent research conducted in the oceans indicated that there were additional glaciations beyond the ones being found on land. Continued use of the old names became difficult and the names Nebraskan and Kansan have been discontinued, now grouped as pre-Illinoisan. The more recent Illinoisan, Sangamonian Interglacial and Wisconsinan names are still in use (Table 1).

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.
	(?)		Paleosol on Till II, SW Staten Island.
Mid-Late Wisconsinan(?)	II	NW to SE	Harbor Hill Terminal Moraine and associated outwash (Bellmore Fm. in Jones Beach subsurface); Lake Chamberlain Till in southern CT.
Interstadial			Wantagh Fm. (in Jones Beach subsurface).
Early-Mid Wisconsinan	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		
Sangamonian			Jacob Sand, Gardiners Clay.
Illinoisan/ Pre-Illinoisan		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.
			No deposits; deep chemical decay of Till 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 – Revised table of New York City area glaciations with updated relative ages in red. Adapted from Sanders and Merguerian, 1998.

Little is known of the earliest glaciations across the area. Much of the research centers on New Jersey, Long Island and New England. What little has been written about the NYC area is vague at best and more often completely contradictory, and dates assigned to the different events are routinely revised. There was an early advance from the NW (Sanders and Merguerian, 1998) that deposited the Jameco Gravel outwash in deep valleys in Brooklyn and Queens (Soren, 1978; Buxton and Shernoff, 1995), followed by an event from the NE. The Sangamonian interglacial deposited the Gardiners Clay around the region. This event is commonly dated at roughly 105,000 to 130,000 BP (Stoffer, 2003). The glaciation from the NW that produced the Ronkonkoma Moraine has been considered either Illinoisan or early Wisconsinan, suggesting dates of either

>130,000 or 90,000 to 70,000 BP. All that is known is that it's older than 43,000 BP. The Gardiners appears to be an often mis-mapped formation, frequently confused with what appear to be other interglacial deposits (Doriski and Wilde-Katz, 1983). It is likely, however, that the Ronkonkoma was deposited above the Gardiners, placing it in the early Wisconsinan. The Harbor Hill event from the NW is the best understood in the area. ^{14}C dates exist, suggesting that the ice started to affect the NYC region after approximately 25,000 BP. The glacier reached its maximum around 21,000 BP, and retreated north of the Bronx roughly 17,000 BP (Stone and others, 2005). There is evidence that a smaller, later glacial readvance from the NNE (Moss and Merguerian, 2007) affected portions of the NYC area, though little is known of this event.

In December of 2008 a portion of the tree branch (Figure 15) was sent to the Radiocarbon Laboratory at the University of Arizona for ^{14}C dating. The date obtained (with 95% certainty) was 49,500 +3050/-2205 BP. Using a more conservative estimate, the sample age was definitely >43,940 BP. These values clearly indicate the till filling the lower 2/3 (and likely upper third) of the depression was deposited by a glaciation prior to the Harbor Hill event. There are 3 possible interpretations available. The till could have been deposited during the Ronkonkoma event, which dates to roughly 50,000 BP, rather than the earlier dates assumed. Or it is possible that there were more glacial advances during the Wisconsinan than originally thought, and the till is associated with an unidentified mid-Wisconsinan event. The third option is a combination of the 2, with the Ronkonkoma event mid-Wisconsinan, in addition to an unidentified early Wisconsinan advance. Sediments found on Long Island suggest that there was at one time an earlier moraine south of the Ronkonkoma Moraine (Sanders and Merguerian, 1998), lending support to this interpretation. Glacial deposits filling a valley in lower Manhattan, just south of the Brooklyn Bridge, show evidence of 3, possibly 4, glacial advances across the NYC area (Moss and Merguerian, 2006).

Figure 15 – Piece of wood found trapped in the till in the western depression. (Digital image by C. J. Moss.)

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On Long Island, there are assorted interglacial deposits present onshore and off, that provide a time frame for the older Ronkonkoma and younger Harbor Hill events. Pollen, shells and ^{14}C dates indicate that between >43,000 and 36,000 BP the climate was colder, then warmed up around 32,000 to 28,000 BP before cooling again prior to the Harbor Hill advance (Sirkin, 1996). These deposits would be consistent with a glaciation around 50,000 BP.

Studies of climate and sea-level change based on data from sources such as ocean sediments, ice cores and oxygen isotope ratios indicate that there were repeated temperature fluctuations during the Wisconsinan. This supports the possibility that there could have been multiple glacial advances, large and small, across the region at the time, including ones at both 80,000 and 50,000 BP.

CONCLUSIONS

Prior to 50,000 BP, sediment-laden water of probable glacial origin eroded and polished the bedrock at the WTC site. The unusually deep erosion (-100' elevation) found at the WTC site is a testimonial to the drop in sea-level and oceanward migration of the shoreline that accompanies glaciation as such deep erosion usually takes place far from the shoreline in coastal areas. As the hard pegmatite resisted erosion the developing whirlpools preferentially scoured out the neighboring softer schist. An advancing pre-Harbor Hill glacier filled the expanding basins with till, periodically breaking off bedrock slabs and adding them into the mix. Overriding ice compacted the mass. The later Harbor Hill event did not visibly erode or contribute to the till, but certainly compacted it further as the ice advanced SE toward Brooklyn.

Sediments buried in New York City's valleys are revealing a very complex glacial history hidden by the overlying Harbor Hill deposits. Continued study of the different strata, their engineering properties and organic clay, peat and shells being found under the more recent glacial deposits will provide information about the number and timing of advances and inter-stadials across the area.

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