

Bedrock Control of a Boulder-Filled Valley Under the World Trade Center Site

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INTRODUCTION

Then the world's tallest buildings, the former World Trade Center Twin Towers were built in lower Manhattan in the early 1970's. A new construction technology at the time, a slurry wall socketed into the bedrock was built to enable the Twin Towers construction. A geotechnical investigation undertaken for the project suggested that the site geology would be fairly typical for New York City. During construction of the slurry wall, however, an unexpected feature was discovered. In the southeast corner of the site the wall cut through a ledge of schistose bedrock and entered a curved, roughly E-W-trending valley filled with well-rounded glacial boulders and cobbles (Figure 1). The slurry wall had to be excavated deeper in two places to get through the boulders and socket back into solid bedrock. The trend of the valley is unusual because other known glacial valleys across Manhattan trend NW-SE including a nearby valley we reported on earlier (Moss and Merguerian 2006).

When it was time to plan reconstruction of the new World Trade Center development, it was clear that extra attention would have to be focused on the southeast quadrant. The unusual geologic conditions present could pose significant difficulties for new design and construction. A more extensive boring program was undertaken by Mueser Rutledge Consulting Engineers, geotechnical engineers for the WTC Memorial and Towers 1, 2, 3 and 4. When the Tower 4 borings were made during Spring 2007, they were studied not only to determine the engineering properties of the rock, but also to understand the nature and possible origin of the glacial valley.

GEOLOGIC BACKGROUND

The boulder filled glacial valley with a NE alignment is an unusual feature for Manhattan. On a 20 foot contour map scale, Baskerville (1994) noted several NW-SE trending valleys that cut through the bedrock across New York City (Figure 2). They are typically filled with glacial sediments, predominantly outwash sand and varved silt and clay. Glacial till is often, though not always, present, usually directly above the bedrock of NYC. Boulders and cobbles can be scattered throughout, though they are typically found in the till. Where the shape of the bedrock surface creates an obstruction to flow, boulders are especially prevalent on the NW side, indicative of NW to SE paleoflow directions. The valleys are well defined in northern Manhattan and there are several present in the subsurface in southern Manhattan. A combination of two different geological processes, faulting and subsequent glacial erosion, are likely responsible for their presence.

