DUKE GEOLOGICAL LABORATORY

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TRIPS ON THE ROCKS

Guide 04: Staten Island and Vicinity, NY and NJ

Trip 04: 15 April 1989; Trip 19: 29 September 1991

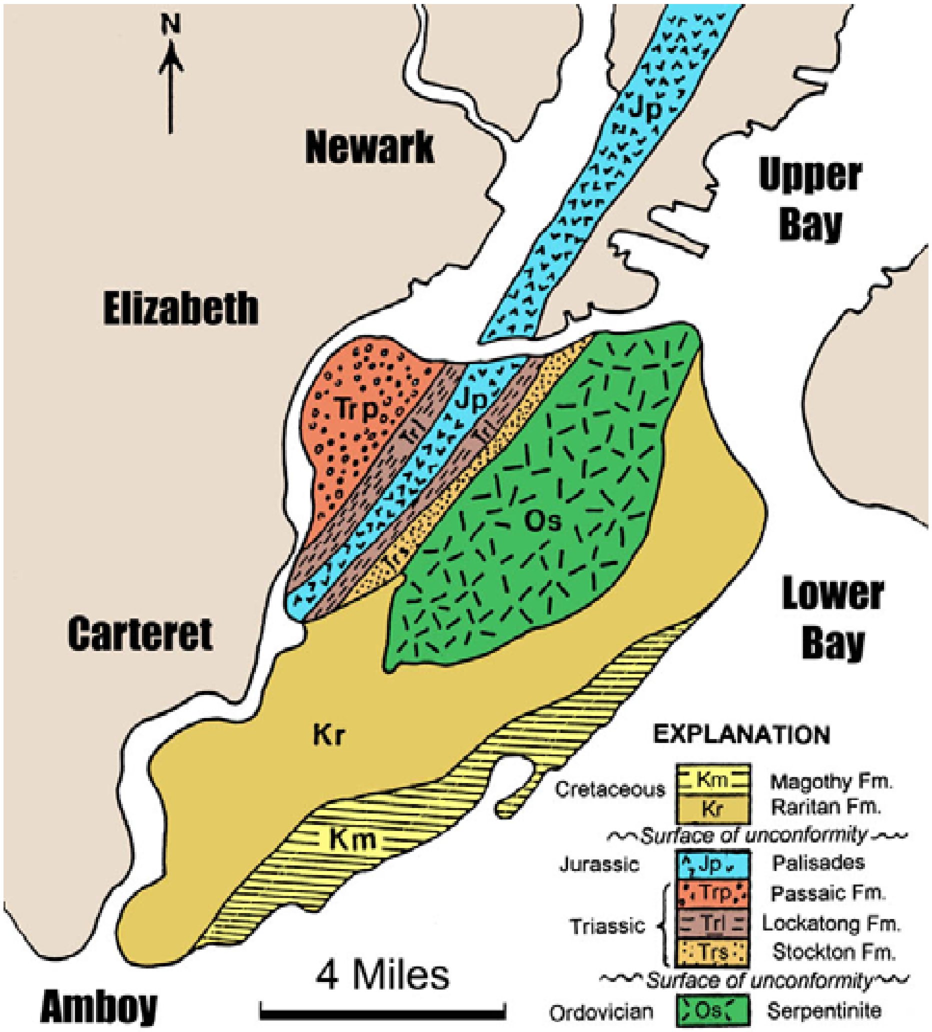

Figure 1 – Geological map of Staten Island, with extension of Palisades intrusive sheet northeastward onto mainland. (After Epstein and Lyttle 1987 and Okulewicz 1988.)

Field Trip Notes by:

Charles Merguerian and John E. Sanders

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INTRODUCTION

Today's field trip to Staten Island and vicinity (Figure 1, on cover) is intended to introduce the participants to the wide range of geologic features to be found southwest of Manhattan Island. Staten Island occupies a strategic position within the New York City region: nearly all the major geologic units are present. Despite this strategic position, however, bedrock exposures are scattered and scarce. Individual units can be examined easily, but the critical contact relationships among them are not visible. After the units of the bedrock had formed, Staten Island experienced a complex history of drainage development through a span of geologic time that is not well constrained and of at least three episodes of glaciation during the Quaternary.

Table 1 presents a version of a geologic time chart for comparing the names of the geologic time subdivisions, such as Ordovician, Triassic, Jurassic, and Cretaceous, shown on the bedrock map, with estimates of numbers of years for their boundaries and a list of some important local geologic events. Table 2 summarizes the major local geologic units in terms of layers designated by Roman numerals. The area of our field trip is shown on the geologic map of the Newark 1/250,000-scale quadrangle (Lyttle and Epstein, 1987). Tables 3 and 4 refer to the Pleistocene formations.

On Staten Island rocks from Layers II, V, and VI are all in erosional contact. That is, the rocks of Layer II, many of which formed at depths of 20 kilometers or more, were elevated, exposed at the Earth's surface and eroded. Later, they subsided once more and materials to form Layer V were deposited above them. Still later, rocks of Layer V and Layer II were tilted, elevated, and eroded. In turn, Layer V subsided and across its truncated, tilted edges, the sediments that form Layer VI were deposited (Figure 2).

The rocks from each of these layers formed in totally contrasting plate-tectonic settings. The rocks of Layer II accumulated as sediments along a passive continental margin that trended E-W and was located near the Earth's Equator. These sediments were deformed and metamorphosed in a convergent-margin setting. The sediments constituting Layer V collected in the Newark Basin, in a rift-valley setting not near any plate margin. The sediments of Layer VI were deposited along the passive continental margin of eastern North America, which came into existence when the Atlantic Ocean began to open and that still prevails today. The settings of Layer VI and the early phase of the formation of Layer II are analogous.

Exposures- and subsurface relationships on Staten Island contribute important information about the Pleistocene history of the New York City region. (See Table 4.) Present on southwestern Staten Island is a Lower Pleistocene (Nebraskan? or Kansan?) till and outwash containing large-scale trough cross strata within which are much-decayed erratics. Enclosed within the outwash associated with a younger till is a great slab of displaced Upper Cretaceous coastal-plain strata. A paleosol, developed on one of the younger tills, forms a stratigraphic datum whose regional significance is yet to be determined. Distinctive glacial features eroded on the bedrock and/or indicator stones within the till prove that glacial ice flowed across Staten Island from two contrasting directions: NNE to SSW (youngest) and NNW to SSE (older).

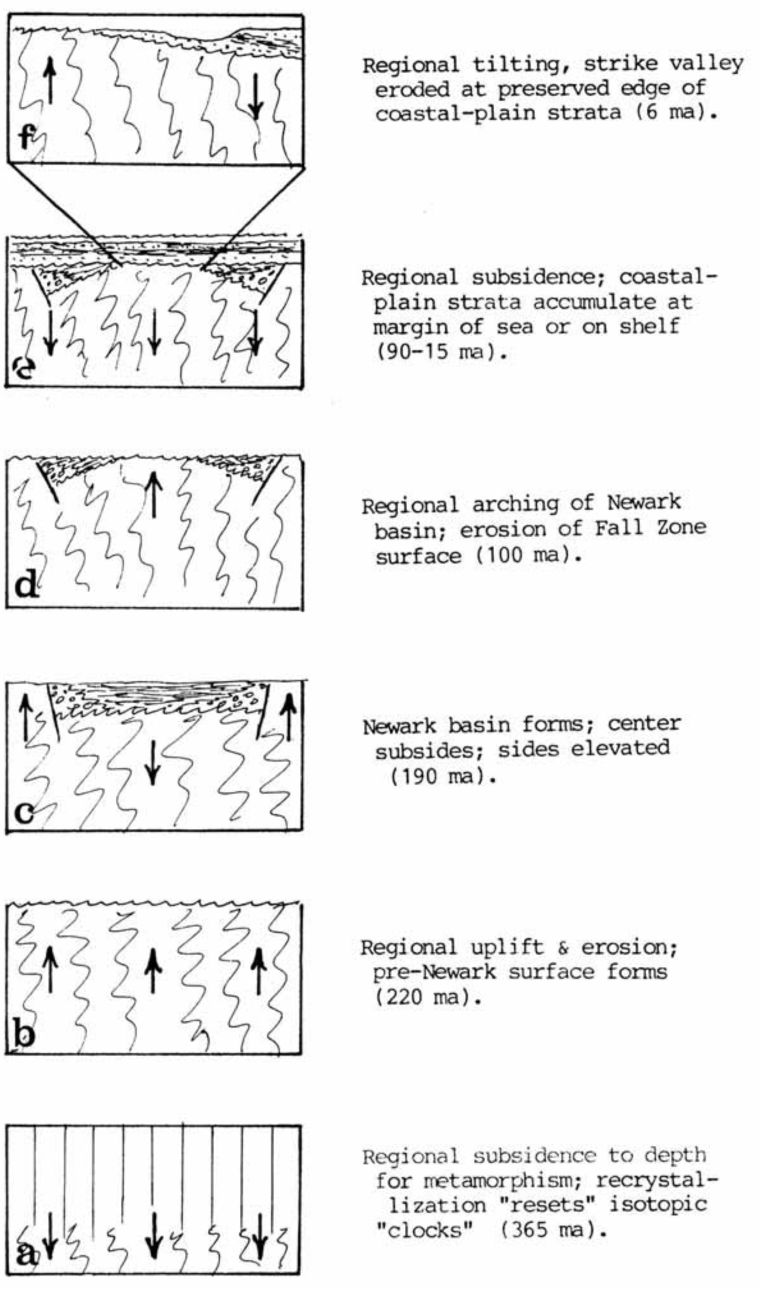


Figure 2 - Stages in development of the New York City region shown by schematic sections. (J. E. Sanders.)

Staten Island contains many important clues to the drainage history of the New York City region. At the base of the tilted strata of the Newark Supergroup is a strike valley that is a prominent part of the modern landscape; the Hudson River flows in it from near Stony Point, New York, to a point above the Lincoln Tunnel. Here, the Hudson River bends about a 15° to its left (as seen looking downstream) and flows out of this basal-Newark strike valley. At that point, the strike valley disappears from the modern landscape, but does not disappear from the geologic record. The basal-Newark strike valley continues to the southwest as a buried valley. It underlies an extensive lowland in Jersey City and crosses western Staten Island.

After this brief introduction, we turn to our other major sections. We begin with the geologic background. Other first-order headings include objectives, list of localities to be visited, driving directions and geologic notes en route, descriptions of individual localities ("stops"), acknowledgements, references, and appendix on the projected future size of the Fresh Kills landfill. The tables and illustrations follow the Appendix A. This weekend's On-The-Rocks trip to Staten Island is being conducted in association with a conference (Friday, October 14, 1994) and field trip (Saturday, October 15, 1994) specific to the geology of Staten Island for the eleventh annual meeting of the Geological Association of New Jersey.

GEOLOGIC BACKGROUND

Under this heading, we take up the physiographic setting, the bedrock units, the glacial deposits, and the drainage history.

PHYSIOGRAPHIC SETTING

Despite its small size, Staten Island includes parts of the four major physiographic provinces of the New York City region: (1) Manhattan Prong of New England Upland; (2) Newark Basin; (3) Atlantic coastal plain; and (4) a terminal moraine from one (or more) of the Pleistocene glaciers. Of these, only Nos. (1) and (4) display noticeable relief; the other two form lowlands that lack characteristic surface expression.

BEDROCK UNITS

One of America's most-successful petroleum geologists, the late A. I. Levorsen, organized his geologic analysis of an area by dividing the rocks into major units bounded by surfaces of unconformity. He referred to these units as "layers of geology." Levorsen published his approach in many articles in the geologic literature and in three books (Levorsen, 1933, 1934, 1943, 1945, 1948, 1954, 1960, 1964, and 1967). The value of Levorsen's approach is best illustrated by the fact that others liked it so much that they used it without mentioning Levorsen.

For example, the current fashion of using "sequences" as in sequence stratigraphy, derives from the analysis of the formations underlying the North American craton (Sloss, 1963, an extension of Sloss, Krumbein and Dapples, 1949). According to Sloss, a sequence is a large assemblage of formations bounded by a surface of unconformity of continent-wide extent. In other words, a "layer of geology" in the language of Levorsen. But Sloss (1984, 1988, 1990) and his students (for example, Vail, Mitchum, and Thompson, 1977) never mention Levorsen. We follow the Levorsen approach, but use the Sloss term "sequences" for some of the "layers" we discuss.

On Staten Island, three of the major bedrock units are in contact: (1) Layers I and II, the pre-Newark complex of Paleozoic and older metamorphic rocks that underlies the Manhattan Prong of the New England Uplands; (2) Layer V, the Newark strata, of Late Triassic-Early Jurassic ages and the associated Palisades intrusive sheet; and (3) Layer VI, the coastal-plain sands and -clays of Late Cretaceous age. Kindly refer to Tables 1 and 2 for the following discussion.

Layers I and II: Pre-Newark Complex of Paleozoic- and Older Rocks

The rocks of the pre-Newark complex, which are exposed in many parts of Manhattan, and in a few places in Queens and Brooklyn, but are present beneath a cover of younger deposits in Queens and Brooklyn where they are not exposed, consist of highly deformed and metamorphosed Lower Paleozoic and older formations. These rocks underlie the Manhattan Prong of the New England Upland physiographic province (Figure 3). The metamorphic rocks of New York City plunge southward beneath younger rocks to the south of Staten Island and reappear again in the Piedmont of eastern Pennsylvania. Together, they mark the deeply eroded internal zone of the Appalachian mountain belt that stretches sinuously from Maine southward to Georgia, where they have been beveled by Cretaceous and younger rocks and sediments of the Atlantic Coastal Plain.

In New York City, a basal unit (Layer I) of Proterozoic Y gneiss (the Fordham Gneiss, 1.1 billion years old) is overlain by Layer II, metasedimentary- and metavolcanic rocks that are inferred to have been deposited along the margin of the ancient North American continent in a long-disappeared ocean, the precursor of the modern Atlantic Ocean (it has been called Iapetus). This layer can be divided into two sub-layers, IIA and IIB. The older of these, IIA, is inferred to represent an ancient passive-margin sequence. Layer IIA can be split into two parts that differ according to their original geographic positions along the inferred ancient passive continental margin.

One part of the older sublayer [Layer IIA(W)] is the Sauk Sequence, which was deposited in shallow water. The oldest unit in the Sauk Sequence is the Lower Cambrian Lowerre Quartzite. The Lowerre is thin and very discontinuous. Next above is the Inwood Marble whose lower part is of Cambrian age and upper part, of Ordovician age. The Inwood Marble resulted from the metamorphism of the extensive sheet of carbonate rocks (mostly from the dolomitic rocks from the Sauk Sequence, but also including the basal limestone of the overlying Tippecanoe Sequence) which was deposited in a shallow, tropical sea that submerged large parts of the proto North American continent during the early part of the Paleozoic Era.

At the same time that the Sauk Sequence was being deposited in shallow water, fine-textured terrigenous sediments of Layer IIA(E), the Taconic Sequence, were being deposited farther east, in deep water (inferred to have been the ancient continental rise). These deep-water deposits of the Taconic sequence and the protoliths of what is now the Hartland Formation and according to CM, parts of the Manhattan Schist Formation.

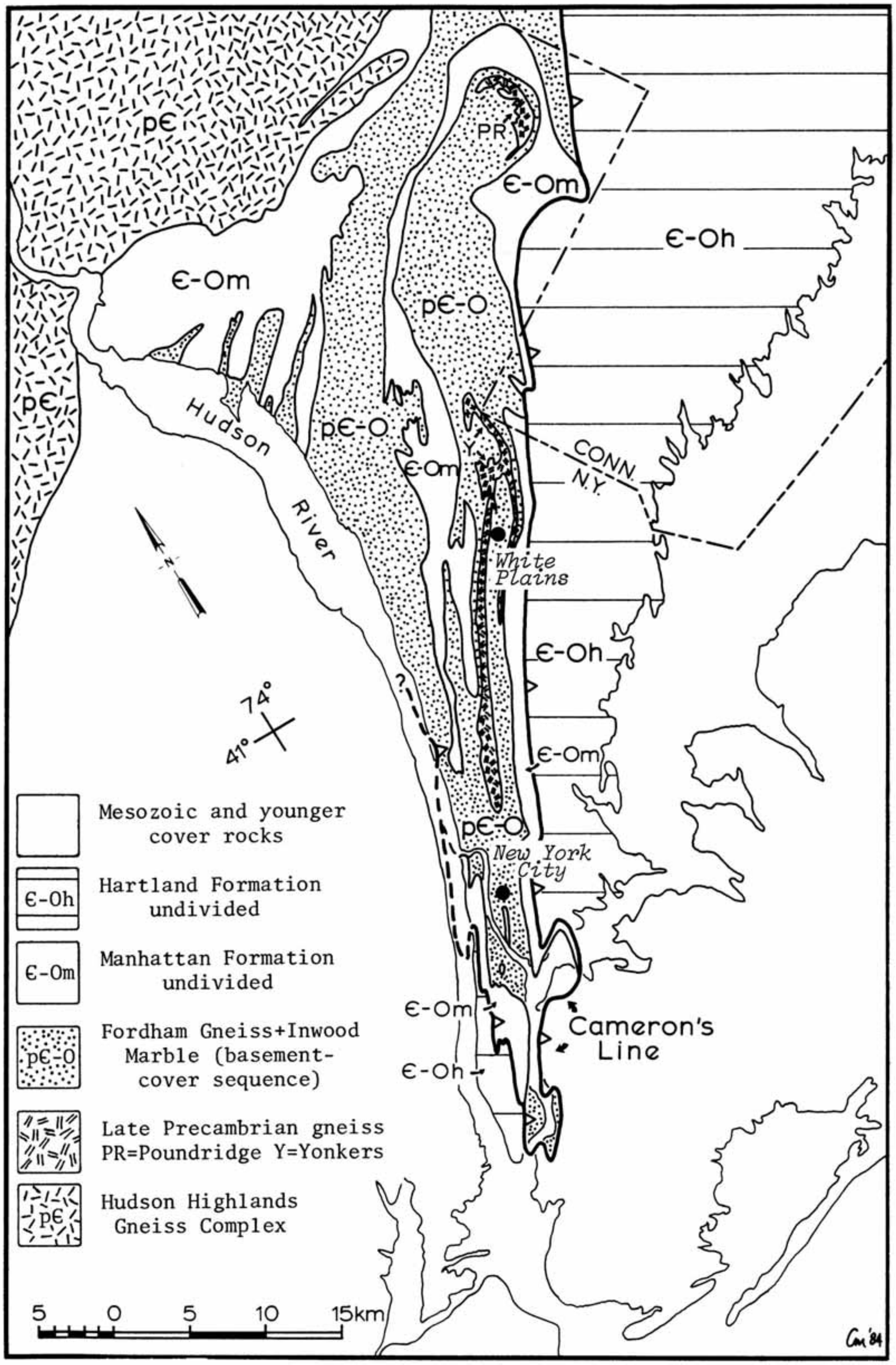


Figure 3 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks ranging in age from Precambrian to Early Paleozoic. Most intrusive rocks have been omitted. (Mose and Merguerian, 1985, fig. 1, p. 21.)

Above the Sauk Sequence are various schistose rock formations that CM has mapped as the Manhattan Schist and the Hartland Formation (Figure 4). Much of what was originally mapped as the Manhattan Schist and thought to be entirely younger than the Inwood Marble (Layer IIB) is now recognized as rock units that are the same age or older than this schist [Layer IIA(W)] and the Inwood Marble. During medial Ordovician time, roughly 450 million years ago, and prior to the main events of the Taconic orogeny, these older eastern, deep-water formations, were overthrust into a position above the Inwood Marble and the younger overlying schist (the Manhattan Schist as originally conceived). As will be discussed in a later section and at Stop 1, the events during the Taconic orogeny (=mountain-building) probably included the initial displacement of a piece of the former oceanic lithosphere that later became metamorphosed to form the Staten Island serpentinite body.

The New York City rocks have been complexly folded together and metamorphosed under amphibolite-facies conditions. This can be inferred from the presence of such "index" minerals as kyanite, sillimanite, and garnet. The presence of these minerals suggests that rocks now exposed at the present land surface of New York City formerly were at depths of 15 to 25 km. If this is correct, it indicates that enormous uplift and vast erosion took place between the middle of the Paleozoic Era, the time of the last great metamorphism, and late in the Triassic Period, when these metamorphic rocks began to be covered by the sedimentary strata filling the Newark basin. Therefore, as you observe outcrops in New York City, you are vicariously walking backward in time and figuratively descending deep within a former mountain zone.

The Fordham Gneiss (Proterozoic Y) crops out in western Queens along the shore of the East River. In isolated exposures in western Queens (Long Island City), a hornblende-rich orthogneiss (metamorphosed igneous rock) that Ziegler (1911) called the Ravenswood Granodiorite. The Ravenswood is exposed in a few localities and has been cut by many drill cores and subsurface structures. According to CM, the Ravenswood intrudes the Hartland Formation and includes foliated, contact-metamorphosed xenoliths. Preliminary Rb/Sr age data by D. Mose suggest that the Ravenswood is of early Paleozoic (probably Ordovician age). However, the reliability of the Rb/Sr dating method used is limited by polymetamorphism and by the complex structural history of the region.

Geology of the Staten Island Serpentinite

The Staten Island serpentinite body is exposed at the southern terminus of the Manhattan Prong, a broad tract of metamorphic rocks now uplifted and eroded to form the core zone of the Appalachian mountain belt in southeastern New York. (See Figure 1 on cover.) The Staten Island serpentinite is one of a large number of similar metamorphosed ultramafic bodies present along the entire length of the Appalachian mountain range. Serpentinites in southern New England are associated with highly sheared rocks of the Hartland formation and correlatives northward (Merguerian, 1979, 1981, 1983, 1985). Because of their ultramafic composition (rich in iron and magnesium) the parent rock for serpentinite (a metamorphic product) is undoubtedly from the Earth's upper mantle. The juxtaposition of high-density ultramafic rocks from the Earth's mantle into lighter density rocks of the continental crust remains an enigmatic question prompting interesting models.

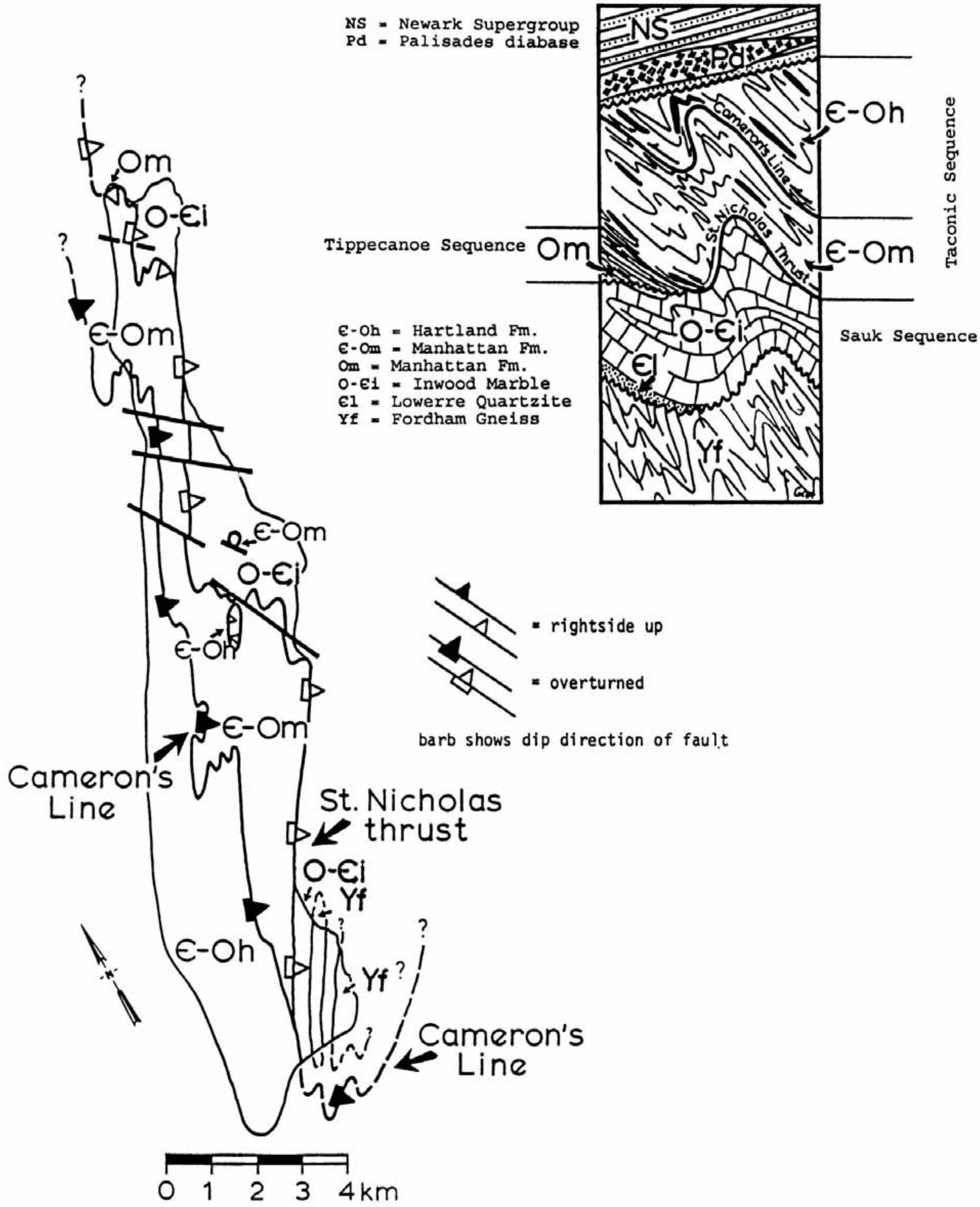


Figure 4 - Geologic map- and stratigraphic section of Manhattan. (Merguerian, unpublished data.)

The oval-shaped Staten Island serpentinite body is about 11 km long and about 5 km in maximum width. (See Figure 1 on cover). It is cut by a number of steep NE- and NW-trending faults (Figure 5) and, based on new field data (Merguerian, 1993 ms.), contains an older shallow-dipping layering. The body underlies a prominent NE-trending ridge (locally called Todt Hill) through the center of Staten Island. The top of Todt Hill, at an altitude 540 feet, is the highest natural point in New York City. The serpentinite body is mantled on its periphery by metamorphic-, sedimentary-, and igneous rocks of varied ages (Figures 5, 6).

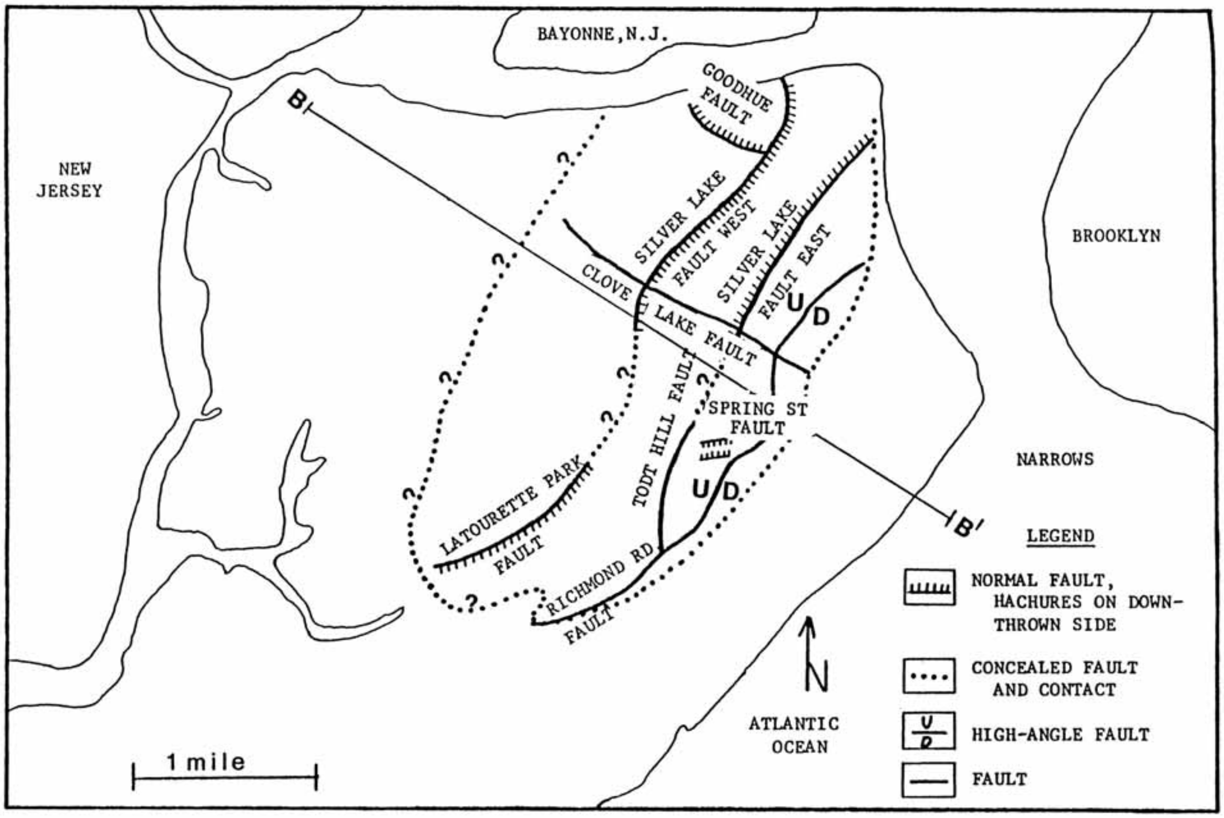


Figure 5 - Fault map of Staten Island Serpentinite. (Miller, 1970 ms., fig. xx, p. yy.)

Glacial deposits obscure the western contact of the Staten Island serpentinite body. Based on engineering-boring data, Mesozoic igneous- and sedimentary rocks of the Newark Basin and overlying Pleistocene glacial drift occupy the subsurface of western Staten Island. The contact is probably composite--partly a fault and partly covered by overlapping sediments as suggested in Figure 6. The eastern contact of the serpentinite is marked by the Richmond Road fault that separates the serpentinite body from buried Lower Paleozoic metasedimentary- and metavolcanic rocks of the Hartland Formation. (See Figures 5 and 6.)

Topographic expression is strong evidence for faulting. The entire eastern boundary of the serpentinite is a fault. (See Figure 5.) The serpentinite mass is cut by a system of NE-trending- and less-extensive NW-trending faults. Rock features associated with the faulted serpentinite include local fault-related breccias, slickensides (gouges in rock surfaces caused by differential motion of rock masses), and local veins of talc, amphibole, and serpentine-group minerals. Fibrous minerals in thin veins are spatially associated with fault zones throughout Staten Island. The buried metamorphic rocks are covered by Upper Cretaceous coastal-plain sediments (the Raritan and Magothy formations) and Pleistocene glacial drift (mostly till with subordinate outwash).

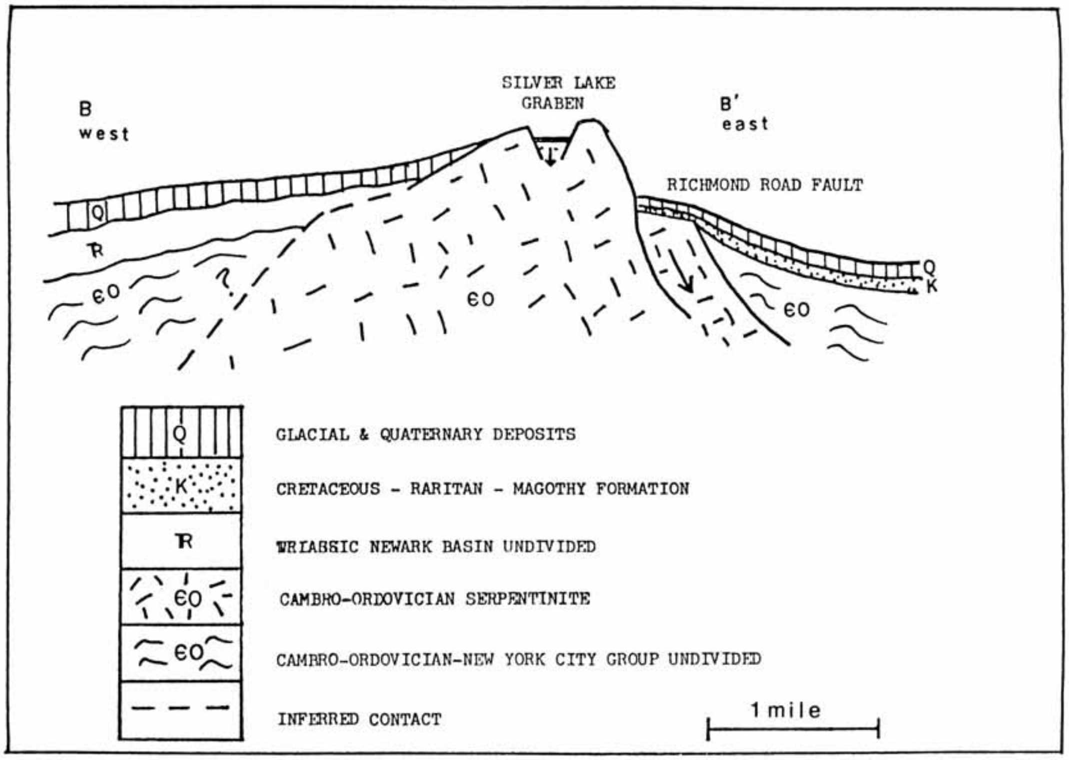


Figure 6 - Profile-section through Staten Island serpentinite body. Line B-B' located on Figure 5. (Miller, 1970 ms., fig. xx, p. yy.)

Origin of the Staten Island Serpentinite

The following is a detailed review of the literature summarizing the landmark papers on the field relationships-, genesis-, age-, and mineral composition of the Staten Island serpentinite. The Staten Island serpentinite body was first described by W. B. Mather (1843), who suggested that it is of igneous origin and had resulted from the melting of a hornblende-rich mass. N. L. Britton (1881) presented one of the first modern scientific papers to discuss the areal extent-, topography-, age-, mineral composition-, and genesis of the various geological units that underlie Staten Island. Britton also listed the three previous references to Staten Island geology, namely, Mather (1842), Cozzens (1843), and Cook (1878). Following the prevailing geological concepts of his day, Britton assigned the age of the serpentinite to the Archean Era, the oldest period of geological time encompassing the time span from 4.0 to 2.5 Ga (Giga = Billion years ago). In the late 1800s, all crystalline rocks were assigned to the Archean. Britton assumed that the granitic rocks underlie the serpentinite body but offered no evidence. Such granitic rocks are associated with the Paleozoic metamorphic strata that are found in fault contact with the eastern margin of the serpentinite body.

Britton described the serpentinite as varying in color from light green to nearly black; the texture is compact to earthy and much of it is fibrous. Its density is 2.55 grams/cm3 (slightly less dense than the crustal rocks in which it is found) and chemically it consists of hydrated magnesian silicate. Britton listed both compact- and fibrous serpentine, marmolite, green- and white talc, gurhotite, dolomite, calcite, chromite, deweylite, magnesite, and brucite as the dominant mineral phases found. He erroneously stated that fibrous amphibole is not present on Staten Island but modern studies indicate that anthophyllite is indeed present. Using five arguments, he correctly assigned the formation of these minerals to metamorphism and correlated the Staten Island serpentinite with similar rocks found to the north in Hoboken, New Jersey and Manhattan Island, New York.

Following the geological wisdom of his day, Britton considered the formation of the serpentinite body to be a product of the metamorphism of highly magnesian limestones, offering four largely negative arguments to support this view. Thus, in this landmark paper on the Staten Island serpentinite body, a basic understanding of the geology of Staten Island was presented.

C. A. Hollick (1896b) reported on the results of a 1896 summer field season in the company of J. D. Irving and D. H. Newland of Columbia University, wherein he examined every natural outcrop of serpentinite. Special emphasis was given to answering the question of sedimentary- vs. igneous origin for Staten Island serpentinite body. This short preliminary report was eclipsed by Hollick's 1909 paper (summarized below).

Hollick (1896b) reported strike-and-dip measurements and rocks were found to have a well-defined strike (although it was not stated what Hollick and coworkers had measured) parallel to the general orientation of the hills at N25°-55°E near St. George. To the south, near Richmond, the strike swings around to an E-W orientation. CM suspects that Hollick was measuring both the high- and low-angle shear surfaces mapped by CM in 1993 (Merguerian, 1993 ms.). Hollick mentioned that the body is cut by numerous fractures, joints, and shear planes and that well-defined stratification is rarely seen. These comments indicate that Hollick's pre-conceived notion was that the body was indeed of sedimentary origin, a view proposed earlier by Britton.

