Newly Mapped Walloomsac Formation in Lower Manhattan and New York Harbor and the Implications for Engineers

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INTRODUCTION

Until the 1980's, geologic mapping in the New York City area identified 3 different major rock formations – the Fordham Gneiss, the Inwood Marble (formerly Limestone) and schistose rock previously called Hudson Schist, more recently Manhattan Schist. With the advent of plate tectonics, the Manhattan Formation was progressively divided into 3 structurally and lithologically separate formations – the Walloomsac, Manhattan and Hartland (Merguerian 2008, Merguerian and Sanders 1991b). While generally schistose in nature with overlapping characteristics, these 3 formations have differences, due largely to their origins, which can significantly affect the engineering properties of the rock.

Newer borings made in recent years in the vicinity of New York Harbor and lower Manhattan allow the ability to refine and update the current USGS geologic maps of Northern New Jersey and New York City. In particular, layers of the more distinctive Walloomsac Formation, previously mapped only in upper Manhattan and the Bronx, are being identified along both sides of the lower Hudson River.

GEOLOGIC HISTORY

New York City bedrock is a product of plate tectonics (more detailed information can be found in Merguerian 2008, and Isachsen and others 2000). As the continent of Rodinia was formed during the Grenville Orogeny roughly 1.1 Ga (billion years ago), a mix of igneous and sedimentary rocks were metamorphosed into the Proterozoic Y age Fordham Gneiss creating the basement rock for the region (Figure 1). Around 660 Ma (million years ago) Rodinia started to rift apart, opening up the Iapetus Ocean. Assorted shallow to deep-water sediments, along with rift-associated volcanics, started to cover the Fordham and the newly formed oceanic crust. About 550 Ma, the rift boundary switched to a converging one, and the North American plate started to subduct below the neighboring Iapetus plate. An arc of volcanic islands formed offshore of North America and the narrowing ocean continued to accept continental and volcanic arc sediments.

During the Cambrian and Ordovician, the shallow waters above the North American continental shelf were filled in with calcareous and dolomitic clean to muddy limestone (Figure 2), with local lenses of chert (the future Inwood Marble). Heading further out to sea, the continental slope and rise was covered with thick massive layers of silt and clay interrupted by occasional flows of continental sand and volcanics (future Manhattan Schist). The oceanic crust was covered with deep-water clay which, as the island arc formed and later advanced from offshore, was intermixed with periodic flows of island arc sand and volcanics (future Hartland Formation). By the Middle Ordovician, the narrowing ocean created a more isolated depositional environment on the shelf. The new sediments deposited over the previous shelf carbonates consisted of limestone layers overlain by organic and sulfide rich clays interlayered with sand (future Walloomsac Schist).

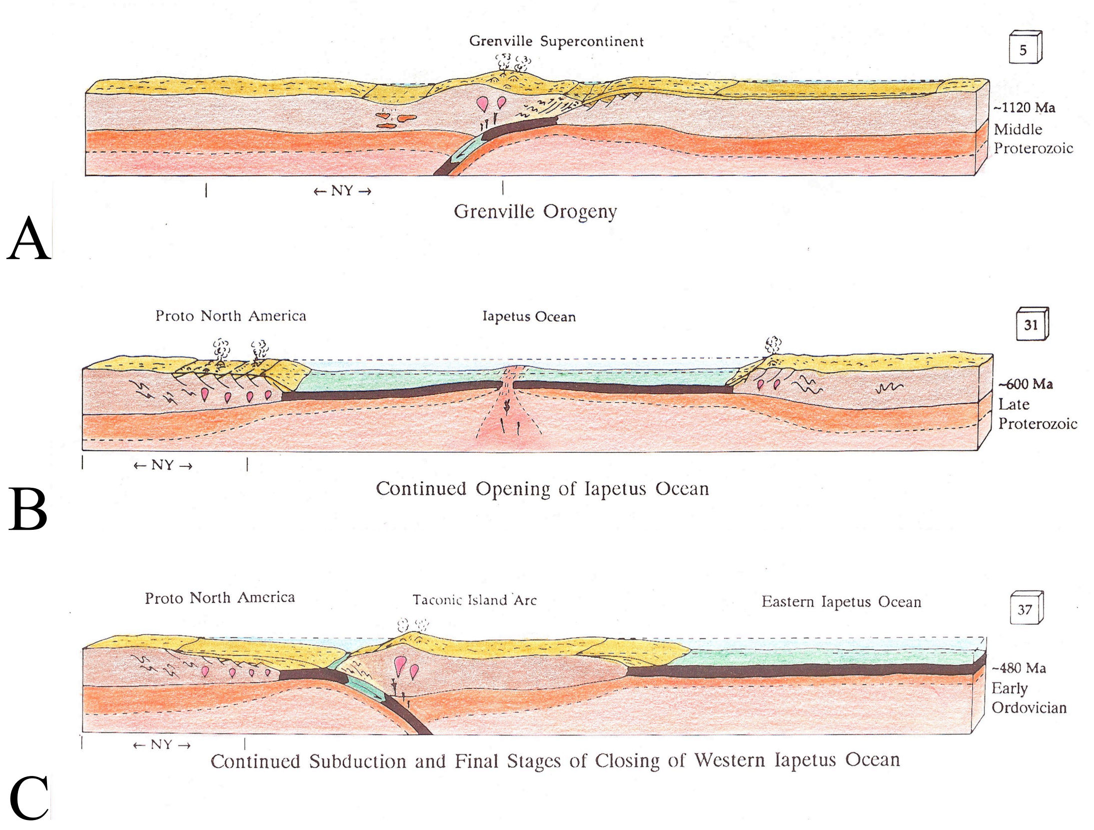

Figure 1 – A – Grenville Orogeny created the Fordham Gneiss, the basement rock for the NYC area. B – Rifting of Rodinia opened up the Iapetus Ocean, which filled with an assortment of sediments. C – Closing of Iapetus Ocean during the Taconic Orogeny thrust and folded the deposits together. Subduction under amphibolite facies metamorphism is largely responsible for producing the rocks seen today. Figures adapted from Isachsen and others 2000.

With continued subduction, the island arc began to scrape up, shuffle together and bury the sediments, marking the start of the Taconic Orogeny (Figure 2). The different sediment layers were folded internally and thrust over each other along ductile faults (Merguerian 2008). The allochthonous (transported) Manhattan formation was shoved over the autochthonous (native) Walloomsac along the St. Nicholas Thrust (called the Inwood Hill Thrust on the Baskerville NYC maps). The allochthonous Hartland was thrust over the Manhattan and underlying formations along Cameron's Line. Slices of oceanic crust were periodically caught up in the midst of this, resulting in small slivers and larger pods of serpentinite injected into and between the Hartland and Manhattan formations. The stacked formations were then pleated into a series of NNE trending, steeply folded anticlines and synclines that plunge gently to the SSW. This is the bedrock pattern that is visible on the regional geologic maps (Figure 3). Buried to a depth of 25 km or more, the formations were all subjected to amphibolite facies metamorphism, producing the rock seen today. While the schistose rocks that resulted are often quite similar, with overlapping characteristics, there are some distinct differences.

