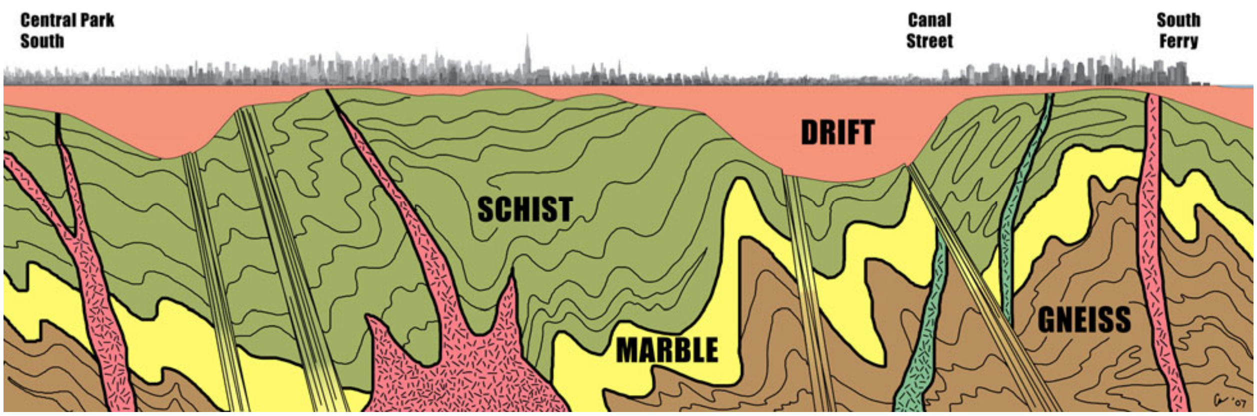
HOFSTRA UNIVERSITY 014 FIELD GUIDEBOOK

A GEOLOGICAL TRANSECT FROM NEW YORK CITY TO NEW JERSEY

21 April 2007



North to south diagrammatic section of the Manhattan skyline and underlying bedrock showing the major regional metamorphic rock types and intrusives. Note the broad U-shaped valleys carved in bedrock by glaciers flowing from NW to SE. Now backfilled with glacial drift and soil, the valleys overlie fault zones that were prone to deep erosion. Because tall buildings must be supported by shallow bedrock, the underlying geology of New York City has a fundamental control on building heights. (Drawing by C. Merguerian, Hofstra University.)

Field Trip Notes by Charles Merguerian
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Geology 014S – Field Geology of New York City and Long Island

Geology Field Trip Guidebook
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INTRODUCTION

Welcome to Hofstra's "Geology Express", an all-day geo-excursion designed to introduce you to the "real world" of how geologists work in the great out-of-doors, or in their terms, "in the field." You are going to see for yourself many of the features that you have been reading about or hearing about in Geology 1C to date plus some features that you will be learning about later in the semester. This trip will take you back in time across terranes that formed as recently as 10,000 years ago, and past those that formed over a billion years ago! All of your favorite Professors from the Geology Department are aboard the geo-excursion buses ready to discuss the geological explanations of features visible out your windows and in the field. They will also serve as your guides and will be available to field questions (yes, dear friends, pun intended!).

So sit back and relax. To get the most from your day, be sure to read this guidebook while we are riding in the bus – rest rooms and reading sickness bags have been provided! The guidebook will explain where you are and where you're going. Participate in the discussions. Ask questions. And, of course, take pictures. In order to maintain a sense of scale, geologists commonly place a ruler or a well-known object in the corner of a photogenic area. (For example, a pen, hammer, coin, B-1 bomber, etc.) Remember, you must produce a photo essay to illustrate twenty different rocks, structures, or products of geologic processes as seen at the field-trip stops. Advanced geology students may be on the trip and will help you, along with your lab and lecture professors, to identify geologically interesting photo opportunities. The guidebook you hold in your hands will help in formulating your captions and detailed instructions on the format and preparation of your **photo essay** are available from your laboratory professor or instructor.

The foremost point to keep in mind today is James Hutton's concept of the **"Great Geological Cycle"** -- how the operations of the natural processes going on around us create a geologic record and how geologists can look at the geologic record and work backward to figure out what happened. In this scheme of working backward from the geologic record into geologic history, geologists operate in a totally different way from experimental scientists, such as chemists, for example. In an experimental science, the investigator tries to control the conditions as carefully as possible in order to relate condition to the result. A geologist usually is faced with the result (the geologic record) and is asked, in effect, to figure out what experiment took place.

The geologic record consists of three components that exist in three dimensions: (1) the **bedrock**, (2) the **regolith**, and (3) the **physiography** of the Earth's surface. Geologists commonly use two-dimensional maps and diagrams to illustrate the three dimensions of study and will invoke a fourth dimension into the equation - namely time. That is, we are concerned with the developmental history of a geologic terrain over the broad expanse of time. In the following introductory paragraphs, we review each of these components and show how they are connected.

GEOLOGICAL BACKGROUND

Bedrock

To the casual observer, bedrock is known as the place that the Flintstones and Rubbles live. Bedrock, to geologists, means the continuous solid crustal rock of a continent that exists everywhere, either exposed at the Earth's surface or occurs buried by loose "dirt" or "alluvium" ("soil" to the engineers). The unconsolidated material that covers the bedrock is collectively designated as the regolith. Bedrock has to be dealt with using hammers and hand lenses. By contrast, one uses a shovel to do business with the regolith.

Bedrock is a collective designation that includes igneous, sedimentary, or metamorphic rocks. On Long Island, bedrock exposures are extremely scarce. A few examples are known near the Queens County Courthouse, and in Long Island City, at the extreme western edge of the island. In Manhattan, the Bronx, and Staten Island bedrock is exposed at the surface in scattered rocky knolls known as **outcrops**. Elsewhere, the bedrock has been buried by sandy regolith to depths of hundreds of meters. The ancient metamorphic and igneous rocks of the continents are largely covered by a veneer sedimentary rock. In areas where no natural outcrops exist, regolith covers the bedrock sequence. Because we want to show you some different kinds of bedrock and regolith, we must travel off Long Island to the Bronx and to northern New Jersey. (See figure on cover.) Let us begin by discussing some basic geological aspects of sedimentary strata.

Regolith

The **regolith** collectively designates the loose, diggable material that overlies the bedrock. The upper part of the regolith may have an organic component and be capable of supporting plant growth. If so, then this upper part is known as a **soil**.

Regolith forms from bedrock or from lava being extruded from a volcano. Some regolith forms by the weathering of bedrock (a slow process). Other regolith is the product of several fast-acting processes by which bedrock can be broken to bits quickly, so to speak. The bedrock forming steep rocky cliffs may cascade downward rapidly in a rock avalanche. A product of such an avalanche is a local body of regolith. The impact of an extraterrestrial object such as a meteorite may create regolith, known as ejecta. Beneath a glacier bedrock is ground into regolith. For those who cannot wait for geologic time to do its thing, during certain kinds of volcanic activity vast quantities of "instant" new regolith are created by explosions (which may involve new igneous rocks in their formative stages or old rocks through which the magma passes on its way to the surface). Because of its enormous surface area and glass content, volcanic regolith can be converted to soil very rapidly. Much volcanic regolith is propelled high into the atmosphere and is responsible for beautiful sunsets.

An important point to be determined about regolith is whether it is forming by weathering of the underlying bedrock (= residual regolith) or whether it is unlike the underlying bedrock and thus has been moved in from some other place (transported regolith). Two common processes by which transported regolith is brought into an area are: (1) glaciers, and (2) the wind.

Physiography of the Earth's Surface

The Earth's landscape has been fashioned by the operation of many distinctive processes that we shall be studying in the next few weeks. Examples are valleys carved by streams, beaches built by waves, intertidal salt marshes growing at the edge of the sea, dunes blown by the wind, ridges heaped up by glaciers, various features eroded by glaciers, deltas built at the mouths of rivers, and the general shapes of the hills and valleys as a result of the general process of erosion. Your instructor will explain the origin of any distinctive surface features that we encounter. Regions within which the bedrock or the regolith display distinctive landscapes are known as physiographic provinces.

In summary, the three components of the geologic record are: (1) the bedrock, (2) the regolith, and (3) the physiography or "shape" of the Earth's surface. All are connected by the operation of the rock cycle by which rocks that form beneath the Earth's surface are rearranged at the Earth's surface and then may be still further changed by being buried again to great depths. Our objectives are to be able to identify the features found in the bedrock, to determine if any regolith is residual or transported, and to understand distinctive surficial features.

This field trip guidebook is arranged to discuss the geologic scenery of driving segments (called legs) and descriptions of the three sites (called stops) that you will examine in detail. Through the aid of sketches, drawings, index maps, geologic maps and cross-sections (collectively called figures in the text), you can follow your field trip along each step of the way and gain some insight into identifying what is "important" in this world of Geology. Most of the detailed stop descriptions and tables provided herein are excerpted from field-trip guides written by Merguerian and Sanders in the interval 1988 to 1998 and from more contemporary research.

An important point to be gained from this trip is familiarity with some parts of the geologic time scale. To help you with this, we have included **Table 1**, a geological time scale that should be consulted while reading the following discussion. We will introduce a given geologic feature by referring to its age in years, but then will shift to the corresponding term from the geologic time scale. **Table 2** is a generalized description of the major geologic "layers" (described below) found in southeastern New York State and vicinity. **Table 3** provides a stratigraphic classification of the Pleistocene deposits of New York City and vicinity. Now, for you, a brief geological primer to give you some instant insights into the world of geology.

A BRIEF GEOLOGICAL PRIMER

Stratification

In dealing with the geologic structures in sedimentary rocks, the first surface one tries to identify positively is bedding or stratification. The boundaries of strata mark original sub-horizontal surfaces imparted to sediment in the earliest stage of the formation of sedimentary rock. As such, strata represent sequences of time. Imagine how such strata, buried by the weight of overlying strata are compressed and lithified to produce sedimentary rocks. If they are subject to compressive forces generated by the advance of convergent lithospheric plates, differential force necessary for rock deformation (folds and faults) can occur. Contrary to older ideas, we now realize that vertical burial cannot cause regional folds (although small-scale slumping, stratal disharmony, and clastic dikes are possible). Rather, resolved differential stress must be applied to provide the driving force to bring about deformation (folds and faults).

Surfaces of Unconformity

Surfaces of unconformity mark temporal gaps in the geologic record and commonly result from periods of uplift and erosion. Such uplift and erosion is commonly caused during the terminal phase of regional mountain-building episodes. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure 1), such surfaces represent mysterious intervals of geologic time where the local evidence contains no clues as to what went on! Usually, they mark periods of tectonism, uplift, and erosion produced during mountain building in adjacent areas. Thus, by looking elsewhere, the effects of a surface of unconformity of regional extent can be recognized and piecemeal discovery of evidence for filling in the missing interval may be found.

Unconformities occur in three basic varieties - **angular unconformities**, **nonconformities**, and **disconformities**. Angular unconformities (such as the River Jed) truncate dipping strata below the surface of unconformity and thus exhibit angular discordance at the erosion surface. Nonconformities separate sedimentary strata above the erosion surface from eroded igneous- or metamorphic rocks below. Disconformities are the most-subtle variety, separating subparallel sedimentary strata. They are commonly identified by paleontologic means, by the presence of channels cut into the underlying strata, or by clasts of the underlying strata in their basal part. The strata above a surface of unconformity may or may not include clasts of the underlying strata in the form of a coarse-grained, often bouldery basal facies.