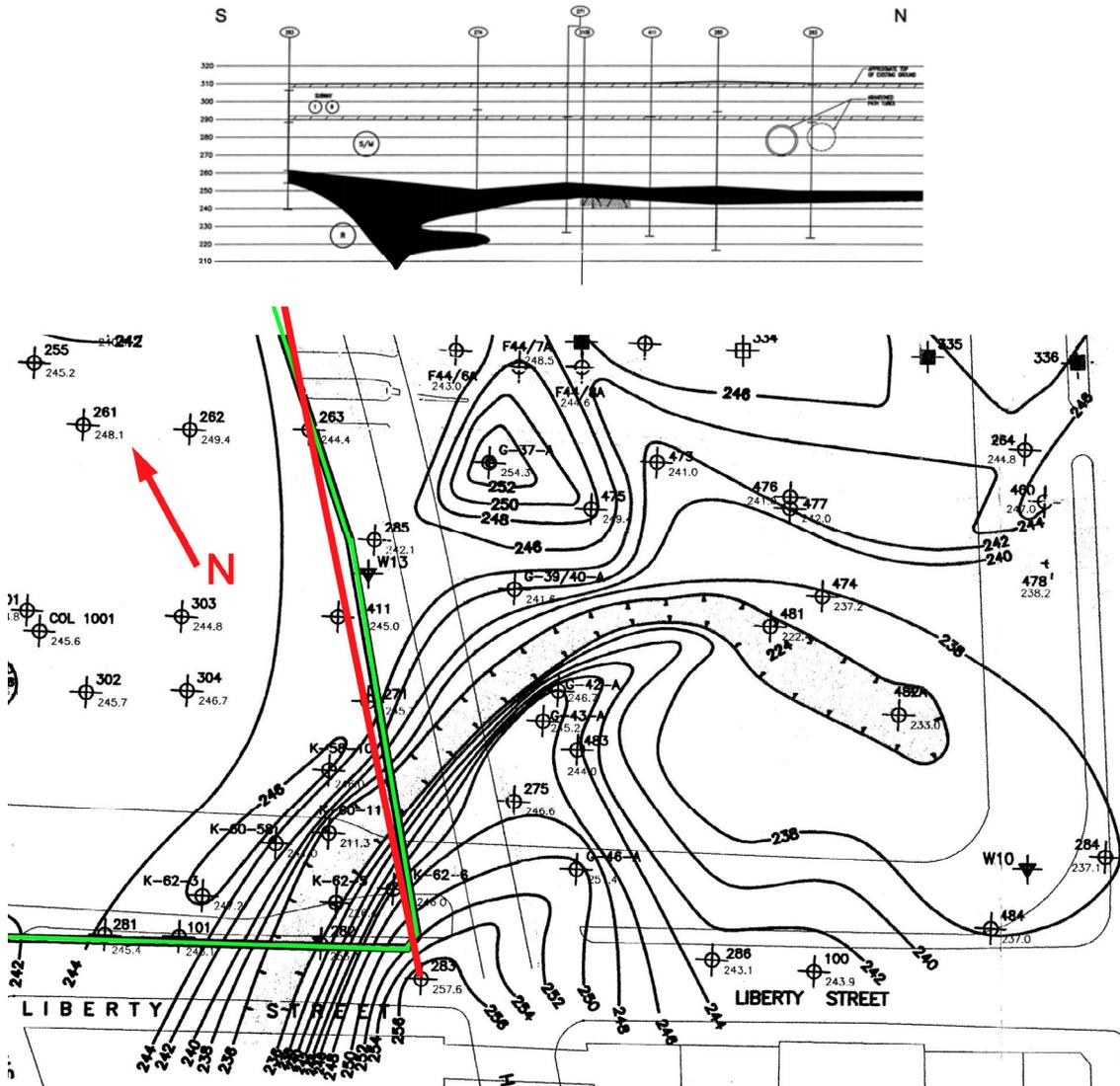


Figure 1 – SE corner of the World Trade Center site. Top - Cross-section along Greenwich Street at the corner of Liberty Street facing west, showing a ledge in the bedrock above a valley filled with boulders. Bottom - A contour map based on old borings shows where the boulder filled valley cuts across the SE corner of the West Bath tub slurry wall (green line). The red line shows the location of the cross-section. Elevation 300' is equal to El +2.653' on USGS Mean Sea Level Datum at Sandy Hook, NJ (1929 NGVD).

Five different episodes of brittle faulting and related jointing have been mapped in the New York City area based on studies in the Queens Water tunnel (Merguerian 2002). The general trends of the features range from the NW to the ENE, along with sub-horizontal structures (Table 1). Two of the fault groups trend NW-SE - the oldest Group A and the youngest (and potentially still active) Group E. The valleys in northern Manhattan along Dyckman Street and 125th Street follow known fault zones associated with Group E. It is very likely that the other NW trending valleys also are associated with zones of jointing and/or faulting.