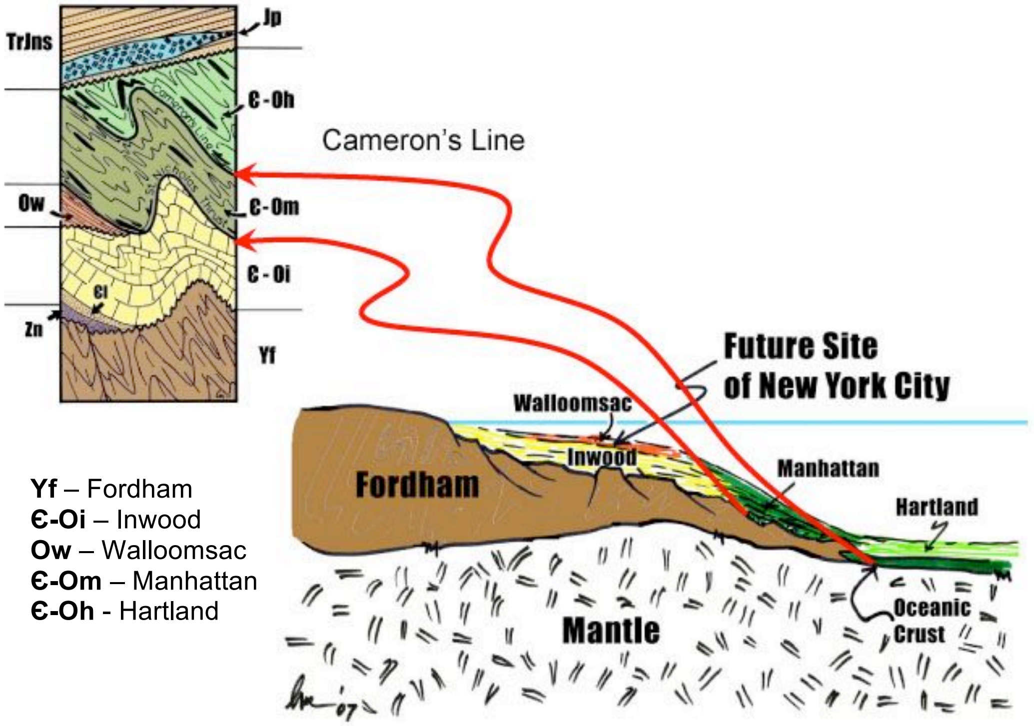

Figure 2 – Original offshore depositional environments of the NYC rock formations, subsequently stacked above each other along ductile faults during the Taconic Orogeny. Adapted from figures by C. Merguerian.

NYC ROCK CHARACTERISTICS

A variety of factors, influenced by the origin and history of the rock mass, can control the engineering properties of a formation (Merguerian 2008). The presence of a higher percentage of harder minerals, especially if the crystals have an interlocking gneissic or granitic texture, can make the rock much harder to drill through. Softer minerals, such as graphite or calcite, are easier to drill, but the rock is much more prone to weathering (Figure 4). A hard interlocking rock mass is produced when layers have been tightly folded in multiple directions and/or melted and recrystallized in place. Conversely, rock with distinct and laterally persistent layering – due to foliation, differences in original composition or highly laminated and/or mylonitic texture along shear zones – is generally easier to excavate by splitting the rock along the layers (Figure 5). (So much so that, depending on the orientation of the feature, extra care may need to be taken to support the rock during excavation.) Nature exploits these weaknesses too, often concentrating joints and/or weathering along the layering.

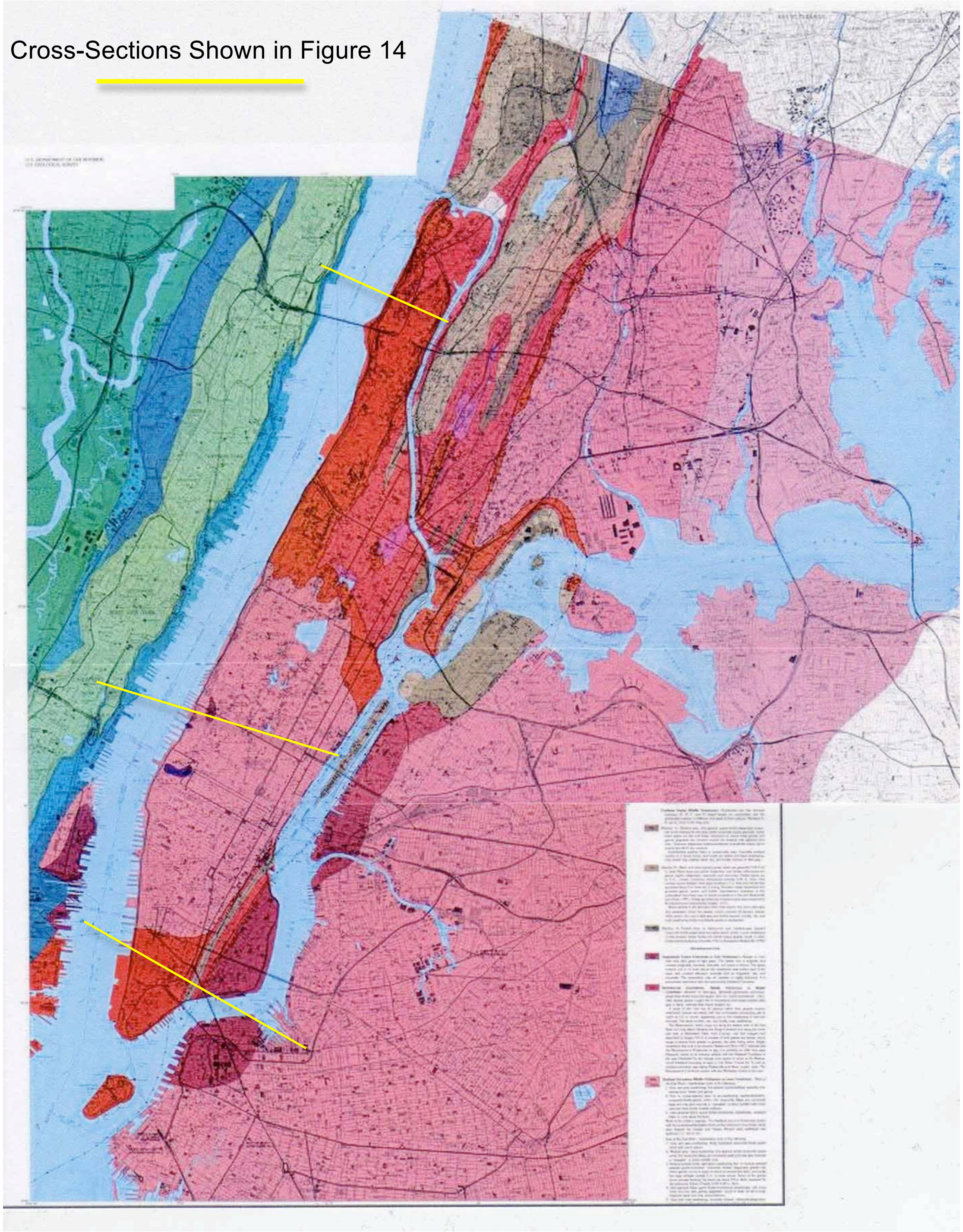

Figure 3 – Two bedrock geologic maps of NYC edited by Baskerville (1992 and 1994) combined into one. Formations have been folded into a series of NNE trending anticlines and synclines that plunge gently to the SSW, producing the elongated and curved patterns seen on the map. Baskerville divides the schistose formations into the 3 separate units – Walloomsac (Ow), Manhattan (Є-Om) and Hartland (Є-Oh).