During today’s trip we will see many different types of unconformities in the field. For example, as we drive across the Hudson River later in the day we travel across a nonconformity, with tilted sedimentary rocks of the Newark Basin resting unconformably upon metamorphic rocks of the Manhattan Prong. (See cover figure.) In this case the unconformity is tilted westward along with the overlying Newark strata.

Following the proposal made in 1963 by L. L. Sloss, surfaces of unconformity of regional extent within a craton are used as boundaries to define **Stratigraphic Sequences**. It's now time to turn to some geometric aspects of the features formed as a result of deformation of rocks in the Earth. We start with folds.

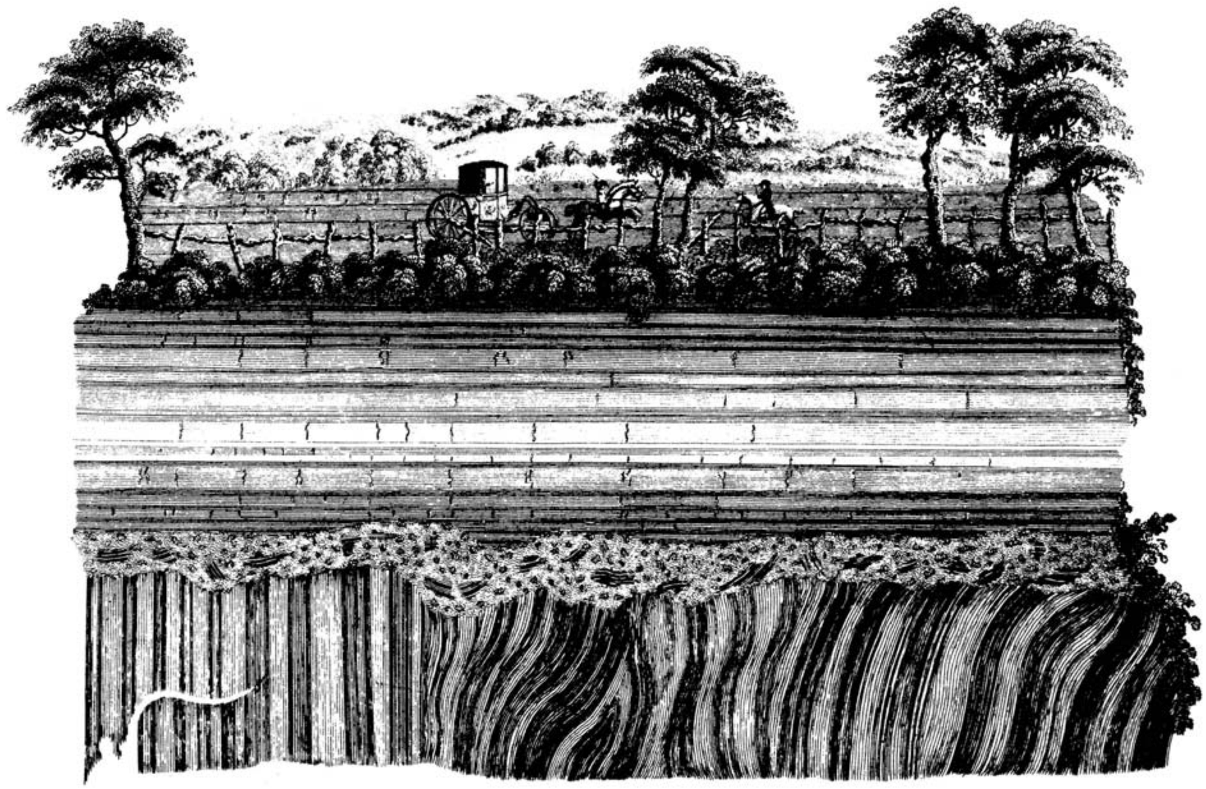

Figure 1 - Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's "Theory of the Earth", (1795).

Folds

The layers present in bedrock may be horizontal, vertical, or disposed at some intermediate angle. An important goal of many geologic field investigations is to work out the arrangement of the layers and to determine the geologic structure of a region. A widespread kind of geologic structural feature is a fold, defined as a bend in the layers. When rocks bend, they are behaving in a condition defined as ductile (as contrasted with brittle). We have not yet discussed folds in class, but we need to know some things about them. At Orchard Beach (Stop 1), for example, it is impossible to find any bedrock that has not been folded.

When subjected to differential forces, under high confining pressures and elevated temperatures, rocks (like humans) begin to behave foolishly, squirming in many directions and upsetting the original orientation of primary- or secondary planar- and linear features within them. New planar and linear fabrics develop in the rock mass. Geologists try to sort out the effects of deformation by working out the relative order in which these structural surfaces or linear features formed. In dealing with the structural geology of sedimentary rocks, the first surface to positively identify is bedding or stratification. At crustal levels below 10 km folds and faults are accompanied by recrystallization and reorientation of newly formed metamorphic minerals. More on metamorphic textures below - for now let's discuss some geometric aspects of structural geology.

If layers are folded into convex upward forms we call them **anticlines**. Convex-downward fold forms are called **synclines**. In Figure 2, note the geometric relationship of anticlines and synclines. In eroded anticlines, strata forming the limbs of the fold dip away from the central hinge area or axis of the structure. In synclines, the layers forming the limbs dip toward the hinge area. As such, older stratigraphic layers are expected to peek through in the axes of eroded anticlines but younger strata are preserved in the eroded axes of synclines. In metamorphic terranes, field geologists are not always sure of the stratigraphic topping direction of the metamorphosed strata. Thus, we tend to use the terms "antiform" and "synform" which describe the shapes of folds but do not imply anything about the relatative ages of the strata.

Axial surfaces of folds physically divide the fold in half. Note that in Figure 2, some folds are deformed about a vertical axial surface and are cylindrical about a linear fold axis that lies within the axial surface. The locus of points connected through the domain of maximum curvature of the bedding (or any other folded surface of the fold) is known as the **hinge line** (which is typically parallel to the fold axis). This is geometry folks and we have to keep it simple so that geologists can understand it.

Realize that in the upright folds shown in Figure 2, axial surfaces are vertical and fold axes, horizontal. Keep in mind that folding under metamorphic conditions commonly produces a penetrative mineral fabric with neocrystallized minerals (typically micas and amphiboles in matrix of recrystallized quartz and feldspar) aligned parallel to the axial surfaces of folds. Such metamorphic fabrics are called **foliation**, if primary, and **schistosity**, if secondary. Minerals can also align in a linear fashion producing a metamorphic **lineation**. Such features can be useful in interpreting a unique direction of tectonic transport or flow direction in ductile rock masses. Because folds in metamorphic rocks are commonly **isoclinal** (high amplitude to wavelength aspect ratio) with limbs generally parallel to axial surfaces, a penetrative foliation produced during regional dynamothermal metamorphism will generally parallel the reoriented remnants of stratification (except of course in the hinge area of folds). Thus, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they mark regional fold hinge areas.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine tilting of the axial surface, to form **inclined** or **overturned folds**, or a sub-horizontal axial surface, to form **recumbent folds**, all accomplished by keeping the fold axis sub-horizontal (Figure 2). In addition, we can keep the axial surface vertical and alter the plunge of the axis from horizontal to some angle other than 0° to produce a plunging fold. Such folds can be **plunging anticlines** (antiforms) or **plunging synclines** (synforms). **Vertical folds** (plunging 90°) also occur, in which case the terms anticline and syncline are not meaningful. Most folds in complexly deformed mountain ranges show the effects of more than one episode of deformation and as such their ultimate configuration can be quite complex (i.e., plunging folds with inclined axial surfaces and overturned limbs).

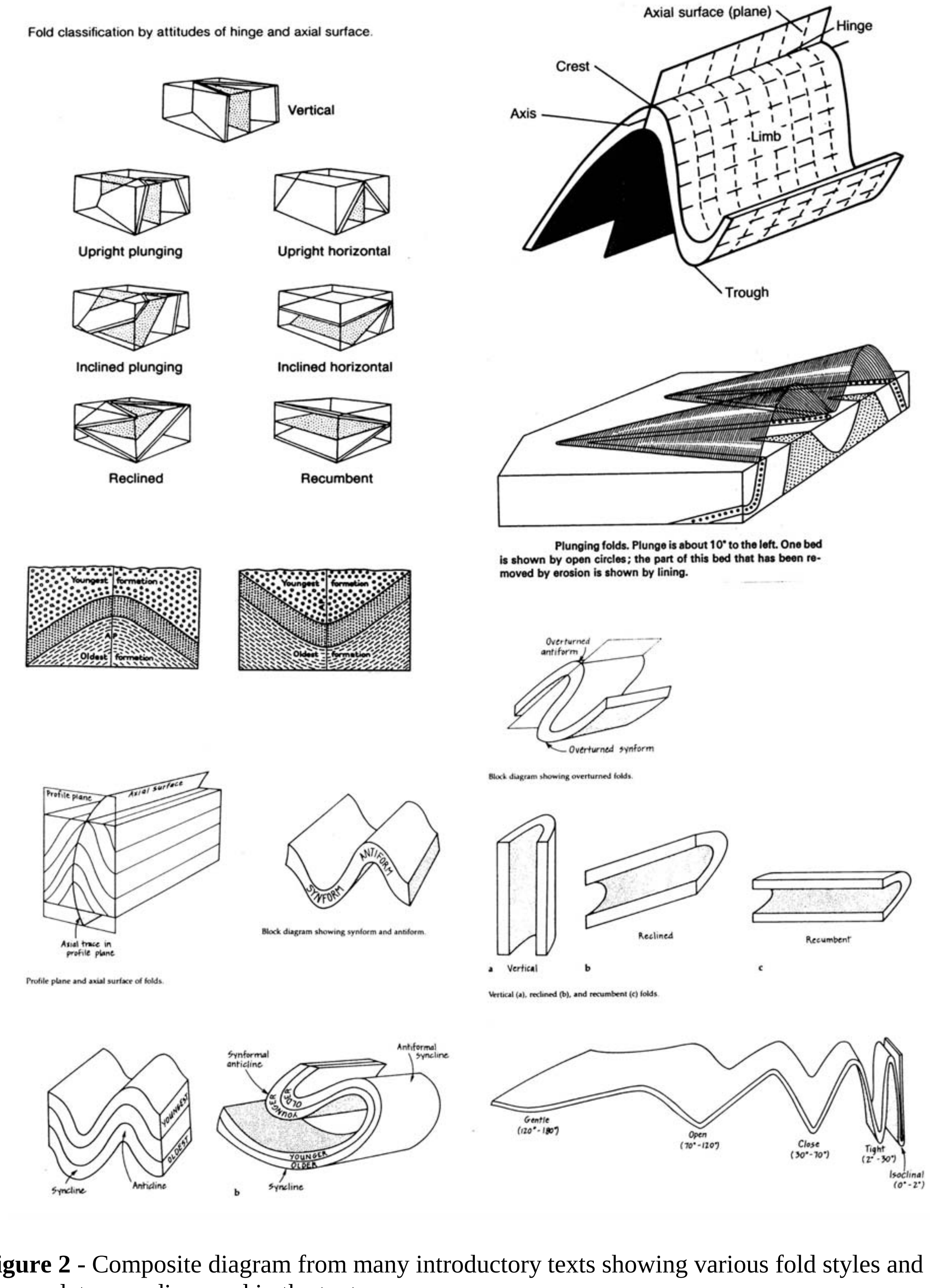

Figure 2 - Composite diagram from many introductory texts showing various fold styles and nomenclature as discussed in the text.