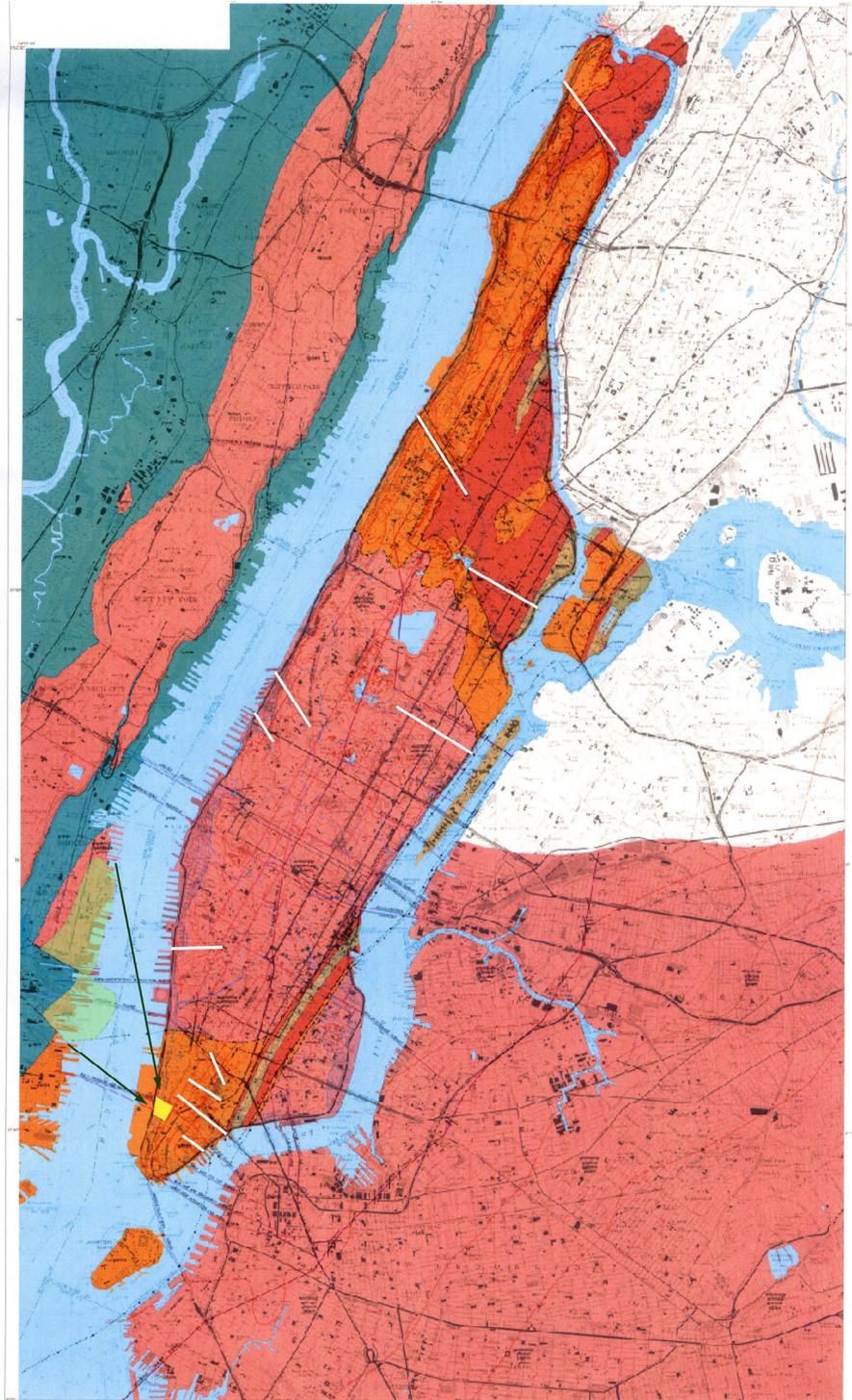


Figure 2 – The yellow box indicates the location of the World Trade Center Site. The white lines trace the locations of valleys that cut through the bedrock across Manhattan. These valleys are typically filled with glacial sediment, predominantly outwash sand and varved silt and clay. When present, glacial till is typically found directly above the bedrock. Areas colored in light green mark bodies of New Jersey serpentinite that are the source of the serpentinite gravel found in the WTC till, indicating glacial flow from the NW. (Basemap from Baskerville, 1994.)