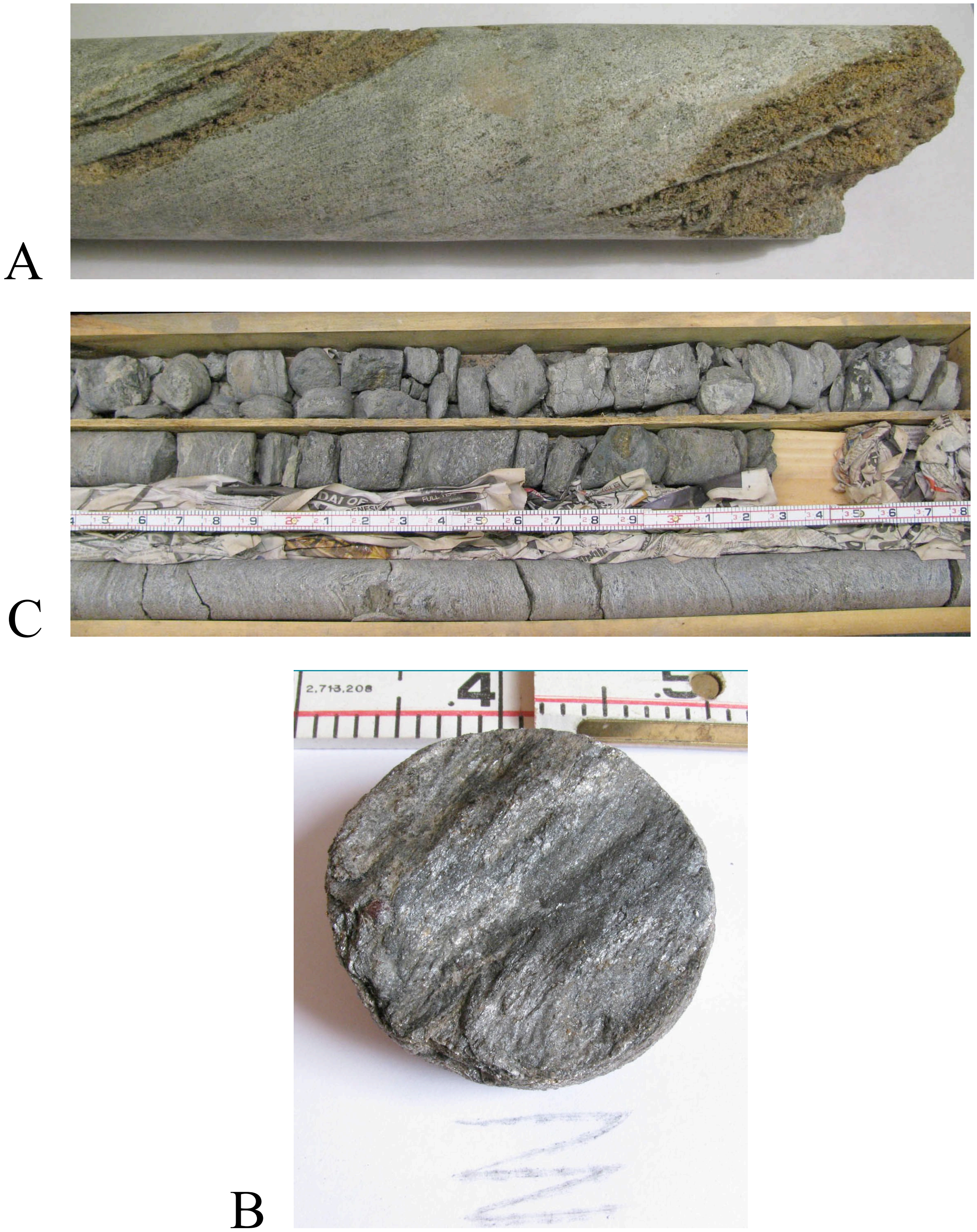

Figure 4 – (A) Walloomsac calcite-diopside marble from a couple blocks SW of the WTC site. The weathered end at right led into a 2 foot void in otherwise solid bedrock. Weathering is concentrated in the more calcitic layers. (B) Walloomsac graphitic schist from New York Harbor/Bayonne. Due to the presence of graphite it "writes". The softer minerals and soluble calcite make the Walloomsac Formation more prone to weathering. (C) From the same site as (B), the top 2 core runs are weathered graphitic schist, the bottom run is unweathered Hartland schist. While the well foliated, highly micaceous Hartland is generally softer than the Manhattan Formation, it is more durable than the graphitic and/or calcitic Walloomsac. (Digital images by C. J. Moss.)