Hollick argued that the serpentinite body is stratified (suggesting a sedimentary origin) and anticlinal in structure (broad arch-like fold) with a 20° to 60° dip toward the north and west and a subvertical dip toward the east and south. He noted spectacular specimens of tremolite observed from the Rapid Transit Railroad excavation in St. George wherein "unmistakable evidence of bedding planes" where found. Also mentioned, was an exposed band of chlorite schist found in a gully north of Richmond Road at the head of Red Lane. This exposure was accompanied by talc and red limonite producing a red, white, and green layering. At this time, Hollick proposed that the serpentinite had formed by coeval metamorphism of crystalline rocks allied with the formation of the Manhattan Schist (now mapped by Merguerian as the Hartland Formation).

By the early part of the twentieth century, D. H. Newland (1901) argued that the body had formed by the metamorphic alteration of peridotite (a high magnesium+iron silicate igneous rock thought to form the Earth's mantle).

C. A. Hollick (1909) described the steepness of the eastern border of the Staten Island serpentinite and focused, in this brief three-page report, on the description of rock specimens and minerals collected by Hollick, and analyzed by C. P. Berkey and A. A. Julien of Columbia University. Noting pervasive closely spaced jointing in the serpentinite body, Hollick justified the notion of previous workers of a sedimentary origin for the Staten Island serpentinite body. Hollick was not convinced, however, that a sedimentary origin is realistic and stated, based on mineralogical studies, that the serpentinite is a metamorphosed former basic (meaning rich in iron and magnesium) igneous rock. He described a sampling program from a trench excavated for a retaining wall near Jay Street in St. George. The trench was driven down twenty feet to about tide level and extended for roughly seventy-five feet.

The St. George serpentinite rock was hard, dark green in color, and cut by a great number of seams and fractures. The fractures were filled with talc, marmolite, magnesite, calcite, and aragonite. Hollick described the spatial association of amphibolite or antholite schists (amphibole-bearing schist in the modern usage) with faults and shear zones and concluded that the eastern escarpment was fault controlled and that the development of serpentine-group minerals was related to shearing- and slippage along fault- and shear surfaces (a view thoroughly endorsed by CM)!. Variations from hard, massive serpentinite to asbestiform fibers were noted.

Expanding on the mapping of Willis and Dodge [New York City Folio, No. 83 of Merrill et al. (1902)], W. O. Crosby (1914) suggested that the body had been physically injected into its present structural position by upward diapiric "intrusion." The near-total lack of original igneous textures in the serpentinite is consistent with Crosby's concept of pervasive hydration of the peridotite, resulting in a 25% volume increase as a result of metamorphic swelling of original igneous minerals that were nonhydrous and enriched in magnesium + iron. Such a volume increase would force an overall decrease in density as the dense, closely packed original minerals were succeeded by the open-framework metamorphic minerals of the serpentine group. Such changes might help to explain how an originally dense rock such as peridotite could "rise" into less-dense crustal rocks. The current fault-bounded horst-block relationship of the Staten Island body (See Figures 5 and 6.) supports Crosby's idea that upward rise of the body resulted from vertical emplacement caused by hydration expansion.

N. L. Bowen and O. F. Tuttle (1949), in one of the classic papers in North American petrology, discussed the phase relationships of the $MgO-SiO_2-H_2O$ system. These simple chemical combinations account for the bulk chemical composition of ultramafic rocks of the mantle and their metamorphosed products, the serpentinites. As such, Bowen and Tuttle's study provides the geochemical background for the metamorphic formation of serpentine-group minerals (chrysotile, in particular), brucite, talc, and periclase from olivine- and pyroxene-rich parent rocks under high water pressures and temperatures up to 1,000°C. Bowen and Tuttle state that magnesian olivine is stable at temperatures above 430°C and that alteration to serpentine-group minerals and brucite occurs below this temperature. They also note that iron-rich olivine is stable at lower temperatures. Their main result is the statement that serpentinite results from a metamorphic process and not the product of a primary igneous process. That is, serpentine magmas do not exist. Rather, the main point of their work is that serpentines are produced from the metamorphism of iron- and magnesium-rich rocks and that an igneous origin for serpentinite is a physical impossibility. In addition, the stability temperatures they have measured for the system MgO-SiO_2-H_2O indicate that the intrusion of ultramafic magmas can be accomplished only in the solid state and not as a liquid (magma). Modern petrologists and field workers (including CM) argue that ultramafic magmas can indeed "intrude" the crust of the Earth but do so as mixtures of crystals and residual liquid.

H. Behm (1954) outlined the petrography of the serpentinite body. Behm's paper, an outcome of his Master's thesis work at New York University, was the first detailed account of the petrography (study of rocks in thin slices under the microscope) of the Staten Island serpentinite body. His study first discussed the geologic literature in the context of the genesis of the serpentine body. He provided a detailed accounting full of quotations of the various lines of evidence that wind a sinuous path (some might say a serpentine path) from early thoughts on a sedimentary origin, to an igneous origin, to our modern views of a former igneous origin now modified by metamorphism into serpentinite. The major contribution of his work lies in the petrography (including photomicrographs) and detailed mineralogical analysis of the serpentinite body and his comments on the petrologic aspects of the mass (set in the context of 1954 petrologic research).

Behm devoted roughly 14 pages of information on the prevailing genetic models for the serpentinite body. His review provides an interesting insight into the migratory patterns of geological thinking on the subject of origin of the serpentinite body. Suffice it to say that Behm's summary is complete with appropriate quotations from the major "players" in the field starting with Britton's pronouncements of a sedimentary origin to Bowen and Tuttle's experimental evidence "proving" a metamorphic ancestry.

Behm's petrographic study of the Staten Island serpentinite body indicates that the pre-metamorphic igneous minerals of the mass consisted of chrysolite (a magnesian olivine [not to be confused with chrysotile, a serpentine mineral]), with associated enstatite and bronzite (both orthopyroxenes with bronzite a variety of enstatite with a sub-metallic luster produced by weathering of minute metallic inclusions). An accessory spinel mineral picotite (a chromium hercynite) is also reported. After metamorphic alteration, the primary igneous minerals were largely replaced by intergrowths of antigorite, serpophite (lizardite in the modern usage), chrysotile, bastite, talc, and anthophyllite. These are largely minerals of the serpentine group and related hydrothermal-alteration products and include two minerals (chrysotile and anthophyllite) whose habits are asbestiform.

In detail, the minerals antigorite, serpophite (lizardite), and chrysotile are the three main minerals of the serpentine group, all of which possess the same chemical formula - $Mg_3Si_2O_5(OH)_4$. Antigorite is micaceous in appearance and is the most-abundant mineral of the serpentine group. Serpophite (or lizardite) is amorphous but recent electron microscopy indicates it possesses a platy structure and chrysotile is asbestiform. According to Behm, these minerals form from the hydrothermal alteration of chrysolite (olivine). Alteration of enstatite and bronzite yields bastite (a replacement product consisting of intergrown serpentine and talc).

Localized alteration of enstatite and antigorite has produced talc and anthophyllite. Along the eastern portion of the serpentinite body, anthophyllite grades into fibrous asbestos and related minerals (cummingtonite, tremolite, and actinolite [rare]). Replacement of chrysolite and picotite by magnetite is reported (especially along the eastern margin of the body). In fact, the famed "iron mines" of the Staten Island serpentinite body are Tertiary weathering products of such magnetite-enriched rocks.

Behm discussed the petrographic details of the serpentinite at various localities. Rather than summarize these areas individually, we list the various areas by page number in the event interested readers need detailed mineralogical data by area. Further, we have indicated the areas where asbestos fibers have been reported by an asterisk (*).

The main outcrop areas described by Behm include:
(Page references are to Behm, 1954)

Castleton Corners - p. 17.
Clove Lakes Park - p. 17-18.
NYC Housing site on Manor Road and Schmidt's Lane - p. 18-19.
Flagg's Quarry, Dongan Hills - p. 19.
Bard Avenue - p. 19-20.
Brighton and Lafayette Avenues, New Brighton - p. 20 and 26.
* - Old Mill Road, Richmond Town - p. 20-21.
Todt Hill Road, Dongan Hills - p. 22-23.
* - Richmond Road and Raritan Avenue - p. 23.
* - Van Duzer Street (Grymes Hill), Homer Street (Ward Hill), St. Paul's Avenue (Pavilion Hill - p. 23-25.

In summary, the main areas where fibrous minerals are developed are the east sides of Pavilion, Ward, and Grymes Hills. Some fibrous minerals are found near Richmond Road and Raritan Avenue and Old Mill Road in Richmond Town.

Behm concluded his report by stating that the Staten Island serpentinite body is a hydrothermally altered olivine-enstatite peridotite (technically a harzburgite). Although less altered in the interior, the serpentinite body is strongly altered along its eastern- and northeastern margins; large masses of anthophyllite (altered from serpentinite) and lesser chrysotile asbestos have formed. Behm includes annotated plates (p. 33-36), two maps (p. 37-38) showing outcrop areas and the general outline of the serpentinite body, and a then-current bibliography (p. 39).

Gilbert Wasserman (1956 ms.) produced a magnetic-anomaly map on which were indicated regions of high- and of low magnetic susceptibility. Later, W. H. Miller (1970 ms.) conducted a detailed structural study of the serpentinite and located the major faults shown in Figure 1. T. E. Yersak (1977 ms.) produced a gravity-anomaly map of the body. Steve Okulewicz (1979 ms.) provided the most-comprehensive review of previous work and performed detailed mineralogical- and geochemical studies on the relict (pre-metamorphic) minerals, investigated the metamorphic-mineral changes, and proposed new ideas on the structural position- and tectonic ancestry of the serpentine body of Staten Island.

According to Okulewicz, the Staten Island body originated as a harzburgite/dunite rock (rich in magnesian orthopyroxene and olivine with subordinate chrome spinel) that was subsequently metamorphosed under greenschist-facies conditions into serpentine-group minerals such as lizardite (75% to 80%), with lesser amounts of chrysotile, antigorite, magnetite, brucite, talc, and amphiboles. Low-temperature chemical weathering has produced numerous interesting- and locally, rare minerals.

Drawing on the earlier mapping of Miller, Okulewicz discovered the presence of northeast-trending folds in the core of the body that he argued were formed during emplacement of the body during the medial Ordovician Taconic orogeny. In contrast, mapping by Merguerian in New York City indicates that the NE-trending folds are relatively young in the sequence of polyphase deformation that affected the region and suggests that folding of the Staten Island serpentine body along northeast-trending axial surfaces postdates the emplacement of the body. High-angle shearing along the edge of the serpentinite to form mylonitic anthophyllite schist is a consequence of such post-emplacement deformation.

Contrasting Ways for Upper-mantle Material to Get Into the Continental Crust

This topic arose from comments to JES and CM from one of the participants of On-The-Rocks Trip 04 (April 15, 1989) to the effect that he was expecting to see evidence for a close connection between the Staten Island serpentinite and the rocks of the Palisades Sill. Our initial reaction was that these two rocks are not connected in any way. But, on further reflection about this point, JES commented that the materials from which both rocks formed are thought to have been derived from the Earth's upper mantle but the final appearances of these two rocks have differed drastically as functions of their loci of crystallization, of modes of emplacement into the continental crust, and post-emplacement histories.

The association of serpentinite with highly deformed rocks of probable oceanic parentage, deep-seated shear zones, and sutures formed between former lithospheric plates, provides the ammunition for interesting speculations as to the plate-tectonic significance of the Staten Island serpentinite and its relationship to the process of mountain building.

According to modern geo-religious beliefs, two contrasting loci of origin for the pre-metamorphic parent rocks of serpentinites are:

(a) beneath the sea floor as the substrate of a three-layer ophiolite succession of new oceanic lithosphere forming at an oceanic spreading ridge, and,

(b) as primitive mantle-derived magma which rose upward through deep-seated fractures that extend all the way from the zone of magma generation in the upper mantle through the continental lithosphere and crust.

Ophiolite successions from the oceanic lithosphere (a) can become part of the continental realm only as a result of great overthrusting, in which the interface of displacement begins say 10 km beneath the ocean floor and eventually steps its way upward toward the Earth's surface along shallow-dipping thrust faults. Examples include the Thetford ophiolite in Quebec, the Bay of Islands Complex in Newfoundland, and the Troodos Igneous Massif in Cyprus (Figure 7).

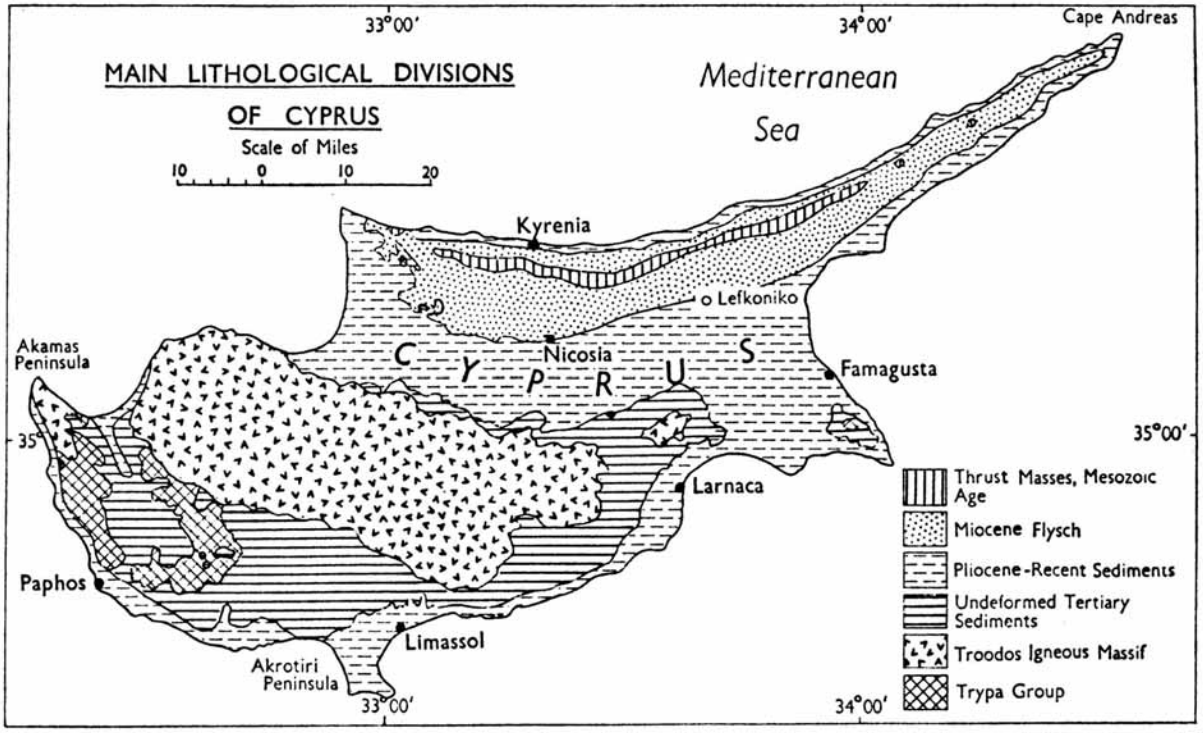


Figure 7 - Geologic map of Cyprus showing the Troodos Igneous Massif. (I. G. Gass and D. Masson-Smith, 1963, fig. 1, p. 421.)

In (b), ultramafic magma from the mantle worked its way upward into the continental lithosphere through deep-seated fractures and crystallized as intrusive igneous rocks at great depth. Such high-density magmas solidify slowly to form bodies of coarse-textured intrusive igneous rocks called plutons. The presence of cumulate-type ultramafic rocks, with associated zones of contact metamorphism, in the deeply eroded core zones of mountain belts indicates that intrusion of high-density magma into lower-density crustal rocks has occurred but the exact mechanism of intrusion is under debate. Most petrologists argue that during regional compression accompanying mountain building, the ultramafic magmas are squeezed upward into the continental crust as semi-solid crystal-rich masses.

The relationship between serpentinites and great overthrusts has always been known. According to the experimental results of Bowen and Tuttle (1949), at high temperatures, olivine and orthopyroxene would remain stable; at medium temperatures, olivine plus talc would form; and at low temperatures, serpentine would form (assuming access to water vapor). Serpentinite cannot exist at depths below 9 miles (15 km) because increased temperature decomposes the serpentinite into talc, olivine, and water vapor with an increase in volume. As suggested by Crosby (1914), increasing volume might initiate diapiric rise of the material to higher crustal levels where serpentinization would be a natural consequence.

The position of the Staten Island serpentinite along the highly deformed axis of the Appalachians and the correlation with similar bodies occurring to the north and south (Figure 8) provides for interesting speculation as to the geologic significance of the body. Earlier ideas concerning an igneous origin for the Staten Island serpentinite viewed the body as an intrusive of molten- or partly molten peridotitic magma (derived from the mantle) that was subsequently metamorphosed in place to form serpentinite. Later diapiric rise of the serpentinized body (per Crosby) evidently took place along the bounding faults shown in Figures 5 and 6.

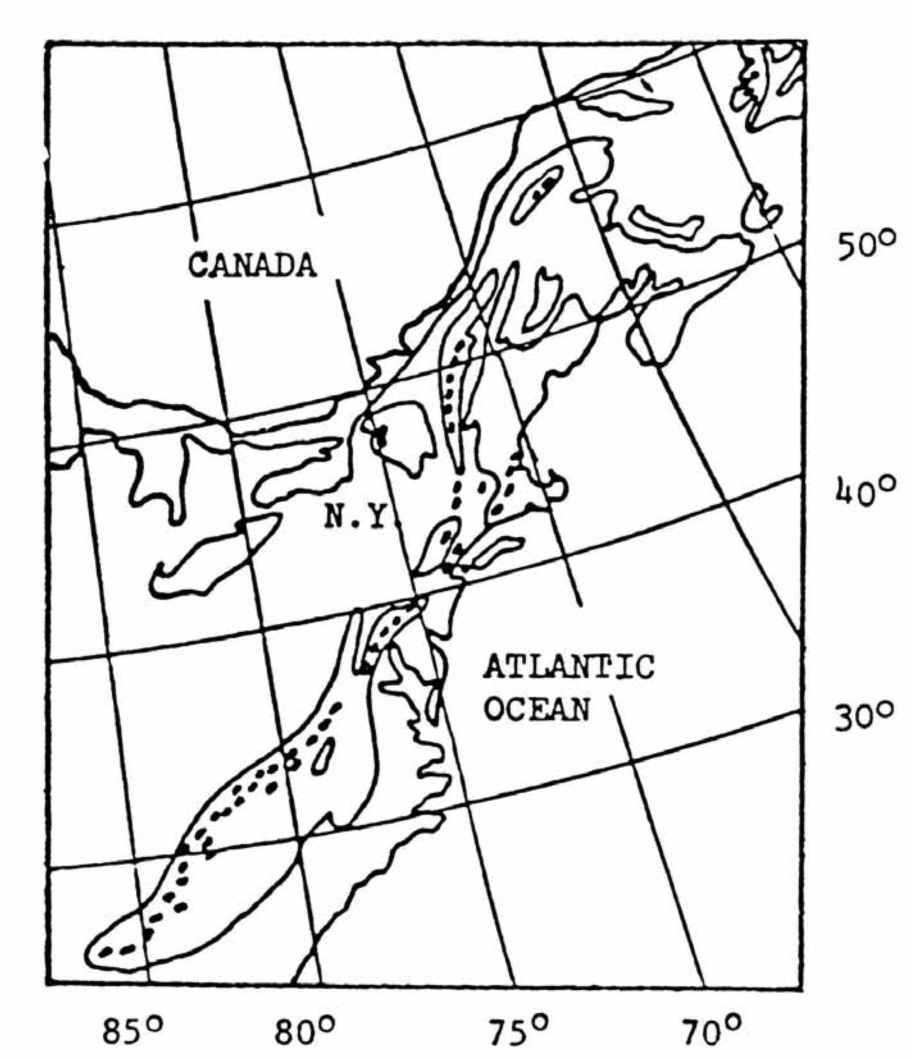


Figure 8 - Map showing the location of the Appalachian ultramafic belt (ultramafic bodies shown in black) along the east coast of North America. (J. Pratt and L. Lewis in F. J. Turner and J. Verhoogen, 1960, fig. xx, p. zzz.)

Given the obscure contact relationships, an intrusive igneous origin for the Staten Island serpentinite is difficult, if not impossible to prove. Because of peripheral faulting, no contact-metamorphic aureole in the bounding rocks has been recognized. Igneous chilled-marginal facies in the body have not been recognized for the same reason and also the high degree of serpentinization has obliterated most vestiges of original igneous textures.

Modern studies of orogenic belts indicate that the occurrence of serpentinite along the internal-, deformed core zones of mountain ranges has resulted from physical injection of partly solidified masses of mantle as tectonic slivers (slices) during compression that accompanies convergent mountain building. Outcrops of complete stratigraphic sections of cumulate ultramafic rocks overlain by gabbro and sheeted basaltic dikes in turn overlain by pillowed basalts and thin oceanic sediments form as sea-floor lithosphere grows at mid-oceanic spreading ridges. Such successions have been named ophiolites and the three major igneous units given layer numbers, from the sea floor downward as Layers 1, 2, and 3. Examples of such ancient slices of the sea-floor lithosphere that have been thrust up onto continental lithosphere are known in many mountain chains.

On the island of Cyprus in the Mediteranean (See Figure 7.) the ophiolite succession forms an east-west-trending outcrop belt in which the various layers dip north. Therefore, if you were to make a continuous north-to-south traverse across Cyprus, you would walk first across metalliferous oceanic sediments resting on ocean-floor pillowed basalts (Layer 1). Next, you would come to a complex of coarse gabbros cut by many dikes (= "sheeted basaltic dikes"; Layer 2). Finally you would come to cumulate peridotites (or ultramafic rocks) (Layer 3). This "trinity" of lithologic units has been interpreted as an intact slice of the oceanic lithosphere (oceanic crust and upper mantle) that was mechanically displaced along a great overthrust that stepped upward from a position in the Earth's mantle beneath a former ocean into a higher position in the continental crust during Alpine mountain building of the late Mesozoic and early Cenozoic eras.

In deeply eroded terrains, such as the Appalachians, where significant deep-seated shearing, metamorphism, and imbrication of rock units have taken place, complete ophiolite sequences are seldom recognized. (See Figure 8.) In fact, given the enormity of shearing in such former deep-seated convergent margins, metamorphosed dismembered ophiolite is the expected norm rather than the exception (Merguerian, 1979). In New England, many separated occurrences of serpentinite, amphibolite (+/- deformed pillow lava), and mica schist with stratabound metalliferous deposits, presumably represent Layers 3, 2, and 1, respectively of the ophiolite trinity. In the Coast Ranges of California, a recognized uplifted subduction complex, exotic blocks of serpentinite and eclogite (high pressure ultramafic rocks) "swim" in a sea of weakly metamorphosed oceanic sediments. They are interpreted to mark slivers of dismembered ophiolite.

If the Staten Island serpentinite body is part of an ophiolite succession, it would be from Layer 3 (peridotitic upper mantle). Regional considerations on the timing of mountain building and deformation of the metamorphic rocks of the Manhattan Prong suggest that the main pulse of deformation occurred during the Taconic orogeny of medial Ordovician age (roughly 450 million years ago) when a volcanic arc off eastern North America collided with the passive continental shelf edge of North America (Figure 9). In this model, the Staten Island serpentinite would represent a dismembered sliver of 450-million-year-old (or older) mantle that occurred beneath oceanic crust formerly situated between the colliding volcanic arc and the stable shelf edge of proto North America.

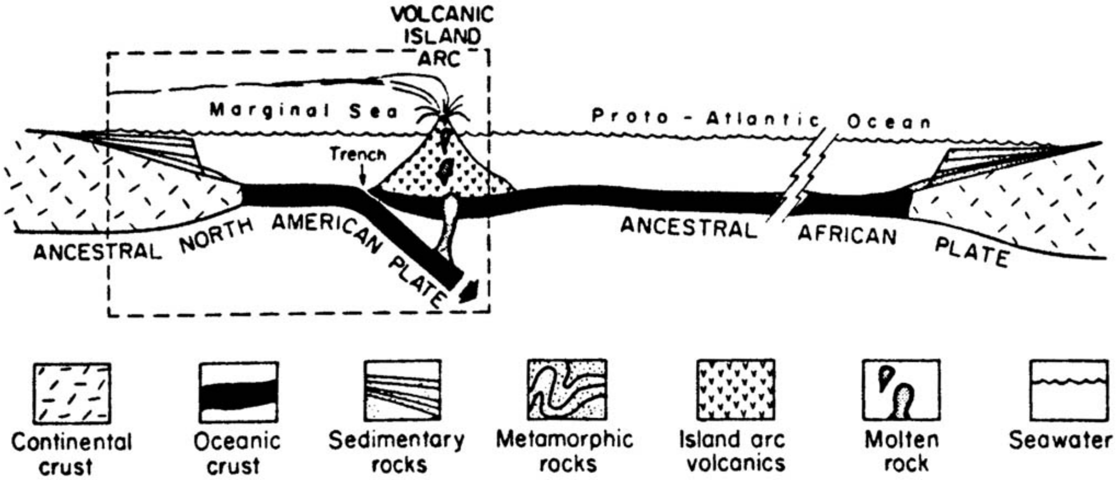


Figure 9 - Plate-tectonic "cartoon" showing inferred reconstruction at beginning of Medial Ordovician time. This interpretation shows the former ocean floor and volcanic island arc moving against North America, with a seaward-dipping subduction zone beneath the island arc. (Y. W., Isachsen, 1980, fig. 4, p. 7.)

Serpentinization and Asbestiform Mineralization

Deep-seated deformation of ultramafic rocks prompts metamorphic recrystallization of original iron- and magnesium-bearing minerals such as olivine and pyroxene. This process, termed serpentinization, hydrates parent silicate minerals producing a host of minerals from the serpentine group and a number of minerals from the amphibole group. The principal minerals formed from the serpentine group include chrysotile, lizardite, and antigorite, all hydrated magnesium silicates with the approximate composition $H_4Mg_3Si_2O_9$. Of this group, chrysotile forms needlelike, elongate crystals with aspect ratio (length:width greater than 3:1) falling into the "Federal Fiber" definition of a carcinogenic mineral substance. Hundreds of amphiboles are known to mineralogists. In the amphibole group, crocidolite, amosite, montasite, anthophyllite, tremolite, and actinolite crystallize in an aspect ratio that places them in the asbestos group.

Both anthophyllite and chrysotile are reported from the Staten Island serpentinite, a natural habitat for these minerals. After uplift and erosion, such minerals begin to weather and erode resulting in the liberation of anthophyllite and chrysotile (both fibrous, asbestiform minerals). Merguerian (1993 ms.) identified areas of Staten Island where samples of fibrous minerals have been found in serpentinite rock in association with steep, NE-trending faults and shear zones. The City of New York is currently monitoring air samples from these potential "hot" areas of airborne asbestos release.

Layer V: Newark Basin-filling Strata and the Palisades Intrusive Sheet

The Newark strata of Layer V nonconformably overlie the older metamorphic terrane of the Manhattan Prong of Layers I and II are themselves overlain in angular unconformity by the virtually horizontal Upper Cretaceous sediments of the Atlantic Coastal-Plain succession of

Layer VI, the basal unit in the wedge of sediments that has been accumulating along the passive eastern margin of the North American continent for the last 170 million years or so. At Sand Hill, NJ, in an outlier, Upper Cretaceous strata rest on the exposed edge of the Rocky Hill-Palisades sill, a relationship that gives a vague limit for the date of deformation of the Newark rocks (Widmer, 1964).

The tilted- and eroded remnants of the Newark strata are exposed along the west side of the Hudson River, from Stony Point south to Staten Island. As shown on the diagonal cut-away slice in Figure 10, the Newark strata generally dip about 15° to the northwest.

The venerable name in American stratigraphy, Newark, taken from Newark, New Jersey, was proposed in 1856 by W. C. Redfield, a student of fossil fishes. Today, the term Newark has been accorded the status of a Supergroup (Cornet, 1977 ms.; Olsen, 1980c, Froelich and Olsen, 1985; Luttrell, 1989). Included within the Newark Supergroup are various sedimentary formations, of which the basal unit is the Stockton Arkose. Above it is the Lockatong Formation, the unit into which the generally tabular Palisades sheet has been intruded. Higher up are other sedimentary units and three interbedded sheets of mafic extrusive igneous rock (ancient lava flows), whose tilted edges are resistant and underlie ridges known as the Watchungs.

The names of the formations of the Newark Supergroup (with thicknesses in the Watchung syncline) are (Olsen, 1980b):

Formation Name	**Thickness (m)**
Boonton (sedimentary strata; top eroded)	500+
Hook Mountain Basalt (two flow units)	110
Towaco Formation (sedimentary strata)	340
Preakness Basalt (2, poss. 3 flow units)	300
Feltville Formation (sedimentary strata)	170
Orange Mountain Basalt (at least 2 flow units, one of them pillowed)	150
Passaic Formation	6,000
Lockatong Formation	150
Stockton Formation	350
Total (Watchung syncline)	**8,070+**

Where the three well-known sheets of extrusive basalt (First-, Second-, and Third Watchung basalts; named by Paul Olsen, the Orange Mountain Basalt, Preakness Basalt, and Hook Mountain Basalt, respectively) and/or the distinctive black argillites of the Lockatong Formation are present, the Newark sedimentary strata are easy to subdivide. But where one is faced with an isolated exposure of a Newark-type reddish-brown sandstone, -siltstone, or -shale, or even a coarse conglomerate with reddish-brown sandstone matrix, the problem of assigning the correct formation verges on hopeless. Ultimately, some mineral- or lithologic criteria may prove to be helpful for stratigraphic assignment.

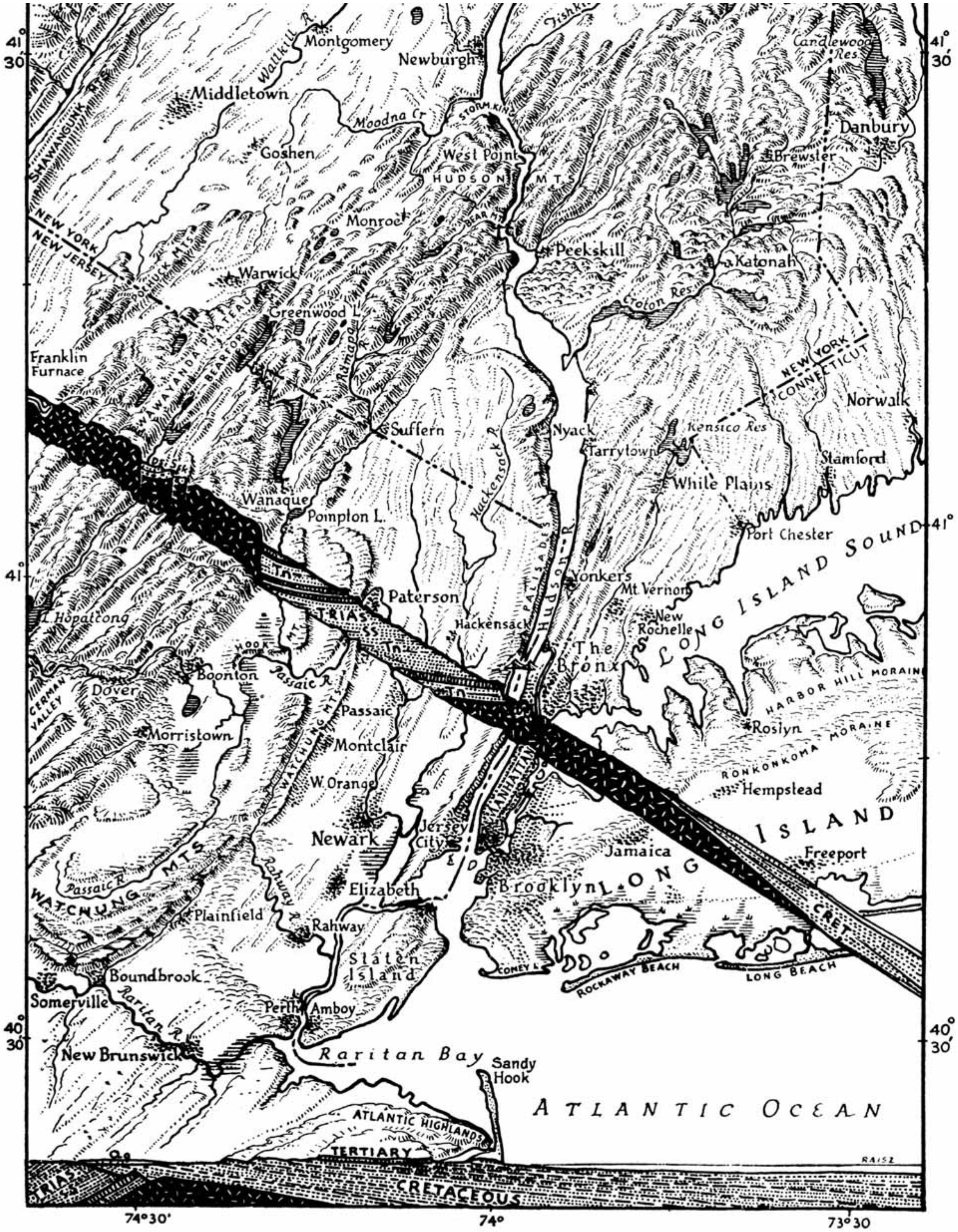


Figure 10 - Physiographic map of New York City and vicinity with two cut-away vertical slices to show geologic structure. (E. Raisz.)

On Staten Island, only the basal formation, the Stockton Arkose and its overlying Lockatong Formation are present (Figure 11). The parts of the Stockton that are not red are light gray. They can be distinguished from the overlying gray Cretaceous sands by the large content (25% to 33% or more) of feldspar. The Lockatong is typically a dark gray, tough rock named argillite. Toward the SW, the thickness of these two formations is much greater than in the Watchung syncline. In the Delaware Valley, for example, the thickness of the Stockton is 1650 m and that of the Lockatong, 1200 m (McLaughlin, 1959, p. 85).

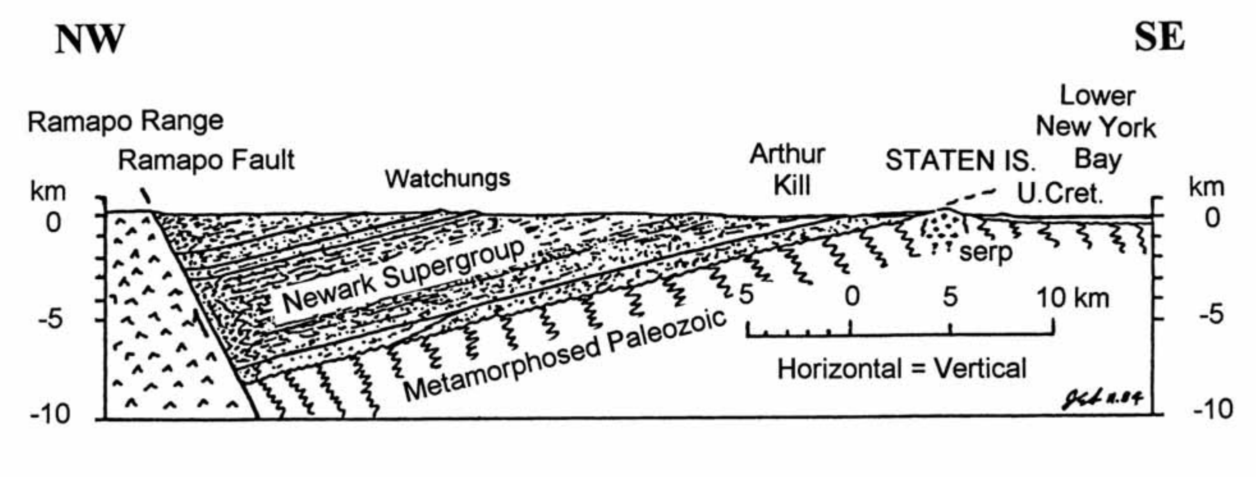


Figure 11 - Profile section from Staten Island to the Ramapo fault showing tilted- and eroded remnants of Newark basin-filling strata. (J. E. Sanders.)

As far as we are concerned today, the important thing about the Newark strata is the red-brown color of most of them. This color has left its imprint on most of the Pleistocene sediments.