Depending upon the direction in which the rocks were being transported when the folds formed, one of three categories of folds may come into being. These three categories of folds are named from the letters of the English alphabet that they resemble: S, M, and Z. As soon as you spot a fold, study it to find out if it belongs to the S category, the M category, or to the Z category. Typically, fold categories run in packs and the place where the folds of the S pack change over to those of the Z pack (or vice versa) is along the median line (axial surface) of a larger fold where M-folds develop.

Structural geologists use a relative nomenclature to discuss superimposed episodes of deformation (D_n), folding (F_n), foliation (S_n), and metamorphism (M_n), where **n** is a whole number starting with **1**. Bedding is commonly designated as S_0 (or surface number zero) as it is commonly overprinted by S_1 (the first foliation). To use this relative nomenclature to describe the structural geology of an area, for example... "during the second deformation (D_2), F_2 folds formed with the development of an axial planar S_2 schistosity under progressive M_1 metamorphic conditions".

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the main stress (force) that produced the fold. Therefore, the orientation of regional fold axial surfaces gives some hint as to the direction of application of the active forces (often a regional indicator of relative lithospheric plate convergence). In complex regions, the final regional orientation of the structures is a composite result of many protracted pulses of deformation, each with its unique geometric attributes.

Faults

A fault is defined as a fracture along which the opposite sides have been displaced. The surface of displacement is known as the **fault plane** (or fault surface). The enormous forces released during earthquakes produce elongate gouges within the fault surface called **slickensides**. They may possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides (Figure 3, inset). The block situated below the fault plane is called the footwall block and the block situated above the fault plane, the hanging-wall block. Extensional force causes the hanging-wall block to slide down the fault plane producing a **normal fault**. [See Figure 3 (a).] Compressive forces drive the hanging-wall block up the fault plane to make a **reverse fault**. A reverse fault with a low angle (<30°) is called a **thrust fault**. [See Figure 3 (b).] In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane and the relationship between the tiny "risers" that are perpendicular to the striae make it possible to determine the relative sense of motion along the fault. Experimental- and field evidence indicate that the asymmetry of slickensides is not always an ironcled indicator of relative fault motion. As such, displaced geological marker beds or veins are necessary to verify relative offset. Fault motion up- or down the dip (as in normal faults, reverse faults, or thrusts faults) is named dip-slip motion.

Rather than simply extending or compressing a rock, imagine that the block of rock is sheared along its sides (i. e., that is, one attempts to rotate the block about a vertical axis but does not allow the block to rotate). This situation is referred to as a shearing couple and could generate a **strike-slip fault**. [See Figure 3 (c).] On a strike-slip-fault plane, slickensides are oriented subhorizontally and again may provide information as to which direction the blocks athwart the fault surface moved.

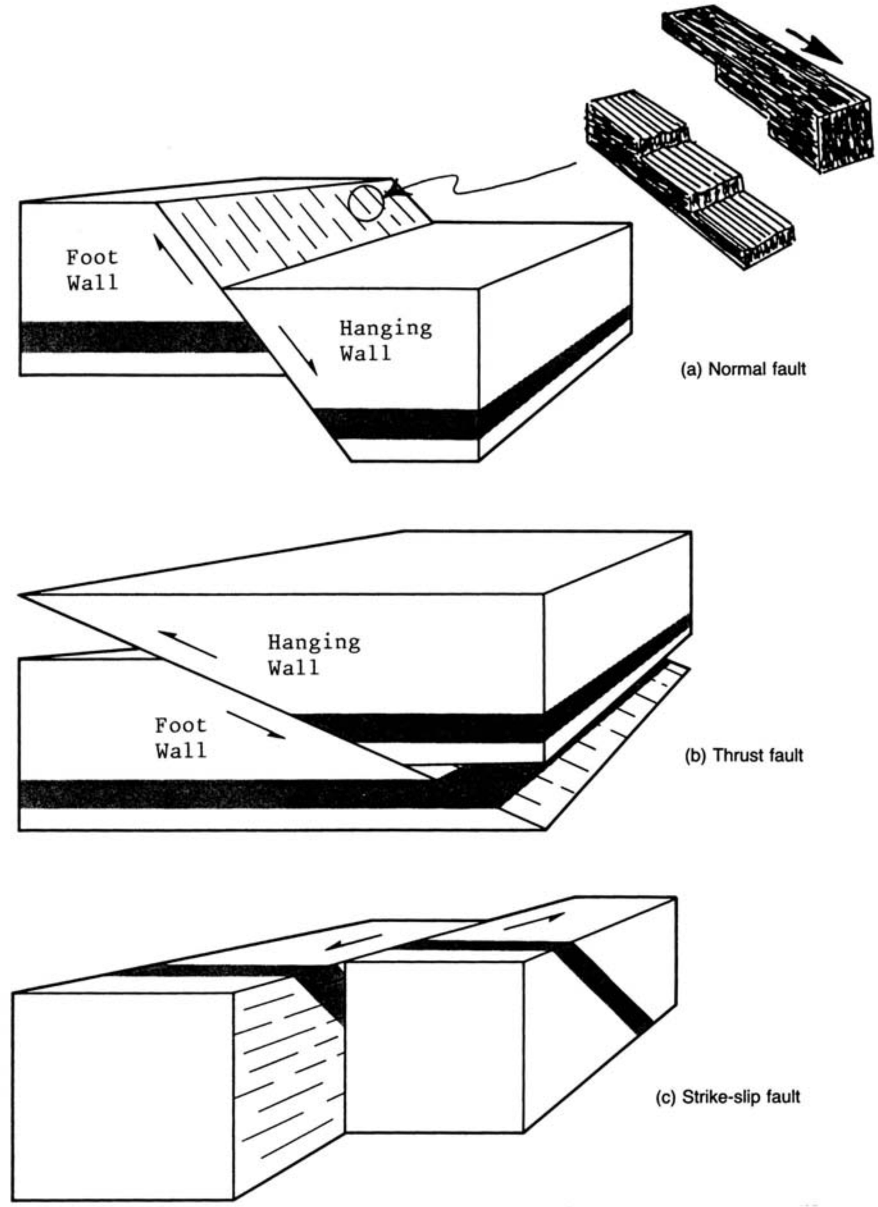

Figure 3 - The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (black) has been offset by horizontal movement (left-lateral offset shown here). Inset (d) shows segments of two blocks along a slickensided surface show how the jagged "risers" of the stairsteps (formed as pull-apart tensional fractures) can be used to infer sense of relative motion. [(a), (b), (c), Composite diagram from introductory texts. (Inset from J. E. Sanders, 1981, fig. 16.11 (b), p. 397.)

Two basic kinds of shearing couples and/or strike-slip motion are possible: **left lateral** and **right lateral**. These are defined as follows. Imagine standing on one of the fault blocks and looking across the fault plane to the other block. If the block across the fault from you appears to have moved to the left, the fault is left lateral [illustrated in Figure 3 (c)]. If the block across the fault appears to have moved to the right, the motion is right lateral. Convince yourself that no matter from which block you can choose to observe the fault, you will get the same result! Naturally, complex faults show movements that can show components of dip-slip- and strike-slip motion, rotation about axes perpendicular to the fault plane, or reactivation in a number of contrasting directions or variety. This, however, is no fault of ours.

Tensional- or compressional faulting resulting from brittle deformation, at crustal levels above 10 to 15 km, is accompanied by seismicicity and the development of highly crushed and granulated rocks called **cataclasites** (including **fault gouge**, **fault breccia**, and others). Begining at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallization and internal flow. These unique metamorphic conditions prompt the development of highly strained (ribboned) quartz, feldspar porphyroclasts (augen), and frayed micas and results in highly laminated ductile-fault rocks called **mylonites**.

The identification of such ductile fault rocks in complexly deformed terranes can be accomplished only by detailed mapping of metamorphic lithologies and establishing their geometric relationship to suspected mylonite zones. Unfortunately, continued deformation under load often causes early formed mylonites to recrystallize and thus to produce annealed mylonitic textures (Merguerian, 1988), which can easily be "missed" in the field without careful microscopic analysis. **Cameron's Line**, is an original ductile fault zone (mylonite) having a complex geologic history that includes recrystallization and post-tectonic brittle reactivation.

Joints

Although we have defined bedrock as being "continuous" and "solid," in reality it may consist of various layers and display several kinds of cracks (syn.: fractures where it has been broken) or partings, which are surfaces between layers along which blocks of the rock can separate. Along the cracks, the facing sides may or may not have been displaced. A fracture along which the adjacent blocks have not been displaced is known as a joint. The existence of joints is a signal that the rock behaved in response to deformation or, perhaps, simple unloading, as a brittle solid. A fracture along which the adjacent blocks have been displaced is known as a fault. Joints rarely exist in isolation. Typically they form a group of parallel fractures known as joint sets. Several joint sets may intersect in such a manner as to break the solid bedrock into many large blocks, each ending at a joint.

Many joint faces are simply planar surfaces that display the fresh bedrock. Other joint faces have been coated with one or more mineral linings. Pyrite is a common deposit on joint faces. The proof that pyrite lines some joint faces comes from deep borings in quarries and holes drilled for other purposes. The rocks from these borings are fresh; the samples come from depths where conditions have excluded rainwater. When it is brought close to the Earth's surface and into contact with oxygen-bearing rainwater, pyrite (a sulfide mineral) decomposes readily.

The iron from the pyrite is oxidized and the yellow-tan mineral limonite and/or its reddish cohort, hematite forms during chemical weathering. The sulfur from the pyrite is oxidized and combines with water to form sulfuric acid. Other minerals commonly found on joint faces include calcite, quartz, and chlorite (a green mineral of the mica group).

The minerals that grow along the joint faces may fill the formerly empty space. If they do this, they form a tabular mineral deposit known as a vein. In their shapes, many veins resemble dikes, which you may recall are discordant tabular plutons - bodies of igneous rock. The difference between a vein and a dike reflects the mode of growth of the crystals. In a vein, the minerals grew outward from a solid-rock face into an opening toward the center. In a dike, the magma wedged itself into the crack and the minerals forming the igneous rock crystallized from countless nucleii scattered throughout the magma.

Joints are the perfect locii for **physical and chemical weathering** to occur. During a rainstorm, rainwater seeps into the openings along joints. The seeped-in water evaporates very slowly; thus, it persists between rain showers. The water stored in the openings found along joints can be used as a solvent for chemically active fluids and by tree roots. The initial roots that grow downward along a joint may be tiny, hairlike features that can insert themselves into the most minute cracks. With time, however, the sizes of the roots enlarge. Eventually, the roots may pry loose large blocks that are bounded by joints. See if you can spot any examples of tree roots growing along joints.

GEOLOGY (SIMPLIFIED) OF THE FIELD TRIP ROUTE

We start by examining the shape of the Earth's surface in the region we plan to visit. Figure 4 is an oblique bird's eye view of the territory included on our field trip. The diagram, drawn to emphasize the contrasts in physiographic characteristics, has numbers of our intended Stops 1 through 3 shown. Because the group is so large, half of the buses will go first to Stop 1 and the other half to Stop 2. Those in the first group will proceed in the order 1, 2, and then 3. Those in the second group will proceed in the order 2, 3, and 1. We hope that you can adjust to the relative order of your field trip route by flipping to the appropriate pages in this guide. If this is confusing to you, we then suggest you take two weeks off from Hofstra – then quit.