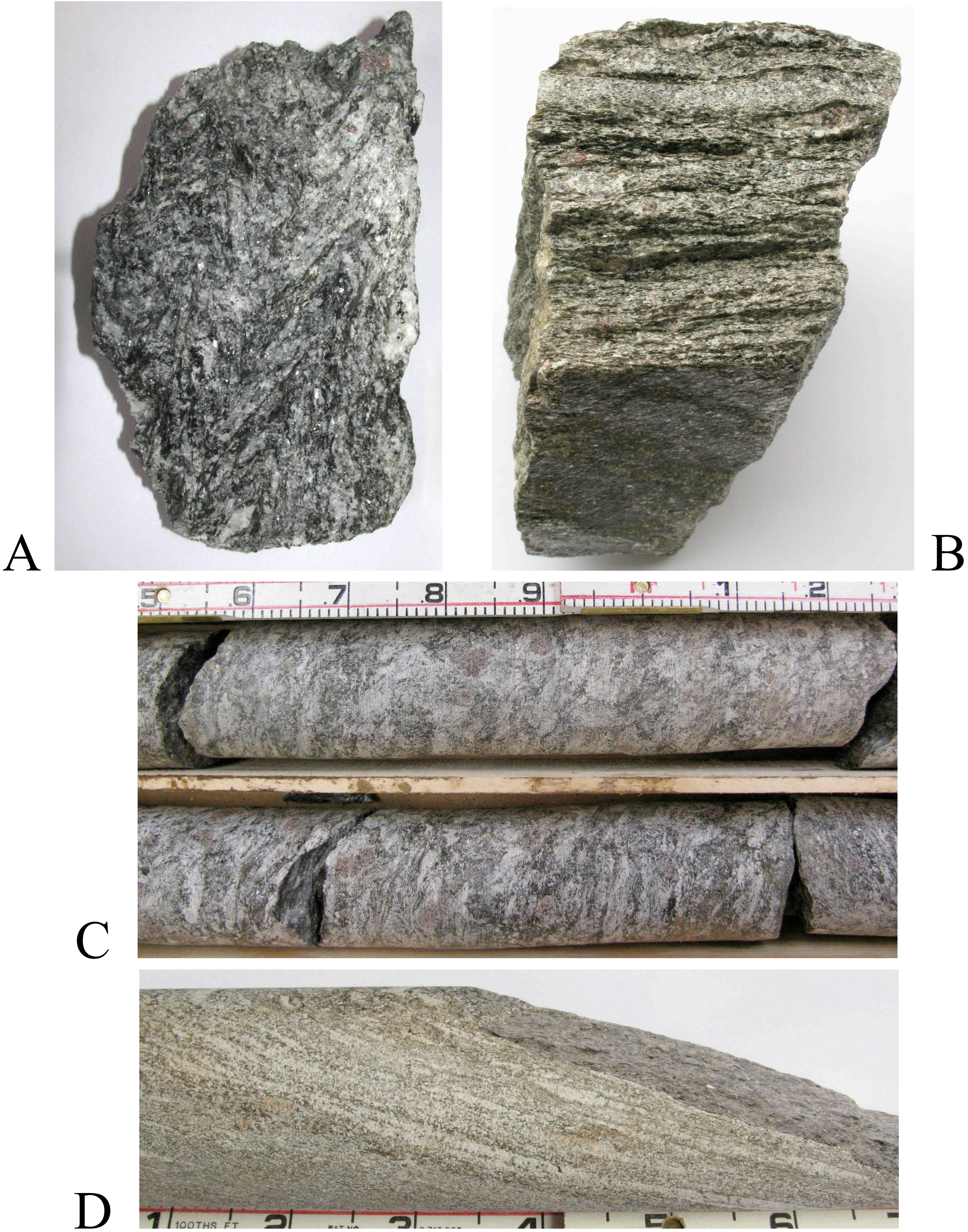

Figure 5 – A rock mass with tight folds (A) or gneissic structure (C) tends to produce an interlocking harder rock mass. Straight layers produced by foliation (B), laminated and/or mylonitic texture from shearing (D), or compositional layering results in a rock mass that is easier to split. (A) is Hartland from the southern tip of Manhattan, (B) is Hartland from the WTC site, (C) is Manhattan Formation from near Marcus Garvey Park in upper Manhattan and (D) is Hartland from near West and Leroy Streets. (Digital images by C. J. Moss.)

The NYC rock formations are described in the Baskerville maps (1992 and 1994) and Merguerian has extensively mapped and explained in great detail the NYC bedrock and its structure (Merguerian 1996, 2008). A more general summary of the dominant units and their properties follows.

Fordham – The basement Fordham Gneiss was originally metamorphosed to the higher-grade granulite facies during the Grenville Orogeny, and subducted a second time during the Taconic. Consequently, it tends to be a very hard, massive, coarse grained, poorly foliated rock, predominantly a gneiss with lesser amounts of schist. The rock consists of quartz, feldspar and mica with varying amounts of amphibole, pyroxene, plagioclase, and garnet (Figure 6).

Figure 6 – Fordham Gneiss. – quite variable, but more often a gneiss than schist. (Digital image by C. J. Moss.)

Inwood – The overlying autochthonous Inwood Marble is typically a coarse to fine grained calcitic or dolomitic marble with layers of calcareous schist and occasional lenses of cherty quartz. The more siliceous layers contain tremolite, phlogopite, actinolite, quartz, and diopside. The calcareous layers are frequently massive, while the more siliceous zones tend to be more foliated and schistose. The schists are still calcareous, so they are easily distinguished from the other NYC schistose rocks. The formation is prone to weathering in general, and it's often especially pronounced in the well-foliated micaceous zones where the phlogopite is commonly replaced by chlorite (Figure 7). Voids, open or sediment filled, are occasionally present.

Figure 7 – Inwood Marble – contains both massive marble (upper left corner) and calcareous schist (bottom). The weathered joint in the calcareous schist is colored green with chlorite. (Digital image by C. J. Moss.)

Walloomsac – The autochthonous Walloomsac is a discontinuous formation deposited above the Inwood. It consists of a fissile fine to medium grained pyritic and/or graphitic schist that contains layers of granofels, calcite and dolomite marble and calc-silicate rock (Figures 4 and 8). Layers of amphibolite are not present. While the schistose layers are generally well foliated, the marble and calc-silicates tend to be more massive. Mineralogically, the schist is composed of biotite, muscovite, quartz, plagioclase, kyanite, sillimanite, garnet, pyrite, and graphite and the marble and calc-silicates contain diopside, tremolite and phlogopite. Due to the presence of softer graphite and/or soluble carbonates, the rock tends to weather more readily than the other NYC area schists and the calcareous portions occasionally contain voids.

Manhattan – The allochthonous Manhattan consists of medium to coarse grained gneiss and schist. The typically massive formation tends to lack internal layering, however it does have present layers of amphibolite and occasional granofels. The primary minerals are biotite, muscovite, plagioclase, quartz, garnet, kyanite and sillimanite. The rock is generally harder and more resistant to weathering due to the presence of the hard minerals garnet, kyanite, and sillimanite, and its more massive, less interlayered structure (Figure 5C).

Hartland – The allochthonous Hartland formation is primarily a fine to coarse grained, well-foliated schist and gneiss, with compositional layers of granofels and amphibolite surviving from strata in the original rock. Dominant minerals are muscovite, quartz, biotite, plagioclase, kyanite and garnet. The Hartland's high mica content, well-developed foliation and frequent interlayering tends to make it softer than the Manhattan, but still more durable than the Walloomsac (Figures 4 and 5).