The Lockatong Formation is the unit into which the tabular, generally concordant Palisades sheet has been intruded. As we shall see, a xenolith from the Lockatong Formation has been melted and converted into a granitic rock.

The age range of the Newark Supergroup has oscillated back and forth like a geological pendulum. During the 19th century, based on studies of their fossil fish (Redfield, 1856, 1857), they were assigned to the Jurassic. By contrast, the dinosaurs suggested Late Triassic. Given this situation, these strata were referred to as the Jura-Trias (for instance, by Dana, 1883; although he had earlier used simply "Triassic"; and by Darton, 1902 in the New York City Folio 83 of the U. S. Geological Survey).

Many geologists, however, took the Newark strata to be synonymous with Triassic (Cook, 1968, 1879, 1882, 1887, 1888, 1889). By contrast, Kümmel (1897, 1898, 1898a, 1898b) initially used only "Newark." When he became associated with the U. S. Geological Survey Folio projects, however, he used "Triassic" (Kümmel, 1914).

But geologists who were inclined toward tidiness in classification were uncomfortable with the notion that a well-behaved formation should span the boundary between two geologic periods. Accordingly, when Pirsson and Schuchert (in their Textbook of Geology published in 1915) proposed the name "Palisades Disturbance" for the episode of crustal unrest that they supposed marked the end of the Triassic Period, they decided that all the Newark strata, having been tilted by the period-ending "disturbance," had to be of Late Triassic age. Thus, they started a line of thought that lasted for 60 years. In addition, they also started a tradition that might be expressed by the title of a modern book: "We learned it all in kindergarten." In my analogy, "we" is all geologists trained in the United States, "kindergarten" is the first-year course in geology, and "learned it all" refers to knowledge about the Newark strata. Based on the Pirsson-Schuchert scheme of things, Widmer (1964, p. 85) wrote: "There are no known Jurassic sediments in eastern North America."

Modern students (Cornet and Traverse, 1975; McDonald, 1975 ms., 1988, 1992; Cornet, 1977 ms.; Olsen, 1978, 1980a, 1980b, 1984 ms.; Olsen, McCune, and Thomson, 1982; Olsen and McCune, 1991; Fowell and Olsen, 1993) have re-established what the real old-timers knew all along: the age range of the Newark strata is Late Triassic and Early Jurassic. The sedimentary units beneath the oldest extrusive sheet are assigned to the Upper Triassic. The remainder of the formations belong in the Lower Jurassic. (For a general summary of the geologic literature on the Newark Group up to 1984, see Margolis, Robinson, and Schafer, 1986.)

Paul Olsen (1986) has given the name Van Houten cycles to lake deposits made during a change from deep water to shallow water (or even no water) and back to deep water again. Such changes characterize lakes in closed drainage basins. The water-level fluctuations are controlled by climatic changes.

Studies of the cyclicity by Van Houten (1962, 1964) and Olsen (1984, 1986, and continuing from the Newark-basin cored borings) have indicated cycles having periods coinciding with the climatic cycles computed by Milankovitch based on variations in the Earth's orbital elements.

The finding of such Milankovitch-type cycles in rocks as old as Late Triassic-Early Jurassic demonstrates that the computer-modelling gurus who claimed that the Milankovitch periodicities break down within a few million years have got their mathematics all wrong.

Newark mafic igneous rocks include both intrusives (the Palisades sheet) and extrusives (the three "Watchung" basalt sheets in the Watchung syncline and several scattered areas along the Ramapo fault and elsewhere).

A subject of recurrent interest among geologists has been about possible identity of times of extrusion and extrusion of the mafic materials. Initially, the Palisades sheet was viewed as a product of a single charge of magma. More recently, however, evidence has been found that this sheet is composite and formed as a result of several discrete injections of magma. The major questions have centered on whether the Palisades sheet was intruded at the same time as one or more of the extrusive basalts.

The Newark sedimentary strata were deposited in a fault-bounded basin (See Figure 2, E.) to which the sea never gained access. In this basin, the filling strata were deposited in various nonmarine environments, including subaerial fans, streams, and shallow- and deep lakes. Lake levels varied according to changes in climate.

After the Newark strata had been deeply buried, they were elevated and tilted, probably during a period of mid-Jurassic tectonic activities. They were then eroded and truncated to form a surface upon which the Upper Cretaceous and younger coastal-plain strata were deposited. (See Figure 2, F.) During the early part of the Cretaceous Period, a moist, tropical climate prevailed locally, and the bedrock was deeply decomposed to form a saprolite whose thickness attains several hundred feet.

Layer VI: The Coastal-plain Strata

The strata underlying the coastal plain began to accumulate after the Atlantic Ocean had started to open and eastern North America had become a passive continental margin. As mentioned, the regime thus established mirrors the kind of setting that prevailed during the deposition of the Cambro-Ordovician Sauk Sequence.

The coastal-plain strata consist of sands that have been cemented only locally (the hematite-cemented sandstones and -conglomerates, or "ironstones"), and the interbedded clays have not become fissile. Hereabouts, the exposures show only the Upper Cretaceous part of the sequence. Elsewhere, however, younger units are present. The youngest widespread marine unit in the coastal-plain succession is of Miocene age.

A characteristic of the coastal-plain sands is their great mineralogic maturity. They generally lack feldspar and contain only quartz and resistant varieties of heavy minerals, such as zircons. Notably absent are any particles derived from the Newark Supergroup. The absence of Newark debris supports the conclusion that the coastal-plain strata formerly extended far enough inland to bury the Newark outcrop areas. Some of the distinctive heavy minerals show that the crystalline central core of the Appalachians was not covered, but was providing debris. Simiarly, sand composed of serpentinite particles indicates that the Staten Island Serpentinite was exposed.

The coastal-plain strata belong to the large category of basin-margin sediment fillings whose interpretations have been revolutionized as a result of new concepts of seismic stratigraphy. These new concepts have grown out of detailed analyses of the new generation of continuous seismic-reflection profile records collected from moving research ships. Instead of confining the analysis of the seismic records to evidence of buried geologic structures, the chief goal of seismic surveys and the only point of interest by most geophysicists, a group of geologists at the Exxon Research Laboratories in Houston, TX, under the leadership of Peter Vail, have shown how these new seismic records contain evidence of the profound influence exerted by changes of sea level on the sedimentary strata that accumulate at the margins of the oceanic basins. Analysis of data from passive continental margins collected worldwide has enabled Vail and his co-workers to compile a sea-level curve. The notion that the stratigraphic record exposed on the continents records numerous changes of sea level had been proposed early in the 20th century, by the American geologist A. W. Grabau (1906, 1913, 1924, 1936, 1940) among others and various European geologists such as the Termier's or Umbgrove.

Subsequently, the pendulum of geologic fashion in interpreting strata swung in the opposite direction and the effects of sea-level changes were not much emphasized. But, now it's back to Grabau and then some, but with one difference: the new "young Turks" think that they invented (not re-invented) the great wheel. They do not mention Grabau, T. C. Chamberlin, Charles Schuchert, E. O. Ulrich, or Stuart Weller, to name a few of the notable early American proponents of the interpretation that the continental stratigraphic record had accumulated in response to numerous, extensive changes of sea level. To be sure, the main emphasis of many of these early American studies was to use the gaps in the stratigraphic record as boundaries between systems, for example. In contrast, armed with the new regional look made possible by the seismic-profile records, the seismic stratigraphers are able to show how sea-level changes are expressed--not only in the areas where formerly the breaks resulting from an episode of emergence were emphasized but also in the basins, where deposition was continuous. The seismic expression of strata deposited at a high stand of the sea differs from that of strata deposited at a low stand. Therein lies the secret of success of the new interpretations.

Given such a powerful stimulus, nearly all stratigraphers are now reevaluating their data in terms of sea-level changes. An example is R. K. Olsson's (1988) use of benthic foraminifera from the Upper Cretaceous in the coastal plain of New Jersey for making estimates of paleodepths of the Cretaceous sea (Figure 12). Combining the information from all sources, Olsson has prepared the stratigraphic chart of the formations of the New Jersey coastal plain shown in Figure 13.

Late in the Miocene Epoch, elevation of the Appalachians generated large quantities of gravel (the "yellow gravel" of New Jersey and Long Island) that were spread eastward and southeastward by streams. The result was a thin apron of debris deposited on fans. Next came a great emergence. Sea level dropped, possibly a result of the initiation of expanded polar ice sheets. The coastal-plain sands and clays were deeply dissected; at their updip preserved edge, a strike-valley cuesta-lowland morphology was established. Downcutting by rivers that began to flow on the sheet of fan gravels formed valleys, including some extant drainage anomalies, and sculpted the surface upon which the Quaternary glaciers acted. During this great interval of erosion, the sheet of fan gravel and the updip edge of the coastal-plain strata that were covering the Newark basins were removed. This allowed the diagnostic reddish-brown debris from the Newark Supergroup sedimentary strata to circulate once again.

Overlying the Staten Island Serpentinite at Stop 1 is a very local patch of breccia containing both Newark clasts and pieces of the serpentinite. No fossils have been found in this breccia. It has been assigned to the Lafayette Gravel. JES is not certain whether the name Lafayette includes the sheet of fan sediments that was prograded across the coastal plain during the Late Miocene-Early Pliocene. If it does, then this local breccia may not properly belong to the Lafayette. The key point is that the sheet of fan gravels was prograded before the blanket of Upper Cretaceous sediments was stripped off the Newark Basin to expose the Newark Supergroup once again. This local breccia contains Newark debris; therefore, its age must be younger than the date of uncovering of the Newark Basin (whenever that was).

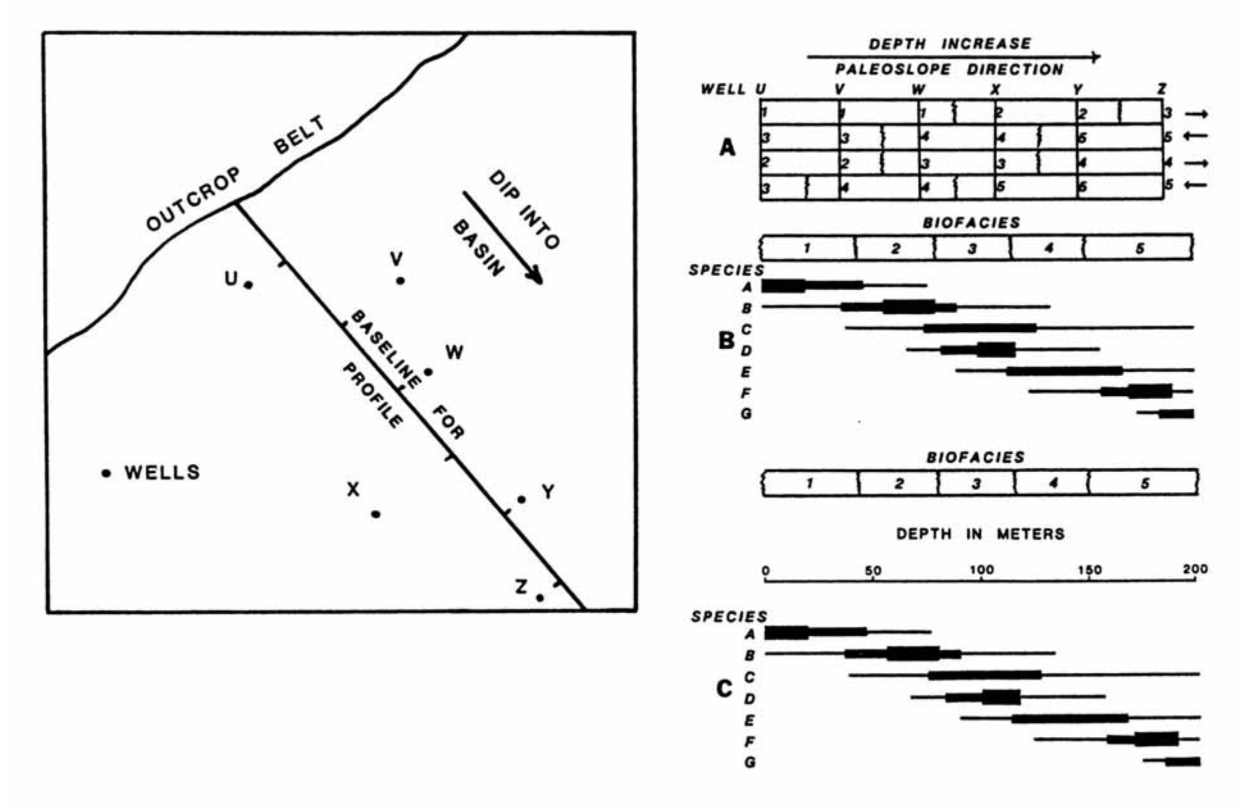


Figure 12 - Basis for paleodepth model using benthic foraminifers. Sketch map shows relationship of baseline for profile with respect to edge of outcrop belt, locations of wells from which material was obtained, and direction of dip of strata into basin. (R. K. Olsson, 1988, figs. 5 and 6, p. 292.)

A. Schematic profile along baseline showing distribution of biofacies (numbered 1, closest to shore, through 5, farthest offshore) inferred from samples collected from control wells.

B. Species distribution in numbered biofacies units.

C. Species arrayed as in B, but with inferred depths shown.

LAYER VII: Glacial Deposits

The glacial deposits are products of several invasions of the New York metropolitan region by thick ice sheets that spread southward from Canada. Many kinds of studies have been made on the glacial deposits. Here we confine ourselves to the kinds of sediments, the evidence on directions of flow of the ice, and the stratigraphic relationships.

Kinds of Glacial Sediment: Till and Outwash

As mentioned earlier, glacial deposits include several contrasting varieties. We will be especially interested in the characteristics of till and outwash. Till is a general name for any sediment deposited directly by the flowing ice of the glacier. Typically, till is not stratified and contains a wide range of particle sizes, from boulders to clay. Outwash is a general term for any sediment deposited by water melted from a glacier. Outwash includes such contrasting sediments as stream sands and lake clays. From the point of view of the relationships to the point of maximum advance, it is important to distinguish the kind of outwash that spread out as fans beyond the most-distal terminus of the glacier from the kind of outwash that formed after the ice had retreated from this terminus. In the case of ice retreat, the outwash sediments may have been deposited in a proglacial lake that was dammed in on one side by the terminal-moraine ridge created by the ice at its most-distal terminus. The key point about recognizing outwash is the stratification that resulted from the action of water.

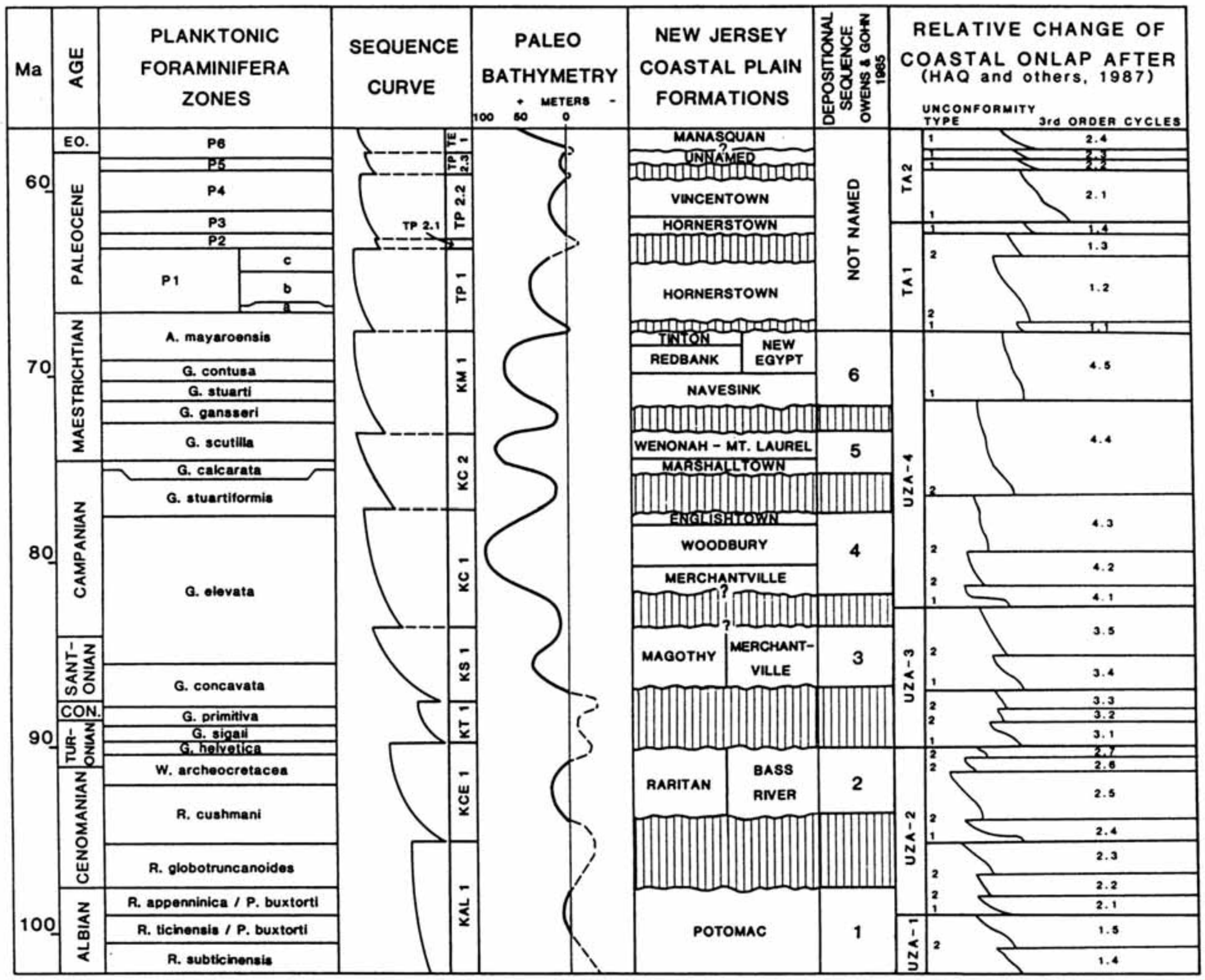


Figure 13 - Chart of Upper Cretaceous formations of New Jersey Coastal Plain (column to right of center) showing inferred ages, zones based on planktonic foraminifera, newly recognized sequences (and sequence curve), paleobathymetry curve, and inferred sea-level curve based on coastal onlap inferred from continuous seismic-reflection profiles (right-hand column). (R. K. Olsson, 1988, fig. 7, p. 293.)

Evidence For Inferring Direction of Flow of Ice

An important point to be determined in studying a glacial deposit is which way the glacier flowed. Features useful for inferring glacial-flow direction include those eroded on the bedrock and those found in glacial sediments. We begin with features eroded on bedrock.

Features Eroded on Bedrock

Because glaciers are the only geologic mechanism for creating extensive scratches and even large grooves on solid bedrock, if any bedrock is exposed, then ice-flow direction can usually be inferred in a straightforward manner. The ice flowed along the trend of the linear grooves and/or striae (Figure 14). Associated with these linear features may be distinctive crescentic marks (Figure 15).

Figure 14 - Sketch of a glaciated bedrock surface exposed by wave action; boulders resting on the linear striae have been eroded out of the bluff of till in the background. This sketch (locality not given) depicts what can be seen along the shore of Long Island Sound at South Twin Island, Pelham Bay Park, New York City. (A. K. Lobeck, 1939, upper right-hand sketch on p. 301, from U. S. Geological Survey.)

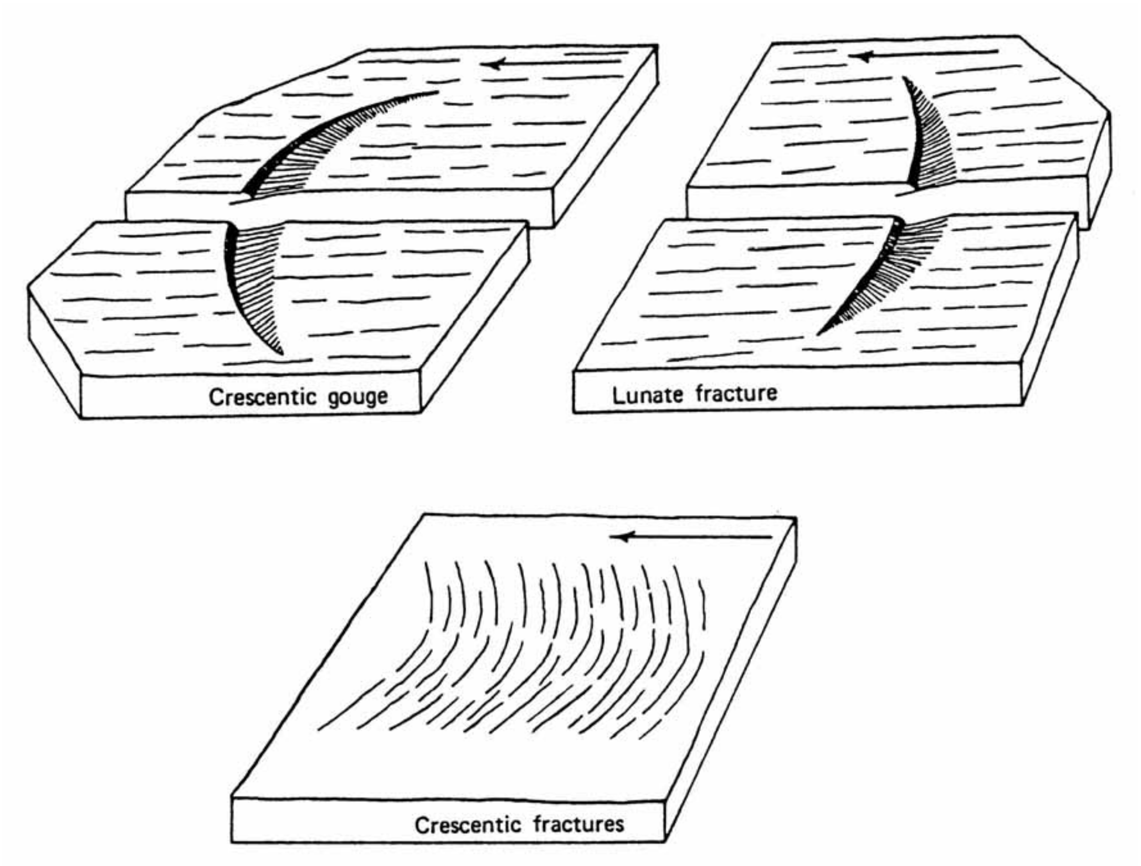


Figure 15 - Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

Glaciers also erode diagnostic asymmetric features known as roche moutonnées (Figure 16) and rock drumlins. In roche moutonnée, the up-ice side dips gently toward the direction from which the glacier flowed and is broadly rounded (forming a feature that we have been referring to as " roche moutonnée" structure). The down-ice side is steep and irregular; it was formed where the glacier pulled away from the bedrock and quarried out blocks bounded by steeply inclined joint faces.

Rock drumlins are asymmetric streamlined features that lack the steep, jagged downice sides so characteristic of roches mouton,es. We do not know the explanation for when a glacier may sculpt roche moutonnées in one place and rock drumlins in another.

Features Found in Glacial Sediments

Direction of flow may also be inferred by studying glacial sediments. One aspect is provenance, that is, the source of the particles in the deposits. Because glaciers can transport stones long distances, one commonly finds a collection of glacial particles unlike the bedrock on which the glacial deposits rest. Such stones are known as erratics. If an erratic can be traced to a distinctive source, it becomes an indicator stone. (Figure 17).

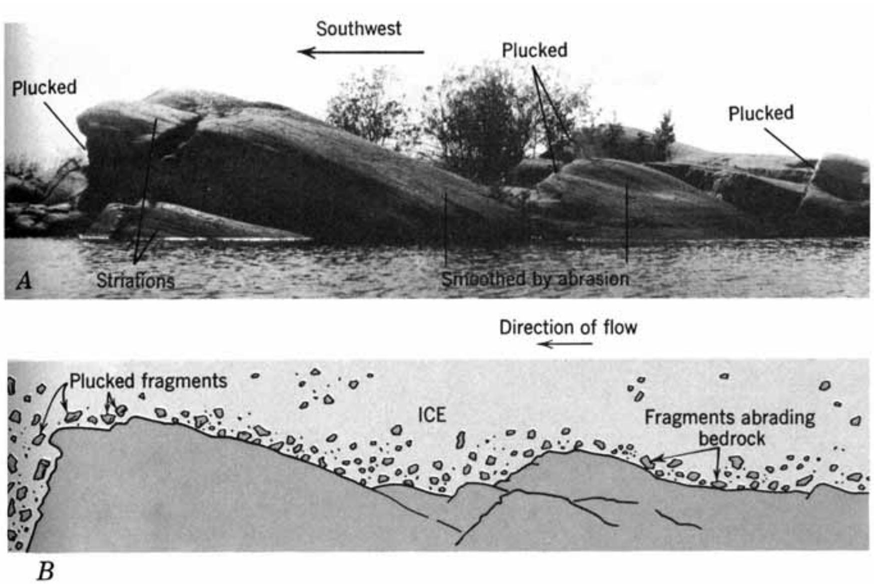


Figure 16 - Roche moutonnées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roches moutonnes sculpted in Proterozoic granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnées beneath a glacier.

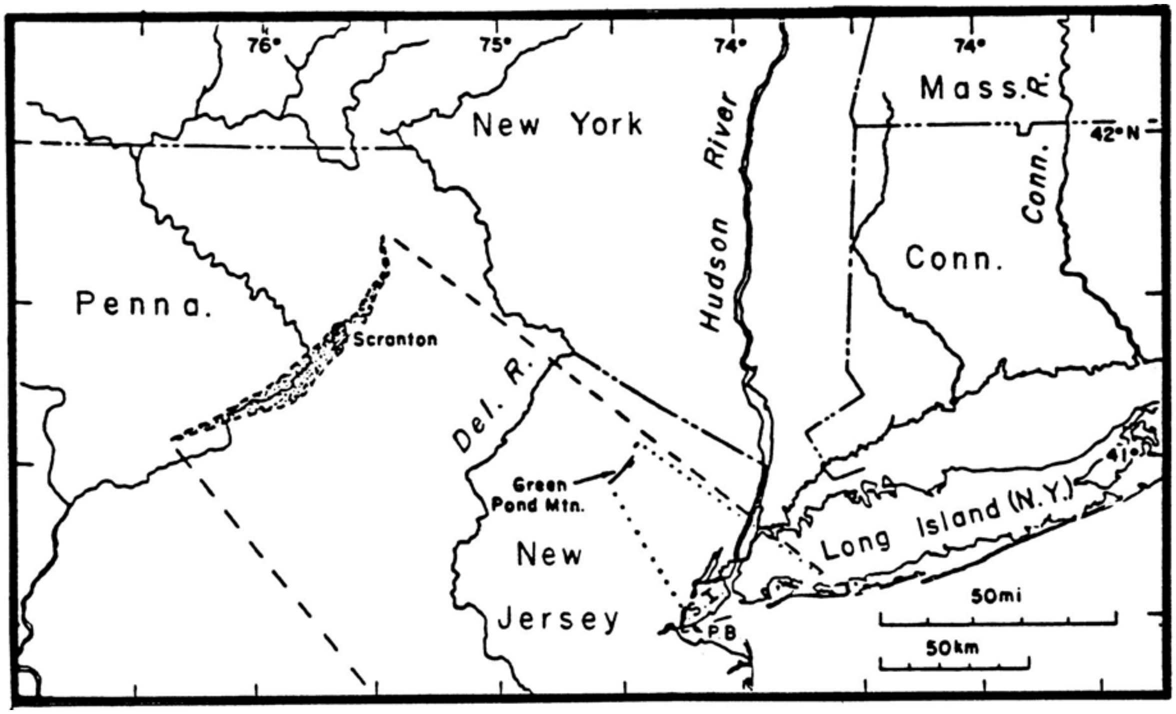


Figure 17 - Distinctive erratics found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten Island; P. B. = Prince's Bay. (G. M. Friedman and J. E. Sanders, 1978, fig. 2-1, p. 27.)

In those parts of New York City lying E of the Hudson River, any reddish-brown glacial sediments serve as a collective "indicator stone" of transport from the Newark lowland on the W side of the Hudson River toward the SE.

Glaciers also shape sediments into elongate, smooth, asymmetric hills known as drumlins (Figure 18). We have already mentioned rock drumlins briefly. If the term "drumlin" is used without any modifier, the presumption is that a feature in question is composed of glacial sediments.

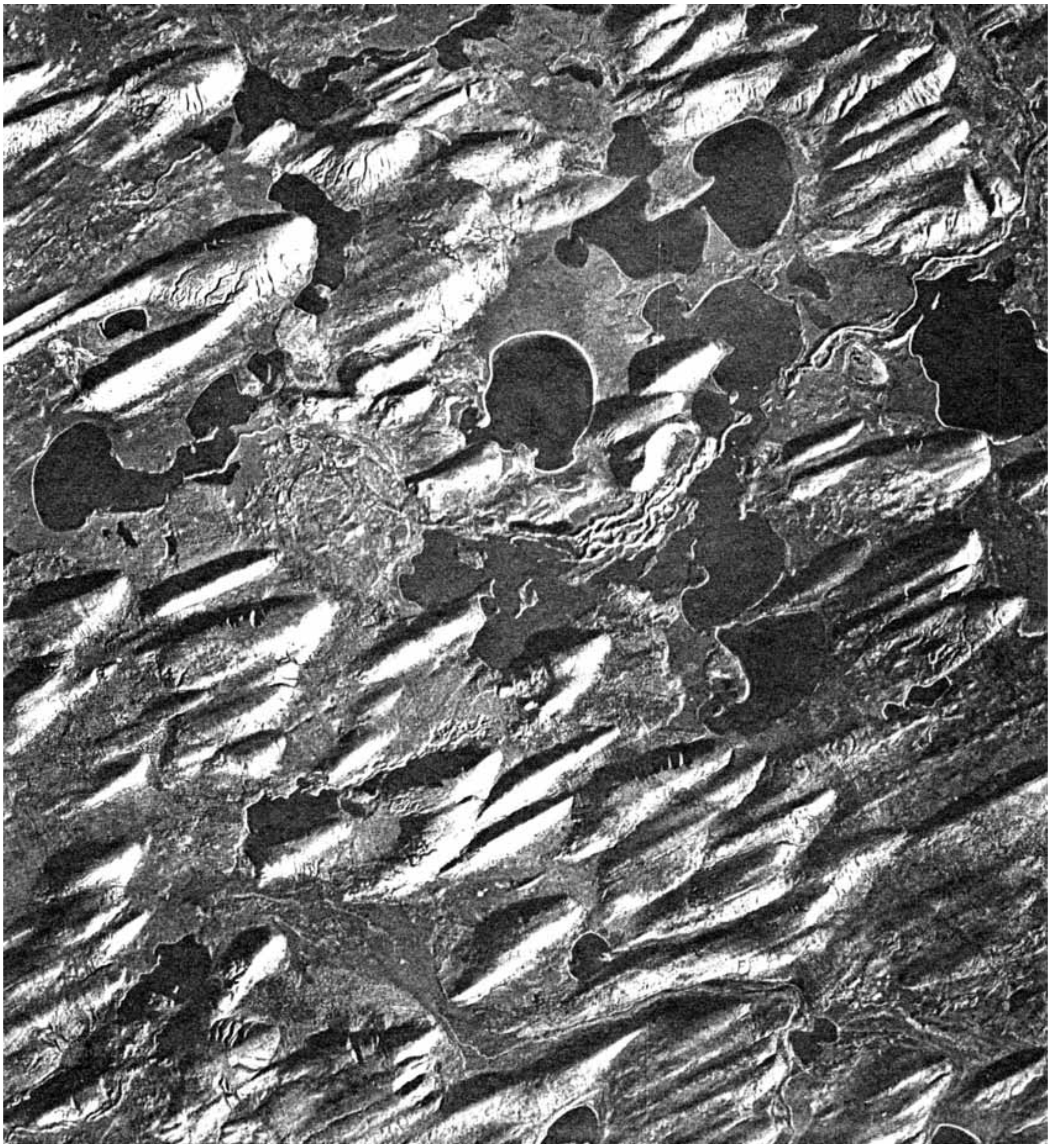


Figure 18 - Swarm of drumlins viewed from vertically above in aerial photograph, northern Saskatchewan, Canada, created by a glacier that flowed from NE (upper right) to SW. The small circular lakes give the scale; their diameters are about 1 kilometer. The thin, curviliner light-toned features extending from the center of the view to the upper right margin are parts of an esker complex. (Geological Survey of Canada, Canadian Government Copyright; published in J. E. Sanders, 1981, fig. 13.24, p. 323.)

The origin of drumlins has worked its way back into a high position on the agenda of modern-day glacial geologists. The problem was discussed long ago by T. C. Chamberlin (1883), Upham (1879; 1889b; 1892; 1893a, b; and 1894), and Tarr (1894). Not many drumlin papers appeared before 1950; exceptions include Alden (1918), Millis (1911), Armstrong (1949), I. B. Crosby (1934), and Ebers (1937). Another flurry of papers about drumlins appeared in the geologic literature in the 1950's and 1960's (Aronow, 1959; Chorley, 1959; Gravenor, 1953; Reed, Galvin, and Miller, 1962). The newest wave of interest has been sparked by the hypothesis that the streamline shapes did not result from the flowing ice, but rather were eroded in the sole of the ice by subglacial floods of water and later filled in with sediment (Shaw and Kvill, 1984; Shaw, Kvill, and Rains, 1989; Shaw and Sharpe, 1987). (JES considers this concept as being analogous to upside-down flutes, which are concave-up, asymmetric features that turbulent eddies within bottom currents erode out of subjacent cohesive-sediment substrates. Flutes are steeper on their upcurrent sides and flare out downcurrent. Deposition of sand-size sediment fills the concave-up flutes. Thus the shapes of the flutes are preserved as convex relief forms on the bottoms of the covering sandstone layer.

As pointed out by R. S. Tarr (1894), the shapes of rock drumlins (clearly features that resulted from glacial-ice erosion) are the same as those drumlins composed of glacial sediments. This coincidence led Tarr and others to adopt the view that drumlins result from glacial erosion.

The internal relationships within drumlins are not commonly known. Many drumlins in northeastern USA are the sites of apple orchards (Millington, 1930) or of housing subdivisions. The farmers and homeowners seldom allow large trenches to be dug on their properties. Moreover, even where digging might not be objected to by the landowners, many glacial geologists avoid the hard labor of digging to reveal sedimentary structures and fewer yet of them have access to backhoes. As a result, the internal anatomy of drumlins is known only where waves have eroded cliffs in drumlins along the shores of large lakes (Slater, 1929) or the ocean (Upham, 1889a, b; 1892; 1893a, b; I. B. Crosby, 1934; W. A. Newman, Berg, Rosen, and Glass, 1987; W. A Newman and Mickelson, 1994).

Drumlins can consist of one or more tills and/or intervening layers of outwash. The drumlin at Enoch's Nose, Croton Point Park, Westchester County, includes two tills and intervening outwash. Coastal cliffs eroded in the drumlins in Boston Harbor, MA, indicate that two tills and intervening outwash are present (Newman and Mickelson, 1994).

Stratigraphic Relationships

The stratigraphic relationships among glacial deposits are worked out by noting evidence of superposition of till, outwash, and sediments that have nothing at all to do with a glacier and, in fact, were deposited under a climate regime that is nonglacial. In a coastal area such as New York, it is reasonable to expect that the glacial deposits may be interstratified with marginal-marine deposits. For example, in Boston Harbor, MA, an oxidized pre-Wisconsinan (Illinoian?) till has overridden shell-bearing marine sediment and contains shell debris eroded from this sediment. This close juxtaposition of till and marine deposits has resulted from the relationship between growth of continental ice sheets and the volume of water in the ocean basins. Professor R. A. Daly, of Harvard, once described this relationships between glacial ice and the water of the oceans as one of "robbery and restitution." By robbery, he meant the locking up of the water in the glaciers. By restitution, he meant the return of the water to the oceans when glaciers melted. Although the exact climate settings involved in these changes are not as securely known as one might suppose, it is well established that when the glaciers reached their maximum extents, the sea was at its lowest stand, a level around 75 m lower than now.

The fundamental study of the stratigraphy of the glacial deposits in the New York metropolitan region is Fuller's (1914) monumental treatise on the geology of Long Island. Fuller found evidence for 4 glacial advances; between some of the glacial sediments, he found nonglacial strata (Table 3). Notice that Fuller assigned the Harbor Hill Moraine and the Ronkonkoma Moraine to the early Wisconsinan. Most later workers, however, have assigned these two moraines to the latest Wisconsinan, to a subdivision known as the Woodfordian. (We do not know where this change was first published. In the Boston area, LaForge (1932) assigned the till in the Boston area to the latest Wisconsinan; by contrast, Judson (1949) preferred an Early Wisconsinan age.