The first driving leg of your journey will take you across a number of distinctive geologic belts (called physiographic provinces) that are roughly oriented northeasterly, parallel to the main trend of the Appalachian mountain belt. We will travel from the buried coastal plain of Long Island across the Manhattan Prong of New York City to the Newark basin of New Jersey. In doing so we will cross major unconformities and former plate boundaries. The major geologic layers on this part of the Appalachian mountain belt are listed, from oldest [Layer I] to youngest [Layer VII] in Table 2 and shown in Figure 4. For ease of discussion, we describe the major geological layers found in the area of your field trip from the top down (meaning from youngest to oldest).

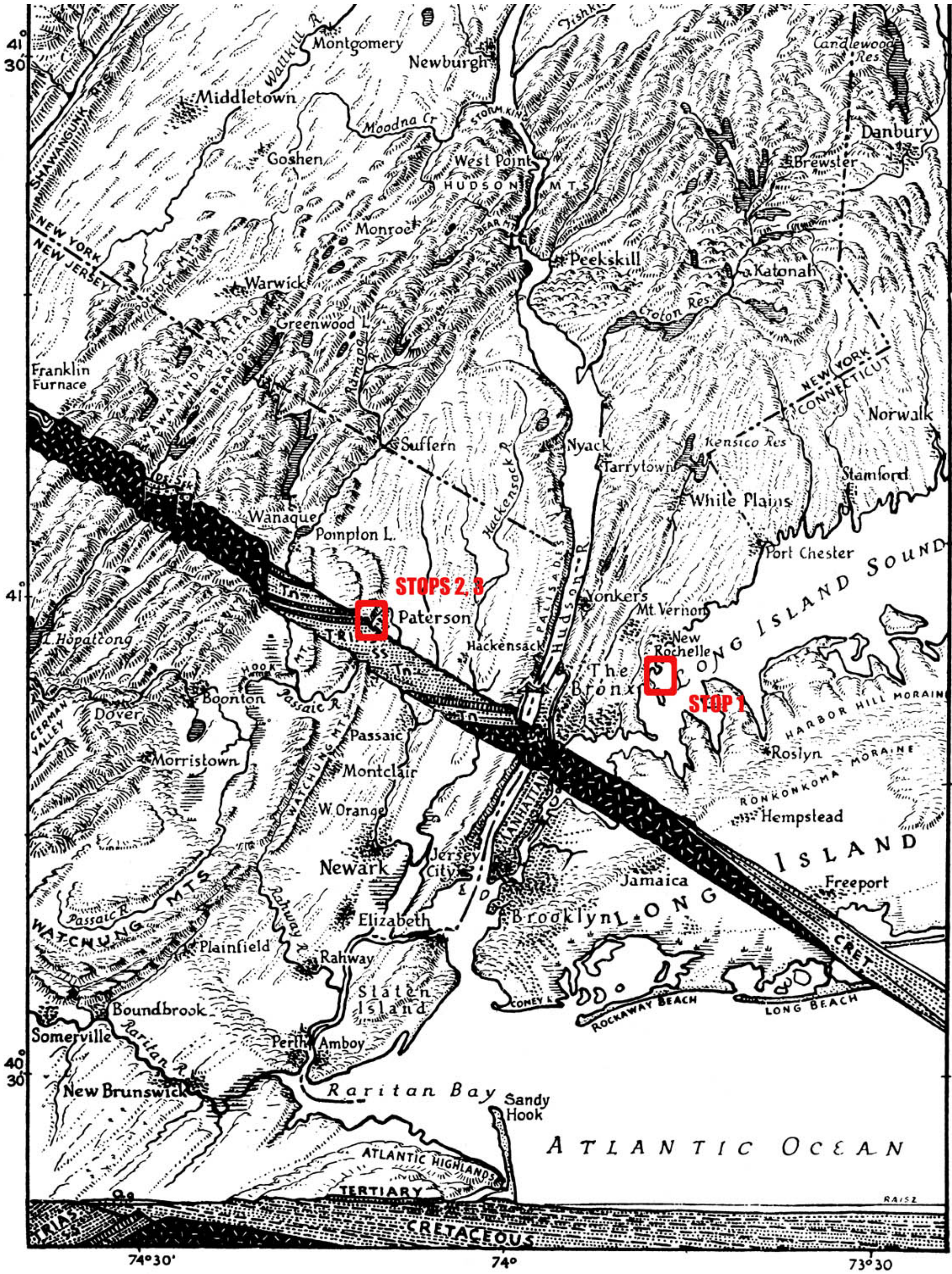

Figure 4 - Physiographic diagram of northern New Jersey and adjacent regions of New York with cut-away vertical slice to show geologic structure. Note positions of our field-trip Stops (1, 2, and 3). Drawing by A. K. Lobeck, Columbia University.

LAYER VII - THE GLACIAL STRATA OF LONG ISLAND

Long Island is capped by a thin veneer of Pleistocene sediment [Layer VII in Table 2] ranging in age from 10,000 years old to possibly much older (perhaps 200,000 years ago). The glacial sediment is collectively called **drift** but consists of **till** and **outwash**. It is not unusual to find large exotic boulders (called **erratics**) in Long Island's glacial drift from New England and Canada. In fact, because the glaciers ground southward from the north in possibly five separate advances from two contrasting directions (NNE and NW), the astute observer can find different striae and erratics from Canada and New England as well as from New Jersey and Pennsylvania on our trip. We will see a number of glacial striae and erratics at all of our stops today!

The prominent lobate, curvilinear fork-like spines of Long Island are ridges composed of material bulldozed at the snout of a glacier to form the Harbor Hill and Ronkonkoma "moraines" (Figure 5). Recent work by Sanders and Merguerian (1991a, b; 1992a; 1994a, b, c) and Sanders, Merguerian, and Mills (1993), indicate that they are largely outwash and not till as advertised and promoted by previous workers (with top-notch PR departments on Madison Avenue). According to these prevailing "experts", the Long Island "moraines" mark the southward terminus of a 10,000 year old event ("Woodfordian" glacier) when meltback of the glacial front and a sudden surge heaped up linear ridges of ground up rocks, clay, and debris (including mature sediments from the underlying Cretaceous) to produce moraine lobes. Not so fast! We have a different idea based on our moronic studies.

After over twenty-five years of combined research, Professors Sanders and Merguerian have compiled ample evidence in the form of crosscutting glacial striae, roche moutonnée structures, superposed tills of contrasting sedimentology and boulder content and by the petrologic and field identification of unique indicator stones, to help develop a more complicated, protracted, and more ancient glacial history for the region (Tables 2, 3). The glaciation of Westchester, New York City, and Long Island included a number of advancing glaciers (five, we think) which typically terminated their southward advance in the present location of Long Island Sound (Figure 6) and deposited outwash fans farther south on Long Island by melt waters above a tilted sequence of older, eroded sediment strata of the Cretaceous Coastal Plain (Layer VI in Table 2). A few advances covered Long Island to create the famous terminal moraine ridges but these are from older glaciers that flowed from the NW and were deposited on older outwash terraces as shown correctly by Fuller (1914) in Figure 5.

According to our combined analysis, the earliest glacial advance (V) flowed from the NW to SE, deposited reddish brown till and outwash in Staten Island and Garvies Point, Long Island and includes the Jameco Gravel. Glacier IV advanced from the NNE to SSW and deposited a gray till at Teller's Point in Westchester and the lower till at Target Rock, Long Island. Glacier III was from the NW and deposited deltaic sediments (Manhasset Formation of Fuller [1914]) into Glacial Lake Long Island and eventually the Ronkonkoma moraine. The Harbor Hill moraine was deposited by Glacier II, also from the NW. The final ("Woodfordian") glacier flowed from the NNE and barely touched Long Island in our view. (See Figure 6.) Instead, great volumes of water once again shed stratified drift southward to cover Long Island. We have no age dating yet but base our model on superposition and careful regional studies. Most modern workers have adopted a multi-glacier hypothesis in recent years based on this new work but the number and timing of glacial advances remains controversial. Suffice to say that the “One glacier did it all” school of geology has increased their acceptance level 100% - they now admit to two. We say, “it’s a good start and a step in the right direction”.

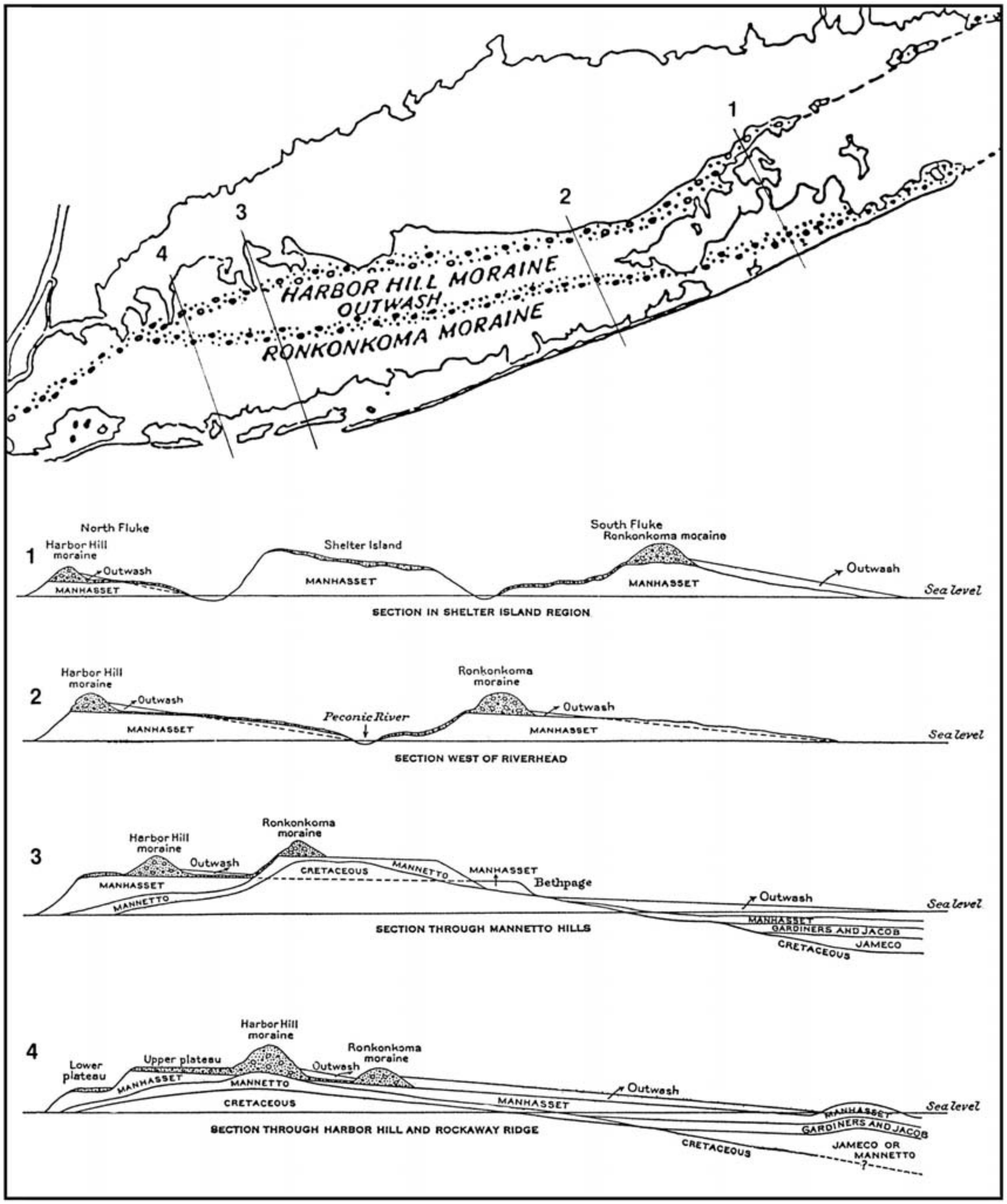

Figure 5 - Map of Long Island showing the two prominent terminal-moraine ridges and profile-sections illustrating Fuller's interpretation of the subsurface relationships. Further explanation in text. (Map from A. K. Lobeck, 1939, fig. on p. 309 with location lines of Fuller's sections added. Profile-sections from M. L. Fuller, 1914, fig. 107, p. 120, rearranged to place easternmost section at top, westernmost at bottom.)