BRITTLE FAULTS IN NEW YORK CITY

| GROUP | TREND | FAULT TYPE | CHARACTERISTICS |
|------------------------------------|---|--------------------|--|
| A Oldest | NW trend Gently SW dip | Normal and reverse | |
| B | ENE trend Moderate to steep dip | | |
| C | Sub-horizontal | | Long faults and fractures |
| D Younger than 295 Ma | NNE trend Steep dip | Dip - slip | Contains thick clay and zeolite-rich highly brecciated gouge zones |
| E Youngest | NW to NNW trend | Strike - slip | Contains sharp quartz filled contacts |

Table 1 – Characteristics of the brittle faults in NYC. There are also parallel joint sets associated with the fault groups. (Adapted from Merguerian 2002.)

According to Sanders and Merguerian (1998), during the Pleistocene, as many as 5 glacial advances passed over NYC, originating from either the NW or the NNE (Table 2). The most significant events, the advances that formed the Ronkonkoma and Harbor Hill terminal moraines, both came from a northwestern direction but predate the Woodfordian advance from the NNE. Glacial ice and meltwater flow was channeled into existing depressions and zones of weakness such as those created by faults and weathered joints. In an act of robbery and restitution, pre-existing features aligned with glacial flow directions were scoured out while those at a high angle to the advance were filled in with till. Glacial drift deposits were distributed throughout the area by melt water streams during retreat.

SITE GEOLOGY

Borings made in 2007, along with information we obtained during site construction, were analyzed to determine what type of bedrock discontinuity allowed a deep valley to be carved across the SE corner. Prior to the investigation three likely explanations were considered. One possibility was that the valley, like most others in Manhattan, followed a zone of faulting and/or jointing. Another option was that the valley ran along a void or dissolution cavity in the bedrock. Our investigations of the borings and early construction in the east bathtub area indicate that the bedrock consists of schist, gneiss, granofels, and amphibolite of the Hartland Formation along with pervasive pegmatite veins. Walloomsac (Figure 3) has been found in the excavations for Tower One, in the World Trade Center Memorial, and in borings made along West Street (Merguerian and Moss 2006). In the west bathtub some of the more calcareous layers

present were deeply weathered and showed signs of dissolution. Small clay-filled voids were encountered in borings and during construction. Thus, it is possible that the carved valley of this report is the result of extension of calcareous rocks into the east bathtub area.

A contact zone between two different rock types was the third explanation considered. It is common for rock to be more weathered at a contact, and consequently presents a path of weakness for a glacier to follow and differentially erode. If one rock type is more resistant to erosion than the other, the softer rock will be scoured away faster leaving an exposure of the harder rock behind.

| 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 Island dammed in on S by pre-Ronkonkoma terminal moraine. |
| | IIIC | | |
| Yarmouthian | | | Jacob Sand, Gardiners Clay. |
| Kansan(?) | IV | NNE to SSW | Gray till with decayed stones at Teller's Point (Croton Point Park, Westchester Co.); gray till with green metavolcanic stones, Target Rock, LI. |
| Aftonian(?) | | | No deposits; deep chemical decay of Till V. |
| Nebraskan (?) | V | NW to SE | Reddish-brown decayed-stone till and -outwash at AKR Co., Staten Island, and at Garvies Point, Long Island; Jameco Gravel fills subsurface valley in SW Queens. |
| | | | Pre-glacial (?) Mannetto Gravel fills subsurface valleys. |

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

Before any new construction could take place at the WTC site east of the existing bathtub, a new eastern slurry wall had to be built. A contour map was made of the top of bedrock in the east bathtub using all available subsurface information (Figure 4). The top of rock surface was gently undulating except in the southern quarter of the site. There the new information revealed that the valley consisted of two large bowl-like depressions in the center of the bathtub. Heading eastward into Church Street, construction of the new slurry wall indicated the depressions narrowed into a deep channel filled with boulders. Anecdotal evidence from drilling operations suggested that a bedrock ledge, similar to the one found in the west bathtub was also present at this point. The bedrock depressions

led west-northwestward into a deep narrow channel, the same one that cut the west bathtub. From the west bathtub the valley curves southwest off site below Liberty Street. The precise nature of this portion of the valley will not be known until the Deutsche Bank building is demolished and new construction can start on the south side of Liberty Street.