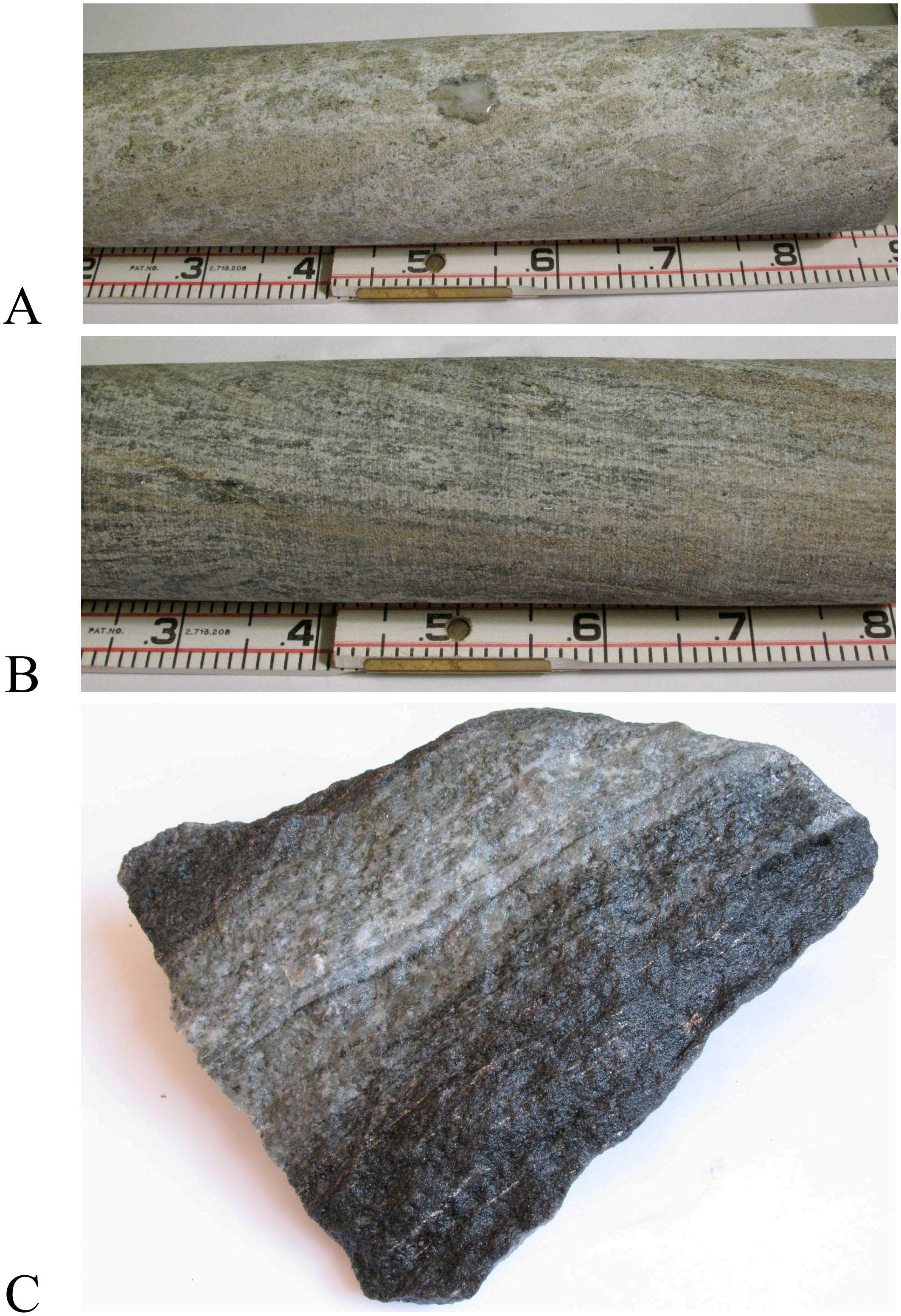

Figure 8 – Walloomsac Formation – (A) Calcite-diopside marble from near West and Leroy Streets. (B) Calc-silicate from West 21st Street near 10th Avenue. (C) Interlayered pyritic Walloomsac schist and calcite-diopside marble from the World Trade Center site. (Digital images by C. J. Moss.)

Granites – All of the NYC rock formations are intruded by fine to very coarse-grained granites. Composed of microcline, orthoclase, quartz, plagioclase, biotite, hornblende, muscovite, and garnet, they take the form of veins, dikes, sills, stocks, and small plutons. Smaller veins of anatectic granite are also present. As igneous rocks, the bodies tend to be unfoliated and are generally very hard (Figure 9).

Figure 9 – Pegmatite. As an igneous rock, the crystals are interlocking and unfoliated. (Digital image by C. J. Moss.)

Sheared Contacts/Serpentinite – Mostly separated by ductile faults, the contact zones between the formations are sometimes defined by highly sheared (Figure 5D), micaceous, laminated and/or mylonitic rock and/or slivers of serpentinite. This rock is often softer and/or more fissile than the main rock mass. When present, the serpentinite takes the form of scattered slivers and pods usually within, or in contact with the Hartland. It is a fine-grained rock containing serpentine group minerals including chrysotile (asbestos), chromite, magnetite, orthoamphibole, magnesite, talc, calcite, chlorite, and relict olivine and pyroxene (Figure 10). The rock ranges from massive to schistose (very rarely fibrous where asbestos is a significant component), often surrounded by zones of chlorite, talc and/or mica schist. Consequently, the rock generally tends to be rather soft, though depending on the specific mineralogy can be quite hard.

Figure 10 – Serpentinite. Serpentinite from near West and West 19th Streets that was interlayered with Hartland schist. A neighboring site reported concerns with soft, highly micaceous and well-foliated rock (Altuntas and others 2008). (Digital image by C. J. Moss.)

GEOLOGIC MAPS

The Bedrock Geologic Map of Northern New Jersey (Drake and others 1996), published by the USGS in 1996, does not differentiate the basement rocks immediately west of the Hudson River, except for the bodies of serpentinite and the neighboring Paleozoic schist, which it identifies only as the Manhattan Formation (Figure 11). The map uses a general version of the Hall (in press) definition of Manhattan, without separating it into the A, B and C members that Hall used for his mapping in Westchester. More recent research (Merguerian 1983, 1986, 1994) has identified the A member as the Ordovician Walloomsac Formation. The B and C members are grouped together as the Cambro-Ordovician Manhattan Formation. Another unit that in the past had been mapped together with the Manhattan was determined to be the Hartland formation. Separated from the Manhattan and the autochthonous rocks by Cameron's Line, the formation was first identified in Connecticut and progressively extended southwest through Westchester and into New York City (Hall 1968, Merguerian 1983, 1986). The USGS New York City maps compiled by Baskerville (1992 and 1994) show all 3 of these map units (Figure 3).

Borings made in recent years in the vicinity of New York Harbor and in lower Manhattan allow the ability to refine the mapping of these schistose formations (Figure 12). On the New Jersey side of the Hudson, much of the rock mapped as Manhattan appears to be Hartland. The northernmost sliver of Manhattan on the New Jersey map was mapped on Baskerville's NYC map as Hartland. Merguerian (2003) also mapped most of the NJ schists as Hartland. However, borings from Bayonne, NJ drilled at piers into the New York Harbor Upper Bay indicate that in that general location the mapped Manhattan is actually the Walloomsac. Previously identified in one boring (Merguerian 2003), new borings made in the vicinity help expand and define the range of the Walloomsac.

In the Harbor, the Walloomsac consists of dark gray graphitic and pyritic schist; the marble and calc-silicates were not encountered. Landward, it lies nonconformably below the overlying Triassic Stockton sandstone and shale. Towards the center of the Harbor, it is in contact with the Hartland at the end of the pier line (Figure 4). This mapping, along with proprietary data in MRCE files, indicates the Stockton is actually found further to the east of the contact that is shown on the NJ map. The absence of serpentinite between the contact of Walloomsac and Hartland indicates that the serpentinite is not a continuous body stretching from Hoboken southward through Staten Island. Instead it is made up of separate, though large, masses along the western side of the Hudson. Landward the surficial Stockton and Walloomsac are badly weathered, but the Walloomsac becomes more competent closer to the contact with the Hartland, which is only slightly weathered, even at top of rock. Soren (1988) places Hartland in the NE corner of Staten Island, and Merguerian (2003) has mapped Hartland across the harbor and into lower Manhattan.