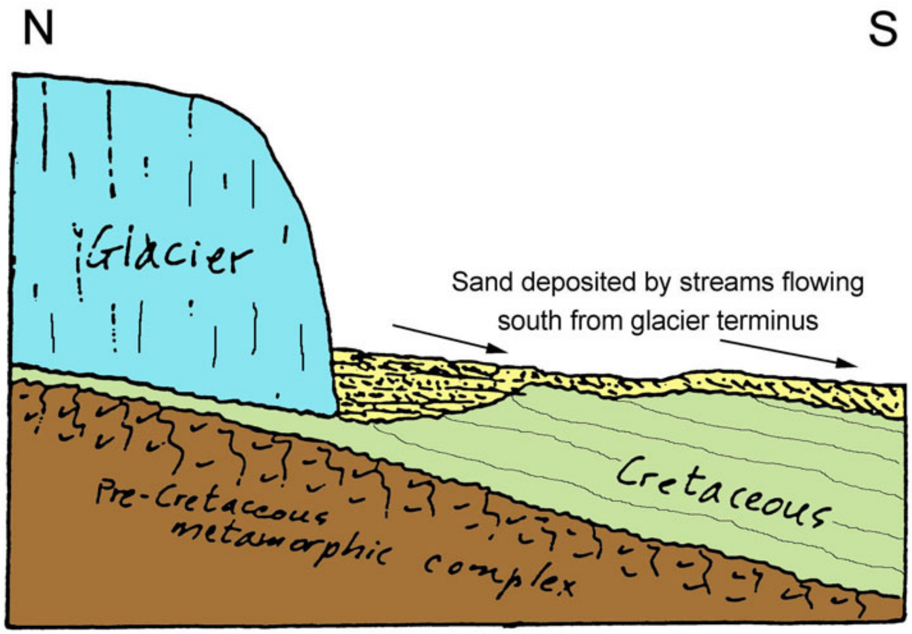

Figure 6 - Restored profile-section from Connecticut to Long Island showing terminus of continental glacier standing in what is now Long Island Sound and spreading compositionally mature outwash sand and gravel southward to bury the Upper Cretaceous strata of Long Island. Extension of Cretaceous beneath glacier is schematic, but is based on the lack of feldspar in much of the Long Island outwash. (Drawn by J. E. Sanders in 1985 using regional relationships shown in W. deLaguna, 1963, fig. 2, p. A10.)

LAYER VI - CRETACEOUS SEQUENCE OF THE ATLANTIC COASTAL PLAIN

The Cretaceous Coastal Plain strata of eastern North America are found to underlie broad areas of the continental margin (Figure 7). Except for limited exposures at Garvey's Point, Sand's Point, and elsewhere on the north shore of Long Island, Cretaceous Coastal Plain strata (Layer VI in Table 2) are generally not directly observed cropping out on Long Island.

Cretaceous strata exist in the subsurface of Long Island, Queens, and in Brooklyn as a sequence of southward tilted layers of gravel, sand, and clay. (See Figure 6.) They overlie crystalline bedrock and Newark strata based on seismic reflection data. North-south-trending stream channels are etched onto the Cretaceous strata. These stream channels were controlled by and etched into the southward tilted Cretaceous layers during and after Pliocene uplift, southward tilting of the Cretaceous strata, and subsequent erosion. (See Table 1.) In addition, the channels were undoubtedly modified by the erosive action of the earliest glacier (V in Table 2) and glacial meltwaters. Thus, after Pliocene oceanward tilting, differential uplift, and erosion, the Cretaceous sequence was beveled and unconformably overlain by several glacial sequences of Pleistocene age (Figure 7).

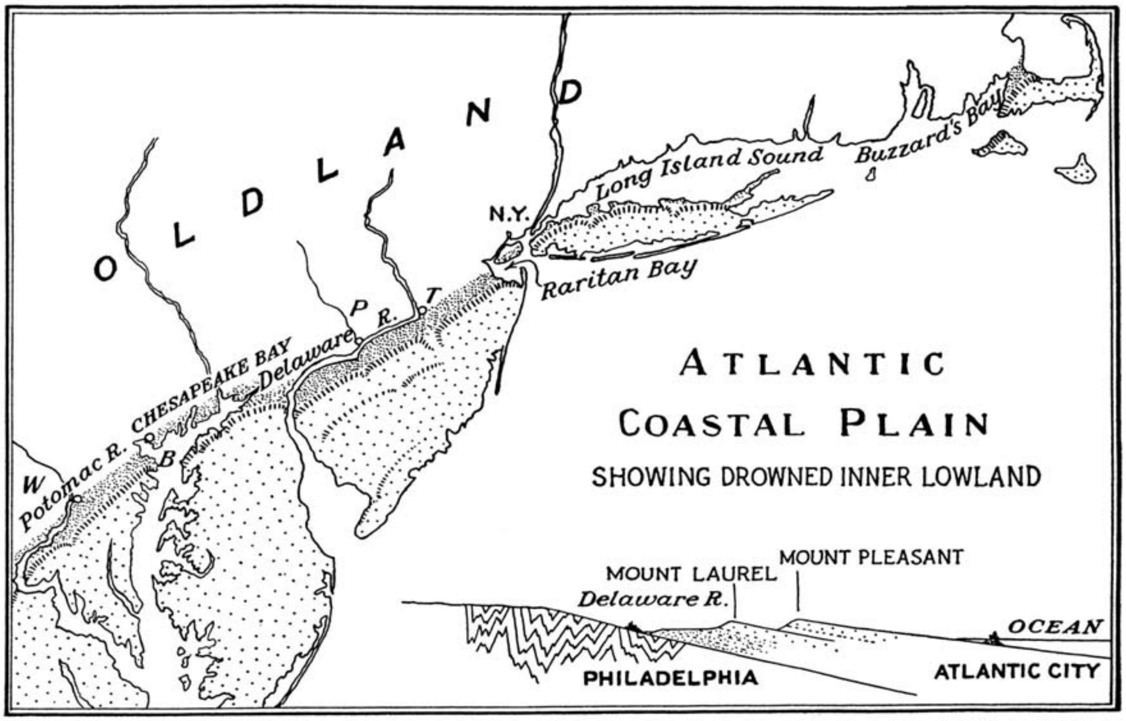

Figure 7 - Diagrammatic map of part of Atlantic Coastal Plain (open stipple) from Washington, D. C. (W at lower L) to Cape Cod, Massachusetts showing how the inner lowland (close stipple) at the preserved edge of the coastal-plain strata has been submerged northeast of New York City (N.Y.). Inset schematic profile-section (large vertical exaggeration) extends SE from Philadelphia, PA (P) to Atlantic Ocean off Atlantic City, NJ (not shown on map). (A. K. Lobeck, 1939, p. 456.)

The overlying glacial deposits form a permeable layer that blankets the Cretaceous strata, two of which (the Magothy and Lloyd formations), consist of highly porous, nonlithified sands. As such, they form an important subterranean reservoir of fresh water (called an aquifer) that is recharged with rain water and partially depleted everytime you turn on a faucet, wash your car, water your lawn, water your hamster, or fill up your swimming pool. Strata of Cretaceous age do crop out locally, as mentioned, and in regions to the south of Long Island from Staten Island to Florida and forms the Atlantic Coastal Plain physiographic province. Professor Bennington has worked on the stratigraphy and fossil distribution patterns of the Cretaceous strata in New Jersey. Autographed copies of his papers and a complete "signature" line of sneakers are available at Hip-Hop clubs across the country and at Geology Club meetings, Wednesdays, during the common hour in Gittleson 135!

LAYER V - NEWARK BASIN-FILLING STRATA

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 (Figure 8). As shown there and on the diagonal cut-away slice in Figure 4, the Newark strata generally dip about 15° to the northwest.

The west side of the Hudson River channel is marked by an impressive cliff face of highly jointed mafic rock. These spectacular cliffs mark the raw, eroded edge of the Palisades intrusive sheet, a concordant tabular sill-like igneous body, formerly intruded at depths of 3 to 4 km into formerly buried Newark strata.

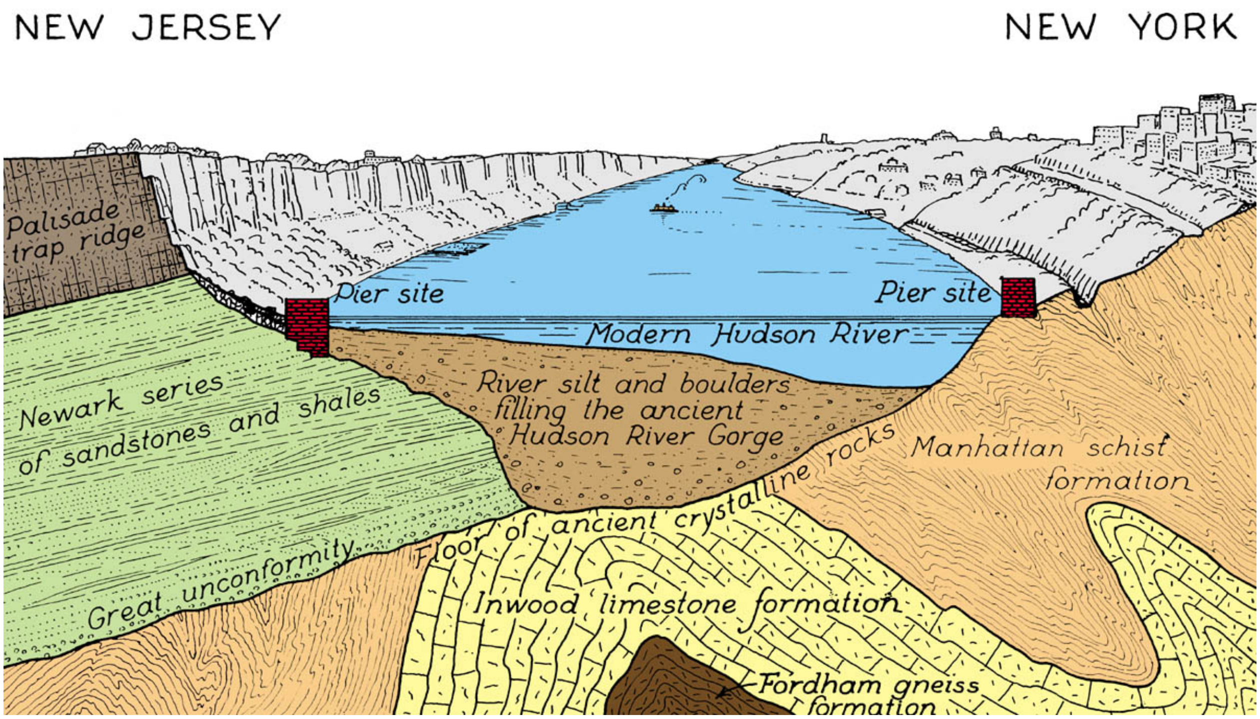

Figure 8 - Interpretive geologic section across the Hudson River in the vicinity of the George Washington Bridge showing westward tilted strata of the Newark Basin and the Palisades intrusive sheet and their nonconformable relationship to folded metamorphic rocks of New York City. (After Berkey, 1948; digitally enhanced by Geology 18 students.)