Figure 3 – Vertical asymmetric fold of Walloomsac calc-silicate and interlayered schist found in an excavation along the eastern edge of the west bathtub. (Digital image by C. J. Moss.)



Figure 4 – Bedrock contours in the East Bathtub based on the newest borings and construction data. The valley consists of two bowl-like depressions that trend WNW before heading SW into a narrow valley that runs offsite, below Liberty Street. Elevation 300' = El +2.653' (1929 NGVD).

Glacial Strata

The new borings indicate that directly above the bedrock the two depressions are filled with a boulder/cobble till. The boulders are very well rounded and range up to at least 4 feet in diameter. There are three locations where it is not clear if the boring was coring through a bedrock ledge before entering the boulders, or if there were boulders of native rock as large as 11 feet thick. It was extremely difficult drilling through the till, so from the samples taken, it could not be determined precisely what kind of matrix surrounds the boulders. The samples suggest it is a mix of gray and brown fine to coarse sand and gravel, with some silt and occasionally clay. The loss of fluid during drilling along with permeability tests run in the boulder till suggest that in places the matrix may be relatively loose and porous, rather than dense and impermeable as is often the case with till. Details will be revealed in Spring 2008 when additional excavation takes place. The layer of till is covered with red brown glacial lake silt. Borings done previously at the WTC site indicate that near West Street gray and brown till above bedrock is overlain by red brown outwash sand. The boulder field is an unusual anomaly.

Bedrock

Based on borings and our field investigations, the bedrock in the east bathtub is predominantly schist and gneiss with pegmatite veins cutting across the site. In the southern third of the site, however, large masses of pegmatite appear. These bodies are essentially identical to the ones that are present in the northwest corner of the west bathtub (Figure 5). At the WTC site schistose rock in contact with pegmatite tends to become more recrystallized and gneissic in character. This rock is significantly harder than the schist across much of the location, so it is typically more resistant to erosion. In each of the borings that contained the bouldery till, it was found directly above a layer of bedrock that was more gneissic than what was typical for the site.

The sediment load carried by the glacial ice and meltwater scoured away the softer rock, eroding it down to the zones of harder gneiss. The resulting depressions were then filled with the boulders and cobbles too large to be carried away by the swift currents and possibly trapped by the steepening walls around them. Ledges of hard bedrock may have been left behind as underlying weaker zones were cut out and glacial streams changed location (Figure 6).

What It's Not

We initially considered that a fault underlies the valley with fractured rock facilitating erosion. But no evidence was provided by the borings to suggest that there was a zone of faulting or jointing running through the site. The rock was generally hard and relatively massive, improving in quality with depth. Acoustic televiewer data obtained during the investigation for Tower One indicated that there was no preferred orientation for joints. Unlike Manhattan's known and likely fault related valleys, this one trends E-W to NE-SW.