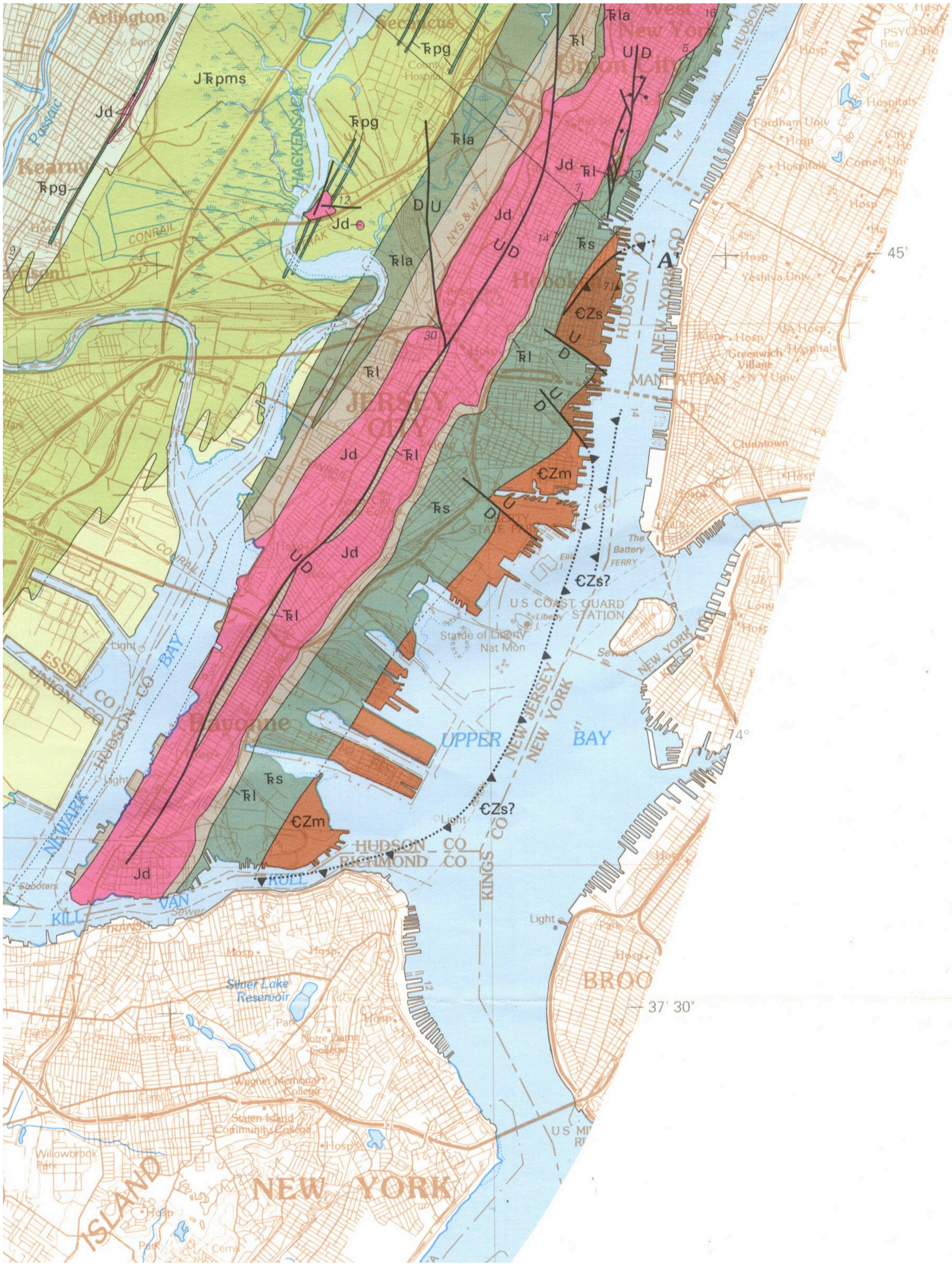

Figure 11 – New York Harbor area of the USGS bedrock geologic map of northern New Jersey (Drake and others 1996). The only basement rock identified on the map is the serpentinite (€Zs) and neighboring schist (€Zm), which is defined using a general description of the Manhattan Formation. The schist is not separated into the 3 formations mapped by Baskerville in the NYC maps.

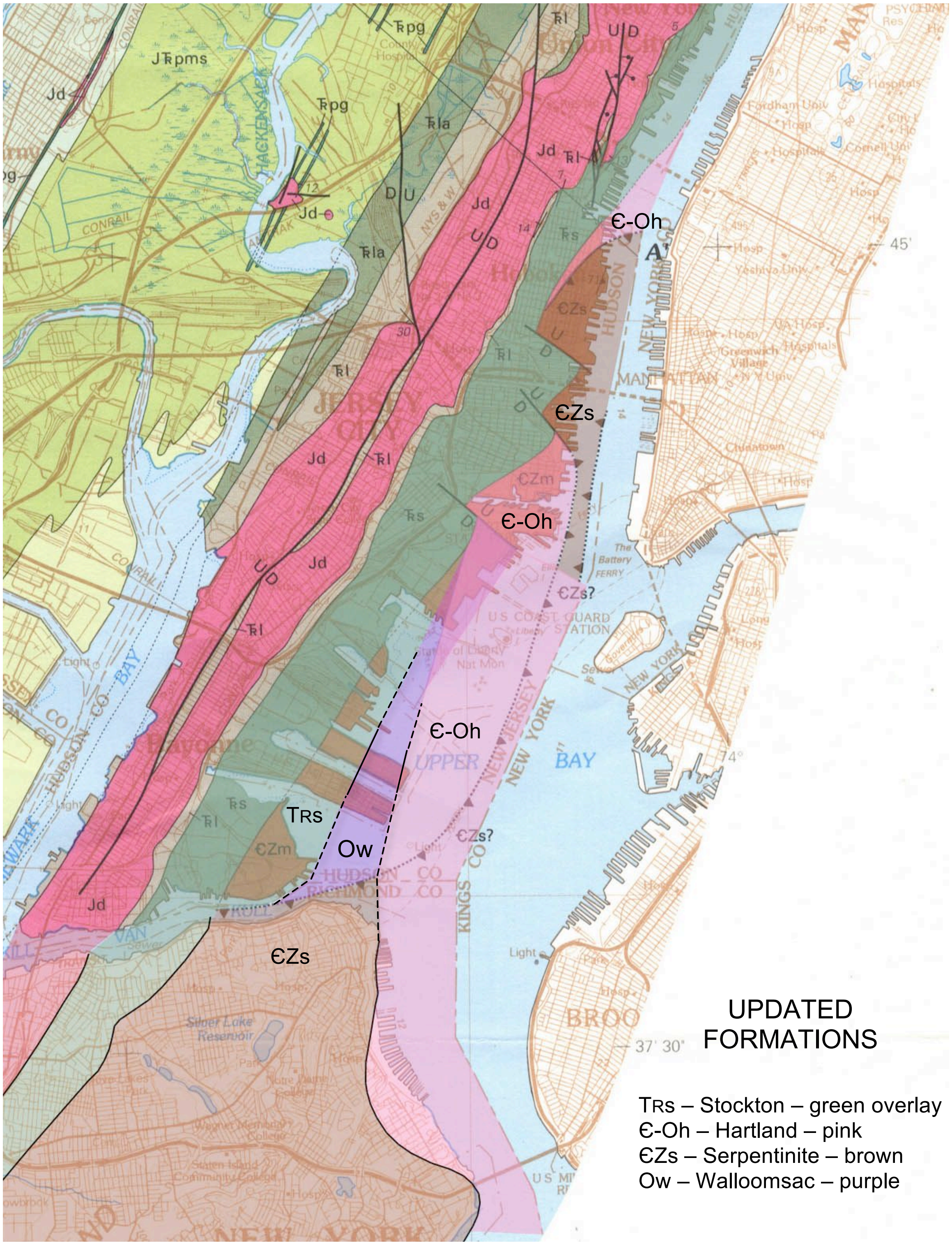

Figure 12 – New Jersey geologic map (Drake and others 1996) updated based on information from new borings. Color overlays show updated contacts. The Stockton Formation is found further to the east, Hartland is further to the west, and in the Harbor the undifferentiated Manhattan is actually the Walloomsac (formerly the Manhattan member A). The serpentinite is made up of separate bodies rather than forming a continuous unit from Hoboken to Staten Island. Updated map also incorporates mapping from Soren (1988), Baskerville (1994), Merguerian (2003), and MRCE files.