The formal stratigraphic name for the Newark strata is Newark Supergroup. Included are various sedimentary formations, of which the basal unit is the Stockton Arkose. Above it is the Lockatong Formation, the unit into which the 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 age of the sedimentary units beneath the oldest extrusive sheet is Late Triassic. The remainder of the formations are of Early Jurassic age. At Stops 2 and 3 you will examine some of the red-colored sedimentary rocks of the Newark Basin and also see basaltic volcanic rocks of the Orange Mountain Formation. (See Figure 4.)

The Newark sedimentary strata were deposited in a fault-bounded basin (Figure 9) 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 (Merguerian and Sanders, 1994b).

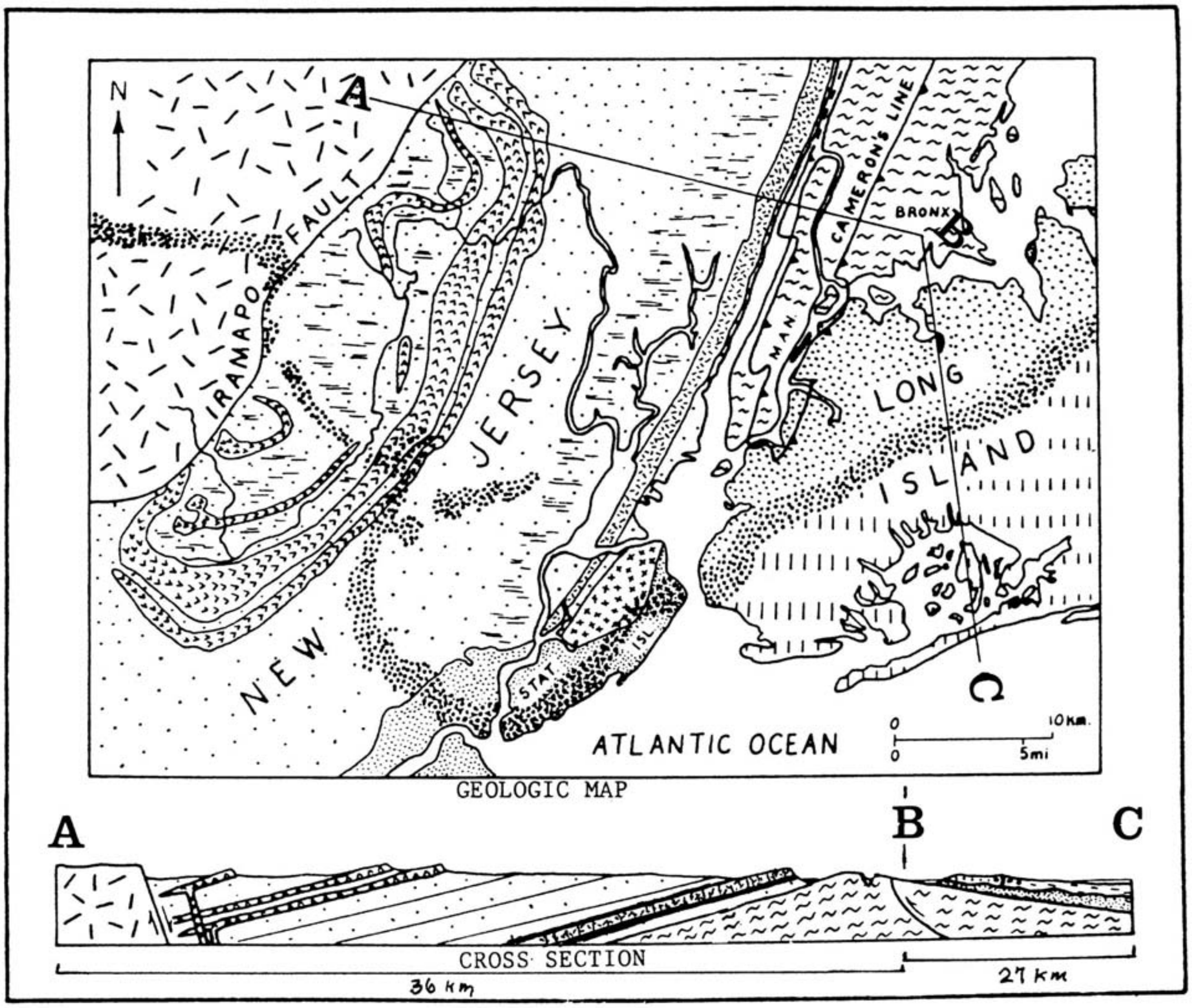

Figure 9 - Sketch map and geologic profile-section, southeastern New York and adjacent New Jersey. Note lack of correspondence in scale between profile-section and map, with resulting expansion of the length of AB and shortening of line segment BC. (From Wolff, Sichko, and Liebling, 1987.)

An important point to be established about the Palisades intrusive sheet is its date of intrusion. Its time of intrusion is thought to coincide with the time of the extrusion of one or more of the Watchung extrusive sheets; the problem is to prove that the Palisades was intruded at the same time as one of the Watchung extrusives. According to Sichko (1970 ms.), Puffer (1988), and Husch (1990), a likely correlation is between the high-Ti magma that solidified to form the Palisades sheet and the various lavas that cooled to form the multiple flows of the Orange Mountain Formation (First Watchung). The general absence of chilled zones within the

Palisades sheet implies that all pulses of magmatic activity took place before the igneous rock had cooled. Based on their interpretation of the time value of sediments deposited under the influence of climate cycles in the associated sedimentary strata, Olsen and Fedosh (1988) calculate that approximately 2.5 Ma elapsed between the time of extrusion of the Orange Mountain Formation and that of the Preakness Formation. This means that if igneous activity within the Palisades sheet took place at the same time as that of the extrusion of these two ancient lava flows, then more than 2.5 Ma were required for the sheet-like Palisades intrusive to cool.

If one can prove the synchroneity of intrusion of the Palisades intrusive sheet with one or more of the Watchung flows, then a further point is settled: depth of intrusion. The depth of intrusion then becomes the stratigraphic thickness of Newark strata between the Palisades and the First or Second Watchung basalt (roughly 3 to 4 km). Thus, the Palisades intrusive sheet may have been dropped to lower (warmer) crustal levels while it was attempting to cool. Using the average geothermal gradient of 30°C/km the increase in temperature would exceed the boiling point for water! This brings the discussion of cooling to a full boil and provides an explanation for long duration cooling history for the Palisades intrusive sheet. Studies by Merguerian and Sanders (1992a, 1994f, 1995a, b) suggest that the Palisades magma was intruded under shallow conditions (~3 to 4 km) and that the magma may have originated from the vicinity of Staten Island and flowed northeastward, rather than toward the southeast from fractures related to the Ramapo fault as most previous workers have argued. Vertical flow features, the great thickness of the Palisades in NYC, and the central location of Staten Island support this hypothesis.

LAYERS I and II - CRYSTALLINE BEDROCK OF THE MANHATTAN PRONG

Figures 4, 7, 8, and 9 show that the deepest layer in this area consists of Paleozoic and Proterozoic metamorphic and metamorphosed igneous rocks crystalline basement rocks. These older strata (Layers I and II in Table 2) are continuous with rocks exposed along the deeply-eroded spine of the Appalachian mountain belt that extends from Georgia northeastward through Maine. Some of these crystalline rocks crop out in the Bronx (Stop 1) and in Manhattan and form the stable bedrock core atop which the skyscrapers of New York City. They are subdivided into two basic sub-layers, an older sequence consisting of ~1.0 Ga (billion year old) gneisses (Layer I) and a younger sequence of complexly deformed and internally sheared schist, gneiss, amphibolite, and marble (Layer II). Included in Layer II are Late Proterozoic former rift-facies rocks found in the Bronx and Westchester known as the Ned Mountain Formation. Rocks of Layers I and II are overlain by Devonian strata of the Catskills (Layer III in Table 2). Dr. Wolff has performed important research on the Catskills. Copies of his publications can be sought at all Geology Club meetings on Wednesdays during the Common Hour in Gittleson 135.

Layer I – Crystalline Rocks of the Grenville Cycle

The rocks of the Grenville cycle (Layer I of Table 2) are the oldest recognized strata in southeastern New York. (Note the black stippled areas in Figure 4.) They include the Fordham Gneiss in New York City area and the Hudson Highlands gneisses (Figure 10). The Highlands gneisses are composed of complexly deformed layered feldspathic gneiss, schist, amphibolite, calc-silicate rocks, and massive granitoid gneiss. They constitute a complex where metamorphosed intrusive rocks form an integral part of the sequence but whose internal stratigraphic relationships are poorly understood. 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 of New England. (See Tables 1 and 2.) Taken as a whole, the ancient Grenville-cycle sequence unconformably underlies the younger Appalachian-cycle rocks (Layer II) described in the next section.

Southeast of the Hudson Highlands, the Grenville rocks are known as the Fordham Gneiss of the Manhattan Prong. Here they have been intricately folded with the Paleozoic-aged rocks of the Appalachian cycle. In the Pound Ridge area (PR in Figure 10), the Fordham Gneiss has yielded 1.1 Ga $^{207}Pb/^{206}Pb$ zircon ages (Grauert and Hall, 1973) that falls well within the range of the Grenville orogeny. Rb/Sr data of Mose (1982) suggest that metasedimentary- and metavolcanic protoliths (parent material) of the Fordham date back to 1.35 Ga.

In Westchester County, subunits in the Fordham are cut by the Pound Ridge Gneiss and correlative Yonkers Gneiss. Using Rb-Sr techniques, Mose and Hayes (1975) have dated the Pound Ridge Gneiss as Proterozoic Z in age (579+21 Ma). This gneiss body shows an intrusive or possibly a nonconformable relationship with the Grenvillian basement sequence (Dr. Patrick Brock, personal communication). The Yonkers Granitic Gneiss (Y in Figure 10) has yielded ages of 563+30 Ma (Long, 1969b) and 530+43 Ma (Mose, 1981). The Pound Ridge along with the Yonkers Gneiss, are thought to be the products of latest Proterozoic alkali-calcic plutonism (Yonkers) and/or -volcanism (Pound Ridge) in response to rifting of the ancient Gondwanan supercontinent.

The Grenville-cycle units are unconformably overlain either by the Lower Cambrian Lowerre quartzite (Hall, 1968a, b, 1976; Brock, 1989) or by a vast rift sequence (now metamorphosed) of potash feldspar-rich felsic gneiss, calc-silicate rock, volcaniclastic rock, amphibolite gneiss, and minor quartzite (Ned Mountain Formation of Brock 1989, 1993). Thus, the Grenville-cycle sequence represents the ancient continental crust of proto-North America that became a trailing edge, passive continental margin early in the Paleozoic Era.