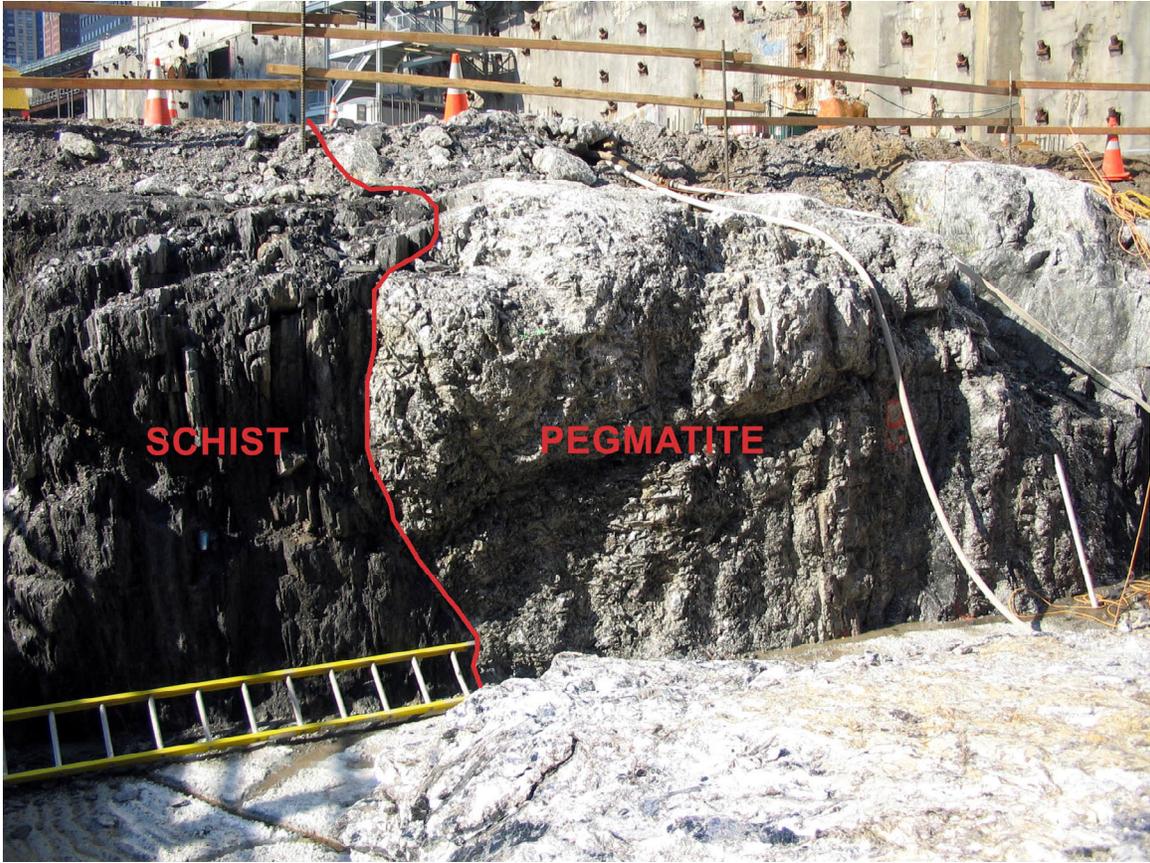


Figure 5 – Pegmatite intrusive (seen on the right) into schistose rock in the NW corner of the WTC site. The pegmatite is essentially the same in both the NW and SE corners of the site. (Image by C. J. Moss.)