Despite the general belief that only one Pleistocene glacier invaded New York City and vicinity and left all the glacial features that have been noticed, a few workers have found evidence for more than one glaciation. In southern CT, Flint (1961) found two tills: an upper Hamden Till with flow indicators oriented NNE-SSW, and a lower Lake Chamberlain Till with flow indicators oriented NNW-SSE, the same two directions of "diluvial currents" shown by Percival (1842). In Boston, MA, and vicinity, C. A. Kaye (1982) found many tills having these same two inferred flow directions (but Kaye assigned them all to the Wisconsinan).

In one of the most-recent papers on this subject, W. A. Newman and Mickelson (1994) have confirmed the results of Upham (1879 and 1899a) that at least one pre-Wisconsinan till is present in the drumlins being eroded in Boston Harbor. This older till contains shells that the ice eroded out of the subjacent interglacial marginal-marine deposit. During a later interval of interglacial subaerial weathering, the carbonate from the shells has been leached from the older till to depths of 8 m. Based on comparative studies of the weathering of the clay minerals, W. A. Newman and Mickelson assigned the older till to the Illinoian. If correct, then the marginal-marine formation from which the Illinoian glacier eroded the shells might be of Yarmouthian age, in which case it would be a correlative of Fuller's Gardiners Clay.

Table 4 shows our proposed stratigraphic classification of the Pleistocene sediments in the New York. Starting from the top, with the youngest (our No. IV) and working backwards, we interpret the record as follows. No. IV, the Woodfordian, the youngest till deposited by a glacier that flowed from NNE to SSW, down the Hudson Valley (the same direction as Flint's Hamden Till in CT). In the New York City region, such a till is gray to light brown in color, contains poikilitic mafic indicator stones from the Cortlandt Complex near Peekskill (which many may have confused with "trap rock" from the Palisades Sill) and erratics of Inwood Marble and other rocks from Westchester County, and totally lacks any erratics derived from the Newark Basin, which is situated on the W side of the Hudson. Till IV is present in Queens and on Staten Island, but is not present on much of Long Island; the terminal moraine of glacier IV lies along the S coast of CT (Flint and Gebert, 1974, 1976).

The next-older till, our III, was deposited by a glacier that flowed over the New York City region following a rectilinear course from NW to SE, across the Hudson Valley (the same direction as reported by Flint from the Lake Chamberlain Till in CT). In New York City, southern Westchester County, and western Long Island, Till III is a distinctive reddish-brown color from its content of pulverized Newark sedimentary rocks. Diagnostic indicator stones from outcrop belts NW of the Newark Basin include Lower Silurian Green Pond Metaconglomerate and Pennsylvanian anthracite coal (Sanders, 1974a; Friedman and Sanders, 1978). In Long Island City (Queens), Woodworth (1901) found glaciated bedrock gneiss with striae and grooves oriented N25°W-S25°E overlain by reddish-brown materials forming the Harbor Hill Moraine. At Corona, Woodworth found reddish-brown sand underlying a gray till containing erratics of what he called "trap-rock." (We have not seen these but suspect that they may not be dolerite from the Palisades as one might suppose from his use of the term "trap rock." Other possibilities are indicator stones from the Cortlandt Complex, or Paleozoic amphibolites and or -mafic igneous rocks from SE New York and/or western CT. In any case, we classify this gray till as our IV, the Woodfordian).

In the subsurface at Jones Beach, on the S shore of LI, the inferred nonmarine upper outwash (of Rampino, 1978 ms.; the Bellmore Formation of Rampino and Sanders, 1981) has been correlated with the Harbor Hill Moraine (Figures 19 and 20). We accept this correlation and assign both the upper outwash (Bellmore Formation) and Till III to the Early Wisconsinan.

The next-older glacial advance, our No. II, which also crossed the New York City following rectilinear flow paths from NW to SE, deposited tills having the same color-distribution pattern as deposits of glacier No. III. We think glacier No. II deposited the Ronkonkama terminal-moraine ridge. In the Jones Beach subsurface, the lower inferred outwash (of Rampino, 1978 ms.; the Merrick Formation of Rampino and Sanders, 1981) is separated from the upper inferred outwash (the Bellmore Formation) by the marginal-marine sediments of the Wantagh Formation (of Rampino and Sanders, 1981; the "20-foot clay" of Perlmutter, Geraghty, and Upson, 1959, Table 1, p. 420, p 422; Doriski and Wilde-Katz, 1983; and others of the U. S. Geological Survey). If the correlations of the two subsurface units of inferred outwash with the Harbor Hill- and Ronkonkama moraines are correct, then they imply that these two moraines were not deposited by the fluctuating margin of the same glacier (whatever its age), but by two different glaciers, as originally visualized by Upham (1879). The Wantagh Formation implies that these two outwash-connected glaciers were separated in time by an interval sufficiently long and with a climate sufficiently "nonglacial" so as to enable the sea to rise to close to its present level to deposit sea-marginal sediments. The age of the Wantagh Formation is not certain. Initially, Rampino and Sanders (1976) assigned it the mid-Wisconsinan and thought it is correlative with the Portwashingtonian warm interval of Sirkin and Stuckenrath (1980). In light of Wehmiller's amino-acid racemization results (reported in Ricketts, 1986), however, we now think the Wantagh is pre-Wisconsinan, possibly Sangamonian. If that is correct, then the next-older slot for the Ronkonkama Moraine and Till II is Illinoian.

Glacier III (and/or II; we cannot as yet distinguish between their erosive effects) sculpted the bedrock with prominent grooves trending NW-SE as found in Manhattan by Dr. L. D. Gale in 1828-29 (published in Mather, 1843), in Central Park by Hanley and Graff (1976) and in many parts of the New York City region by us (Merguerian and Sanders, 1988; 1991a, e; 1993a, c;

1994a; Sanders and Merguerian, 1991a, 1992). We ascribe the numerous effects of glacial flow oriented NW-SE, as reported from the erratics in the Brooklyn Botanical Garden (Gager, 1932) as shown on the Glacial Map of North America (Flint, 1945) and also as found by C. A. Kaye (1964a) in southeastern MA, and in Boston, MA, and vicinity (1982) to glacier(s) II and/or III.

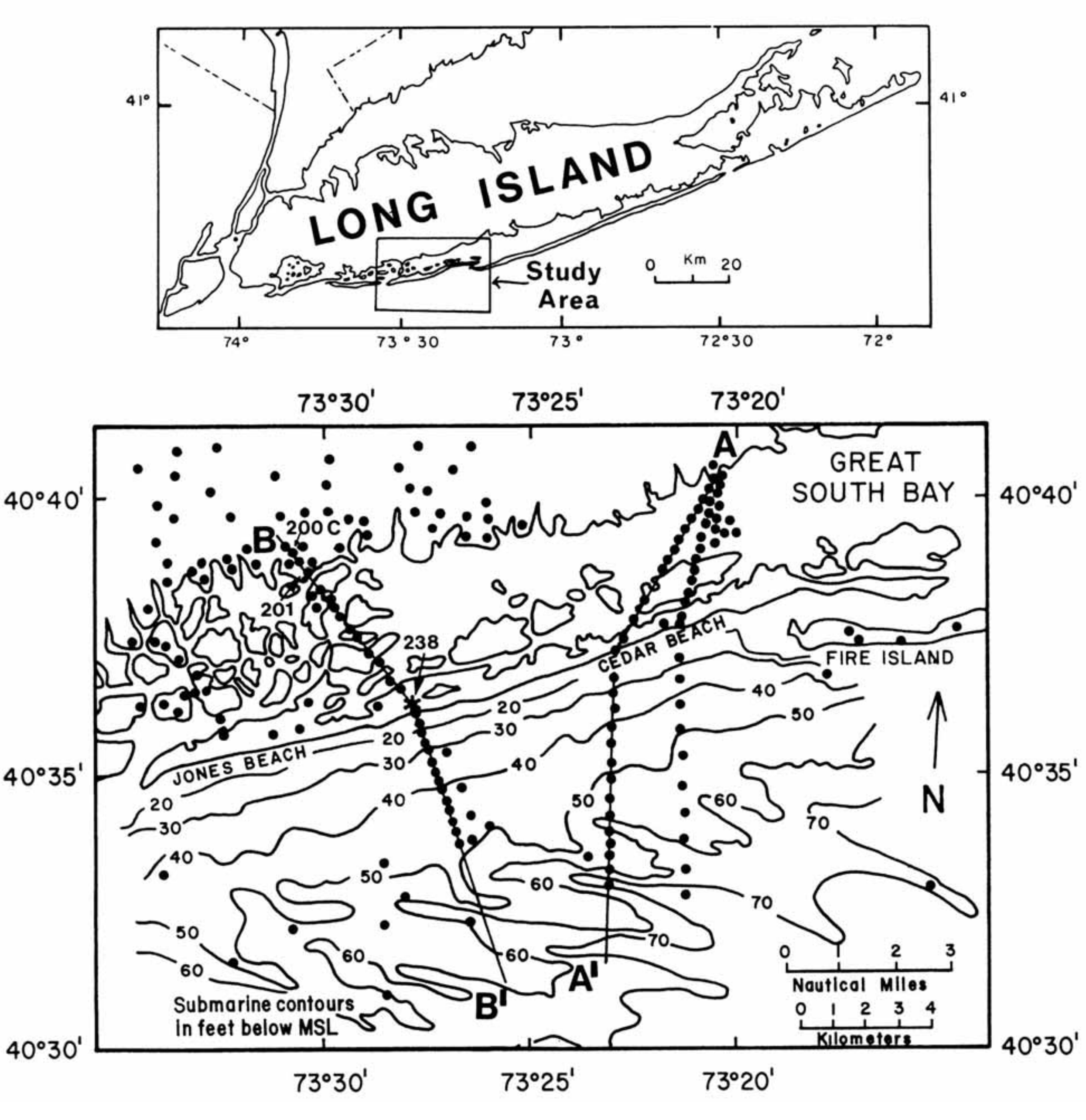


Figure 19 - Index map, location of Jones Beach profile-sections. (Rampino and Sanders, 1981, fig. 3, p. 118.)

Tills II and III, separated by a few meters of reddish-brown outwash of the kind deposited in a proglacial lake, are exposed in eroding bluffs along the E shore of the Hudson River at Croton Point Park, Westchester Co. At Enoch's Nose, they underlie yellowish-brown till IV that has been shaped into a drumlin whose long axis trends N-S; at Squaw Cove, they are overlain by gray varved clay containing scattered dropstones (assigned to the meltdown phase of glacial-episode IV); and at Teller's Point, they are underlain by a grayish-brown till (our Till No. I) containing indicator stones from the Cortlandt Complex and granitic rocks in which the feldspars have been totally decomposed to clay. Reddish-brown tills II/III underlie the terminal-moraine ridge being eroded in southern Staten Island; a prominent paleosol caps the upper reddish-brown till. The youngest unit in the coastal cliffs is a brownish loess (the "surficial loam"? of R. D. Salisbury (in New York City Folio of the U. S. Geological Survey).

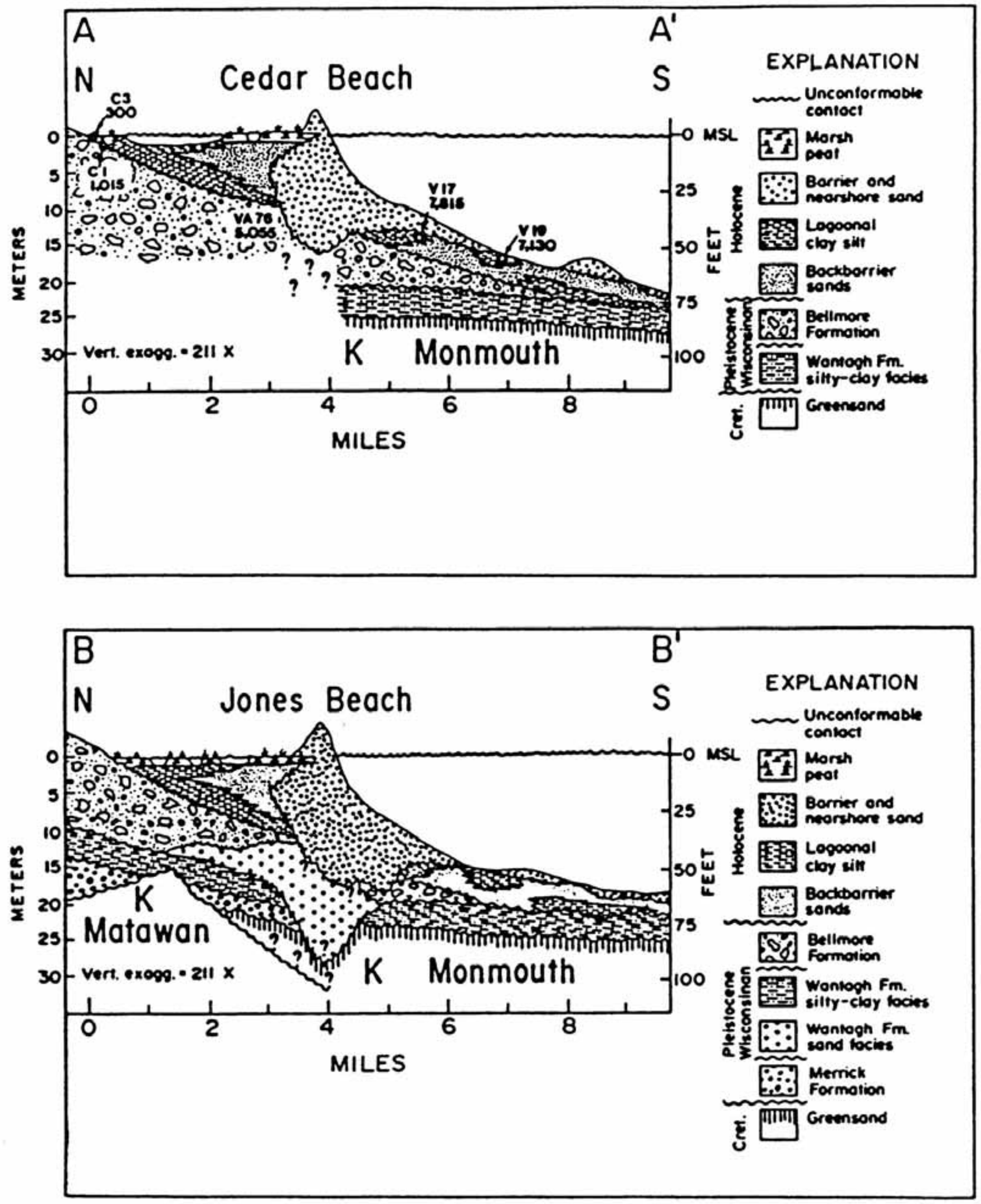


Figure 20 - Profile-sections subsurface of Jones Beach. (Rampino and Sanders, 1981, fig. 4, p. 119.)

The earliest glacier to leave its mark in New York City and vicinity (from our Episode I) flowed from the NNE to the SSW. It eroded the prominent rock drumlin at Fort Tryon Park, Manhattan, and many elongate rounded features eroded on the bedrock that constitute the smoothed, upglacier parts of typical roche moutonnées but lack the diagnostic steep, quarried-and-plucked down-ice sides. We have been using the term "roche moutonnée structures" for these partial- or modified roche moutonnées. Examples are known from Bear Mountain, Orange County; from FDR Veterans Hospital, Westchester County; and in various parks in New York City (Sanders and Merguerian, 1994b).

Glacier No. I deposited the gray-brown till that underlies red-brown till (No. II?) at Teller's Point, Westchester Co. and the gray-brown till at Target Rock, L.I., which contains "greenstone" indicator stones from the Maltby Lakes metavolcanics SW of New Haven [misidentified by Sirkin and Mills (1975) as Palisades Dolerite and thus assigned by them to a till that was deposited by a glacier that flowed NW-SE; the upper till here, deposited by a glacier that did flow from NW to SE, is gray and contains no Newark erratics but rather indicator stones, such as Inwood Marble and the Cortlandt Complex, derived from what we have called the "crystalline corridor" of southeastern NY and western CT].

At least two pre-Woodfordian glaciations are implied by the relationships at three localities on Staten Island: (1) Till, exposed in coastal cliffs eroded into a terminal-moraine ridge in southern Staten Island, containing but-minor quantities of decayed pebbles (only the "greenstones") and capped by a well-developed paleosol, yields provenance data which prove that at least one glacier flowed regionally across Staten Island from NW to SE (across the Hudson Valley, thus our Till II and/or III) not NNE to SSW, (down the Hudson Valley) with local diversions to the SE, the pattern inferred for the Woodfordian ice by R. D. Salisbury (1902) and accepted by many one-glacier advocates. (2) At the AKR Excavating Corp., much-decayed stones in outwash gravels that underlie comparatively fresh red-brown till and overlie Cretaceous sands imply a pre-Wisconsinan age (possibly a product of our Episode I). (3) Superposed glacial striae and -crescentic marks on the dolerite exposed at the Graniteville quarry are inferred products of two ice-flow directions: an older NW to SE (our II and/or III) cut by a younger NNE to SSW (our No. IV).

We infer that on Staten Island are products of at least 3, possibly 4, glacial advances. We regard their ages as: Kansan (?) or even Nebraskan (?) for the much-decomposed outwash at AKR; Early Wisconsinan +/- Illinoian (?) for the coastal exposures of "terminal-moraine" materials derived from the NNW (capped by a well-developed paleosol and including a giant "erratic" slab of displaced Cretaceous sediments); and Wisconsinan (Woodfordian) for the till overlying the striae trending NNE-SSW at Graniteville. We do not know the location on Staten Island of any Woodfordian terminal-moraine ridge. Elsewhere, this ridge follows the south coast of Connecticut.

We have not yet turned up any absolute-age data that would settle the age assignments of our multiple-glacier interpretation and that would totally destroy the one-glacier-did-it-all view that we think is not correct. However, we think the case we have made for the pre-Woodfordian age for the Harbor Hill Moraine is very compelling. If we have correctly interpreted the subsurface relationships Rampino (1978 ms.) established at Jones Beach, then Long Island's two world-famous terminal moraines were not only not made by the fluctuating margin of the Woodfordian glacier, as has been universally believed for many years, but were made by two different glaciers whose appearance on Long Island was separated by an interglacial episode when the glacier retreated back into Canada and the sea rose nearly to its present level.

At present, the best hope for settling our chronological impasse is amino-acid-racemization analysis of shells from the Wantagh Formation. Our inference is that the Wantagh is Sangamonian, but as noted above, it could be mid-Wisconsinan or even Yarmouthian.

Discussion of Ice-flow Evidence

Use of striae and indicator stones shows that glaciers flowed across the New York region from several directions. Figure 21 shows a map of North America with what was for a long time the "standard" view of how the Pleistocene ice covered Canada and northern United States. Notice that New York is within the flow pattern shown for the Labrador Ice Sheet.

Figure 21 - Reconstruction of North American Pleistocene Ice Sheets with Keewatin center and Labrador center shown as attaining simultaneous maxima. Further explanation in text. (U. S. Geological Survey.)

Given the concept that ice from the Labrador center should have been present in New York City, then the expected direction of such glacier flow is from the NNE to the SSW, a direction that is parallel to the Hudson River. However, in Manhattan and on the top of the Palisades Ridge, striae are oriented from about N20°W to S20°E, or even more toward the NW-SE direction. A previous generation of glacial geologists adopted the view of deviated flow from a central lobate glacier (Figure 22). According to this concept, the main flow of the latest (and, according to many, the only Wisconsinan) glacier was concentrated down the Hackensack lowland, but the ice deviated to its left and crossed the Palisades ridge and New York City on a NW to SE course.

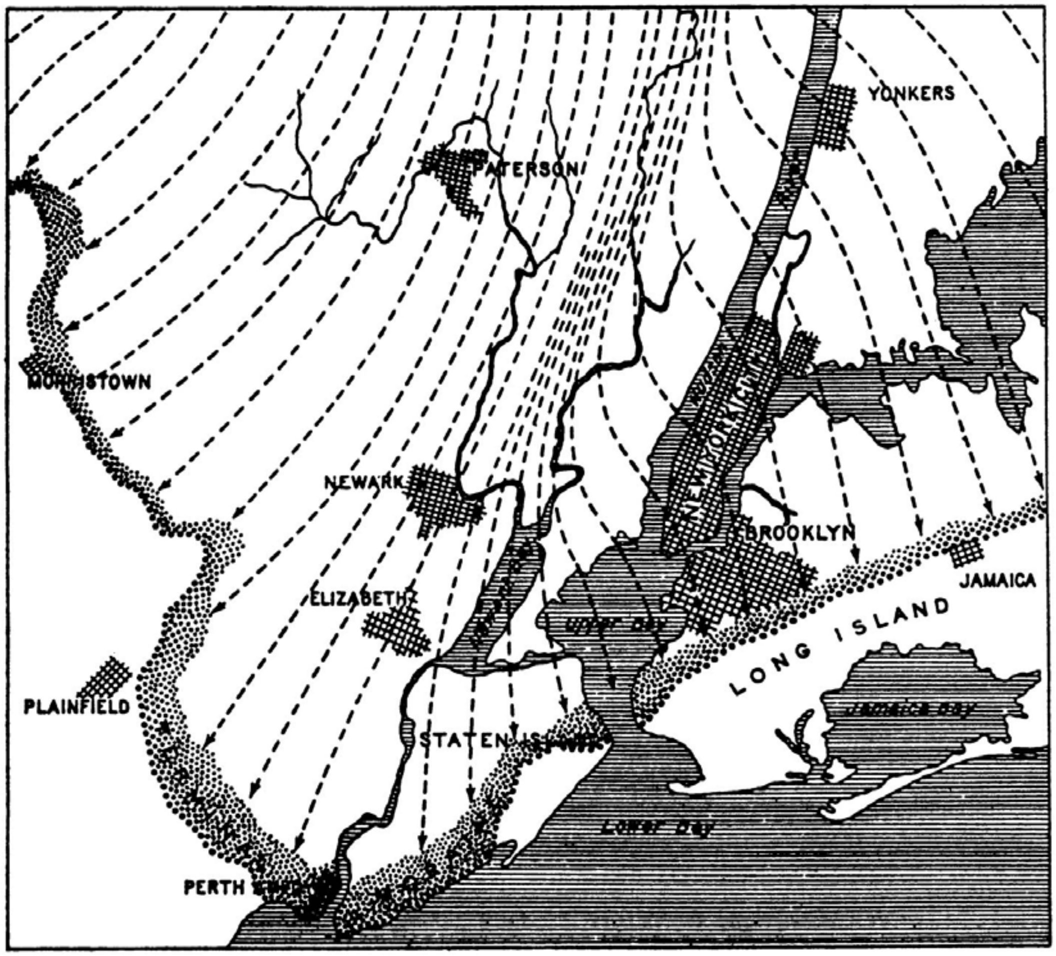


Figure 22 - Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (R. D. Salisbury, 1908, fig. 11.)

From studying the stratigraphic relationships, provenance, and grooves on the bedrock, we propose an alternative view. In our scheme of things, the flow indicated in Figure 22 is not the product of one glacier, but of more than one (two, possibly more). Figures 23 and 24 show our interpretation of the glaciers in the same area of Figure 22. In Figure 23, we show rectilinear flow of ice from NW to SE, across the highest ridges and across the Hudson Valley without deflection. This suggests a thick ice sheet whose flow pattern was governed by the gradient on the top of the glacier. Figure 24 shows the flow from NNE to SSE as resulting from a later glacier. The two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 23. The latest glacier, shown in Figure 24, did not reach much of Long Island. (See Sanders and Merguerian, 1991, 1994b.) It covered parts of Queens and Brooklyn, Manhattan, and Staten Island. What its terminal moraine was like is not yet known. Table 4 shows our current interpretation of the various tills and their inferred directions of flow.

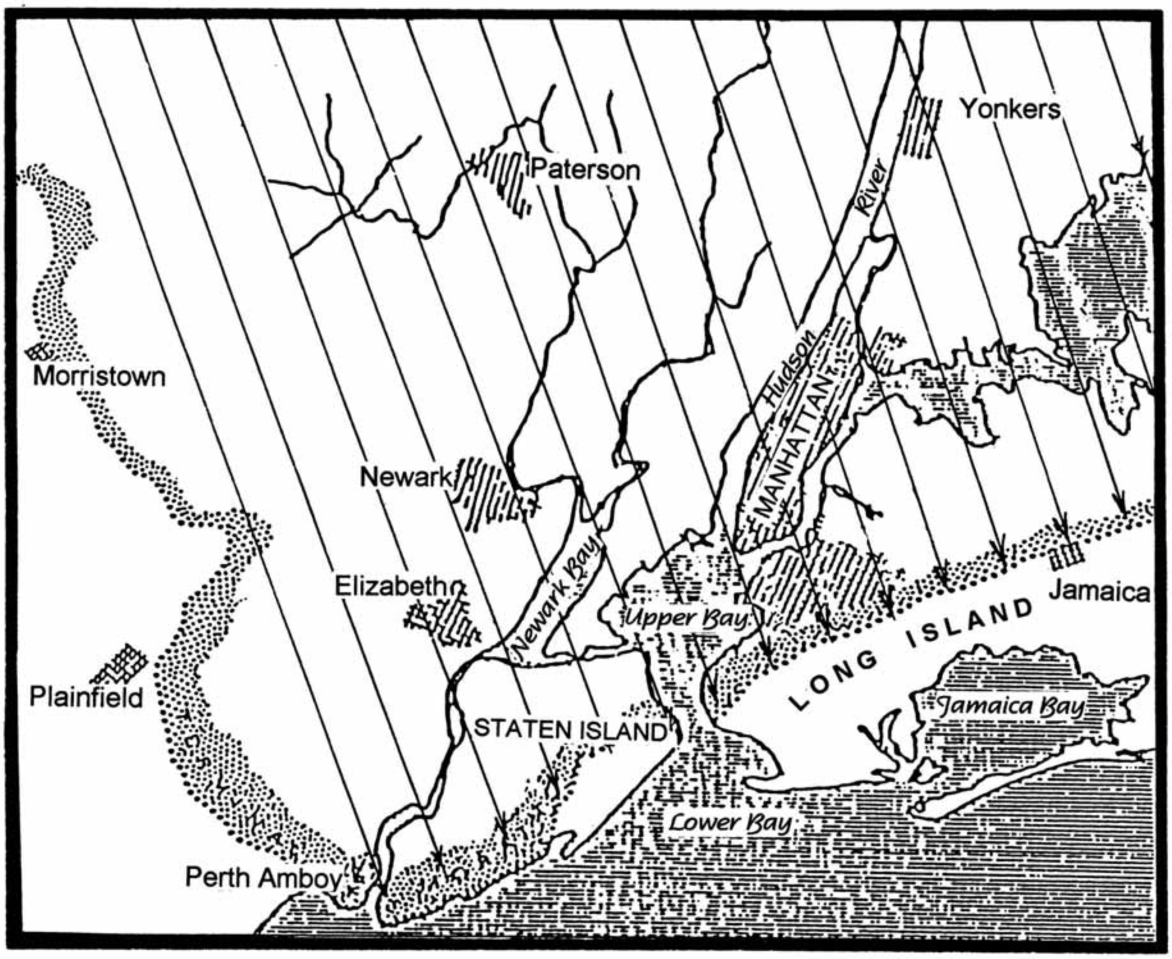


Figure 23 - Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders.)

The distribution of erratics has attracted the attention of numerous geologists, starting with Dr. L. D. Gale early in the 19th century. Other authors of papers about glacial erratics have included Gager (1932 for Brooklyn), Gratacap (1890), and Hollick (1893c, 1895, 1908a, and 1915). In the red-brown tills and -outwash on Staten Island and elsewhere in New York City, JES has found erratics derived from as far away as the anthracite district in eastern Pennsylvania. (See Figure 17.) These findings lend strong support to the interpretation shown in Figure 23, as contrasted to Figure 22. (See contrasting interpretation by Zen and Mammay, 1968).

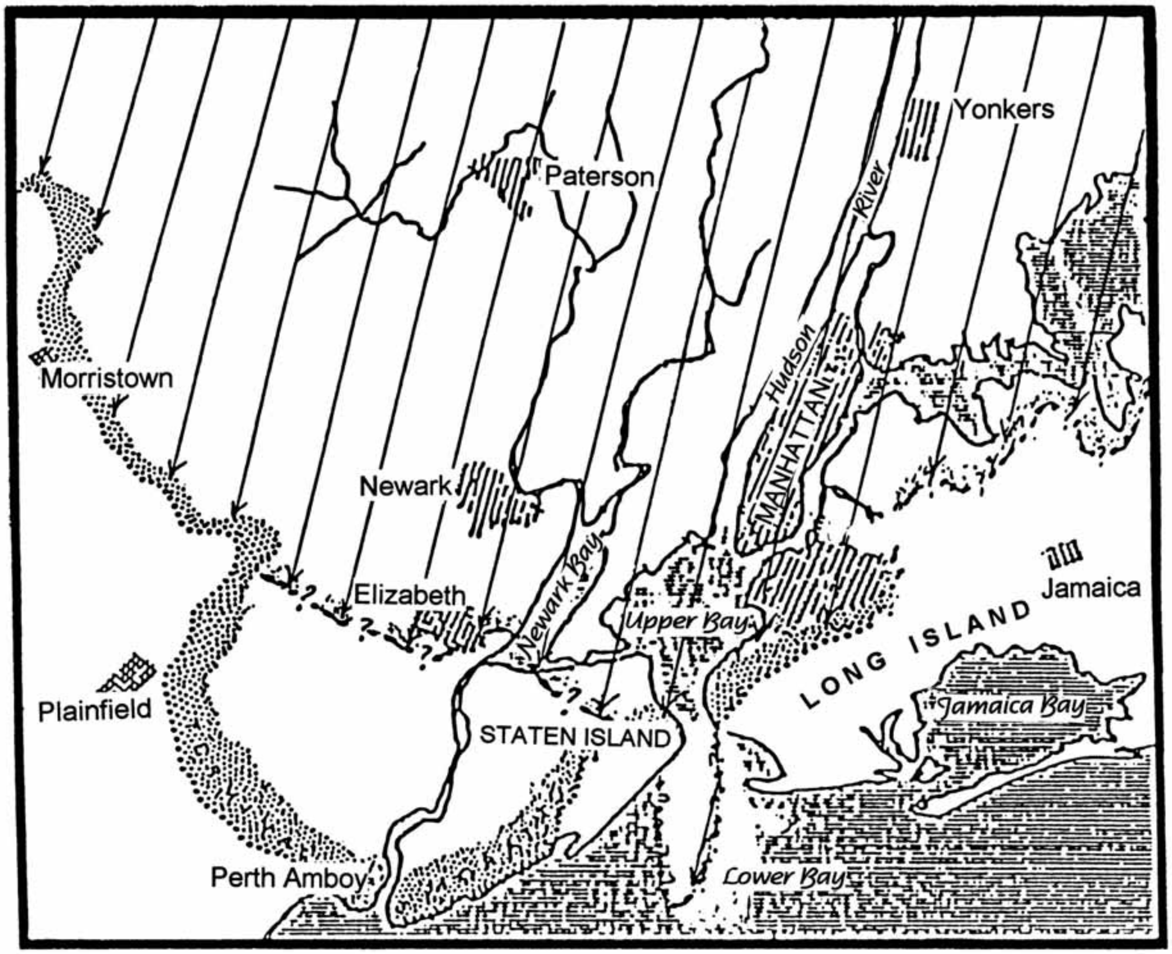


Figure 24 - Inferred flow pattern of latest Wisconsinan glacier, the Woodfordian, down the Hudson and Hackensack lowlands from NNE to SSW. As shown here, the Woodfordian glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders.)

Comparison of Pleistocene Sediments of the New York City Region With Those of Boston, Massachusetts

In the discussion of the stratigraphy of the Pleistocene formations and of the previous interpretations of the Pleistocene sediments of the New York City region, JES mentioned that the one-glacier view for the Wisconsinan was based on the engineering borings which show one till overlain by outwash overlain by Holocene estuarine sediments in the Hudson and Hackensack valleys. As a result, the "standard" interpretation has been that of a single Wisconsinan glacier that is inferred to have deposited both of the moraine ridges on Long Island. Without going into all the details, JES summarized the provenance data and how it fits with the directions of striae and grooves cut into the bedrock. JES mentioned that Clifford Kaye (1982) had found evidence of several Wisconsinan glaciers in the Boston area and that these showed flow directions similar to those JES infers for the New York City region. To quote from Kaye's paper:

> "The direction of ice flow in the Boston Basin and adjoining uplands was studied by means of the orientation of striations (sic) and grooves on the bedrock surface, the orientation (sic) of the long axes of drumlins, the direction of transport of erratics in till, and the direction of thrusting and overturning of bedding in glacially deformed drift. These data range through 360 degrees in azimuth. Analysis of this confusing message shows the existence not of an ever-shifting ice current but of at least four separate and distinct ice currents of different ages. Three of these flowed fairly rectilinearly, but one (the last) was multicomponent and marked by strong lobation" (1982, p. 31).

Kaye numbered these tills from I (oldest) to IV (youngest). Tills I, II, and III flowed from the NW to the SE, with means as follows:

Till	Mean flow direction
III	S31°E, +/- 02°
II	S64°E, +/- 18°
I	S23°E, +/- 01°

In addition to ripping up individual fragments from the material over which it passes, a glacier may also deform the strata it overrides. One of the Pleistocene glaciers profoundly affected some of the Upper Cretaceous strata: it stripped several large thin slabs (up to 0.5 km in one dimension and a few tens of meters thick) away from their pre-glacial positions and incorporated them as great thrust slices in the till.

DRAINAGE HISTORY

The following remarks are intended to provide an answer to the question: "Just how does one go about trying to work out drainage history of an area?" The "tools of the drainage-history trade," so to speak, include: (a) "prospecting" the geologic record for times when the lands stood high and were being eroded; (b) actually finding valleys and then using geologic evidence to infer their ages; (c) using provenance data and relating such data to regional geologic history (with reference to times when particular rock types may or may not have been available to circulate as sediment at the Earth's surface); (d) using cross strata and other features within sediments to infer which way the currents flowed when these sediments were being deposited; and (e) trying to figure out anomalous relationships in the drainage pattern. We review these and then discuss some local examples.

Times of Erosion

Reference to Table 1, the geologic time chart, and Figure 2, sketches of stages in the geologic development of the New York City region, shows that after the Newark basin-filling strata ceased to accumulate and before the Pleistocene glacial ages, two times of significant erosion are: (i) post-Newark and pre-coastal-plain strata (from about 180 million years ago to about 100 million years ago); and (ii) after the spreading of fans away from the Appalachians late in the Miocene Epoch until the first Pleistocene glacier arrived (from about 6 million years ago to about 1.5 million years ago). The Pleistocene Epoch included several times of erosion and the start of new drainage networks. Each arriving glacier covered and possibly obliterated previous river systems. As each glacier melted, a possibility existed for establishing new drainage networks. Although these Pleistocene times of erosion were short (possibly not longer than a hundred thousand years), they included powerful agents of erosion: glacial ice and torrents of meltwater.

Buried Valleys

Buried valleys are "fossil" evidence for ancient drainage. The significance of a buried valley in drainage history depends on how closely one is able to determine its age. The age of a buried valley can be bracketed by finding the youngest strata the valley cuts and the oldest sediments in the valley fill. Complications exist because an old valley may have been filled and later uncovered in part or in whole and re-occupied by a river that was not responsible for the original erosion of the valley.

Provenance Data

Provenance data can become evidence for inferring drainage history in that such data suggest directions of travel of distinctive debris and imply that certain areas may have been eroded to contribute sediment and, by contrast, that other areas may have been covered and thus could not have contributed sediment. Both of these aspects of provenance data affect reconstructions of ancient drainage networks.

Features in Sediments Made by Currents

Many kinds of features are made in sediments by currents and some are particularly useful for inferring the directions of flow of the ancient currents. Cross strata furnish a useful example. Cross strata, defined as layers that are oblique to their enclosing strata, result from the migration of bed forms or from the building of "embankments" (Figure 25). The direction of dip of the cross strata formed by downcurrent migration of a bed form or from the forward growth of an "embankment" is downcurrent.