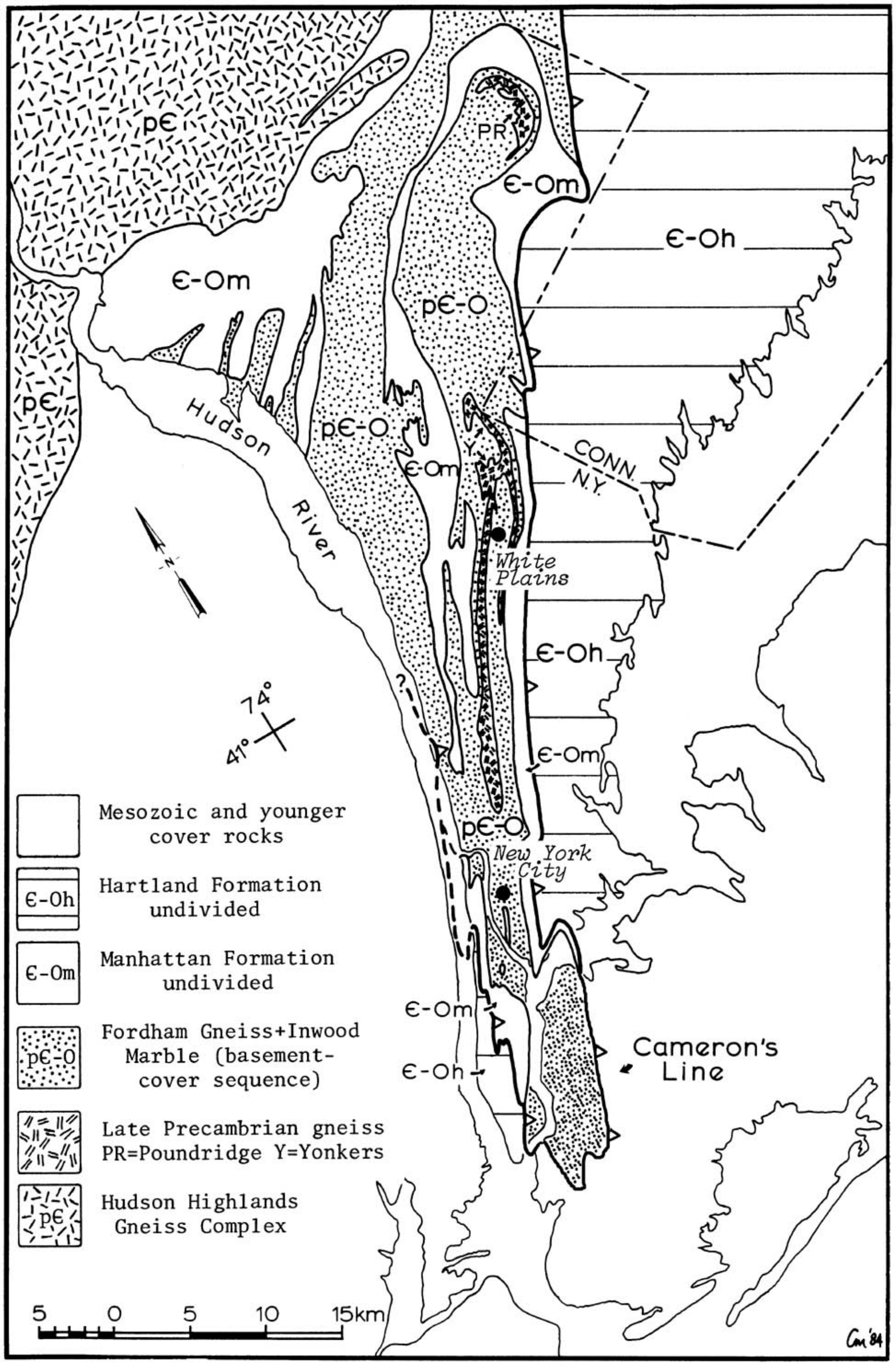

Figure 10 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks from Grenville cycle (Layer I; rocks of Proterozoic Y age) and early phases of Appalachian cycle (Layer II; rocks of late Proterozoic to Early Paleozoic age). Most faults and intrusive rocks have been omitted. (From Mose and Merguerian, 1985, fig. 1, p. 21.)

Layer II – Metasedimentary and Metavolcanic Rocks of the Appalachian Cycle

The crystalline bedrock of New York City originated as sedimentary and volcanic rocks that originally formed adjacent to the early Paleozoic shelf edge of eastern North America (Figure 11). The sedimentary apron was deposited across a passive continental margin and produced two sub-parallel belts – a shallow water sequence adjacent to the shoreline consisting of sandstone, limestone, and shale and a deeper water sequence away from the shelf edge consisting of greywacke, shale, and volcanic strata (Figure 12). During the Taconic orogeny of medial Ordovician age (See Tables 1 and 2), these disparate sequences were juxtaposed, highly folded and metamorphosed in a subduction zone that formerly operated adjacent to the east coast of North America. An arc-continent collision (Figure 13) was the first in a series of Paleozoic plate tectonic events that ultimately produced the Appalachian Mountain chain.

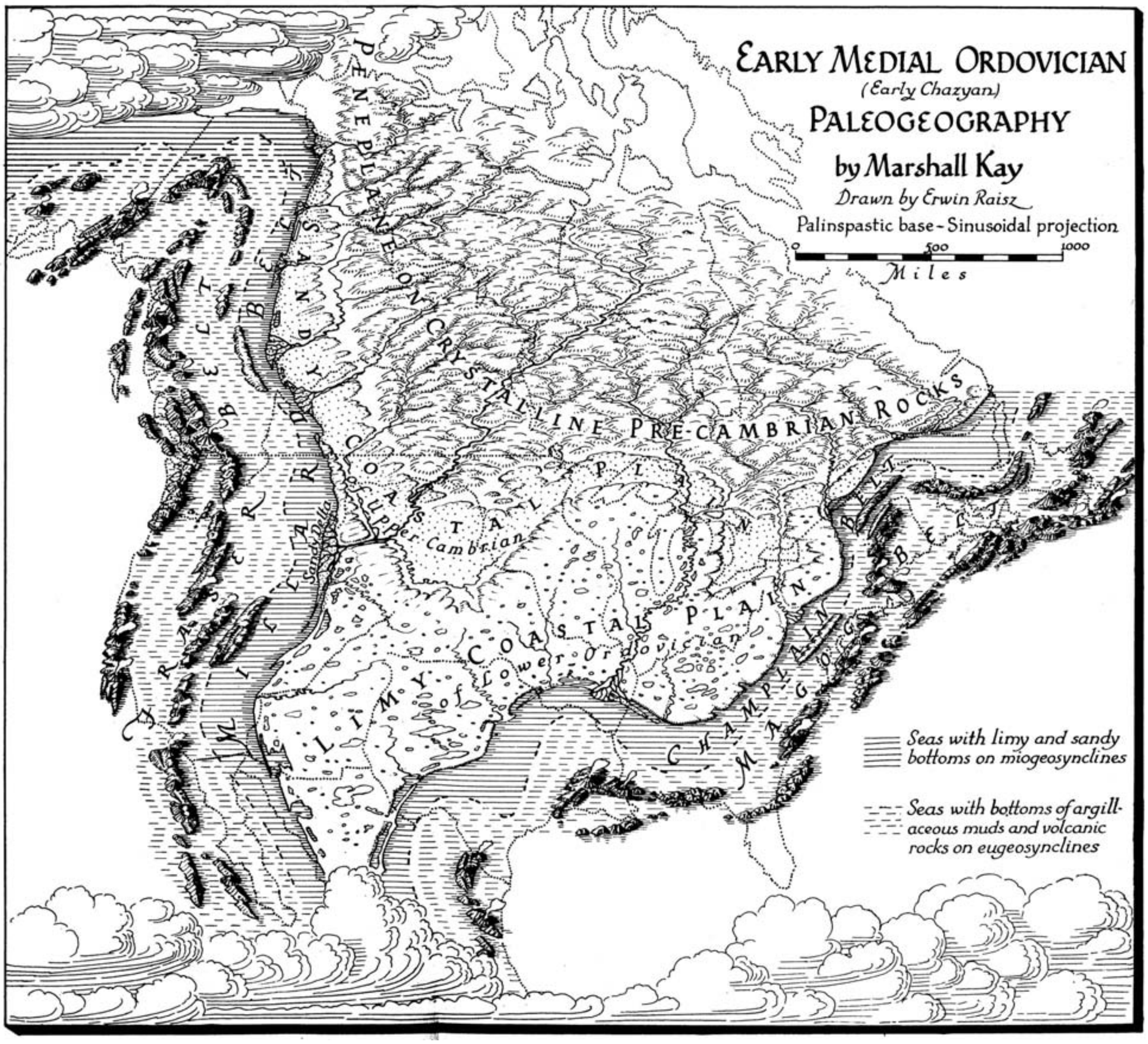

Figure 11 - Paleogeographic map of North America in Early Paleozoic time showing how the east coast on North America was awash in volcanic island arcs (Kay, 1951).