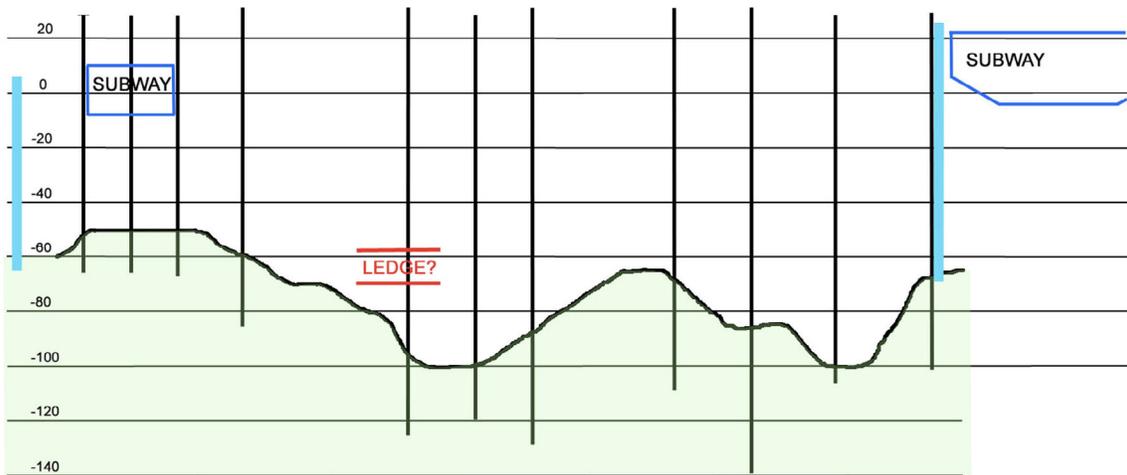


Figure 6 – Cross-section through the depressions in the east bathtub, facing north. Red lines show the location of either a ledge of bedrock or an 11 foot thick pegmatite boulder. Location of cross-section is shown in Figure 7. Elevation 0' is equal to El +2.653' on USGS Mean Sea Level Datum at Sandy Hook, NJ (1929 NGVD).

The boring program provided no evidence that the Walloomsac Formation was present in the eastern bathtub. Most of what was found in the west bathtub, however, was discovered during excavation rather than from the borings. If there is any dissolved calc-silicate present, it doesn't appear to have an influence on the E-W trending eastern stretch of the valley. As the valley heads offsite to the west it narrows and its trend turns to the SW. Acoustic televiwer data from Tower One indicated that foliation is generally very steep, almost vertical, and trends N-S to NE-SW. These orientations correspond to the limbs of vertical folds observed in the rock during construction, including a large fold of calc-silicate present in an excavation toward the east side of the west bathtub. (See Figure 3.) At this point, we can not rule out the possibility that calcareous rock influences the orientation of the valley offsite to the south.

What It Is

The contact zone between the pegmatite intrusives and the surrounding schistose rock is what controls the presence and nature of the glacial valley in the southeast corner of the WTC site. Along the western and southern sides of the east bathtub the bedrock is comparatively high and level compared to the rest of the site (Figure 7). This "plateau" is underlain by pegmatite. Towards the north and east, at the edges of the depressions, the rock becomes a mix of pegmatite and more schistose rock. Farther to the northeast, below the depressions, the rock is predominantly schistose. A mass of pegmatite was also found just east of where the valley crossed the slurry wall in the west bathtub. The pegmatite intrusives typically altered the surrounding rock infusing it with quartz and recrystallizing it as a more gneissic material. The hard pegmatite and gneiss are more resistant to the effects of glacial scour than the more schistose country rock.

Glaciers flowing from the NW would have carried sediment native to New Jersey, including markers such as red-colored sandstone, siltstone, shale and greenish serpentinite over the site. The sediments embedded in the ice and emanating from it in streams of meltwater exploited existing weaknesses and ground down the areas of softer rock. It is likely that meltwater, rather than ice, is primarily responsible for many of the features seen. Circular depressions with possible ledges filled with smooth and well rounded boulders and cobbles suggest raging meltwater swirling around, scouring out the bedrock while polishing the boulders until the more resistant underlying rock is reached.

IMPLICATIONS

The valley is significant in terms of construction, not just as a geologic curiosity. A "conventional" foundation for a high-rise would not be an option for this portion of the site. Numerous different designs were considered for the foundation of Tower 4, which is to sit directly above the valley. Ultimately, it was considered that the most prudent and cost effective solution would be to remove the boulder till completely. This excavation is currently underway.