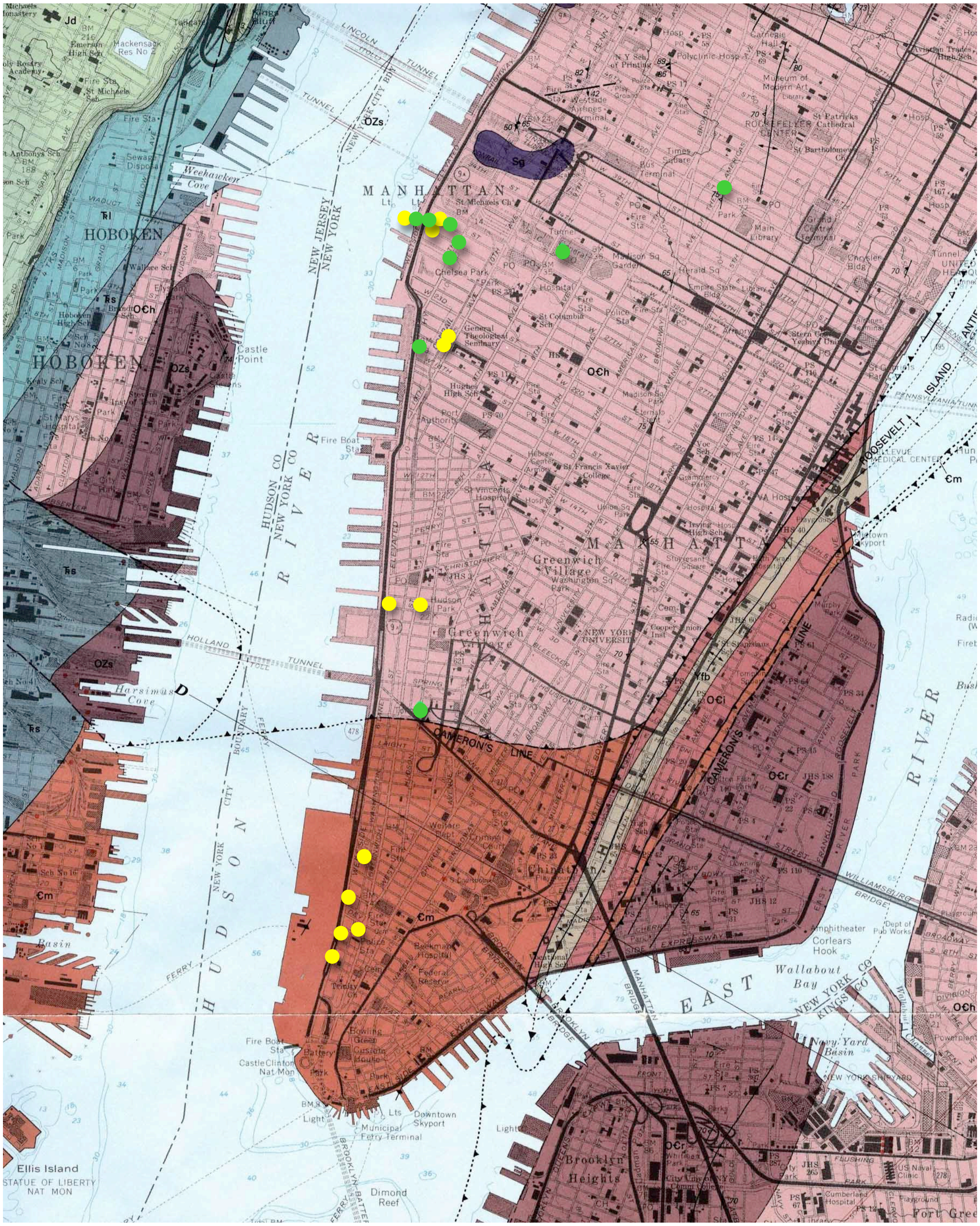

Figure 13 – Baskerville (1994) NYC bedrock geologic map updated with newly identified locations of the Walloomsac Formation. Yellow dots are sites containing layers of Walloomsac mixed with Hartland – a contact associated with Cameron's Line. Green dots are locations of serpentinite – also associated with Cameron's Line. The sites lie in a roughly 2 block wide zone along the shoreline that stretches from Albany Street northward to around West 29th Street.

Borings made in lower Manhattan at, and in the vicinity of, the World Trade Center also encountered layers of Walloomsac. Pyritic schist, calc-silicate and calcite-diopside marble (Figure 8) were all mapped at the WTC site (Merguerian and Moss, 2006), interlayered with the Hartland. Bedrock excavated at the site was quite hard and massive, with the few zones of minor weathering and voids (likely filled with soil) concentrated in the Walloomsac. These units were also mapped at several locations in lower Manhattan running in a N-S trending line between West and Greenwich Streets from Albany Street just south of the WTC northward to around West 29th Street (Figure 13), which is roughly where the orientation of the island's shoreline shifts to the NNE. Serpentinites have also been found in or near this zone at several locations in the 20's (MTA/NYCT 2006, THEP 2007, 2009) and in the vicinity of Canal Street (Ciancia 2007). Mylonites are reported around W 29th Street (THEP 2009).

In Baskerville's NYC maps (1992 and 1994), Walloomsac is only seen in small zones in the Bronx and northern Manhattan. Along Manhattan's lower west side; the Manhattan is mapped south of Watts St., the Hartland to the north, with the associated Cameron's line running in an east-west orientation (possibly to connect serpentinite in Manhattan with serpentinite in NJ). Neither of the ductile thrust faults is mapped at the bedrock surface following the N-S trend of the shoreline. The map's cross-section through lower Manhattan shows all of the strata shoved into a series of steep folds (Figure 14), with only the Manhattan reaching the surface along the lower west side. The cross-section that cuts through mid-town shows a thick, flat layer of Hartland over the Manhattan, lacking the folded strata below. The steep folds reappear in the cross-section cut through upper Manhattan.

Mapping in the vicinity of the WTC indicates folds and/or thrusts of the Walloomsac surface through "windows" in the Hartland, with the usually intervening Manhattan Formation absent (Merguerian and Moss 2006). Apparently one of these windows runs along the N-S trending stretch of Manhattan's southwest shore, although further mapping would be needed to determine the precise nature of the structure. One possibility is that the window roughly follows the western limb of a SSW plunging anticlinal fold of Walloomsac. Another is that numerous smaller folds and/or slivers, likely following the regional NNE trend seen in both northern and southeastern Manhattan, periodically rise up into a window of unknown origin that extends up to at least 29th Street (Figure 15). Merguerian (2010) places the sheared mix of Walloomsac, Hartland and serpentinite within a larger regional antiform that loops around the southern end of New York City.

While most of these slivers of Walloomsac are likely too small to be mapped at 1:24,000 scale in Manhattan, their presence should not be ignored. The West Street zone of interlayered Walloomsac and Hartland should be of interest to engineers. The zone has the potential to have the voids (open or sediment filled) and/or more highly weathered pockets associated with the Walloomsac. It can also have the sheared rock and/or slivers of serpentinite associated with rocks adjacent to Cameron's Line.