If the downcurrent-dipping face where new sediment is added is a more-or-less plane surface, then the cross strata will be planar. By contrast, on lunate megaripples, the downcurrent face where sediment is added is curved. Downcurrent migration of these curved surfaces creates trough cross strata (Figure 26).

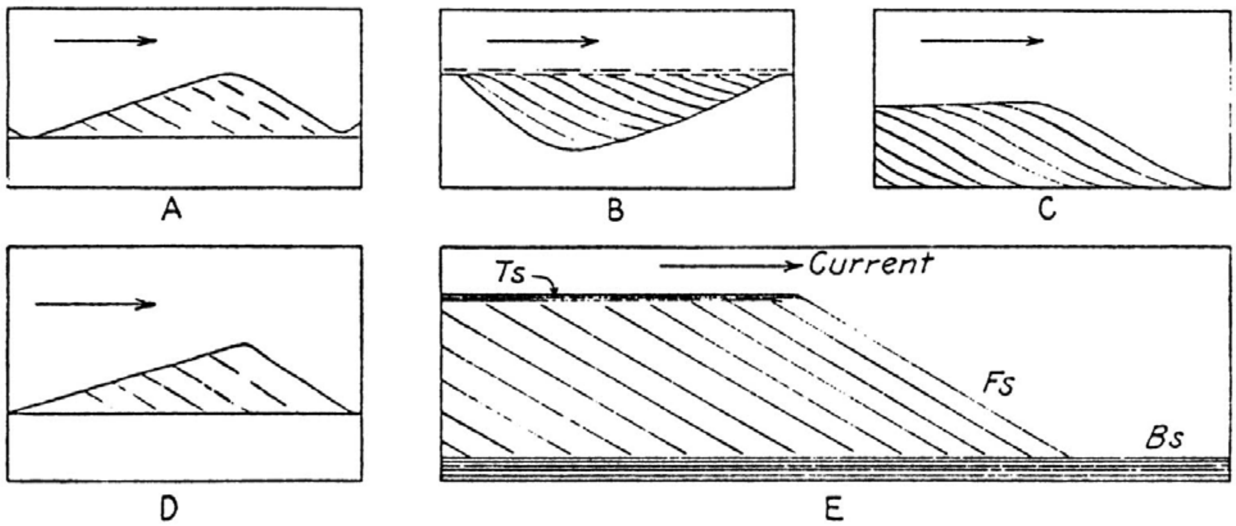


Figure 25 - Sketches of cross strata dipping to the right and formed by current flowing from left to right.
A and D, Longitudinal profiles through individual bed forms that have migrated to the right (downcurrent) by at least one
wavelength, thus preserving as internal cross strata many former downcurrent faces.
B, Longitudinal profiles through cross strata that have filled in an asymmetric depression.
C and E, Longitudinal profiles through cross strata deposited by downcurrent growth of an embankment (such as a delta lobe), built where the flow enters slightly deeper water. (R. R. Shrock, 1948, fig. 207, p. 245.)

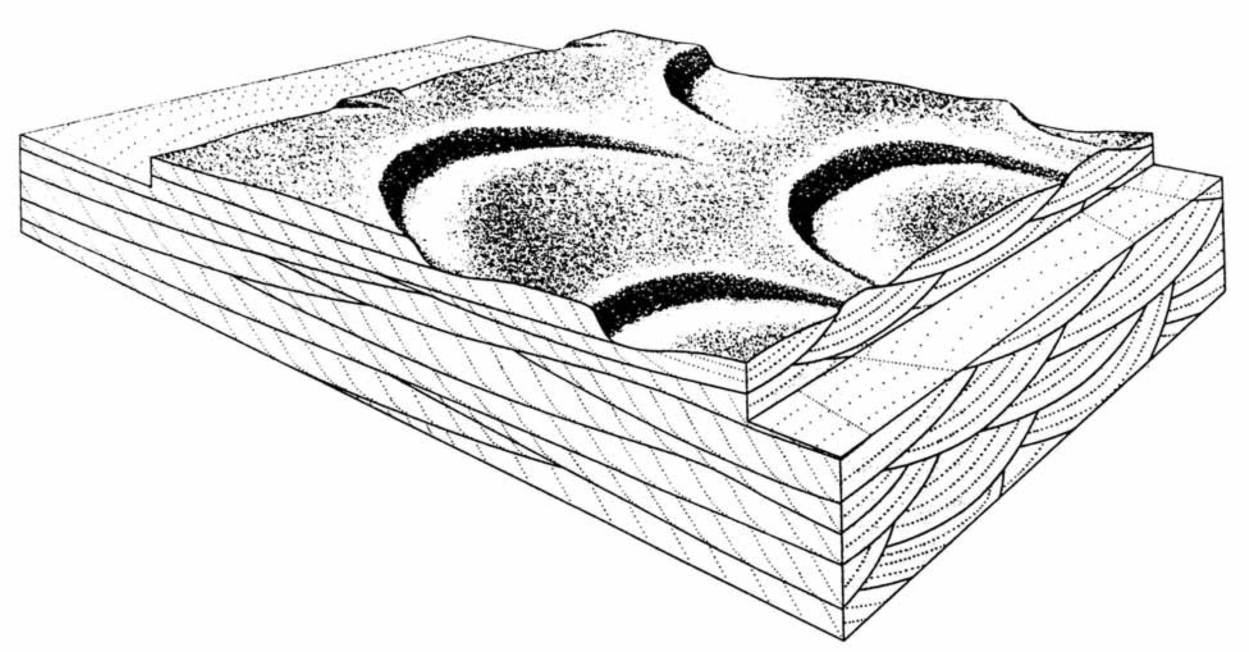


Figure 26 - Block diagram showing cuspate (lunate megaripples) and how their downcurrent migration forms trough-type cross strata. Current from upper left to lower right. (H. E. Reineck and I. B. Singh, 1980, fig. 52, p. 43.)

Drainage Anomalies

Anomalous drainage is a term applied to any drainage network in which the predominant flow is not down the regional slope. Obviously, water does not flow uphill, but it can flow along the contours of the slope rather than straight down the slope. Another category of drainage anomalies includes rivers that cut across high-standing areas of resistant rocks, collectively designated as cross-axial drainage. A water gap is the name given to a river valley that cuts across a resistant layer (Figure 27, A). Cross-axial drainage can result from several combinations of geologic circumstances. For example, after a stream has become well established in a valley, an anticline or fault may grow along a line trending across the stream. If upward growth is slow and stream power sufficient, the stream may maintain its course and eventually, can cut a water gap (Figure 27, B). Such a stream is known as an antecedent stream; it is older than the axis it has cut across. Another possiblity is superposition (Figure 27, C).

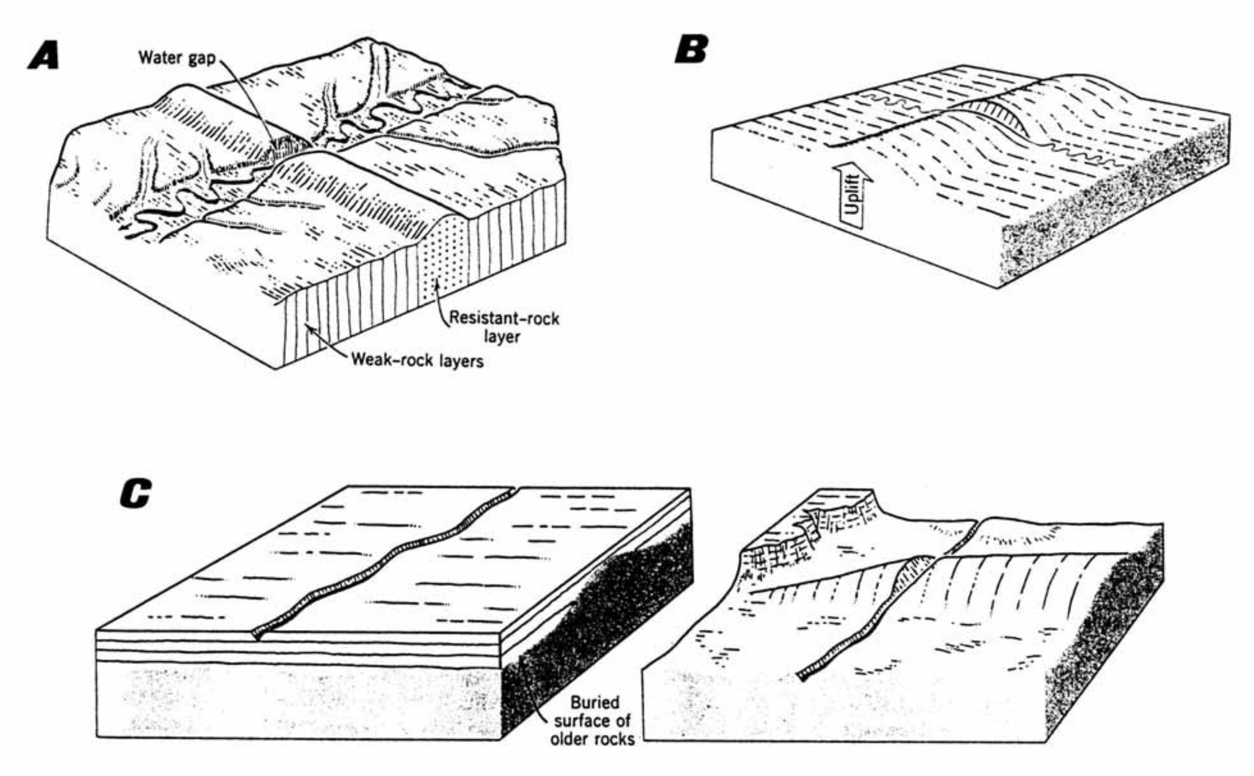


Figure 27 - Drainage anomalies associated with cross-axial stream flow, schematic block diagrams. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969: A, fig. 10-12, p. 225; B, fig. 10-15, p. 227; C, fig. 10-16, p. 227.)
A. Stream cuts a water gap through a ridge formed by resistant rock.
B. Stream continues to flow as anticline is uplifted across its path; downcutting equals or exceeds rate of uplift, thus enabling the stream to maintain its course. The stream, which is older than the uplift of the anticline, is named an antecedent stream.
C. Two stages in the history of a superposed stream. In block at left, a prominent ridge has been buried by horizontal strata, on which the stream establishes its course. In block at right, all covering strata except for a small remnant at upper left have been removed and the stream has cut a cross-axial path through the ridge of resistant rock.

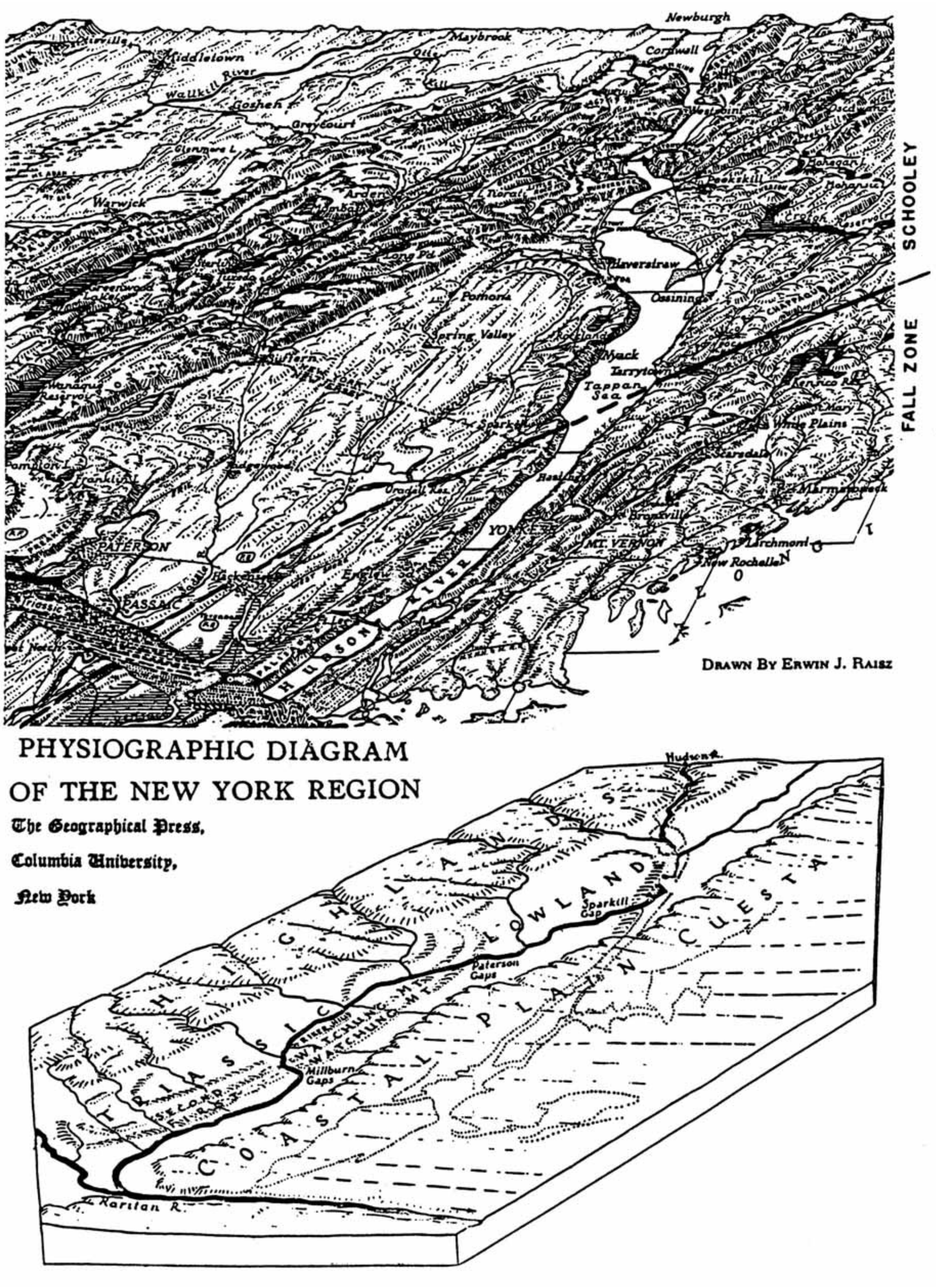


Figure 28 - Physiographic diagrams of the New York region and the Hudson Highlands and hypothetical course of the Hudson River in Schooley time. (D. W. Johnson, 193? fig. p. ; drawn by E. Raisz.)

Superposition results from a multi-stage geologic history. First the belt of resistant rock is established. Then it is buried. The stream becomes established on the covering strata and commences downcutting. After the stream has cut through the cover, it "discovers" the buried transverse axis. But, because its course has been locked in, so to speak, on the covering strata, it is able to cut a water gap through the resistant transverse axis and may do so in more than one place as has been inferred for the ancestral Hudson across the Watchung mountains, New Jersey (Figure 28, bottom).

A final category of drainage anomaly is what is known as a barbed tributary, defined as a tributary that enters the master stream in such a way as to make an acute angle with a segment of the main stream that is downstream from the point of junction (Figure 29). The usual arrangment is that the tributary joins the main stream and makes an acute angle with a part of the main stream that is upstream of the point of junction. This follows from the fact that the slope of the master valley is downstream. Therefore, any tributary from the side tends to flow down the master valley before it joins the master stream. In so doing, it makes an acute angle with the part of the master stream that is upstream from the junction.

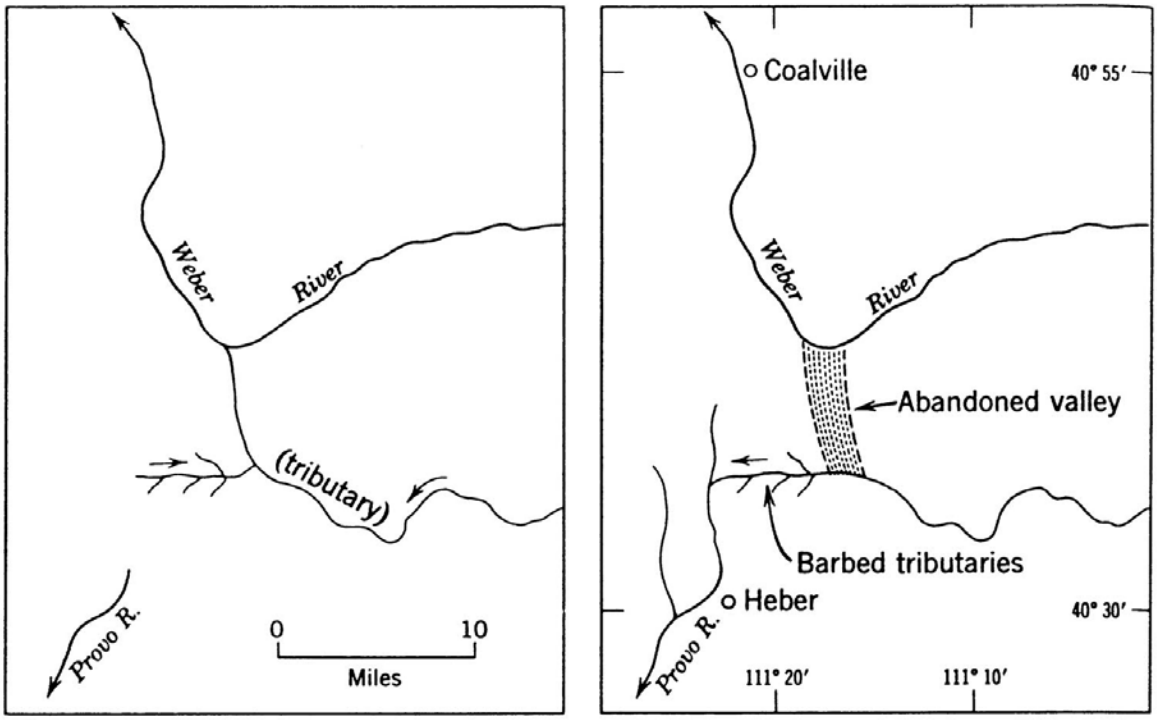


Figure 29 - Two stages in formation of barbed tributaries, sketch maps of Weber River and Provo River south of Coalville, Utah. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 10-17, p. 228.)
A. Inferred earlier drainage network in which Provo River is confined to extreme southwestern part of area shown and tributary drainage flows north to the Weber River. Short tributary below center of map flows eastward (to right); its even-shorter tributaries make acute angles on the upstream sides of the larger stream.
B. Headward erosion by Provo River has captured former tributaries to the Weber River, reversing the direction of flow of the short tributary below center of map and establishing the barbed relationship with the even-shorter tributaries.

Local Examples

In the drainage history of the New York City region, the oldest clear-cut records date from the Late Triassic, when the Newark basin was being filled. Reference to the physiographic diagram of Figure 10 shows the morphologic expression in today's landscape of what is left after elevation- and erosion of the Newark basin-filling strata. The longer of the two profile-sections (the one that extends diagonally across the middle of the page) displays the existing arrangement of the basin-filling strata (eroded base in contact with the metamorphic complex of the Manhattan prong, northwest dip along the line of this profile-section, and abrupt ending on the northwest against the Ramapo fault).

The northwest-dipping Newark strata are truncated along a line at the base of the Ramapo Mountains. Geologic analysis indicates that this line marks a fault, the Ramapo fault, which has been active for more than a billion years (Ratcliffe, 1971). During Late Triassic and Early Jurassic time, this fault separated an actively elevated block on the northwest from an actively subsiding block on the southeast. From the elevated block came sediment composed almost entirely of Paleozoic formations. The sediments were transported to the southeast and accumulated to form the Newark Supergroup. Near the Ramapo fault, these sediments are coarse; but, with distance from this fault, they become finer. Cross strata also indicate that ancient streams flowed from the northwest to the southeast. By contrast, both provenance data and the cross strata prove that some of the sediments composing the basal strata of the Newark Supergroup, namely the gray arkoses within the Stockton Formation, were derived from the southeast and were deposited by rivers that flowed westward, a direction that is down the present-day dip of the strata (Glaeser, 1966; Klein, 1969). This general pattern of sediment supply and transport directions has been further supported by geochemical provenance studies based on determining radiometric ages of the feldspars (Abdel-Monem and Kulp, 1968).

One of the major mysteries associated with the Newark basin-filling strata is what happened (and when) to disrupt the drainage and to end the episode of sediment accumulation in the Newark basin. The drainage pattern that began with the initial elevation of the marginal blocks and initial subsidence of the basin block fed sediments into the basin. This drainage pattern persisted for perhaps 30 million years. Then, something happened to disrupt it. Sanders (1963) argues that the elevation of the central part of the formerly subsided basin block, as indicated by the modern-day dip of the strata, was the event which changed the drainage pattern and caused the basin-filling strata to be eroded. As a result of this change, the Newark basin changed from being an importer of sediment into a condition of being an exporter of sediment.

As the Newark strata were elevated and eroded, a strike valley is inferred to have formed along the base of the Newark strata. A strike valley is a linear- or curvilinear valley whose axis is parallel to the strike of non-horizontal strata. An example of a strike valley is the Hudson Valley between Stony Point, New York, and a point opposite Hoboken, New Jersey. (Figure 30; no label for Hoboken appears on the figure, but the short sector of the river under discussion is the north-south segment just east of the "y" in the label for Jersey City.) At Hoboken, the Hudson makes about a 15° bend to its left (facing downriver). In so doing, it flows out of the strike valley at the base of the Newark Supergroup. However, the strike valley continues to the SSW. It goes under Jersey City, western Staten Island, and into New Jersey. (See Figure 30 and

Figure 10, profile-section along the bottom margin of the map, just above the "30'" of the label for 74°30'.) The fact that this basal-Newark strike valley passes beneath the coastal-plain strata proves that the initial age of this valley is pre-Late Cretaceous. How long the Hudson has flowed in it is not securely known. Presumably, this whole strike valley is the same age throughout. It has been reoccupied by the Hudson from Haverstraw to Hoboken. Another valley, not a strike valley and now completely full of sediment and thus hidden from view and that may pass beneath the cover of the coastal-plain strata, extends on a WSW trend out of New Haven harbor and into Long Island Sound (Haeni and Sanders, 1974; Sanders, 1989 ms.).

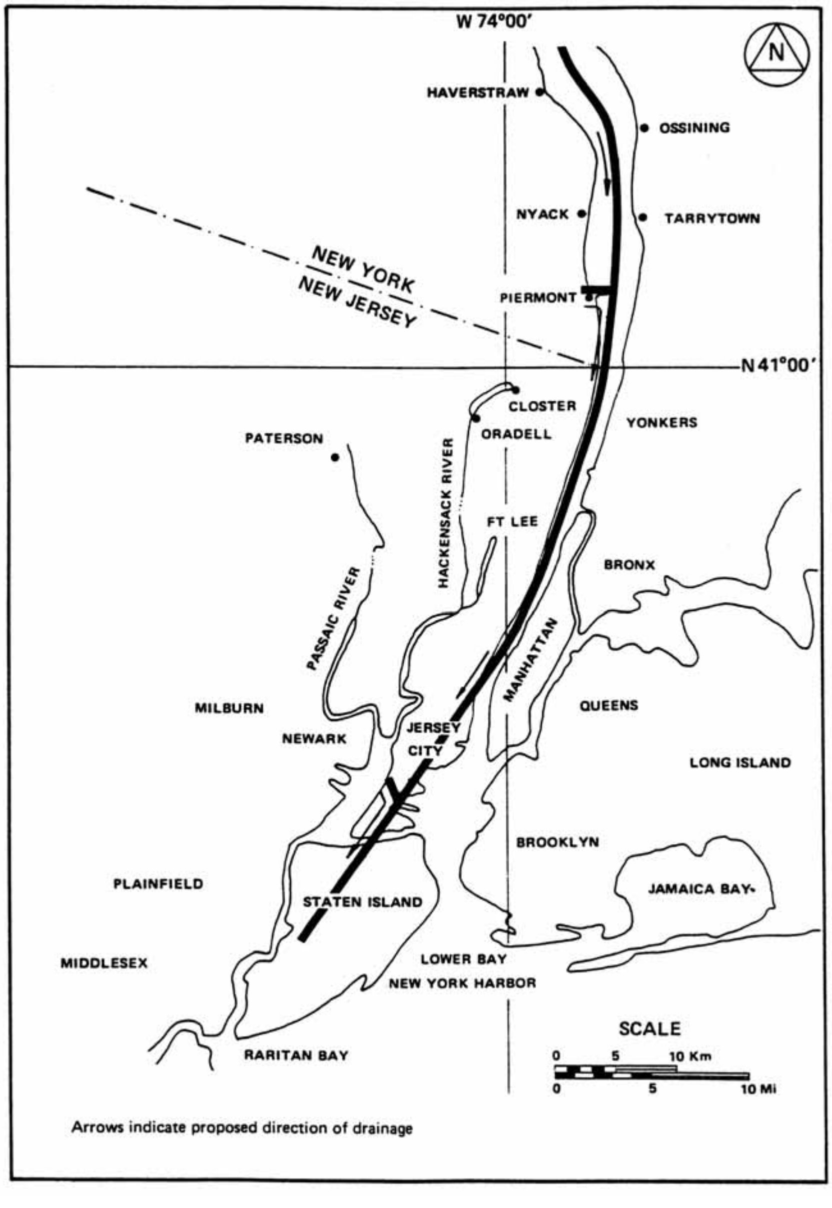
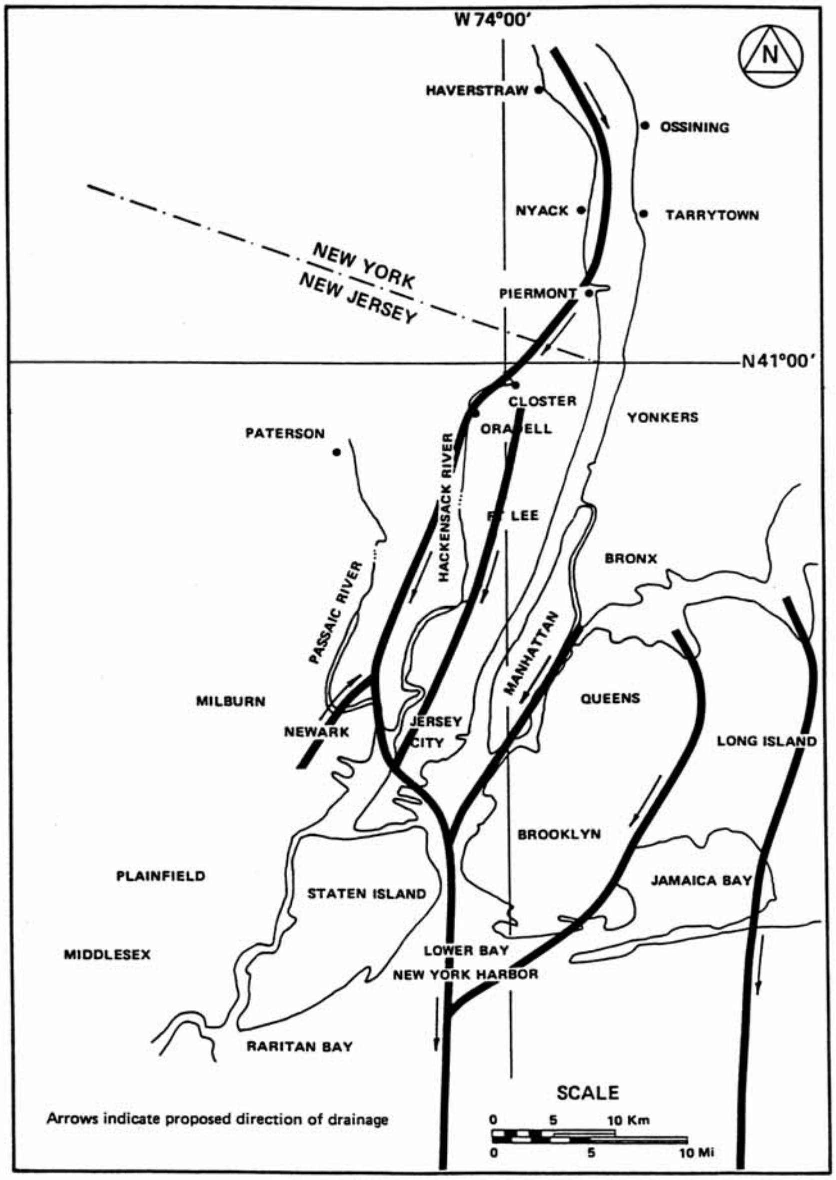


Figure 30 - Strike valley at base of Newark Supergroup as inferred during the late Cretaceous, after tilting and erosion of Newark strata but prior to submergence and deposition of coastal-plain strata. (J. Lovegreen, 1974 ms., fig. 19, p. 148.)

A second strike valley exists at the base of the tilted and eroded coastal-plain strata. Locally, ocean water fills this basal-Cretaceous strike valley and we call it Long Island Sound. This valley and many others (Figure 31) resulted from erosion associated with the post-Miocene elevation of the Appalachians and of New England and the accompanying drop of sea level.



Arrows indicate proposed direction of drainage

Figure 31 - Inferred drainage channels, Late Pliocene (before first glacier arrived). (J. Lovegreen, 1974 ms., fig. 22, p. 151.)

Modern rivers are flowing in lowlands some of which have been in existence for hundreds of millions of years, and others of which are only a few tens of thousands of years old. The oldest probable lowland is the strike valley at the base of the Newark Supergroup, now followed by the Hudson River from Stony Point, New York, to Hoboken, New Jersey. At Hoboken, the Hudson River makes a turn to its left of about 15° (from about N15°W-S15°W to about N-S). It follows this N-S course past Jersey City and into Upper New York Bay. The strike valley, however, continues to the SSW and eventually passes beneath the coastal-plain Cretaceous on Staten Island. (See Figure 30.)

Figure 31 shows buried valleys inferred to be of Late Pliocene age. (Drainage changes from Lovegreen, 1974 ms.) The post-Miocene interval was marked by the first of the great swings of sea level and stream erosion of the lowland now occupied by Long Island Sound (and the inner lowland elsewhere along the eroded edge of the coastal-plain strata). After the last glacier melted, the rising water of the modern ocean has drowned and submerged low-lying areas.

So much for geologic background. We now turn to the specifics of the trip, starting with the objectives.

OBJECTIVES

1) To study the four major units that are in contact on Staten Island (from the top downward, Layer VII, Quaternary sediments; Layer VI, Coastal-plain strata; Layer V, Newark strata; and IIAE, Paleozoic deep-water metamorphosed strata, and included Staten Island serpentinite). We will start with the oldest unit and study progressively younger units.

2) To examine the serpentinite of Todt Hill in light of W. O. Crosby's (1914) idea that the serpentinite body which we see now has resulted from two notable modifications to the original rock, or protolith. As a second topic, we shall consider the possible age and origin of the associated breccia that contains clasts of both serpentinite (and relatated talc "schist") and red siltstones from the Newark Supergroup.

3) To examine the petrologic relationships in the Palisades intrusive sheet; to see the effects of high-temperature reaction between the mafic magma of the sill and a xenolith of Lockatong Argillite of the Newark Supergroup, which forms the country rock into which the "city rock" of the Palisades was intruded. The argillite that became engulfed in the mafic magma was not only heated, it actually was melted and the small bit of felsic magma that formed did not mix into the mafic magma, but cooled to form a felsic igneous rock unlike that formed by solidification of the mafic magma. We shall also study the morphologic relationships of the sill and discuss our new model designating Staten Island as a potential magma feeder for the Palisades intrusive sheet.

4) To see what happens to a beach when its supply of sand is cut off.

5) To study Pleistocene sediments (tills and outwash); soil-forming reactions; mineralogic immaturity; provenance of erratics; sedimentary characteristics of braided-stream deposits; state of decomposition/preservation of stones as basis for relative ages of units; hematite-cemented sandstones and /or conglomerates.

6) To find out the current status of the continuous interaction between the beach whose predominant direction of longshore transport is toward the SW and the mouth of a small stream.

7) To examine a stratigraphic succession (possibly not needing to be converted by us into an SSF) in which a much-decayed immature Quaternary braided-stream outwash deposit rests unconformably on mineralogically mature Upper Cretaceous sands and clays.

8) To examine the contrasting kinds of strata in the coastal-plain Cretaceous, notably the effects of marine transgression whereby open-shelf sediments came to overlie sediments deposited on an intertidal flat.

LIST OF LOCALITIES TO BE VISITED

(Localities 1 through 5, on Staten Island, are shown by number on the road map, Figure 32.)

Stop 1. Serpentinite, Todt Hill.
Stop 2. Palisades sheet, Graniteville quarry.
Stop 3. LUNCH; eroding beach, Great Kills Park.
Stop 4. Pleistocene till with giant "erratic" of Cretaceous, coastal cliff, Princess (or is it Prince's?) Bay.
Stop 5. Trough-cross-stratified Pleistocene outwash resting on Cretaceous, cut at entrance, AKR Excavating Co., Arthur Kill Road.
Stop 6. (Optional stop depending on visibility); scenic view; Cretaceous sands, Atlantic Highlands, NJ.
Stop 7. (Optional stop depending on time); marine Cretaceous sand overlying sediments of intertidal flat, old sand pit, S of Matawan, NJ.

DRIVING DIRECTIONS AND GEOLOGIC NOTES EN ROUTE

(NYAS to Staten Island via Brooklyn and Verrazano-Narrows Bridge).

Turn L on 5th Ave., drive S to 59th St., turn L; cross 59th St. bridge to Queens. Continue E past Jackson Avenue (NY 25A); turn R on Van Dam St., follow signs for Long Island Expwy (I-495) eastbound. From LIE service road enter Brooklyn-Queens Expwy (I-278) toward Brooklyn and the Verrazano-Narrows Bridge.

As we drive eastward toward the Queensborough (59th Street) Bridge, we pass over folded- and deeply eroded units of the Fordham-Inwood-Manhattan-Hartland sequence. Although we shall not be exactly over the new water tunnel, our line of travel is approximately parallel to the tunnel (dashed line with arrows on Figure 33). Figure 34 shows the profile-section along the route of City Water Tunnel No. 3, Stage 2, in southern Manhattan.

At some point after we have entered the Brooklyn-Queens Expressway, a point not well defined on Figure 33, we shall cross the buried northwestern limit of the coastal-plain strata (dots and question marks on Figure 33).

Figure 32 - Road map showing driving route and localities.

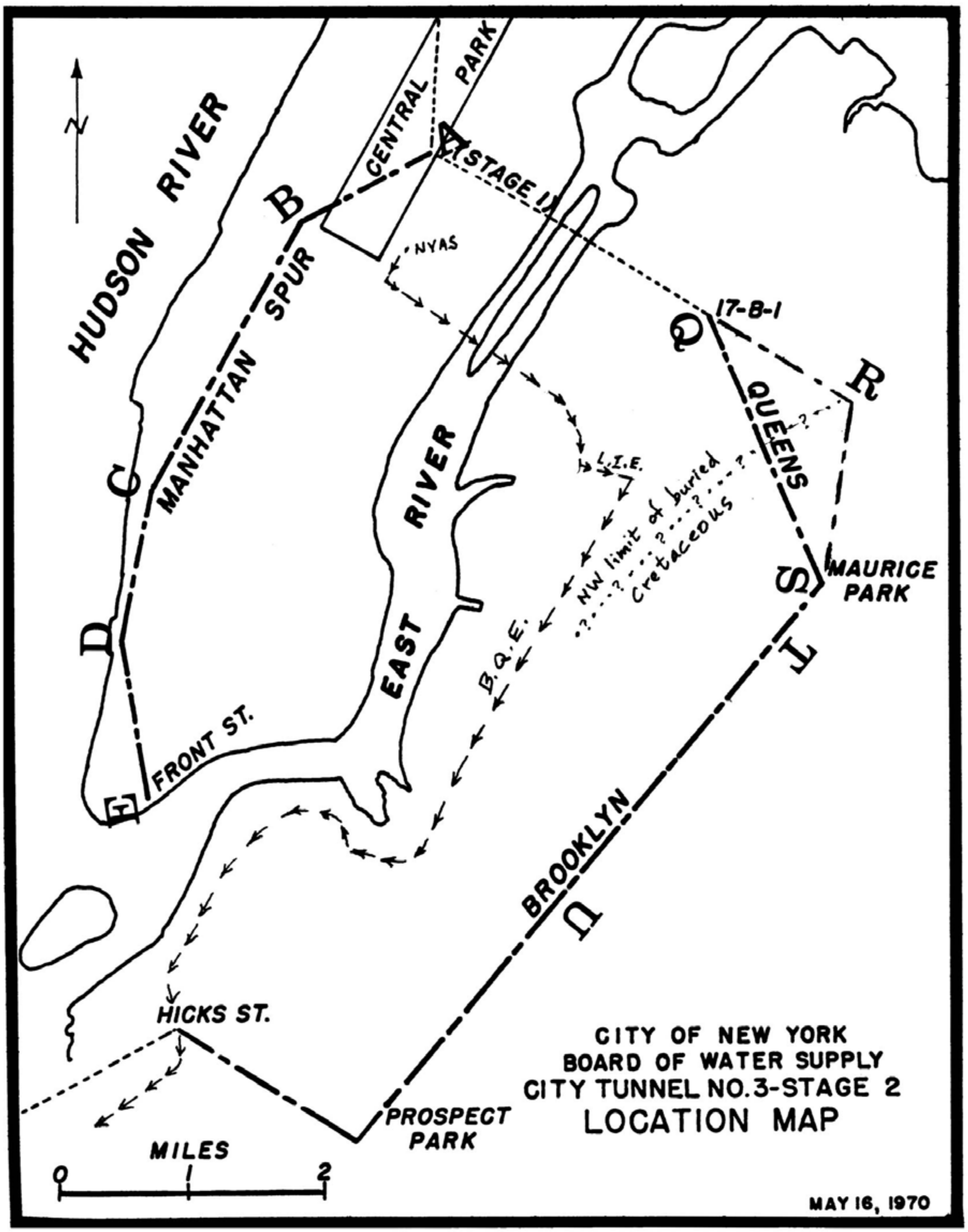


Figure 33 - Location map of City Water Tunnel No. 3, Stage 2. Route in Queens modified by JES by adding in point R off line between Q and S to conform to strip map on profile-sections of Figure 34, A. (T. W. Fluhr and C. G. Terenzio, 1984.)