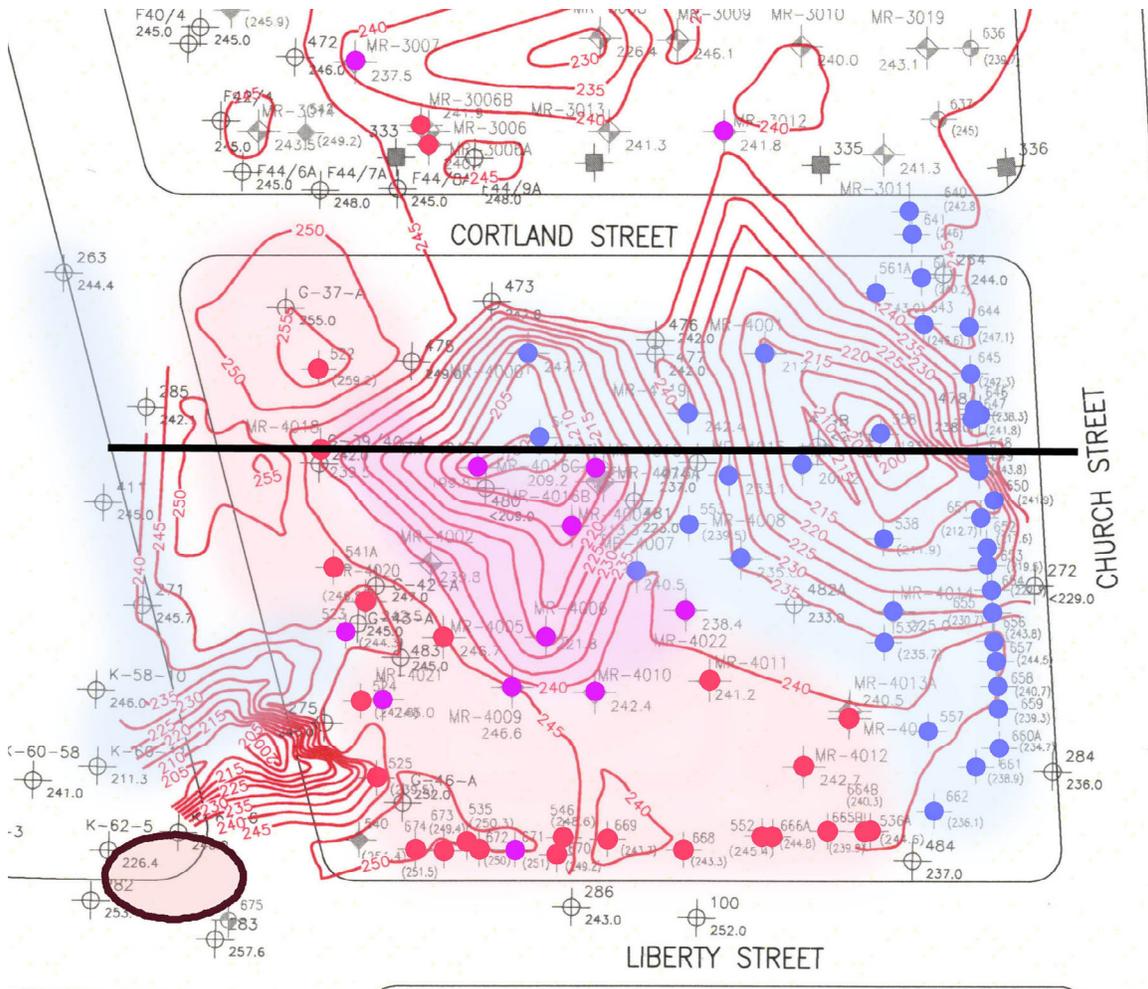


Figure 7 – Borings in pink are pegmatite, blue indicates schist and gneiss, purple indicates that a mixture of pegmatite and schist/gneiss is found in the boring. Construction of the west bathtub revealed a mass of pegmatite (circled) at the SE corner, on the SE side of the glacial valley. The valley and the rest of the slurry wall was in schistose rock. The black line shows the location of the cross-section in Figure 6. Elevation 300' is equal to El +2.653' on USGS Mean Sea Level Datum at Sandy Hook, NJ (1929 NGVD).

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