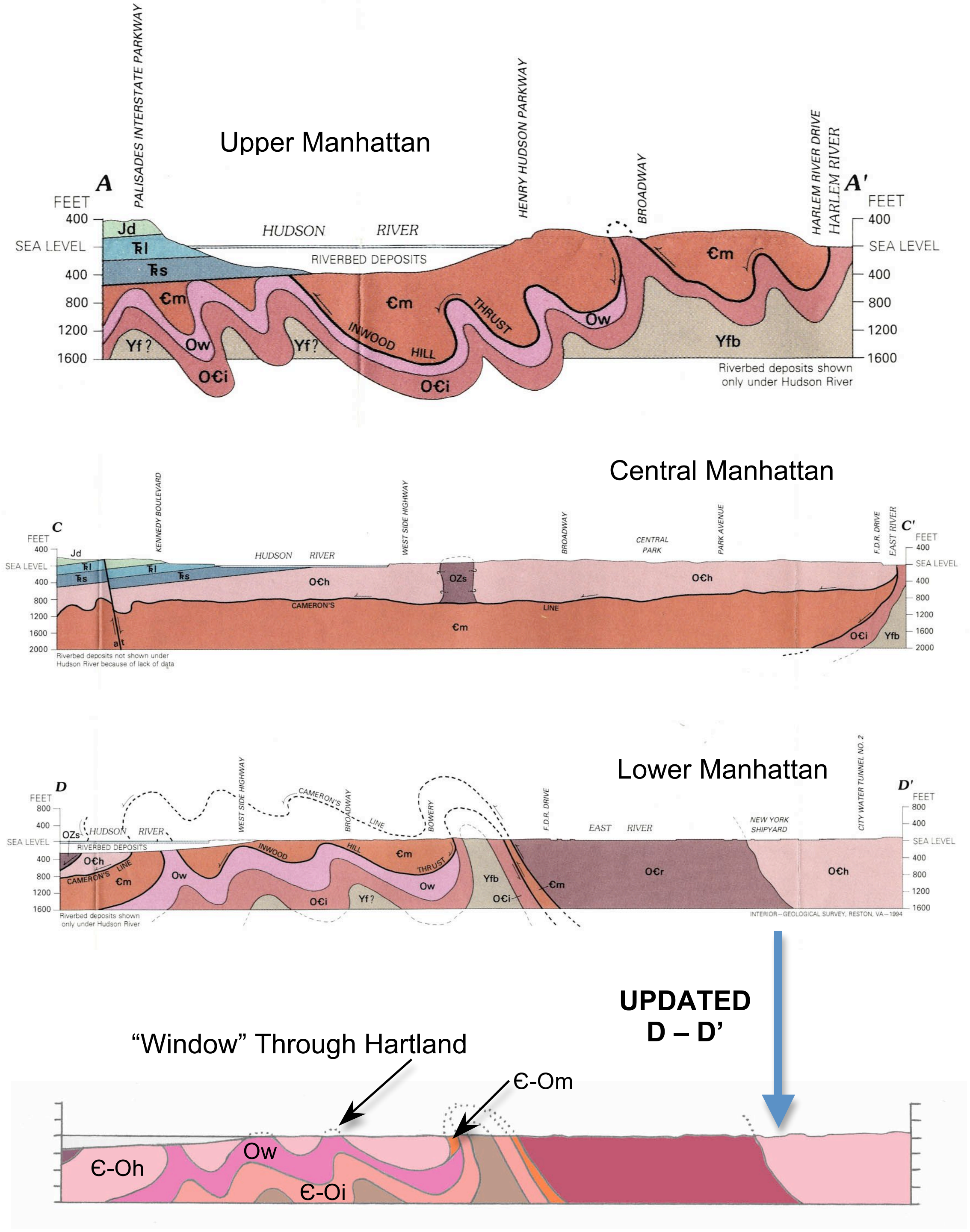

Figure 14 – East-west cross-sections through upper (A-A'), central (C-C') and lower Manhattan (D-D') from the Baskerville (1994) NYC geologic map (Figures 3 and 13). Bottom – Cross-section D-D' can be updated schematically by recent mapping at the WTC site (Merguerian and Moss 2006) that indicates that folds and/or thrusts of the Walloomsac (Ow) are seen through "windows" in the structurally overlying Hartland (Ꞓ-Oh). Manhattan (Ꞓ-Om) is not continuously present between the two formations.

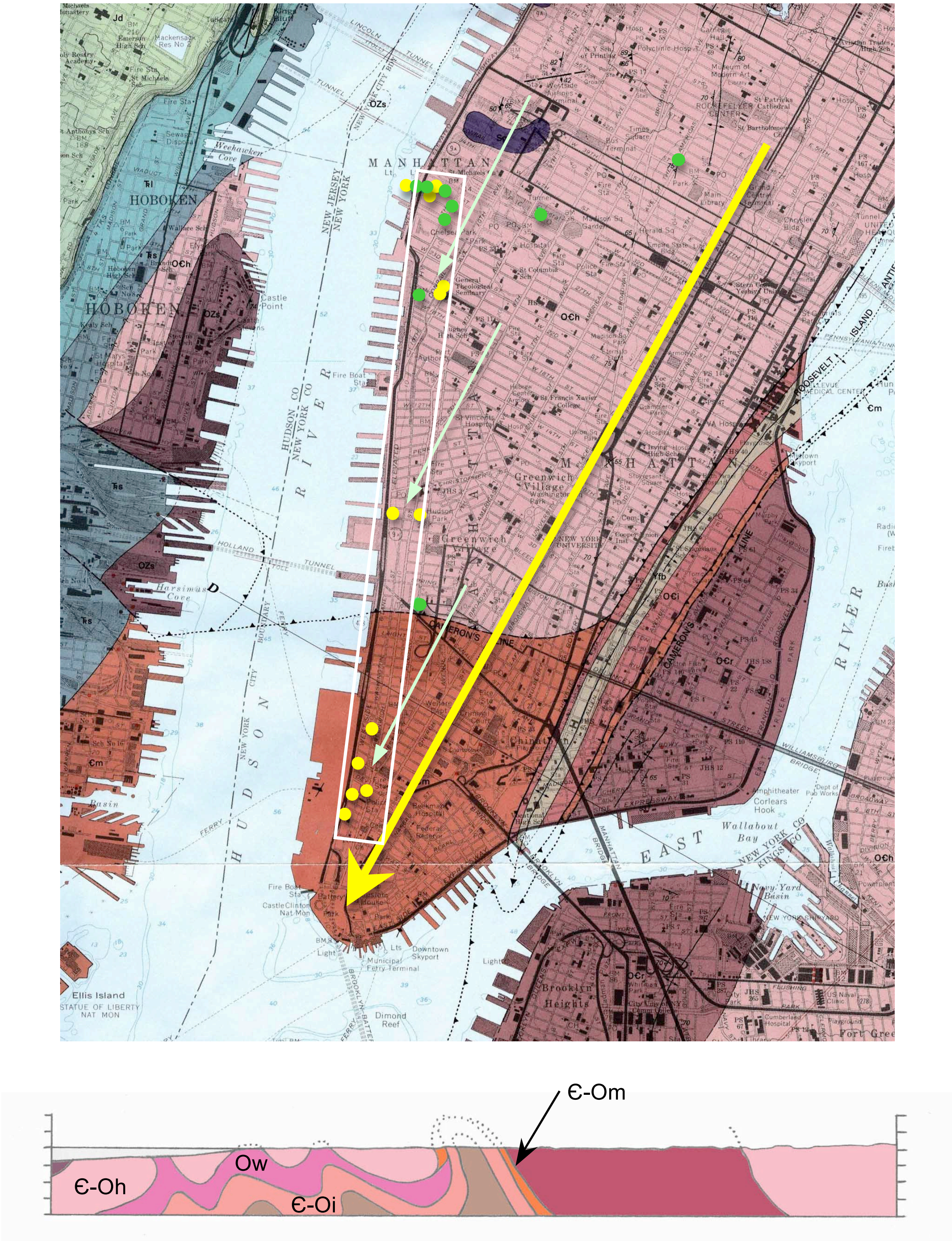

Figure 15 – A structural window that exposes the Walloomsac Formation runs along West Street. Possibilities – it may follow the trend of a western limb of a SSW plunging anticline (represented by the yellow arrow), or expose the ends of multiple folds likely following the NNE regional trend (represented by the light green lines).

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