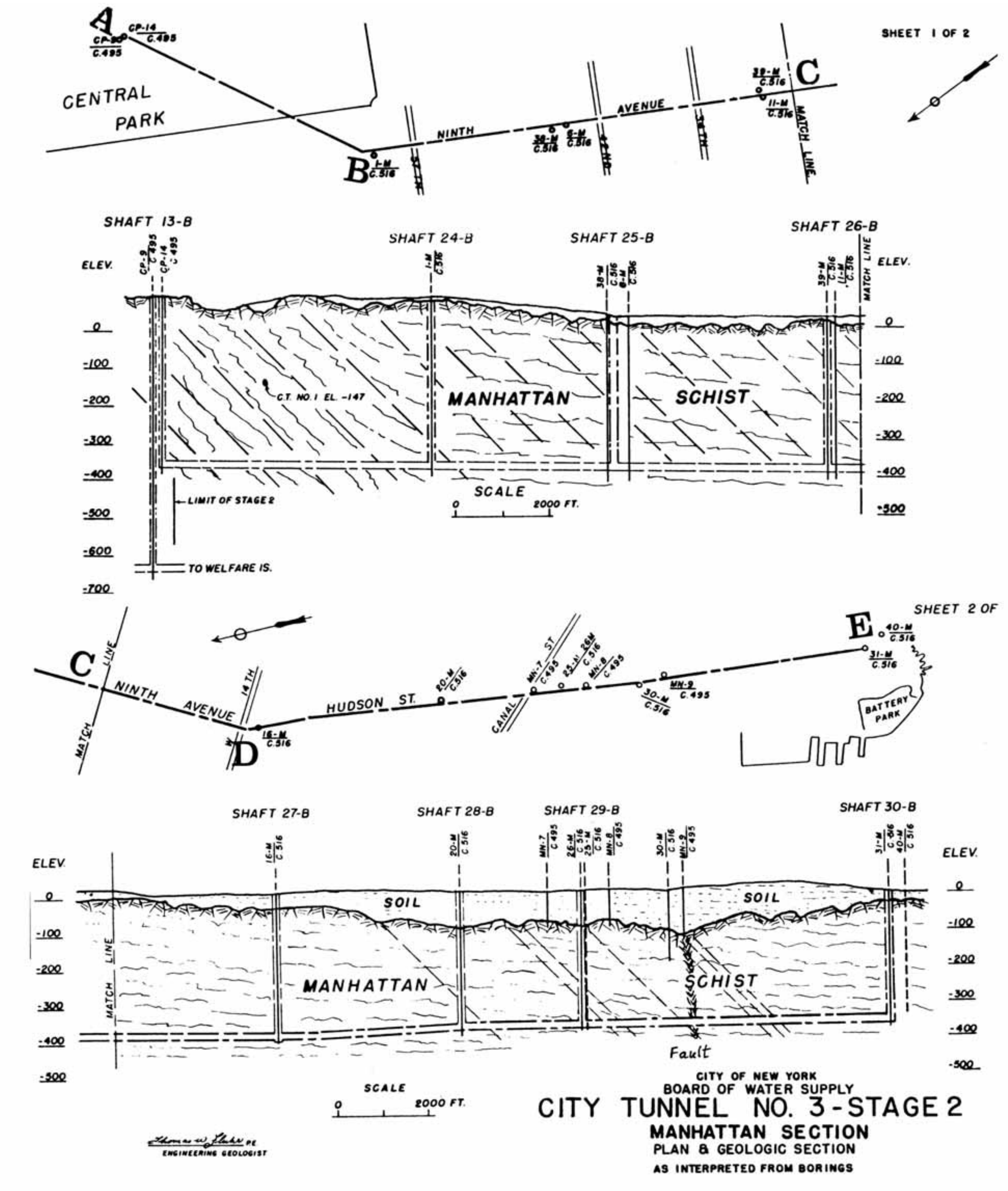


Figure 34 - Profile-sections along southern Manhattan route of City Water Tunnel No. 3, Stage 2. Location of profile-sections shown on Figure 33. (T. W. Fluhr and C. G. Terenzio, 1984.)

The East River channel is partly controlled by the composition of the formations and partly by faults. [Geologic sections of the East River Channel are included our guidebook for OTR April 1991 trip to Manhattan and the Bronx (Merguerian and Sanders, 1991a). The topographically high areas (east edge of Manhattan, Roosevelt Island, and western Queens) are composed of resistant rocks (Fordham, Manhattan, and Hartland). By contrast, the low area, the channel of the East River, is underlain by the easily eroded Inwood Marble. This is because in a moist climate, carbonate rocks, such as marbles and limestones, are easily dissolved by rainwater. (Just the opposite is true in dry climates, where carbonate rocks are resistant and hold up the highest mountain peaks.) In addition to this lithologic control on the location of the East River, CM has mapped many brittle- and reactivated ductile faults in the NYC water tunnel that passes on a line about 800 feet beneath the surface of the East River (between A and Q on Figure 33). His mapping and previous engineering-boring data indicate that the straight course of the East River valley beneath the Queensborough Bridge is controlled, in part, by the easily eroded northeast-trending brittle faults present there.

While we drive south on the Brooklyn-Queens Expressway (BQE), hold onto the dental fillings in your mouths. (The jolts are not the result of our driving into meteorite-impact craters, but only New York City potholes!) For a while, we shall travel over buried Ravenswood. Eventually, we shall cross onto another buried rock unit, the Brooklyn Injection Gneiss (BIG). The BIG occupies the subsurface of most of southeastern Brooklyn (Blank, 1973; + both profile sections in Figure 35).

The BIG has not been much studied. This is not surprising; after all, it is hard to work on a unit that is rarely exposed within the largely urbanized area. However, help is on the way. Exploratory drilling for construction of the third NYC water tunnel should provide new data and new samples. Moreover, actual tunnel contruction in a few years will afford geologists a first look at the lithologic variations and contact relationships of this unit.

Possible models to be tested include: 1) that the BIG is a former igneous component of the Ravenswood orthogneiss; 2) that the BIG is a separate metamorphosed intrusive of unknown age; 3) that the BIG is remobilized Proterozoic crust (i.e., Fordham equivalent); or, 4) that the BIG is migmatitic (a rock that was partly molten) Hartland Formation. Clearly, more work is necessary before it will be possible to decide among these, or possibly other, hypotheses.

Since this guidebook was written, Scott Chesman of the NYC DEP has mapped the Brooklyn Tunnel segment of the Third NYC Water Tunnel and Merguerian has mapped the structural geology of the 5-mile Queens Tunnel segment at a scale of 1"=10'. The rocks of the Queens Tunnel have been studied utilizing petrographic-, geochemical-, and geochronologic methods (Merguerian, Brock, and Brock, 2001). The south part of the Brooklyn Tunnel exposes migmatitic metasedimentary rock but the northern part of the Brooklyn Tunnel and almost all of the Queens Tunnel exposes Proterozoic orthogneiss cut by syntectonic Paleozoic plutons. These studies indicate that the rock mass of the Queens Tunnel is largely granulite-grade orthogneiss correlative with the Fordham gneiss. Thus, the early thoughts of Berkey (1936) were on target concerning the correct correlation of the Brooklyn Injection Gneiss.

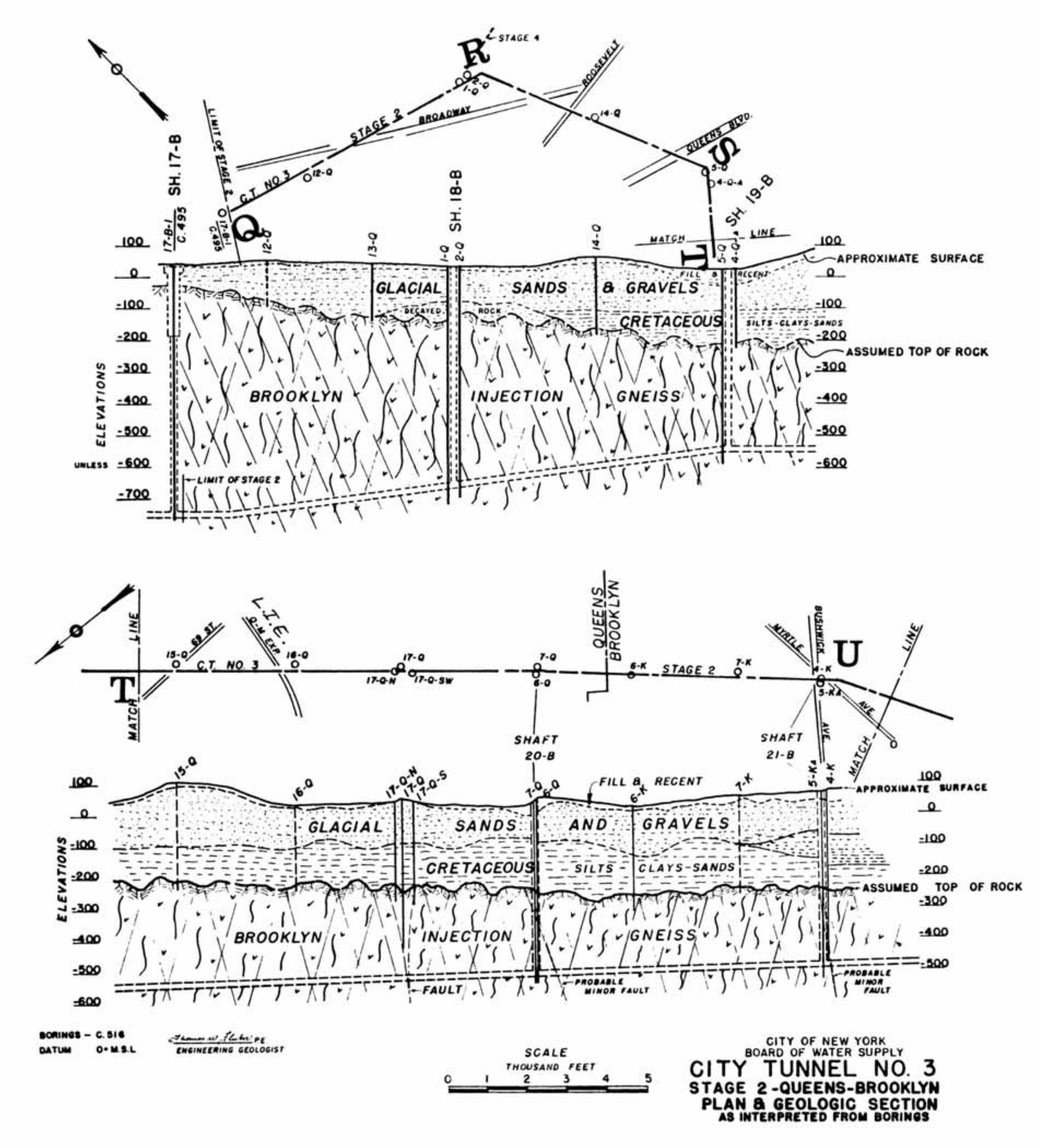


Figure 35 - Profile-sections in Queens and Brooklyn along City Water Tunnel No. 3, Stage 2. Locations on Figure 33. (T. W. Fluhr and C. G. Terenzio, 1984.)

In the Greenpoint section of Brooklyn (on the NE corner of Siegel and White Streets--near the corner of Bushwick and Flushing Avenues), construction of a vertical access shaft to the water tunnel encountered a flow of ground water that complicated the situation enormously. The project made use of a technique known as slurry-wall construction. In this technique, drilling mud, such as is employed in petroleum test borings (such mud is pumped under pressure down from the surface through the drilling pipe, circulated out through the bit, and comes up to the surface again via the annular space between the outside of the drilling pipe and the wall of the hole) is used to hold open the sides of a trench. The "soil" is taken out by a clam-shell digger, and when all the digging has been finished, one is left with a circular slot full of mud. (In this case, the circular slot is 40 feet in diameter.) Then, concrete is pumped in to displace the mud. After the concrete has hardened (in the ground, no forms needed), the "soil" between the inner walls can be removed. Early in February 1991, after the excavation inside the concrete wall had been completed, CM and JES visited this site, hoping to be able to go down into the shaft to view the stratification of the Pleistocene sediments that had been excavated (displayed in relief in the surface of the concrete on the inside of the circular wall). No such trip was possible. Water was flowing into the shaft and pumps were being installed to get rid of it. Extensive pumping succeeded in lowering the water table in the surrounding areas. As a result of removal of the ground water, the land surface subsided. Sidewalks have buckled and walls of newly built public-housing units have cracked. All kinds of litigative hell has broken loose. In order to get this genie back inside the bottle, it was necessary to resort to refrigeration techniques. Pipes were installed to carry the refrigerant and the whole site was cryogenically frozen to keep out the water. We visited it in 1992 or 1993?. Armies of lawyers will get rich in the lawsuits that will surely flow from this watery site and some folks will get soaked.

From our route in Queens and Brooklyn, it should be possible to look westward to the Manhattan skyline and to notice the dropoff in heights of the buildings, from the collection of skyscrapers in midtown Manhattan to the lower buildings south of about 34th Street to another collection of skyscrapers in the Wall Street area of southern Manhattan. This arrangement of the buildings is not fortuitous; rather, it is controlled by faults producing the relief on the bedrock surface. In midtown (ABC of Figure 34, A) and in the Wall Street-Battery area (E of Figure 34, B), bedrock is exposed at the surface or is covered by only thin Pleistocene deposits. By contrast, in between, the surface of the bedrock has been eroded into a broad valley that trends NW-SE, whose deepest part (= what geologists refer to as a talweg), about under Chambers Street on the water-tunnel line), coincides with a fault (Figure 36). In the axis of this valley, depth to bedrock reaches about 35 meters below modern sea level. After this valley had been eroded, it was backfilled with sediment. (On Figure 34, this fill is shown simply as "soil.") The age of the filling sediment has not been well determined. It presumably includes Pleistocene and Recent sediments, but no Cretaceous.

The profile-sections of Figure 35 show the relationships in Queens and Brooklyn. The detailed location strip map of Figure 35A does not match the line on the general index map of Figure 33. JES has tried to rectify this situation by locating point R. The line QRS on the strip map clearly has a sharp bend that is not present on the index map between Shaft 17-B-1 and Maurice Park (underneath the label "Queens").

A point of interest is the relationship of the decayed rock under point R. A zone up to about 10 m thick of decayed rock is shown above the bedrock and beneath the "Glacial sands & gravels" at Shaft (Sh.) 18-B (Point R). Here, the Cretaceous is shown as overlying the decayed rock. In Sheet 3 of 3, not shown here, is more-convincing evidence that the Cretaceous overlies the decayed rock and thus that the weathering responsible for the decay is of pre-Cretaceous age (Blank, 1973).

According to on-strike projections from CM's work in Manhattan, the rocks beneath the Verrazano-Narrows Bridge should be units of the Hartland Formation. This projection has been verified by drill-core data. The projected units probably traverse the New York harbor channel beneath the bridge and form the buried schistose rocks beneath the eastern edge of Staten Island as described in detail below.

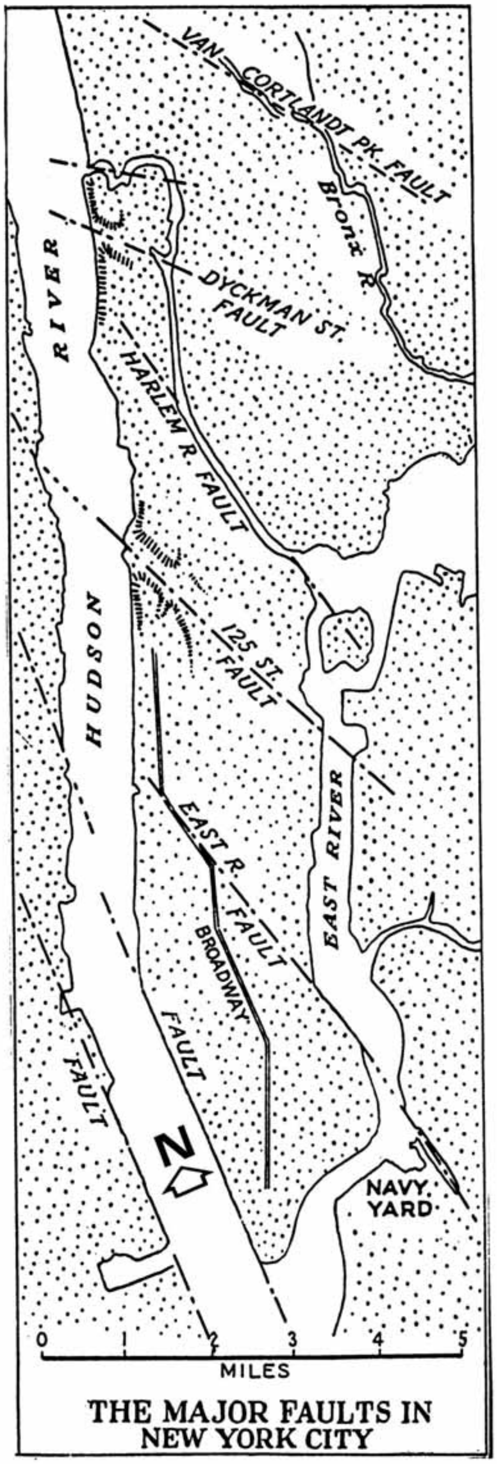


Figure 36 - Fault map of Manhattan. (Lobeck, 1939, p. 568.)

Structural Geology of New York City

The crystalline rocks of the Manhattan prong are divided in half along a complexly deformed, northeast-trending ductile thrust fault mapped as Cameron's Line (Merguerian, 1983a) which separates contrasting sequences of metamorphosed Lower Paleozoic strata. To the east of Cameron's Line, rocks of the Hartland Formation (Ꞓ-Oh in Figures 3 and 4) underlie the Manhattan Prong and consist of amphibolite-facies gneiss, schist, amphibolite, and garnet-quartz granofels. This terrane, which widens northeastward to form the bulk of the crystalline highlands of western Connecticut, is interpreted to mark the eroded remains of former oceanic sediments and interlayered volcanic rocks deformed in a deep-seated subduction zone (Merguerian, 1983a, 1985). Rocks found to the west of Cameron's Line (Figure 3) include the Proterozoic Y Fordham Gneiss (Yf - a massive to well-foliated felsic gneiss with interlayers of biotite schist and diopsidic calc-silicate rock) and unconformably overlying Cambrian Lowerre Quartzite (Ꞓl - only locally present), the Cambrian to Ordovician Inwood Marble (Ꞓ-Oi - a calcite- to dolomite marble, typically well-layered), and overlying Manhattan Schist of presumable medial Ordovician age (Om). This western sequence is interpreted to represent former 1.1-billion-year-old continental crust (Yf) and overlying 500-million-year-old shallow-water shelf sediments, now metamorphosed into marble, gneiss, and schist (Ꞓ-Oi, Om).

Based on detailed mapping and petrographic studies (Merguerian, 1983b, 1986, 1994; Merguerian and Baskerville, 1987) the schist on Manhattan Island is subdivided into three lithologically distinct, structually imbricated units of kyanite- to sillimanite metamorphic grade. (See Figure 4.) The structurally lowest unit (Om) crops out in northern Manhattan, the west Bronx, and in the subsurface of western Queens and Brooklyn. This unit consists of brown- to rusty-weathering, fine- to medium-textured, typically massive, biotite-muscovite-quartz-plagioclase-kyanite-sillimanite-garnet-graphite gneiss and -schist containing interlayers centimeters- to meters thick of calcite + diopside marble.

Both the lower schist unit and the Inwood Marble are structurally overlain by the middle schist unit (Ꞓ-Om) that forms the bulk of the "schist" exposed on the island of Manhattan. (See Figure 4.) The middle schist unit consists of rusty- to sometimes maroon-weathering, medium- to coarse-textured, massive biotite-muscovite-plagioclase-quartz-garnet-kyanite-sillimanite gneiss and, to a lesser degree, schist. This unit is characterized by the presence of kyanite + sillimanite + quartz + magnetite layers and lenses up to 10 cm thick, cm-to m-scale layers of blackish amphibolite (metamorphosed basaltic rock), and quartzose granofels. The middle unit is lithologically identical the Waramaug and Hoosac formations of Cambrian to Ordovician ages in New England (Hatch and Stanley, 1973; Hall, 1976; Merguerian, 1981, 1983a, 1985; Mose and Merguerian, 1985). The rocks of the middle unit are older than the Manhattan Schist (Unit Om) found "in situ" above the Inwood Marble and its presence mandates thrust faulting (the St. Nicholas thrust).

The structurally highest, upper schist unit (Ꞓ-Oh) is dominantly gray-weathering, fine- to coarse-textured, well-layered muscovite-quartz-biotite-plagioclase-kyanite-garnet schist, -gneiss, and -granofels with cm- and m-scale layers of greenish amphibolite + garnet. The upper schist unit, based on CM's study of more than 500 outcrops in Manhattan and the Bronx and a multitude of drill core and construction excavations, underlies most of the western- and southern flanks of Manhattan and the eastern half of the Bronx, is lithologically identical to the Cambrian and Ordovican Hartland Formation of western Connecticut and southeastern New York. On this basis, they are considered correlative. The regional contact between the Manhattan (Ꞓ-Om) and Hartland Formations (Ꞓ-Oh) is a mylonitic shear zone known as Cameron's Line.

In summary, the belt of rocks originally lumped together as the Manhattan Schist is now known to consist largely of gneissic rock that is structually imbricated along two major ductile faults. The base of the middle schist (Ꞓ-Om) is truncated by a ductile shear zone, informally named the St. Nicholas thrust (open thrust symbol in Figure 4). The upper schist unit (Ꞓ-Oh) is in ductile-fault contact with the middle schist unit along Cameron's Line in New York City.

The exposed bedrock of Manhattan and the Bronx consists of amphibolite-facies metamorphic rocks that have been intensely folded (three superposed episodes of folds with local shearing and development of related penetrative fabrics). After the first two stages of deformation, the rocks were imbricated by two major syntectonic ductile thrust faults (Cameron's Line and the St. Nicholas Thrusts), and intruded by late-syntectonic calc-alkaline magmas (now preserved as orthogneisses such as the Ravenswood Granodiorite Gneiss). These metaplutonic rocks vary from granitoids through diorite and gabbro and are well foliated indicating a relatively early intrusion age with respect to structural deformation and regional shearing. Since their initial deformation during the Paleozoic Era, all of these rocks subsequently have been affected by at least three, comparatively weak open- to crenulate folding episodes (obvious, folds of the foliation) at significantly lower metamorphic grade, cut by a great number of Mesozoic- to Cenozoic brittle faults of various orientations, uplifted roughly 20 to 25 km, and much eroded.

Cameron's Line and the St. Nicholas thrust developed during two progressive stages of ductile deformation accompanied by isoclinal folding (F_1+F_2). An annealed, highly laminated mylonitic texture occurs at these thrust zones (Merguerian, 1988). Recrystallized mylonitic layering is marked by ribboned and locally polygonized quartz, lit-par-lit granitization, and quartz veins developed parallel to the axial surfaces of F_2 folds. During D_2, a penetrative foliation (S_2) and metamorphic growth of lenses and layers of quartz and kyanite + quartz + magnetite up to 10 cm thick formed axial planar to F_2 folds which deformed the bedrock into a large-scale recumbent structure that strikes N50°W across Manhattan Island and dips 25°SW.

Although the regional metamorphic grain of the New York City bedrock trends N50°W, the overall shapes of map contacts are regulated by F_3 isoclinal- to tight folds overturned toward the west and plunging SSE to SW at 25°. (See Figure 4.) S_3 is oriented N30°E and dips 75°SE and varies from a spaced schistosity to a transposition foliation often with shearing near F_3 hinges. The F_3 folds and related L_3 lineations mark a period of L-tectonite ductile flow that smeared the previously flattened quartz- and kyanite lenses and -layers into elongate shapes.

Geology of Western Queens and Southwestern Brooklyn

CM's detailed mapping, which was accomplished between May and August of 1985, before the tunnel was lined with cement, has identified the late-syntectonic intrusive contact of the Ravenswood Granodiorite with rocks of the Hartland, identified the ductile fault known as Cameron's Line in two places with repetition resulting from brittle faulting, showed complex folding of the Inwood Marble, and showed how in the vicinity of the East River in New York City, Cameron's Line places Hartland rocks structurally against the Fordham Gneiss.

Here, Cameron's Line is marked by a 3-m sliver of sheared diopsidic marble and by intense F_2 intrafolial folds, 1 cm- to 4 cm-scale mylonitic layering, and protomylonitic syntectonic pegmatite in the wallrocks. Locally, highly laminated Hartland rocks are in mylonitic contact with units of the Fordham Gneiss suggesting that in NYC, Cameron's Line cuts across the basal Paleozoic unconformity into Proterozoic Y basement. The St. Nicholas thrust, to the west of and structurally below Cameron's Line, places the Hartland and parts of the Manhattan Formations structurally above units of the Inwood Marble and Fordham Gneiss. Thus, along the length of Cameron's Line from western Connecticut to New York City, the Hartland is in structural contact with stratigraphically lower bedrock units.

Synorogenic Plutonism Along Cameron's Line

Numerous lower Paleozoic calc-alkaline plutons occur in southeastern New York and in western Connecticut. Near West Torrington, Connecticut, the Hodges mafic-ultramafic complex and the Tyler Lake Granite were sequentially intruded across Cameron's Line (Merguerian, 1977, 1985, 1987). Because of their formerly elongate shapes and because the regional metamorphic fabrics related to the development of Cameron's Line in both the bounding Waramaug and Hartland formations display contact metamorphism, these plutons have been interpreted as syn-orogenic. The recognition of significant medial Ordovician plutonism across Cameron's Line (Mose, 1982; Mose and Nagel, 1982; Merguerian and others, 1984; Amenta and Mose, 1985) establishes a medial Ordovician or possibly older age for the formation of Cameron's Line and the syntectonic development of regional metamorphic fabrics in western Connecticut (Merguerian, 1985).

In western Queens, the Ravenswood Granodiorite of Zeigler (1911) crops out. (Unit ORg in Figure 37.) Field relationships in the water tunnel beneath western Queens and in surface exposures in Long Island City (Merguerian, unpublished data), indicate that the Ravenswood is a foliated metaplutonic rock (hornblende gneiss) which encloses foliated screens and xenoliths of Hartland rocks. A poorly constrained, Early Paleozoic Rb/Sr date on the Ravenswood [Baskerville and Mose (1989)] seems to fit the age pattern of intrusive rocks observed along Cameron's Line in western Connecticut.

Horace Blank introduced the name Brooklyn Injection Gneiss and argued that the bedrock in Brooklyn marked an extension of the Ravenswood locally comingled with stratified marble, schist, and gneiss of the New York City Group. He described [Blank (1973)] the bedrock beneath western Brooklyn as consisting of Fordham Gneiss, granodiorite (Ravenswood?), laminated mica schist, and amphibolite (City Water Tunnel #2 - Sections A through U). Baskerville and Mose (1989) suggest that Brooklyn is underlain by either the Ravenswood or the Hartland Formation but give no specific details as to why these selections were made. CM's observations are limited to published- and photographic evidence but it seems that the Brooklyn Injection Gneiss varies greatly from migmatitic gneiss and subordinate schist (mixed metaigneous- and metamorphic rock), to massive felsic- to intermediate gneiss, to laminated quartzofeldspathic gneiss. As such, the terrane underlain by the Brooklyn Injection Gneiss is heterolithic and poorly understood.

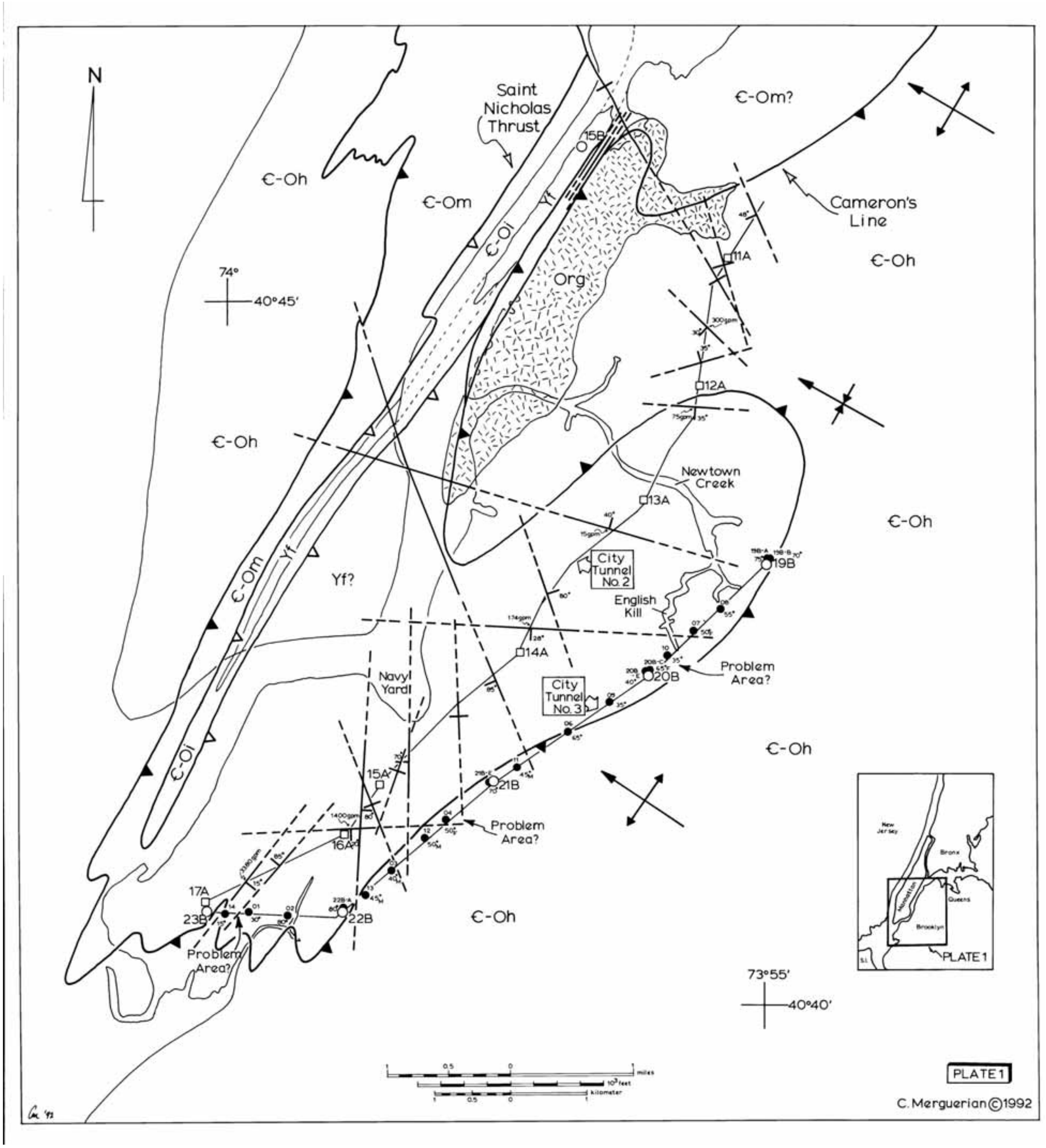


Figure 37 - Interpretive geologic map of western Brooklyn, western Queens, and southeastern Manhattan, originally compiled at 1:24,000 scale, indicates the positions of the tunnel line and shafts (open squares) of City Water Tunnel # 2 and the construction shafts (filled circles) and proposed tunnel line of City Water Tunnel # 3. Geologic units include Org - Ordovician Ravenswood Granodiorite Gneiss, Є-Oh - Cambrian to Ordovician Hartland Formation (Upper Schist Unit), Є-Om - Cambrian to Ordovician Manhattan Formation (Middle Schist Unit), Om -Ordovician Manhattan Formation (Lower Schist Unit), Є-Oi - Cambrian to Ordovician Inwood Marble Formation, Yf - Proterozoic Y Fordham Gneiss Formation. (From Merguerian, 1994, figure 1, p. 50.)

Geologic Map of New York City Water Tunnel Number 3

Figure 37 is an interpretive geologic map of western Brooklyn, western Queens, and southeastern Manhattan, originally compiled at 1:24,000 scale. Figure 37 includes the positions of the tunnel line and shafts of City Water Tunnel # 2 and the construction shafts and proposed tunnel line of City Water Tunnel # 3. Also included, with annotations, are the positions of borings examined along the tunnel line. The bore-hole data are limited to the depth interval of tunnel penetration.

The rocks encountered by the bore holes along the proposed tunnel line of CT #3 include garnetiferous quartzofeldspathic gneiss and subordinate schist, foliated orthogneiss (metaplutonic rock), and subordinate pegmatite. All of the rocks are strongly migmatitic thus resulting in use of the term "injection" gneiss for the dominant lithologies in the region. Ductile-fault-rock textures (mylonitic rocks) are well represented as are zones of mixed rock typical of Cameron's Line. In Figure 37 the position of Cameron's Line is a "best fit" based on lithology, recognition of ductile-fault textures, and mixed rocks. The lithologies appear to be representatives of the Fordham Gneiss (Yf), the middle unit of the Manhattan Schist (Ꞓ-Om), the Hartland (Ꞓ-Oh), and migmatitic gneiss of unknown lithologic affinity. Thus the Cameron's Line contact places Hartland rocks against units of the Manhattan Schist and the Fordham Gneiss, a relationship noted beneath the East River.

Note that in the vicinity of western Queens and Brooklyn, Cameron's Line has been strongly folded. The bulbous shape of Cameron's Line is the result of superposed F3 and younger folds (with possible NW-trending anticlinal- and synclinal fold axes illustrated on Figure 37 to the SE of Cameron's Line) that have warped the thrust surface into a subhorizontal flap that has been breached by erosion. Thus in the area of western Queens, Hartland rocks and the Ravenswood Granodiorite Gneiss are exposed but in western Brooklyn, rocks of the Fordham-Inwood-Manhattan sequence occur in a structural window beneath Cameron's Line. A similar, structurally lower window (might this qualify as a double-hung window?) exposes the St. Nicholas thrust and underlying units Yf and Ꞓ-Oi in southeastern Manhattan. Tunneling of CT #3, which is underway at the present, should better constrain the configurations of the geologic contacts in this area.

Cameron's Line trends westward near Shafts 23B and 17A in southwestern Brooklyn (closed thrust symbol on Figure 37) and must traverse northward into the south part of Manhattan as mapping constrains the position of Cameron's Line to the southern portion of Central Park northward along the western edge of Manhattan. It passes offshore into the Hudson River near 165th Street. (See Figure 4.) The St. Nicholas thrust (open thrust symbol on Figure 4) follows a somewhat similar pattern as it was also deformed by F_3 and younger folds.

Brittle Faults

All geologists and seismologists agree that earthquakes result from dislocations known as faults and that new earthquakes tend to be localized along preexisting faults. The bedrock of New York City, always considered to be solid and impervious to seismic activity, is cut by a great number of ductile- and brittle faults. In addition to Cameron's Line and the St. Nicholas thrust, numerous northwest-trending brittle faults are indicated on Figures 4 and 36. One of these, the famous 14th Street fault, controls the lower-than-average height of buildings of the New York skyline in the area of Manhattan between 23rd and Canal streets. The fault at 125th Street underlies a broad, U-shaped valley.

Two contrasting sets of brittle faults are superimposed upon isoclinally folded imbricate ductile thrusts (Cameron's Line and the St. Nicholas thrusts) and amphibolite-facies metamorphic rocks in New York City. Field evidence and subsurface data indicate that trends of these sets are: 1) approximately N30°E (roughly parallel to the trend of lithologic contacts and the axial surfaces of F_3 folds) and 2) ranging from N20°W to N50°W (across the NE trend, roughly parallel to the S_2 axial surface of the F_2 folds). Thus, the orientation directions of brittle faults in the vicinity of New York City are the products of emphatic structural control in the form of lithologic layering (S_0), the S_1+S_2 metamorphic fabrics, and the S_3 axial surfaces of major F_3 folds.

The NE-trending faults are steep to vertical and show dominantly dip-slip motion with offset up to 1 m in zones up to 2 m thick. Locally, where they parallel NE-oriented mylonite zones (Cameron's Line and the St. Nicholas thrust), they are cataclastic (broken) and marked by greenish clay-, calcite-, and zeolite-rich gouge up to 30 cm thick. More commonly, they are healed shut by quartz, calcite, or zeolite minerals. Elsewhere, the NE-trending faults are developed parallel to an S_3 transposition foliation or spaced schistosity and/or transposed compositional layering and foliation (S_1+S_2).

The NW-trending faults exhibit the greatest amount of offset of geological contacts, dip steeply to moderately, and their movement histories are complex: left-lateral strike-slip offset predominates, but commonly has been followed by secondary dip-slip or oblique-slip reactivation. A case in point was mapped in the east channel of the East River, where a NW-trending, steep NE-dipping left-lateral strike-slip fault bearing sub-horizontal slickensides, shows overprint by N- to NE- plunging slickensides. This composite movement has resulted in roughly 7 cm of offset of a quartzose segregation in gneisses of the Hartland. The NW-trending faults are lined by zeolites, calcite, graphite, and sulfides. Composite offsets average a few cms to more than 35 cm but, in brecciated zones, local offset may exceed 100 meters. The NW-trending faults may have been structurally controlled initially by an anisotropy produced by A-C joints related to southward-plunging F_3 folds and/or by the NW-trending S_1+S_2 metamorphic fabric of the bedrock. Thus, the intersection of these two important fault sets has cut New York City into mand blocks. Protracted dislocations along the NW-trending faults may be the result of stress propagated through the continental crust along oceanic fracture zones in response to spreading of the North American plate away from the mid-oceanic ridge of the Atlantic Ocean. Field observations support a conclusion that of all th faults in the region, the seismic potential of the NW-trending faults is by far the greatest. As an example, in the New York Botanical Garden, a NW-trending fault has produced post-Pleistocene diversion of the Bronx River from its former channel.

We shall arrive at Staten Island via the Verrazano-Narrows Bridge, completed in 1964 by none other than that great builder of things, Robert Moses. The bridge has been built on the highest ground available, which is on top of the ridge of glacial debris that was heaped up at the margin of one of the continental ice sheets that spread into the New York area during the Pleistocene. Just which glacier formed this ridge (known as a terminal moraine because it is inferred to mark the outermost limit of the ice sheet) is not so securely known as many believe. The ridge at The Narrows is continuous with the more-northerly of the two moraine ridges of Long Island, which has been named the Harbor Hill moraine. (See Figure 10.)

The Harbor Hill moraine clearly is younger than Long Island's more-southerly moraine (the Ronkonkoma moraine); southwest of Roslyn, the Harbor Hill Moraine truncates the Ronkonkama moraine. [Glacial geologists invite ambiguity and confusion by using the term "moraine" in several different ways. In one sense, it refers to any material deposited by the glacier. In another sense, it is applied according to the surface expression of these deposits. Thus, the term "ground moraine" has been applied to widespread sheets lacking any particular ridge-like aspect. As such, ground moraine is a synonym of till, the sediments deposited directly by a glacier (no reference to the shape of the deposit nor to the morphology of its upper surface). The term "moraine" by itself usually refers to a ridge built at the margin of a glacier. For example, a terminal moraine is, as mentioned, the outermost ridge. As a glacier retreats, it deposits a succession of marginal ridges; these are recessional moraines. Glacial deposits are complex, and any ambiguity in the language only adds to the complexity.]

To Stop 1: Leave I-278 by taking exit on R after Hylan Blvd. (exit for Richmond Road). Turn L on Richmond Road (one way to S). Cross under I-278; at second traffic light, turn R on Spring Street. At traffic circle at end of Spring Street, make a U turn and head east; turn R at entrance to The Heights Emerson Valley and park. Stop 1 is the serpentinite knoll behind the fence. (We have obtained permission to go through the gate, which normally is locked.)

To Stop 2: Drive downhill to E on Ridge Ave. Cross Richmond Rd. and turn L on Targee St. Continue beneath I-278 and turn L on Narrows Road N for westbound ramp on I-278. After about 4 miles, turn R on NY 440 northbound toward Bayonne Bridge. Take the first exit on R (for Forest Road). At end of ramp, turn L on Forest Road and cross beneath NY 440. Rest stop at Dakota Diner on left after a few blocks.

After leaving diner, continue W on Forest Road. At Van Pelt Ave., make U turn and park on R opposite vacant lot W of school building. To see the rocks at Stop 2, leave the sidewalk at the cement driveway, then turn R onto trail into old Graniteville quarry. The xenolith is at crest of small rise about 200 m from the sidewalk. (The abundant vines, possibly still lacking leaves, are those of poison ivy. Beware!)

To Stop 3: Drive E on Forest Ave. toward NY 440. Just before NY 440, turn R on Richmond Avenue. Follow Richmond Ave. south, cross beneath I-278. Pass Willow Brook Park; after Travis Avenue enters on R, prepare for L turn onto Richmond Hill Road. After passing through Tourette Park, Richmond Hill Road ends against Arthur Kill Road-Richmond Road. Turn L then at next light turn L into Clarke Ave. At Amboy Road, make another jog L, then R onto Guyon Avenue. Turn R on Hylan Blvd., then L at traffic light for entrance to Great Kills Park. Drive to headquarters building. Pit stop. Lunch.

Just after we have turned onto Hyland Boulevard from the intersection of Richmond Avenue (Figure 38), we arrive at Manhole No. 2 of the Oakwood Beach Water Pollution Control (sic) Project, Contracts 6b-2 and 6B-3, East Heading. On our last trip (in 1991), where the contractors encountered an unexpectedly large amount of coarse, permeable outwash beneath the surface till, and with it, unexpectedly large flows of ground water, construction had been stopped and the contactor and the city were locked into serious financial negotiations about the added costs of completing the job. We take our information about the extent of this water problem and a recommendation that compressed air be used to abate it, from a report from Mueser Rutledge Consulting Engineers to Moretrench American Corporation dated 05 January 1990, a copy of which we have been able to study via the courtesy of Dr. Alan Benimoff, Staten Island Community College of CUNY. From the maps in this report (all of which were drawn with N at the bottom!), JES has recomposed the information as shown in our Figures 39, 40, and 41, which are based on numerous borings and, locally, on what was visible in the walls of the excavation. The sewer line slopes northeastward. The depth of the tunnel invert at Manhole No. 2 is -55.02 ft; at Manhole 16 (corner of Hylan Boulevard and Colon Street), it is -40.39 ft.

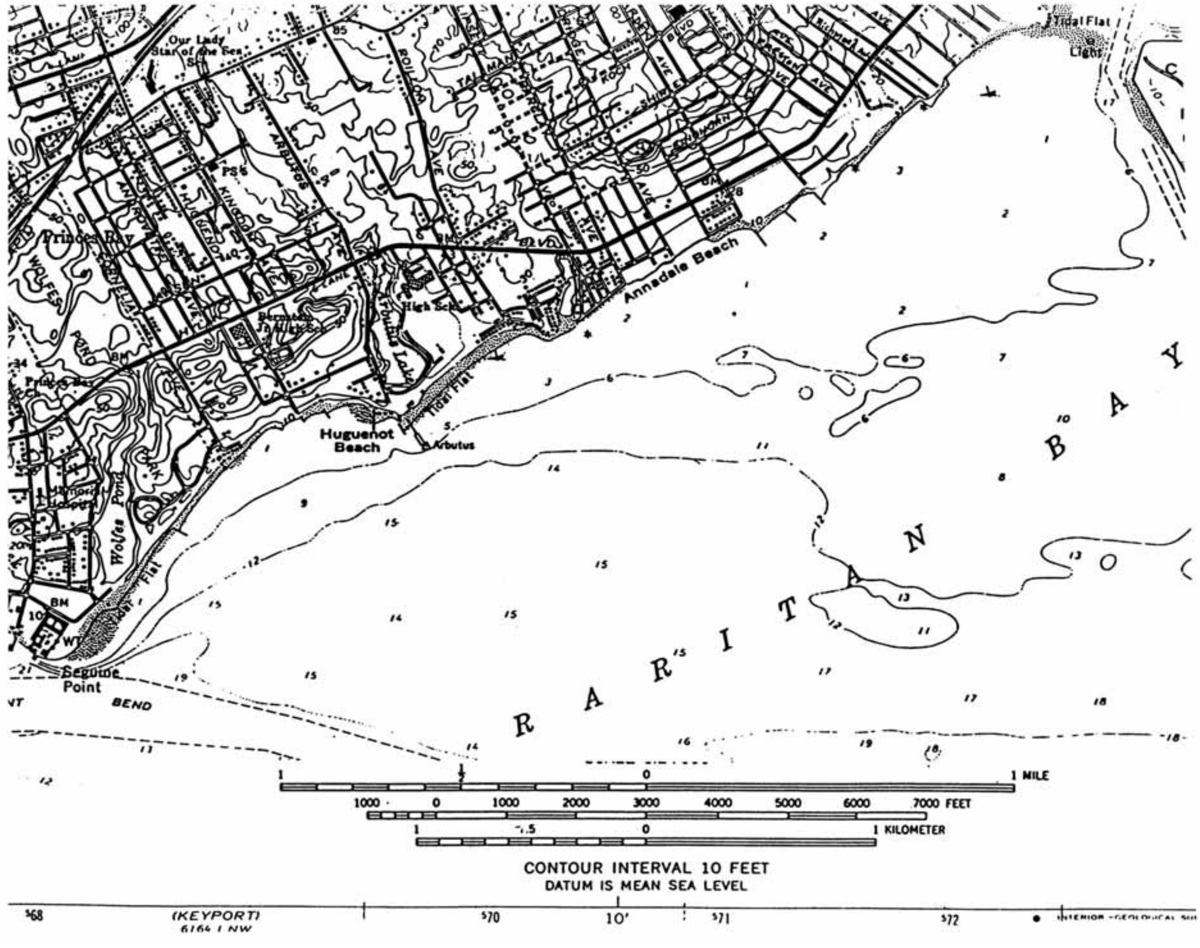


Figure 38 - Segment of the Arthur Kill 7.5-minute topographic quadrangle map of the U. S. Geological Survey (edition of 1966) showing stretch of Hylan Boulevard between Richmond Avenue and Seguine Point. The major flow of ground water that caused so many problems during construction of the sewer line under Hylan Boulevard took place near the bend in Hylan Boulevard that is just north of Arbutus Lake (between Arbutus and Poillon Avenues).

The key points are the the depth- and shape of the contact between the Quaternary and Upper Cretaceous, and where the top of the Cretaceous is low, the presence of layers of both reddish-brown- and brown outwash and of other reddish-brown till beneath the reddish-brown till at the surface. At Manhole No. 2, the top of the Cretaceous is at about +5 ft and it is overlain by the surface till. (See Figure 39.) Here, the tunnel lies entirely within the Upper Cretaceous sands and -clays. Between Manhole No. 3, at Preston Avenue, and Manhole No. 4, at Orchard Lane, the top of the Cretaceous descends to about -15 ft and outwash appears beneath the surface till. The water-problem area is located between Manholes No. 13 (at Poillon Avenue) and No. 15 (Arbutus Avenue) (See Figure 40.), where the tunnel is in the coarse, brown outwash and the depth of the top of the Cretaceous lies between -45 and -60 ft. (See Figure 41.)

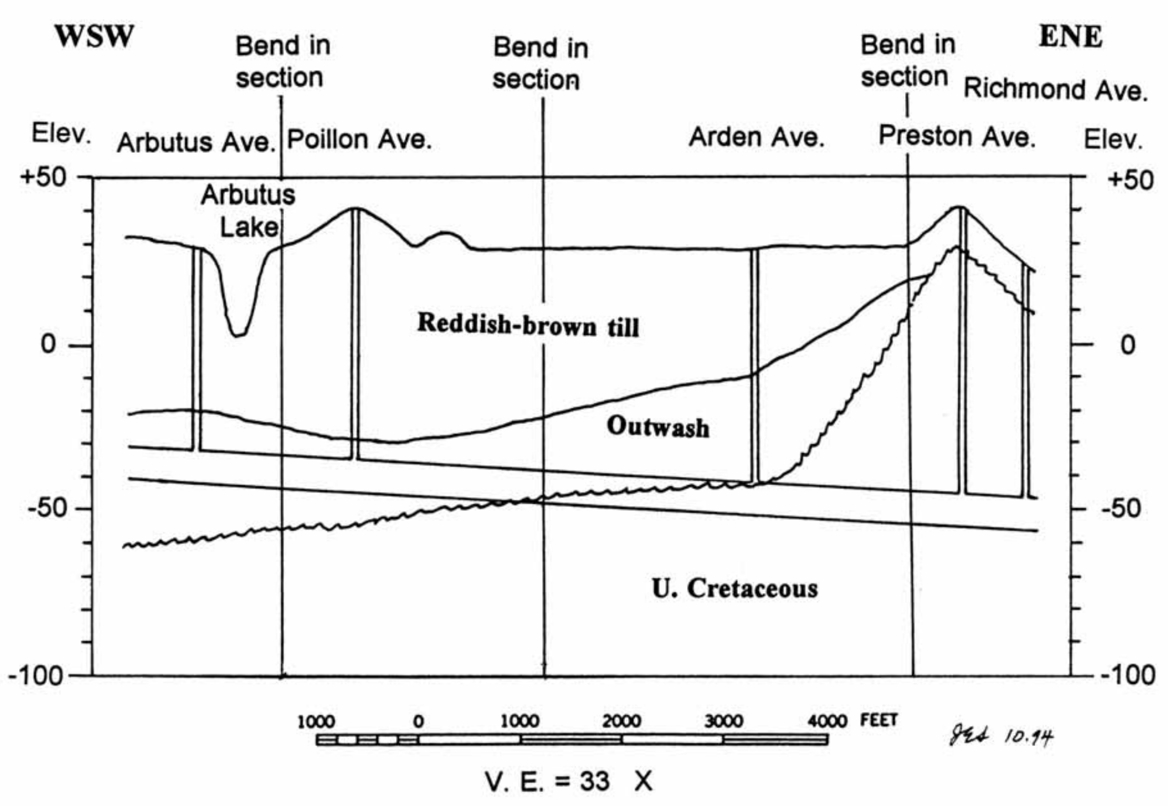


Figure 39 - Generalized profile-section along the Hylan Boulevard sewer line from Manhole No. 2 (Richmond Avenue) to Manhole No. 16 (Colon Street). Notice that from the ENE end of the section to the WSW end, the elevation of the top of the Upper Cretaceous drops about 60 feet. (Drawn by JES from data in Mueser Rutledge Consulting Engineers Report to Moretrench American Corporation dated 05 January 1990.)

Not shown on the borings in this section of the sewer line are examples of Upper Cretaceous sediments enclosed within the Pleistocene sediments. Such relationships were encountered farther SW, but we have not yet obtained copies of the borings that show this remarkable situation.

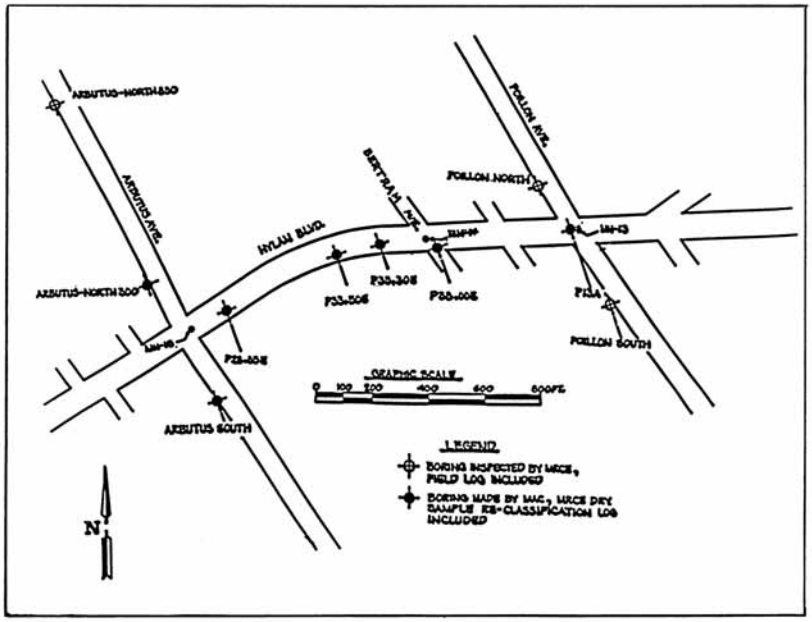


Figure 40 - Index map showing locations of borings and manholes, Hylan Boulevard sewer line, where the water problem took place. (Meuser-Rutledge Consulting Engineers Report to Moretrench American Corporation dated 05 January 1990, fig. C-1, orientation reversed and layout rearranged by JES.)

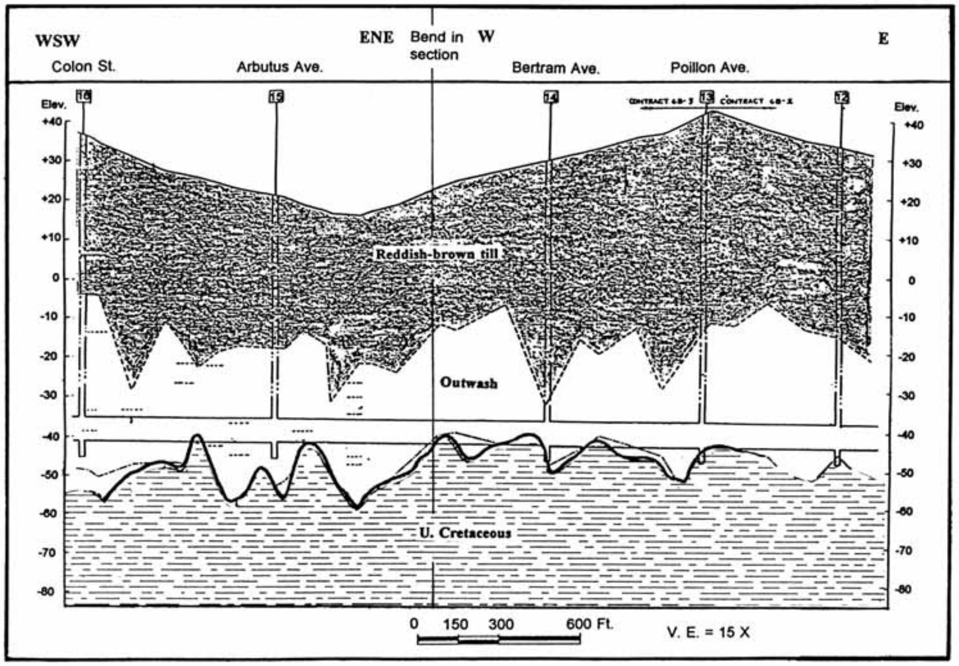


Figure 41 - Detailed profile-section along Hylan Boulevard sewer line between Manhole No. 12 (450 ft E of Poillon Avenue) and No. 16 (Colon Street) based on borings and visual observations during construction. Notice that the sewer lies largely in the coarse, very permeable brown outwash that appears beneath the reddish-brown surface till (irregular shading). Heavy line = surface of unconformity at top of Upper Cretaceous. (Mueser-Rutledge Consulting Engineers Report to Moretrench American Corporation dated 05 January 1990, fig. 3, which JES changed by reversing the orientation, deleting the layer labels, rearranging the layout, and adding the pattern for the Upper Cretaceous.)

To Stop 4: Retrace route to Hylan Blvd.; turn L at traffic light. Drive 6 mi SW on Hylan Blvd. past Seguine Ave. and turn L on Sharrott Ave., a short dead-end street that leads to the beach. Find parking place at turnaround on R. Walk to Stop 4 along beach near light tower.

To Stop 5: Return to Hylan Blvd., turn L, then R at light into Page Ave. Follow signs to Outerbridge Crossing, but once on Veterans Blvd., do not enter ramp for Outerbridge Crossing (on L), but continue ahead to end of street. Turn R on Arthur Kill Rd. In about l mile, turn R into AKR Excavating Co., 4288 Arthur Kill Rd. Stop 5 is large cut at L of entrance.

The sequence of stops planned for this trip is such that our line of travel did not take us past the Fresh Kills landfill, which is now reaching truly epic proportions. Richard Severo's article in the New York Times of 13 April 1989 comparing the Fresh Kills accumulation with the Egyptian pyramid is a dramatic way in which to convey some idea of the scale of New York's trash dump. We have included Severo's article (cut and pasted into a format that fits on guidebook-size pages) in the appendix.

To Stop 6: Turn L onto Arthur Kill Rd. After l mile, turn L into Veterans Blvd., then R into entrance ramp for Outerbridge Crossing and NJ 440 westbound. Continue W on NJ440 to Garden State Parkway S bound (Interchange 127). After toll booths, use express lane. Rest stop at first service center. Leave GSP at Interchange 117 (Matawan, Keyport). Take NJ 36 E toward Atlantic Highlands and Sandy Hook. After about 9 miles, look for left turn to local park.

To Stop 7: Follow NJ 36 westward. At Interchange 117 of GSP, turn into Lloyd Road southbound. Follow Lloyd Road S past Church St. to NJ 34. Turn L on NJ 34 and follow it S past Dietrich Trailer Sails to furniture store on L. Turn L into parking lot of furniture store and drive to far end of parking lot. Walk to far end of the old sand pit to faces of Stop 7.

Back to NYAS: Turn R onto NJ 34; R on Lloyd Road; Enter Garden State Parkway northbound. After Crossing Raritan River, join New Jersey Turnpike northbound. At Newark Airport, take NJ Tpk Extension east toward Holland Tunnel. Local streets back to NYAS.

DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

STOP 1 - The Staten Island serpentinite, local serpentinite-clast breccia, and the scarce mineral artinite, east side of Todt Hill. [UTM Coordinates: 576.35E / 4495.10N, The Narrows quadrangle.] ***Note:*** *This exposure is on private property owned by the homeowners association consisting of local residents. Permission may or may not be available.*

Stop 1 is a glaciated knoll forming the south part of Emerson Hill at an elevation 260'. The nearest cross streets are Medford Road and Keune Court. Here, the bedrock juts up from street level roughly 10 m and displays classic roche moutonnée structure with steep, plucked southern margin.

As discussed earlier, the Staten Island Serpentinite occurs at the southern terminus of the Manhattan Prong. (See Figure 1 on cover and Figure 5.) This serpentinite is one of a large number of similar bodies scattered along the entire length of the deeply eroded core zone of the Appalachian mountain range. (See Figure 8).

The oval-shaped Staten Island body is about 11 km long and about 5 km in maximum width and underlies a prominent northeast-trending ridge (locally called Todt Hill) through the center of Staten Island. The top of Todt Hill, altitude 540 feet, is the highest natural point in New York City. The contact of the Staten Island Serpentinite body with the Mesozoic rocks of the Newark Basin to the west is composite--partly along a fault and partly by overlap of the Mesozoic. The eastern contact with metamorphosed sedimentary- and metavolcanic rocks of the Hartland Formation (a significant portion of rocks formerly mapped in New York City as the Manhattan Schist according to CM) is a fault. (See Figures 5 and 6.)

The current fault-bounded relationship of the Staten Island body (See Figures 5 and 6.) supports Crosby's idea that expansion resulting from hydration of the magnesium-silicate minerals caused the body to rise upward intermittently, in diapiric fashion. Topographic expression is strong evidence for faulting. In addition, are found local fault-related breccias, slickensides (gouges in rock surfaces caused by differential motion of rock masses; compare with glacial striae), and local veins of talc and other serpentine-group minerals.

The weathered knoll at Stop 1 is known to mineral collectors as the "Spring Street" locality, famed for its artinite, a hydrated alteration product of serpentinite. First described in 1902, the rare hydrated mineral artinite forms pure white- to transparent needle-like monoclinic crystals. These are found in association with hydromagnesite and also as hemispheres of radiating crystals. The minerals occur as aggregates and are extremely beautiful when viewed with a hand lens, or better still, back at home under a binocular microscope. Micromineral collectors from around the world desire and trade for specimens of artinite from this unique locality on Staten Island.

Along the south-facing raw edge of the outcrop, steep NE-trending faults crosscut shallow SE-dipping shears formed axial planar to overturned folds with sheared-out limbs. Offset indicates that the shallow faults are thrusts (top to the NW) and they antedate the steep, brittle faults. The initial orientations of the layers in the serpentinite body that have folded by the deformation related to thrusting must have been low (roughly parallel to the thrusts).

The serpentinite is highly sheared at this locality. The many vertical faults and local low-angle faults together have produced a source of friable, weathered serpentinite rock. Indeed, chips- and boulders of serpentinite are strewn on every square inch of the site and locally drape downward into resident's backyards. We suspect that asbestiform minerals may present a hazard in this area and would hope that environmental remediation at this site would include vegetative cover of plants suitable for growth on serpentine rock.

During the Cretaceous, the Staten Island serpentinite probably maintained sufficient positive topographic relief to project as an island in the marginal sea (as discussed at Stops 3 and 4). It has been sculpted during numerous pulses of Pleistocene glaciation. The thick ice layers produced an overall classical roche moutonnée outcrop shape. Other glacial effects included plucking, valley widening, and deposition of till and outwash.

After we have examined the serpentinite, we shall study the associated breccia. In Crosby's profile-section, on the SE side of Todt Hill, occurs a small body of Lafayette Gravel, a post-Miocene formation on the Atlantic Coastal Plain. No fossil proof verifies this age assignment. The breccia contains clasts of Mesozoic Newark red-brown siltstones and coarser rocks; white talc-bearing rocks that look like talc schists, but could come from the white talc veins in the serpentinite; and pieces of the serpentinite itself. The Newark clasts prove a post-Jurassic age for the breccia. If the concept is valid that the Upper Cretaceous formations of the Coastal-Plain sequence and the Late Cenozoic sheet of fan gravel buried the Newark and kept Newark debris out of circulation until after the post-Miocene uplift, then the correct age is post-Miocene.

STOP 2 - Palisades Intrusive Sheet in the old "Graniteville" quarry (a misnamed place; had a knowledgeable geologist given the name it might have been Doleriteville or even "Diabaseville". [UTM Coordinates: 571.60E / 4497.72N, Elizabeth quadrangle boundary.]

Walk south on trail for a few hundred meters to the crest of a small rise. The elevation here is about 20 feet. Near the corner of Victory Boulevard and Travis Avenue (Arthur Kill quadrangle, UTM 570.0E / 4494.5N) the top of the sill is being covered by modern saltmarsh deposits. South of Fresh Kills, also on the Arthur Kill quadrangle, the top of the sill lies below sea level. The regional southward gradient on the top of the ridge underlain by the eroded edge of the tilted sill is 20 feet per mile. This is based on the crestal elevation of about 800 feet at Haverstraw, which is 40 miles north of Staten Island, the point where the top of crest underlain by the sill is at sea level.

This is the locality studied by Benimoff and Sclar as the basis for their 1984 article in the American Mineralogist. We shall go to the exact spot where their specimens came from and to study the effects of the interaction between the xenolith of argillite from the Lockatong Formation (formerly considered to be a small dike intruding the dolerite) and the mafic magma of the sill.

Two important points about magmas and igneous rocks are exemplified here. First of all, within the mafic (rich in magnesium and iron) magma that crystallized to form the sill, opportunities existed for growing crystals to settle through the hot liquid. Rocks formed by the segregation of crystals in a magma (by sinking or by flotation) are known as cumulates or cumulus rocks. Some such rocks exist in the Palisades sill. In addition to the crystal separation (mostly by settling in this sill), the effect of gravity on the cooling magma gives rise to compositional gradients across the sill. Thus, after one has analyzed a series of specimens showing what this gradient is, one can take specimens from unknown positions and infer more or less their positions with respect to the top- and bottom of the sill.

Secondly, proof exists here that a chunk of the Lockatong Formation was not only internally altered by the heat from the surrounding magma, but that some of the Lockatong actually melted to form a felsic magma (magma rich in sodium/potassium feldspars). The rock which crystallized from this small amount of magma has been identified as a trondhjemite (Benimoff and Sclar, 1984).

Examination of the orientations- and marginal relationships of xenoliths in the Palisades intrusive sheet of New York and New Jersey suggests that one of the feeder areas for the intrusive sheet was in the vicinity of Graniteville, Staten Island. Geological relationships in Fort Lee, New Jersey, indicate that internal flow of the magma was directed northward, perhaps away from the Graniteville feeder area (Merguerian and Sanders, 1992a, 1994c). Similar relationships are present at an exposure of the Palisades at Kings Bluff. Such flow to the N is consistent with evidence from the Graniteville quarry, Staten Island, where a partially fused, Lockatong xenolith is vertical and is surrounded by annular fractures. The dips of all other xenoliths in the New York City area are gentle; the xenoliths are oriented parallel to the contact of the Palisades intrusive sheet. This unique vertical xenolith and the annular cooling fractures imply upward flow of the magma and thus proximity to the feeder channel. If this is correct, then from Staten Island to Fort Lee, the lateral paleoflow pattern would have been from SSW to NNE. South of Staten Island, we predict NNE- to SSW-directed lateral paleoflow.

The buried strike valley at the base of the Newark strata (See Figure 30.) passes between this old quarry and the hills underlain by serpentinite to the east (of which Todt Hill, on whose slope we were at Stop 1, is the highest). On the existing land surface, the distance between the exposures of bedrock is about 2 km. Between Graniteville and Todt Hill, thick till makes low hills (Westerleigh and Fairview Heights). Thus, the modern landscape gives no hint that a large buried valley lies below. Borings for water wells (Perlmutter and Arnow, 1953) indicate that the till at the surface (age not known exactly) is underlain by thick (several tens of meters) outwash sands that are high-yielding aquifers.

Now for the Pleistocene. Along the sidewalk, we noticed a place where red-brown till rests on the mafic bedrock along a sharp contact. We dug back the till here to expose the contact, hoping to find some well-defined striae that would indicate the direction of flow of the glacier. We found only the general rounded shape of the surface cut on the bedrock. Using the direction of its long axis, we think glacial flow here was from about N10°E to S10°W. If this is correct, then it is the first confirmation known to us of an effect of the Woodfordian glacier on

Staten Island. (On Staten Island, red-brown color of till is not diagnostic of flow from NW to SE; till from a glacier that flowed from NNE to SSW is also reddish brown.)

On the surface of the bedrock in the quarry area, numerous ice-sculpted features are present. These include shallow trough-like grooves, striae, and crescentic marks. Crossing sets of features eroded by the ice on the mafic bedrock confirm the effects of at least two glaciers: an older one from NW to SE and a younger one from NNE to SSW.

STOP 3 - Great Kills (Oakwood Beach) Park - Modern beach rapidly advancing landward by marine erosion. [UTM Coordinates: 574.15E / 4488.30N, The Narrows quadrangle.]

The Oakwood Beach (Figure 42) is undergoing rapid erosion that has intensified during the last 14 years. The subject has been examined by Steven Okulewicz, who provided us with a copy of his report on the matter (Okulewicz, 1988 ms. b) from which these remarks have been abstracted. The main bathhouse and building that is the office for the Park Police is in great jeopardy. A scarp, 2 to 3 meters high, has formed by the undercutting action at water level. This edge is an active slope subject to collapse and is marked by a snow/sand fence. Only a few years ago, the water's edge was 100 feet or more from this building and in April 1989 the water's edge was beneath the building (which is built on piles). We look forward to checking this area out on today's field trip to see what has happened in the two and a half years since our last visit.

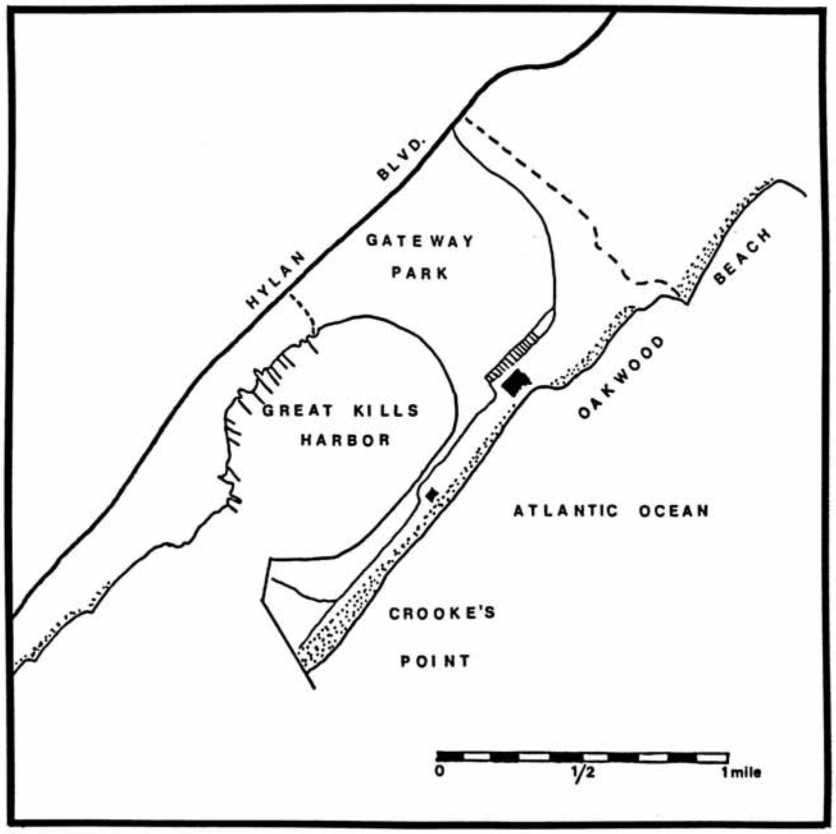


Figure 42 - Map of Gateway Park, Great Kills (Oakwood Beach).

This area is the only place on Staten Island underlain by a large body of outwash. Elsewhere, the Pleistocene deposits consist mainly of till. (This is the opposite of the relationships on Long Island, where outwash predominates and till is very localized.) The supply of sand to Oakwood Beach formerly came from the nearshore bottom and from longshore drift from the northeast. Sand from both sources has been cut off. From offshore, the waves have built a boulder armor comparable to a desert pavement formed by the wind. They have winnowed out the fines and left a firm armor of cobbles and boulders that prevent the waves from getting any sand that may lie below. The longshore drift supply has been cut off by exposure of an old marsh deposit of clay and peat that is acting as a natural groin, and by the construction in 1975 of a sewer-outfall pipe that extends one mile out into the water at right angles to shore from the new Oakwood sewage-treatment plant. The waves now go after the sand from the outwash, causing the scarp to retreat by undercutting its base.

STOP 4 - Cliffs of deformed and overthrust Pleistocene and Cretaceous strata along Princes Bay. [UTM coordinates: 566.7E / 4484.2N, Arthur Kill quadrangle.]

En route to cliff, notice the relationships between the beach and the mouth of the small stream that flows into Raritan Bay here from the marshes to the west. Several topics will engage our attention here. As we approach the cliffs, notice how a small stream draining a marsh has been diverted and forced to flow southwestward along the cliffs before it finally turns eastward and enters the bay. This path followed by the stream has resulted from longshore drift of sand from the northeast to the southwest.

The cliffs expose several tills and interbedded outwash. In the face closest to the creek, the sequence from beach upward is red-brown till, red-brown outwash, and red-brown till, capped by what may be about a half meter of loess and the modern soil.

Near the navigation tower, a considerable body of yellowish and whitish sands and light-colored clays [some layers containing bits of charcoal that Hollick (1906d) inferred came from ancient forest fires]. Included are firmly cemented quartz-rich sandstones and -conglomerates. The cement is hematite. Although we do not know of any fossils that have been obtained from these yellowish-whitish-brownish sediments exposed near the navigation tower, on the basis of their mineralogic maturity and general appearance, they can be identified confidently as being part of the coastal-plain Cretaceous. The face by the navigation tower clearly shows brownish, immature outwash and possibly till beneath these Cretaceous strata. Evidence found in the 1987 borings for the sewer line now recently completed along Hylan Boulevard (See Figures 38-41) show the same relationships as seen here: till at the surface, outwash below, and at still-greater depth, the in-situ Cretaceous. Notice on the profile-section of Figure 41, the closest to this locality, the till-outwash countact liest about 10 to 20 ft below zero datum and the top of the in-situ Cretaceous at about -50 to -60 ft. In some of the borings JES examined (not shown here), Pleistocene was found above and below, with Cretaceous in the middle, at still deeper, the in-situ Cretaceous.

Our subsequent studies have indicated that the Cretaceous surrounded by Pleistocene sediments is part of a gigantic glacial erratic that the ice tore loose and incorporated in the till

(Sanders, Merguerian, and Okulewicz, 1995a, b). The geometry of folds bounding the Cretaceous slab indicate ice-shove deformation from NW to SE. Keep in mind that such Pleistocene thrusting took place under permafrost conditions when the Cretaceous sequence was undoubtedly still frozen! Here, the displaced Cretaceous is encased in outwash, which implies that the dislocation involved ice rafting of a frozen slab in a shallow stream.

STOP 5 - AKR Excavating Co., 4288 Arthur Kill Road, Kreischerville, Staten Island, about 1 mile N of Outerbridge Crossing. Red-brown till overlying decayed-pebble outwash, which rests on white, charcoal-bearing Cretaceous micaceous sands and gray clays. [UTM coordinates: 564.68E / 4487.42N, Arthur Kill quadrangle.]

The owner of this stop is Mr. Frank Agugliario, one of the good-old boys, who has always cordially approved our requests to dig in this bluff, not only for today's trip, but on many previous occasions.

The face to the left of the entrance displays significant geologic relationships that are nowhere else exposed in the New York metropolitan area. These include both sedimentologic- and stratigraphic features. In the Pleistocene outwash are spectacular examples of trough cross strata. Among the clasts in this outwash are abundant recycled sedimentary strata including many Newark red-brown siltstones, white quartz, and pieces of the Cretaceous ironstone sandstone and -conglomerate; and rare granitic rocks. The siltstones have been decomposed; they can be easily broken by hand. The feldspars in the granites have been completely decomposed.

The degree of decomposition of the feldspars in the granitic rocks here matches those in Fuller's Mannetto Gravel on Long Island. However, unlike the examples of tills containing decayed feldspars that we have seen on Long Island and at Tellers Point at Croton Point Park in Westchester County, all decomposable clasts at this AKR site have been decomposed. Because of the possibility that the ice could have picked up frozen pieces of granitic rocks containing already-decomposed feldspars at the locality found in the Delaware aqueduct (Berkey and Fluhr, 1948), decomposed feldspars alone are not necessarily indicators of intense postdepositional weathering, hence of great age. Rather, such decayed-feldspar-only sediments may contain unique indicator stones.

We take the evidence of decomposition of all susceptible clasts at AKR to imply great age; we correlate this decayed-pebble outwash with our till No. I and assign an Early Pleistocene (Nebraskan) age. This place appears as a tiny black dot on the map of the surficial geology of Staten Island (Figure 43).

This decayed-pebble outwash overlies light gray- to white, cross-stratified sand containing lignitic plant debris and interbedded layers of light gray clay (Raritan Formation, Upper Cretaceous, the oldest exposed part of the coastal-plain succession).

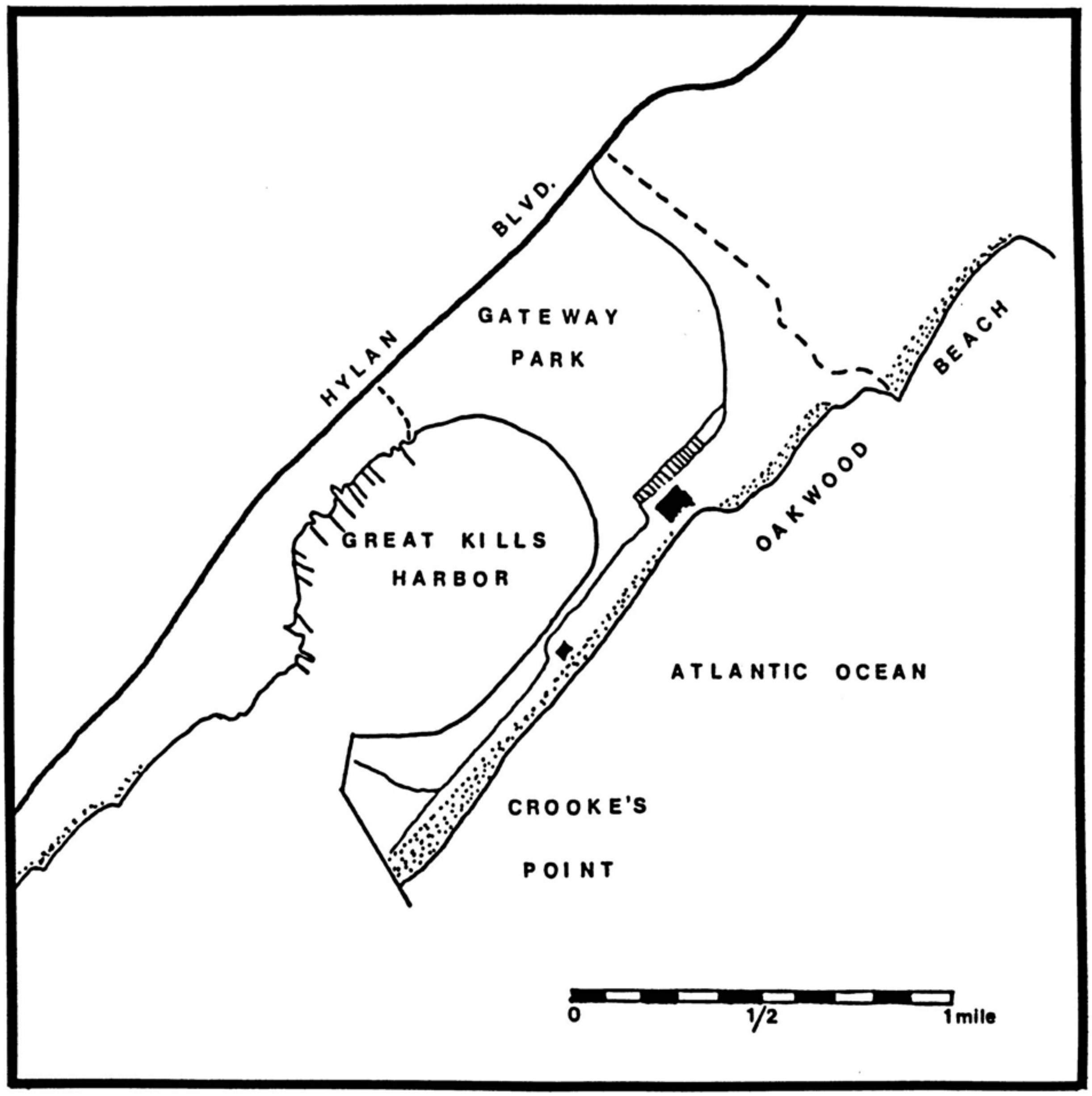


Figure 42 - Map of Gateway Park, Great Kills (Oakwood Beach).

Special features include:

(A) Trough cross strata on all scales in decayed-pebble sands.

Trough cross strata result from the forward migration of sand ridges whose downstream sides consist of a series of spoon-shaped, or cuspate faces (comparable to the curving slip face on a barchan dune). As sand avalanches down all parts of the curving downcurrent face, it deposits layers having comparable curvature. Such trough cross strata (See Figure 26.) are found in many modern settings, but are particularly common in braided streams.

(B) Extreme degree of decomposition of pebbles.

A comparison of the degree of hardness of the pebbles in this deposit with those just seen at Stop 4 (coastal cliffs at Princess Bay). At Stop 4, only the green rocks show much indication of decomposition. Here, all pebbles have been much decomposed. A few white granitic rocks are present. The feldspar in them has become clay.

(C) Abundance of Newark debris in decayed-pebble, cross-stratified sands and the total lack of Newark debris in the Raritan Formation (Cretaceous).

In the decayed-pebble, cross-stratified sediment, Newark debris is extremely abundant. The first pebble from the Newark has yet to be found in the Upper Cretaceous sands. As mentioned, clasts of Upper Cretaceous ironstone-conglomerate clasts been found in the outwash.

(D) Contrasting compositional maturity of the Pleistocene sands vs. Cretaceous sands.

Rock fragments and minerals that readily decompose during chemical weathering (such as feldspars) are parts of the definition of compositional maturity. The presence of such particles indicates immaturity and their absence, maturity. Examination with a hand lens of some of the outwash will demonstrate its maturity contrast with the Cretaceous sand.

(E) Planar contact between the two contrasting units.

Not a large area is visible here, but what can be seen indicates a planar boundary between the outwash and the Cretaceous sand. However, on a larger scale, this contact displays considerable relief. (See Figures 35 and 37.) As far as we know, the pits nearby that were formerly worked as sources of clay show that this Cretaceous is in situ. As mentioned above, the age of the outwash is not known, but from the extreme degree of decomposition displayed by its susceptible clasts, we have assigned it to the Nebraskan.

(F) Colors of sediments below the contact between the two contrasting units.

On several occasions, we have dug out the contact between the decayed-pebble, cross-stratified sand and the Upper Cretaceous sands/clays. Red and purplish iron stains are present in the otherwise-white Cretaceous sands. We have not made a detailed study of the significance of these iron stains. They could have resulted from the effects of pre-Pleistocene erosion of Cretaceous strata exposed at a former land surface, or from the effects of circulating ground water after the Pleistocene sediments had covered the Cretaceous.

(G) Composition of the Cretaceous strata.

For the most part, the Cretaceous exposed in the face of the exposure that parallels the driveway consists of mineralogically mature white sand. Planar cross strata on several scales (set thicknesses from a few cm to half a meter or more) are present. The sand contains much detrital muscovite and also bits of carbonized plant debris (charcoal; Hollick took this charcoal to be products of ancient forest fires). At a dig at the extreme western end of the exposure that is not parallel to the driveway, we found that the Pleistocene is underlain by gray Cretaceous clay. This is not surprising; many of the abandoned pits in this are were dug in the days when the clay was removed and sold commercially.

As mentioned in (C), the Upper Cretaceous sands lack any reddish debris recycled from the Newark basin fill. This point was first emphasized by Douglas Johnson (1931). We agree with Johnson that this absence of Newark debris can best be explained by inferring that the Upper Cretaceous sea lapped far enough inland to have submerged the Newark outcrop areas.

STOP 6 - Park at Atlantic Highlands, New Jersey, with view into Lower New York Bay from a local park. [UTM Coordinates: 581.75E / 4474.31N, Sandy Hook quadrangle.]

Cross-stratified Cretaceous sands are exposed near the parking lot. Depending on the time situation, we may carry out a short dig to show the cross strata.

STOP 7 - Cretaceous sand pits behind new furniture store south of Matawan, New Jersey. [UTM Coordinates: 566.38E / 4470.91N, Keyport quadrangle.]

Professor Richard Olsson, of Rutgers, New Brunswick, told JES recently that the sand from this pit is highly prized for making the "dirt" of baseball diamonds. He says the owner operates the pit just to provide sand for new baseball fields. The upper parts of the face consist of marine sands, and the lower parts, of sediments from intertidal flats. We shall try to dig out the contact to illustrate the relationships. (All this as functions of time and the weather.) In the coarse debris at the base of the marine strata are pebbles of ironstone conglomerate.

ACKNOWLEDGEMENTS

Mr. Steven Okulewicz has been extremely generous with us, providing copies of his reports and accompanying us during the afternoon of 03 April 1989, when we checked out the localities and found out how to obtain permission to get to the serpentinite behind the locked fence. Dr. Alan I. Benimoff guided us to the Graniteville quarry. We thank Mr. Frank Carpenito for arranging access to the serpentinite body at Stop 1 and thank Mr. Frank Agugliaro, Sr. of the AKR Construction Company for access to Stop 5. We thank Matt Katz and Executive Superstar Secretary Marcie Brenner of the New York Academy of Sciences for their logistical help in organizing our field-trip series.

APPENDIX

The New York Times

B1

Metropolitan News

NEW YORK, NEW JERSEY, CONNECTICUT / THURSDAY, APRIL 13, 1989

Monument For Today: 'Alp' of Trash Rises on S.I.

By RICHARD SEVERO

With a little help from some audacious engineers and dedicated landscape architects, New York City is quietly creating a 399-acre, 505-foot-high pyramid of garbage at the Fresh Kills Landfill on Staten Island. And yes, they're going to use a deodorant specialist, too.

When it is completed, in the year 2005, it will be a veritable colossus of waste — at least 79.6 million cubic yards of trash weighing nearly 50 million tons. In its height and volume, it will dwarf the pyramid of Khufu, the largest of the great pyramids of Egypt, and most of the best-known urban landmarks of the world, though the Eiffel Tower, at 1,056 feet, is higher.

And although it will be much shorter than most of the modern buildings that dominate New York City's skyline — the World Trade Center is more than twice as tall — mere skyscrapers pale before its sheer mass, which even now workers are shaping into the landmark of trash that began as a lowly dump in 1948.

The New York pyramid will literally become the crown for the landfill at Fresh Kills, which has received an estimated 100 million tons of garbage within the working portion of its 3,000 acres since it started operations.

Because the city did not know what to do with its trash and recycling had not yet been accepted, officials let the landfill become higher and higher.

The alp it now plans to build will be fully 200 feet higher than the Statue of Liberty, which stands a few miles to the north and east of it.

It will rival even the creations of nature and will be the tallest mountain on the Atlantic coast between Florida and a cluster of higher mountains in Maine, according to the Earth Science Information Center at the United States Geological Survey. There are no landfalls, palisades, ridges, humps or hills touching the sea or its immediately adjacent inlets that are more formidable.

New York's upwardly mobile garbage pile may not scar the seascape for mariners, however, because of intervening hills and buildings; it will be a matter of perspective.

The top of the New York pyramid will be reached by a curving two-lane paved road and served by power lines. The city already has plans to turn it into a park, once the process of decomposition has run its course. City engineers are not sure how long it will take, but they speculate that some sort of park will exist there before the next century is a third over. With grades of 40 degrees on its slopes, it would appear to offer some potential for hikers who seek new and different challenges.

'Politics of the Landfill'

The pyramid has already reached nearly 130 feet in one spot and there are predictions that the public response, which has been muted, will rise in concert with the pyramid itself.

"People aren't aware yet of what a 500-foot sharply sided event will look like," said Thomas C. Jorling, Commissioner of the New York State Department of Environmental Conservation. "The politics of the landfill will become more apparent when it passes 200 feet."

Final Resting Places Compared

The Great Pyramid of Khufu (Cheops)

Built by Khufu (lived early 26th century B.C.), second king of the fourth dynasty in Egypt. It is made of 2.3 million blocks of sandstone and weighs about 5.8 million tons. Herodotus said it took 100,000 men 20 years to build it. It is at Giza.

The Fresh Kills Garbage Pyramid

Being built by New York City, the pyramid should be completed in 2005. Its 79.6 million cubic feet of garbage will weigh almost 50 million tons. It is on Staten Island.

Sources: Encyclopedia Americana, New York City Department of Transportation

THE NEW YORK TIMES, THURSDAY, APRIL 13, 1989

Monument to Modern Man: S.I. Tower of Trash

"Perhaps as it gets taller, people will be more clearly reminded that this is of their own doing," said the city's Sanitation Commissioner, Brendan Sexton. "This is something that has been made possible by the contributions of all New Yorkers."

Mr. Sexton said the pyramid would not be visible from the Battery, the Statue of Liberty or ships in New York Harbor because two other hills on Staten Island intervene. But it will be visible from the higher floors of downtown office buildings and from parts of New Jersey.

Vito A. Turso, a public relations specialist for the city's Department of Sanitation, suggested that the pyramid would actually enhance life's vistas for some Staten Islanders, since it would block the unprepossessing view they now have of "the liquefied gas tanks in New Jersey."

Robert Moses's Vision

The high-rise garbage repository is a metaphor for both accomplishment and failure; accomplishment in its engineering, failure because of what it says about the city's ability to deal earlier and more vigorously with solid-waste problems that were underestimated for many years.

In 1951, when Fresh Kills was barely three years old, a team consisting of City Construction Coordinator Robert Moses and others wrote a report to Mayor Vincent R. Impelliteri advising him: "The Fresh Kills landfill project cannot fail to affect constructively a wide area around it. It is at once practical and idealistic."

Not everyone agrees that Fresh Kills has been all that good for Staten Island or that the mound now rising there bodes well for the future.

City Councilwoman Susan Molinari, Republican of Staten Island, whose grandfather, Assemblyman S. Robert Molinari, opposed the creation of the landfill in the early 1940's, said her constituents did not have to wait for the pyramid to grow taller to know what it meant to them.

'Living, Working Proof'

And certainly the Sanitation Department, which had a hand in the 1951 report to Mr. Impelliteri, has long since moved from the suggestion that Fresh Kills can be viewed as a boon.

"Fresh Kills is the living, working proof that we throw away as much as we consume," Mr. Sexton said. "Each New Yorker contributes a ton a year to that site. I talk to people about the wasteful society but nothing impresses them more than to see Fresh Kills."

The New York Times/Keith Meyers

An aerial view of the Fresh Kills Landfill on Staten Island. The veritable colossus of trash will be 505 feet high and weigh nearly 50 million tons by its completion in 2005.

THE NEW YORK TIMES, THURSDAY, APRIL 13, 1989

Mr. Sexton said the city spent $11.5 million for 500,000 saplings, shrubs and bulbs, as well as 2,000 mature trees to screen the pyramid and trash-filled approaches to it from nearby residential areas. They now adorn the margins of the landfill, and more ground cover will be put down as the pyramid grows higher.

"Let's put it in a condition we can be proud of," said Bill Young, a landscape architect and urban design specialist who is one of those working to make the mountain of garbage as nice as such a thing can be.

He recently looked about the site where the pyramid was growing, in the southwestern corner of the landfill. The seagulls nearby all faced the same direction and looked as sedate as bored waiters as they strutted amid yellow and red and white shards of plastic wrap, the flotsam and jetsam of food markets and department stores.

Fighting Odor

The gulls seemed to be everywhere, but Mr. Young knew there was other wildlife nearby, too, in the William T. Davis Wildlife Refuge — herons, marsh hawks, black ducks, quails and even some pheasants. He spoke of the current plantings and of those that would come after the pyramid was filled. "One day," he said, "our grandchildren will be able to play here."

The flowers that Mr. Young and his associates have planted are as fragrant as they are colorful, but the city knows they will not be enough to overcome the odors of Fresh Kills.

Dr. Amos Turk, a professor of chemistry emeritus at City College and the man the city turns to for advice on such things, explained that decomposing garbage forms hundreds of odor-causing compounds, among them amines, which have a fish smell; aldehydes, which produce a smell that is sickeningly sweet, and organic acids, which produce an aroma that Dr. Turk called "goat-like."

The pyramid will be 200 feet higher than the Statue of Liberty.

Clearly, the current perceptions are not positive. "The bulk of my constituent work has to do with odor, sea gulls and rats," Ms. Molinari said. "It is a scar that Staten Island will permanently bear."

By the time the pyramid is complete, in about 2005, it will have been covered with clay and soil and adorned with a wide variety of grasses and flowers to enhance its esthetics and help reduce the intrusion of water on the garbage mass. Mr. Massi said his department wants to avoid ponding — the collection of water within the pyramid — that would promote leachate, the toxic substance that usually results when water percolates through waste.

Sanitation Department officials hope that within a few years after the pyramid's completion, the pyramid might be used for recreational purposes, like other former landfills in New York and elsewhere. Examples include Marine Park in Brooklyn, Casino Park in Queens and the ski bowl in Farmingville, L.I.

Table 01

GEOLOGIC TIME CHART

(with selected major geologic events from southeastern New York and vicinity)

ERA **Periods (Epochs)**	**Years (Ma)**	**Selected Major Events**
CENOZOIC		
(Holocene)	0.1	Rising sea forms Hudson Estuary, Long Island Sound, and other bays. Barrier islands form and migrate.
(Pleistocene)	1.6	Melting of last glaciers forms large lakes. Drainage from Great Lakes overflows into Hudson Valley. Dam at The Narrows suddenly breached and flood waters erode Hudson shelf valley. Repeated continental glaciation with five? glaciers flowing from NW and NE form moraine ridges on Long Island.
(Pliocene)	6.2	Regional uplift, tilting and erosion of coastal-plain strata; sea level drops. Depression eroded that later becomes Long Island Sound.
(Miocene)	26.2	Fans spread E and SE from Appalachians and push back sea. Last widespread marine unit in coastal-plain strata.
MESOZOIC	66.5	
(Cretaceous)		
	96	Passive eastern margin of North American plate subsides and sediments (the coastal-plain strata) accumulate.
	131	(**Begin Atlantic Passive-Margin Stage II**).
(Jurassic)		Baltimore Canyon Trough forms and fills with 8,000 feet of pre-Cretaceous sediments.
		Atlantic Ocean starts to open. Newark basins deformed, arched, eroded.
	190	Continued filling of subsiding Newark basins and mafic igneous activity both extrusive and intrusive.
(Triassic)		Newark basins form and fill with non-marine sediments.

PALEOZOIC	245	
(Permian)		Pre-Newark erosion surface formed.
	260	**Appalachian orogeny.** (Terminal stage.) Folding, overthrusting, and metamorphism of Rhode Island coal basins; granites intruded.
(Carboniferous)		Faulting, folding, and metamorphism in New York City area. Southeastern New York undergoes continued uplift and erosion.
(Devonian)	365	**Acadian orogeny.** Deep burial of sedimentary strata. Faulting, folding, and metamorphism in New York City area. Peekskill Granite and Acadian granites intruded.
(Silurian)		
	440	**Taconic orogeny.** Intense deformation and metamorphism.
	450	Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line and St. Nicholas Thrusr Zone). Arc-continent collision. Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata.
(Ordovician)		Ultramafic rocks (oceanic lithosphere) sliced off and transported structurally above deposits of continental shelf. Shallow-water clastics and carbonates accumulate in west of basin. (= **Sauk Sequence**; protoliths of the Lowerre Quartzite, Inwood
(Cambrian)		Marble, Walloomsac Schist). Transitional slope/rise sequence (Manhattan Schist) and deep-water terrigenous strata (Hartland Formation) form to east. (= **Taconic Sequence**).
PROTEROZOIC		
	570	Period of uplift, rifting,and erosion followed by subsidence of margin and development of **Iapetan Passive-Margin Stage I**.
(Z)	600	Rifting with rift sediments, volcanism, and intrusive activity. (Ned Mountain, Pound Ridge, and Yonkers gneiss protoliths).
(Y)	1100	**Grenville orogeny.** Sediments and volcanics deposited, compressive deformation, intrusive activity, and granulite facies metamorphism. (Fordham Gneiss, Hudson Highlands and related rocks).
ARCHEOZOIC		
	2600	No record in New York.
	4600	Solar system (including Earth) forms.

Table 02

Generalized Descriptions of Major Geologic "Layers", SE New York State and Vicinity

This geologic table is a tangible result of the On-The-Rocks Field Trip Program conducted by Drs. John E. Sanders and Charles Merguerian between 1988 and 1998. In Stenoan and Huttonian delight, we here present the seven layer cake model that has proved so effective in simplifying the complex geology of the region. Under continual scrutiny and improvement, we provide this updated web-based information as a public service to all students and educators of geology. We encourage any comments, additions, or corrections. References cited can be sought by following this link.

LAYER VII - QUATERNARY SEDIMENTS

A blanket of irregular thickness [up to 50 m or more] overlying and more or less covering all older bedrock units. Includes four or five tills of several ages each of which was deposited by a continental glacier that flowed across the region from one of two contrasting directions: (1) from N10°E to S10°W (direction from Labrador center and down the Hudson Valley), or (2) from N20°W to S20°E (direction from Keewatin center in Hudson's Bay region of Canada and across the Hudson Valley). The inferred relationship of the five tills is as follows from youngest [I] to oldest [V]. [I] - Yellow-brown to gray till from NNE to SSW, [II] - red-brown till from NW to SE, [III] - red-brown till from NW to SE, and [IV] - yellow-brown to gray till from NNE to SSW, and [V] - red-brown till from NW to SE containing decayed stones (Sanders and Merguerian, 1991a,b, 1992, 1994a, b; Sanders, Merguerian, and Mills, 1993; Sanders and others, 1997; Merguerian and Sanders, 1996). Quaternary sediments consist chiefly of till and outwash. On Long Island, outwash (sand and gravel) and glacial lake sediment predominates and till is minor and local. By contrast, on Staten Island, tills and interstratified lake sediments predominate and sandy outwash appears only locally, near Great Kills beach.

[Pliocene episode of extensive and rapid epeirogenic uplift of New England and deep erosion of major river valleys, including the excavation of the prominent inner lowland alongside the coastal-plain cuesta; a part of the modern landscape in New Jersey, but submerged in part to form Long Island Sound].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER VI - COASTAL-PLAIN STRATA (L. Cretaceous to U. Miocene; products of Passive Continental Margin II - Atlantic).

Marine- and nonmarine sands and clays, present beneath the Quaternary sediments on Long Island (but exposed locally in NW Long Island and on SW Staten Island) and forming a wide outcrop belt in NE New Jersey. These strata underlie the submerged continental terrace. The basal unit (L. Cretaceous from Maryland southward, but U. Cretaceous in vicinity of New York City) overlaps deformed- and eroded Newark strata and older formations. Also includes thick (2000 m) L. Cretaceous sands and shales filling the offshore Baltimore Canyon Trough. At the top are Miocene marine- and coastal units that are coarser than lower strata and in many localities SW of New Jersey, overstep farther inland than older coastal-plain strata. Capping unit is a thin (<50 m) sheet of yellow gravel (U. Miocene or L. Pliocene?) that was prograded as SE-directed fans from the Appalachians pushed back the sea. Eroded Newark debris is present in L. Cretaceous sands, but in U. Cretaceous through Miocene units, Newark-age redbed debris is conspicuously absent. This relationship is considered to be proof that the coastal-plain formations previously buried the Newark basins so that no Newark-age debris was available until after the Pliocene period of great regional uplift and erosion. The presence of resistant heavy minerals derived from the Proterozoic highlands part of the Appalachians within all coastal-plain sands indicates that the coastal-plain strata did not cover the central highlands of the Appalachians.

[Mid-Jurassic to Late Jurassic episode of regional arching of Newark basin-filling strata and end of sediment accumulation in Newark basin; multiple episodes of deformation including oroclinal "bending" of entire Appalachian chain in NE Pennsylvania (Carey, 1955), and one or more episodes of intrusion of mafic igneous rocks, of folding, of normal faulting, and of strike-slip faulting (Merguerian and Sanders, 1994b). Great uplift and erosion, ending with formation of Fall-Zone planation surface].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER V - NEWARK BASIN-FILLING STRATA (Upper Triassic and Lower Jurassic)

Newark-age strata unconformably overlie folded- and metamorphosed Paleozoic strata of Layer II and some of the Proterozoic formations of Layer I; are in fault contact with other Proterozoic formations of the Highlands complex. Cobbles and boulders in basin-marginal rudites near Ramapo Fault include mostly rocks from Layers III, IIB, and IIA(W), which formerly blanketed the Proterozoic now at the surface on the much-elevated Ramapo Mountains block. The thick (possibly 8 or 9 km) strata filling the Newark basin are nonmarine.

In addition to the basin-marginal rudites, the sediments include fluvial- and varied deposits of large lakes whose levels shifted cyclically in response to climate cycles evidently related to astronomic forcing. A notable lake deposit includes the Lockatong Formation, with its analcime-rich black argillites, which attains a maximum thickness of about 450 m in the Delaware River valley area. Interbedded with the Jurassic part of the Newark strata are three extrusive complexes, each 100 to 300 m thick, whose resistant tilted edges now underlie the curvilinear ridges of the Watchung Mountains in north-central New Jersey. Boulders of vesicular basalt in basin-marginal rudites prove that locally, the lava flows extended northwestward across one or more of the basin-marginal faults and onto a block that was later elevated and eroded. The thick (ca. 300 m) Palisades intrusive sheet is concordant in its central parts, where it intrudes the Lockatong at a level about 400 m above the base of the Newark strata. To the NE and SW, however, the sheet is discordant and cuts higher strata (Merguerian and Sanders, 1995a). Contact relationships and the discovery of clastic dikes at the base of the Palisades in Fort Lee, New Jersey, suggest that the mafic magma responsible for the Palisades was originally intruded at relatively shallow depths (roughly 3 to 4 km) according to Merguerian and Sanders (1995b).

Xenoliths and screens of both Stockton Arkose and Lockatong Argillite are present near the base of the sill. Locally, marginal zones of some xenoliths were melted to form granitic rocks (examples: the trondhjemite formed from the Lockatong Argillite at the Graniteville quarry, Staten Island, described by Benimoff and Sclar, 1984; and a "re-composed" augite granite associated with pieces of Stockton Arkose at Weehawken and Jersey City, described by J. V. Lewis, 1908, p. 135-137).

[**Appalachian terminal orogeny**; large-scale overthrusts of strata over strata (as in the bedding thrusts of the "Little Mountains east of the Catskills" and in the strata underlying the NW side of the Appalachian Great Valley), of basement over strata (in the outliers NW of the Hudson Highlands, and possibly also in many parts of the Highlands themselves), and presumably also of basement over basement (localities not yet identified). High-grade metamorphism of Coal Measures and intrusion of granites in Rhode Island dated at 270 Ma. Extensive uplift and erosion, ending with the formation of the pre-Newark peneplain].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

Mostly nonmarine coarse strata, about 6 km thick, including thick coals altered to anthracite grade, now preserved only in tight synclines in the Anthracite district, near Scranton, NE Pennsylvania; inferred to have formerly extended NE far enough to have buried the Catskills and vicinity in eastern New York State (Friedman and Sanders, 1982, 1983).

[**Acadian orogeny**; great thermal activity and folding, including metamorphism on a regional scale, ductile deformation, and intrusion of granites; dated at ~360 Ma].

LAYER III - MOSTLY MARINE STRATA OF APPALACHIAN BASIN AND CATSKILLS (Carbonates and terrigenous strata of Devonian and Silurian age)

(Western Facies)	**(Eastern Facies)**
Catskill Plateau, Delaware Valley monocline, and "Little Mountains" NW of Hudson-Great Valley lowland.	SE of Hudson-Great Valley lowland in Schunnemunk-Bellvale graben.
Kaaterskill redbeds and cgls.	Schunnemunk Cgl.
Ashokan Flags (large cross strata)	Bellvale Fm., upper unit
Mount Marion Fm. (graded layers, marine)	Bellvale Fm., lower unit (graded layers, marine)
Bakoven Black Shale	Cornwall Black Shale

Onondaga Limestone	
Schoharie buff siltstone	Pine Hill Formation
Esopus Formation	Esopus Formation
Glenerie Chert	
Connelly Conglomerate	Connelly Conglomerate
Central Valley Sandstone	
Carbonates of Helderberg Group	Carbonates of Helderberg Group
Manlius Limestone	
Rondout Formation	Rondout Formation
Decker Formation	
Binnewater Sandstone	Poxono Island Formation
High Falls Shale	Longwood Red Shale
Shawangunk Formation	Green Pond Conglomerate

[**Taconic orogeny**; 480 Ma deep-seated folding, dynamothermal metamorphism and mafic- to ultramafic (alkalic) igneous intrusive activity (dated in the range of 470 to 430 Ma) across suture zone (Cameron's Line-St. Nicholas thrust zones). Underthrusting of shallow-water western carbonates of Sauk Sequence below supracrustal deep-water eastern Taconic strata and imbrication of former Sauk-Tippecanoe margin. Long-distance transport of strata over strata has been demonstrated; less certain locally is proof of basement thrust over strata and of basement shifted over basement. In Newfoundland, a full ophiolite sequence, 10 km thick, has been thrust over shelf-type sedimentary strata]. In NYC and throughout New England, dismembered ophiolite is common (Merguerian 1979; Merguerian and Moss 2005, 2007).

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER II - CAMBRO-ORDOVICIAN CONTINENTAL-MARGIN COVER (Products of Passive Continental Margin I - Iapetus). Subdivided into two sub layers, IIB and IIA. Layer IIA is further subdivided into western- and eastern facies.

LAYER IIB - TIPPECANOE SEQUENCE - Middle Ordovician flysch with basal limestone (Balmville, Jacksonburg limestones).

Not metamorphosed / Metamorphosed
Martinsburg Fm. / Walloomsac Schist
Normanskill Fm. / Annsville Phyllite

Subaerial exposure; karst features form on Sauk (Layer IIA[W]) platform.

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER IIA [W] - SAUK SEQUENCE LAYER IIA [E] - TACONIC SEQUENCE

Western shallow-water platform (L. Cambrian - M. Ordovician)	**Eastern deep-water zone** (L. Cambrian-M. Ordovician)
Copake Limestone (Stockbridge,	
Rochdale Limestone (Inwood Marble)	
Halcyon Lake Fm.	
Briarcliff Dolostone	(Ꞓ-Oh) Hartland Fm.
Pine Plains Fm.	(Ꞓ-Om) Manhattan Fm.
Stissing Dolostone	
Poughquag Quartzite	
Lowerre Quartzite	
Ned Mtn Fm.	

[**Pre-Iapetus Rifting Event**; extensional tectonics, volcanism, rift-facies sedimentation, and plutonic igneous activity precedes development of Iapetus ocean basin. Extensional interval yields protoliths of Pound Ridge Gneiss, Yonkers granitoid gneisses, and the Ned Mountain Formation (Brock, 1989, 1993). In New Jersey, metamorphosed rift facies rocks are mapped as the Chestnut Hill Formation of A. A. Drake, Jr. (1984)].

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

LAYER I - PROTEROZOIC BASEMENT ROCKS

Many individual lithologic units including Proterozoic Z and Y ortho- and paragneiss, granitoid rocks, metavolcanic- and metasedimentary rocks identified, but only a few attempts have been made to decipher the stratigraphic relationships; hence, the three-dimensional structural relationships remain obscure. Followed by a period of uplift and erosion.

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

[**Grenville orogeny**; deformation, metamorphism, and plutonism dated about 1,100 Ma. After the orogeny, an extensive period of uplift and erosion begins. Grenville-aged (Proterozoic Y) basement rocks include the Fordham Gneiss of Westchester County, the Bronx, and the subsurface of western Long Island (Queens and Brooklyn Sections, NYC Water Tunnel #3), the Hudson Highland-Reading Prong terrane, the Franklin Marble Belt and associated rocks, and the New Milford, Housatonic, Berkshire, and Green Mountain Massifs.]

~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

In New Jersey and Pennsylvania rocks older than the Franklin Marble Belt and associated rocks include the Losee Metamorphic Suite. Unconformably beneath the Losee, in Pennsylvania, Proterozoic X rocks of the Hexenkopf Complex crop out.

Table 03

Fuller's stratigraphic classification of the Pleistocene deposits of Long Island G = glacial; I = interglacial. (Fuller, 1914, p. 20.)

Early Wisconsinan G	Harbor Hill Terminal Moraine
Ronkonkama Terminal Moraine	
Sangamonian I	Vineyard Formation (marine deposits and peat); surface of erosional unconformity with relief of about 300’.
Illinoian G	Hempstead Gravel Member; Manhasset Formation "Ice-erosion" unconformity; Montauk Till Member; "Ice-erosion" unconformity; Herod Gravel Member; Jacob Sand
Yarmouthian I	Gardiners Clay
Kansan G	Jameco Gravel
Aftonian I	Unconformity surface of great erosion
Pre-Kansan G	Mannetto Gravel

Table 04

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

Age	Till No.	Ice-flow Direction	Description; remarks
Late Wisconsinan ("Woodfordian"?)	I	NNE to SSW	Gray-brown till in Westchester Co., Staten Is., Brooklyn, & Queens (but not present on rest of Long Island); Hamden Till in CT with terminal moraine lying along the S coast of CT; gray lake sediments at Croton Point Park, Westchester Co.
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.

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