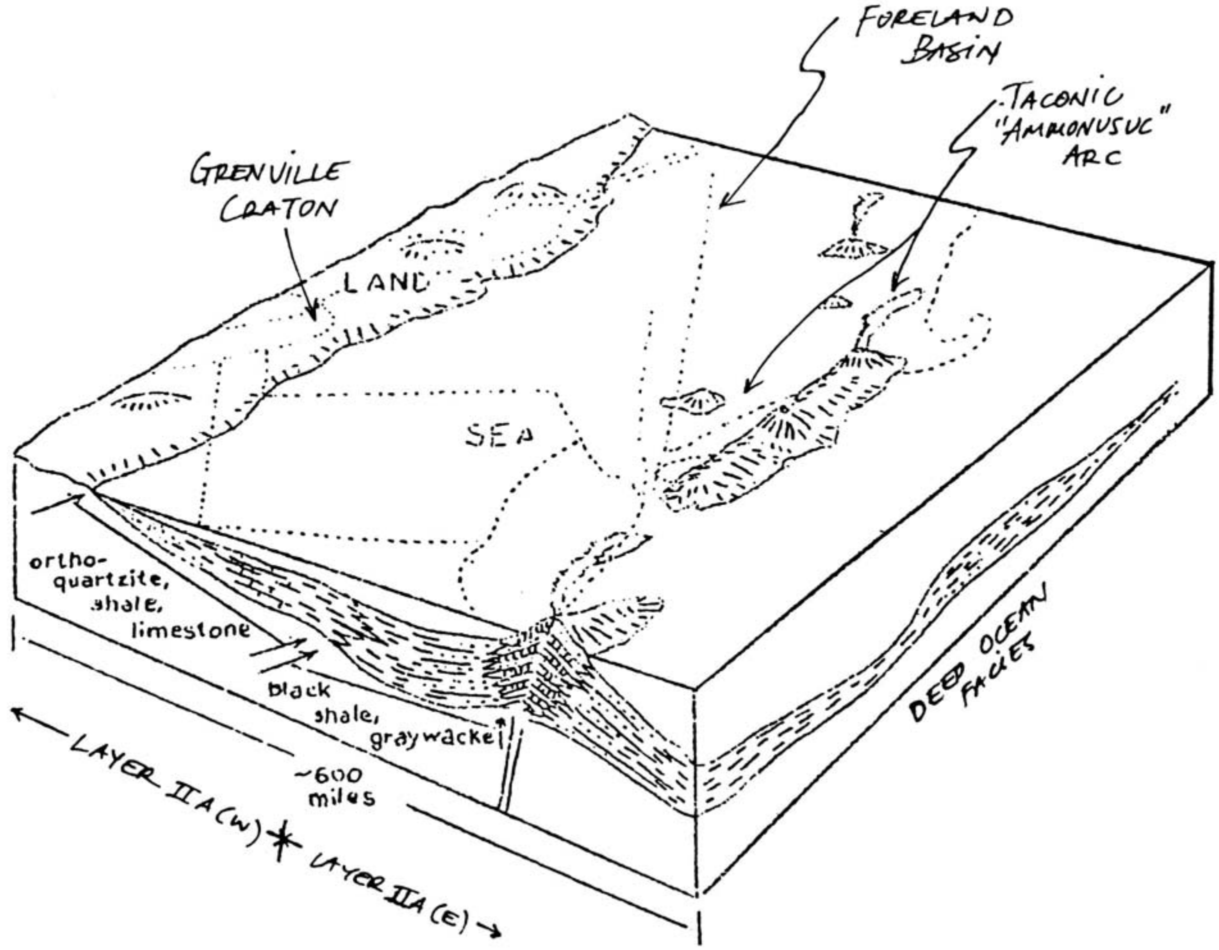

Figure 12 - Block diagram showing the Lower Paleozoic continental shelf edge of embryonic North America immediately before the deposition of Layer IIB. Current state outlines are dotted. The depositional areas for Layers IIA(W) and IIA(E), and the position of the Taconic arc and foreland basin are shown.

Thus, in western Connecticut and southeastern New York, Layer I rocks of the Grenville cycle are overlain by Cambro-Ordovician formations that are products of the early (Taconian) part of the Appalachian cycle (Layer II of Table 2). These sedimentary- and igneous rock units have been highly metamorphosed, folded, and faulted. They began their geologic lives roughly 550-450 million years ago as thick accumulations of both shallow- and deep-water sediments adjacent to the Early Paleozoic shores of proto-North America. (See Figures 10-12.) For ease of discussion, Layer II can be divided into two sub-layers, IIA and IIB.

The older of these, IIA, represents strata deposited along the ancient passive-margin of North America. The passive-margin deposits of Layer IIA can be subdivided into two varieties (facies) [IIA(W) and IIA(E)] that differ in their original geographic positions with respect to the shoreline and shelf edge. A nearshore facies [Layer IIA(W)], deposited in shallow water, is collectively designated as the **Sauk Sequence**. This sequence includes former conglomerate, feldspathic sands, and volcanic rocks of the late Proterozoic Ned Mountain Formation, basal Cambrian sandy sediment and overlying thick Cambro-Ordovician carbonate sediments, which were predominantly dolomitic in nearshore areas. The Sauk clastics and -carbonates in New York City are the Lowerre Quartzite and Inwood Marble. In western Connecticut and Massachusetts, the basal-Sauk sandy unit is the Cheshire Quartzite and the carbonate rocks, here containing more limestone than in localities closer to the ancient shoreline, are named the Woodville- and Stockbridge Marble. Thus, the Sauk strata began life as sandy- and limey sediments in an environment not significantly different from the present-day Bahama Banks. In fact, during the Appalachian cycle, New York City was situated in the tropical parts of the Southern Hemisphere (~20°S latitude); what is now east was then south and what is now west, north (Figure 14).

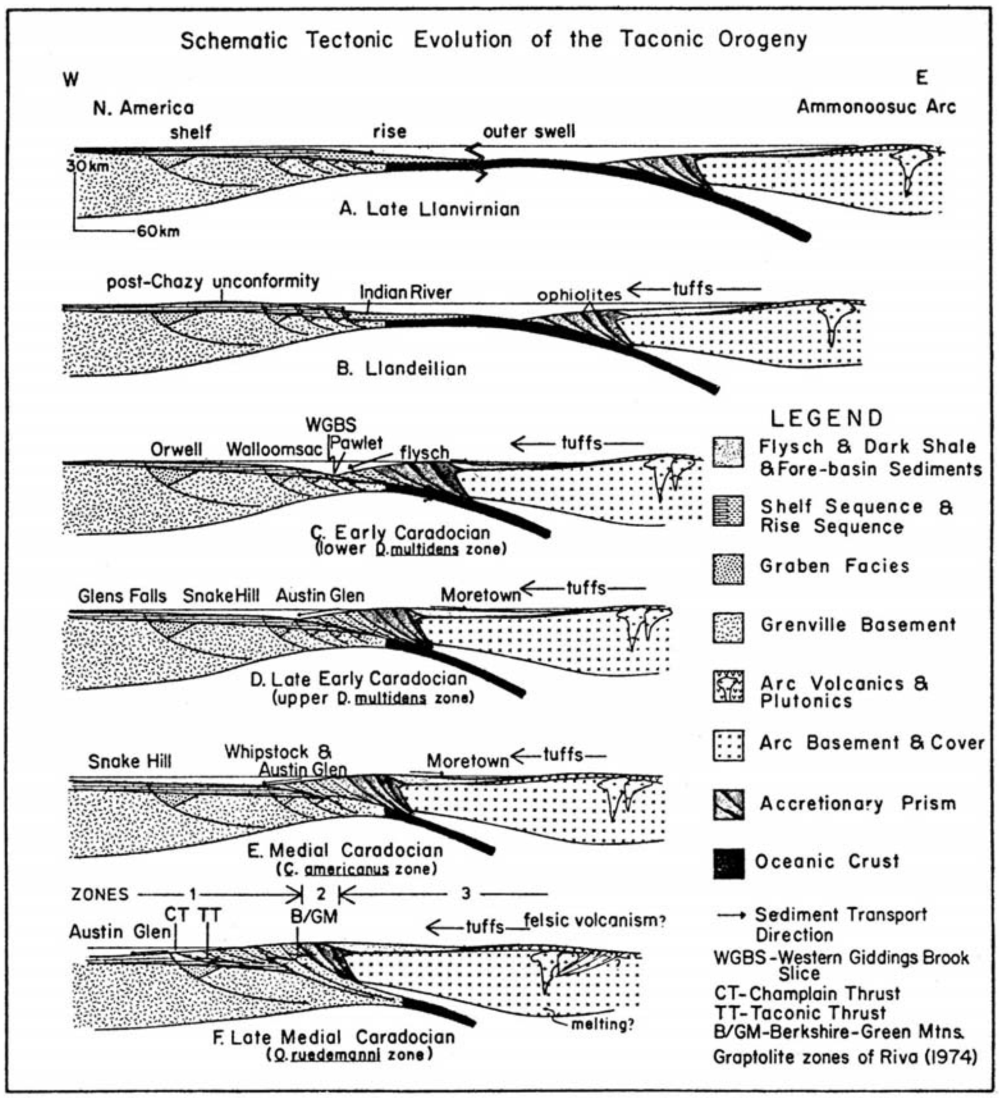

Figure 13 - Sequential tectonic cross sections for the Taconic orogeny in New England. From the top down the collision of a volcanic arc (on right) with the passive continental margin of North America (on left) produced the ancestral Appalachians. (From Rowley and Kidd, 1981.)

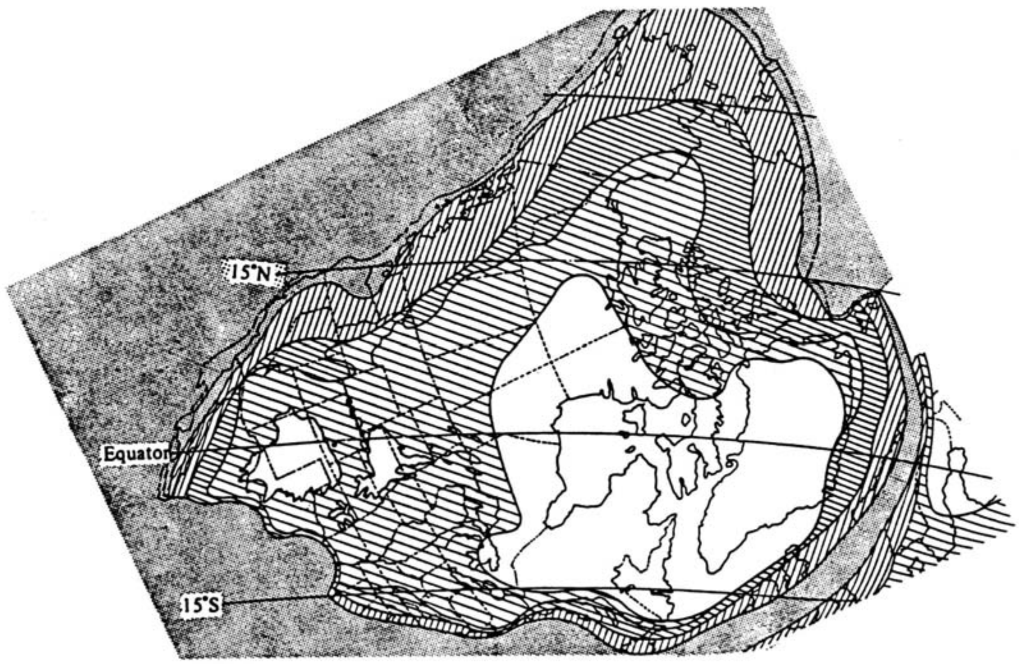

Figure 14 - Paleogeographic map showing North America in its Early Paleozoic position astride the Earth's Equator. (C. Merguerian and J. E. Sanders, 1996, fig. 2, p.118; after C. K. Seyfert and L. A. Sirkin, 1979.)

Farther offshore, fine-textured terrigenous time-stratigraphic equivalents of the shallow-water Sauk strata (shelf sequence) were deposited in deep water on oceanic crust [Layer IIA(E)]. This deep-water sequence is also of Cambrian- to Ordovician age. In upstate New York, it is known as the **Taconic Sequence**.

Layer IIB consists of younger strata designated collectively as the **Tippecanoe Sequence**. The Tippecanoe strata overlie the Sauk Sequence [Layer IIA(W)] above a surface of unconformity of regional extent. The change from passive margin to convergent margin took place while the Tippecanoe Sequence was accumulating. The basal unit of the Tippecanoe Sequence is a limestone (the "Balmville") deposited at the end of the passive-margin phase. Overlying this limestone is a thick body of dark-colored terrigenous strata, the filling of a foreland basin that formed during the earliest part of the convergent-margin regime that supplanted the passive-margin regime in mid-Ordovician time. (See Figure 13.)

Bedrock Geology of New York City

Merrill (1890) and Merrill et al. (1902) established the name Manhattan Schist for the well-exposed schistose rocks of Manhattan Island. A new picture of the geology of New York City has evolved from the combined work of many geologists over the past century. Huge capital construction projects, both on the surface and in the subsurface, have allowed geologists to examine and map large parts of the city where no natural bedrock is exposed. Since the early

1980s CM has been able to examine most of the NYC Water Tunnel #3 during various construction phases. Based on this work and surface mapping in NYC over the same time period, a much more complex stratigraphy and structure has been found in comparison to earlier maps and reports. Indeed, the bedrock of New York City consists of three ductile fault bounded sheets of rock that are intricately folded together as shown on Figures 15, 16, and 17.

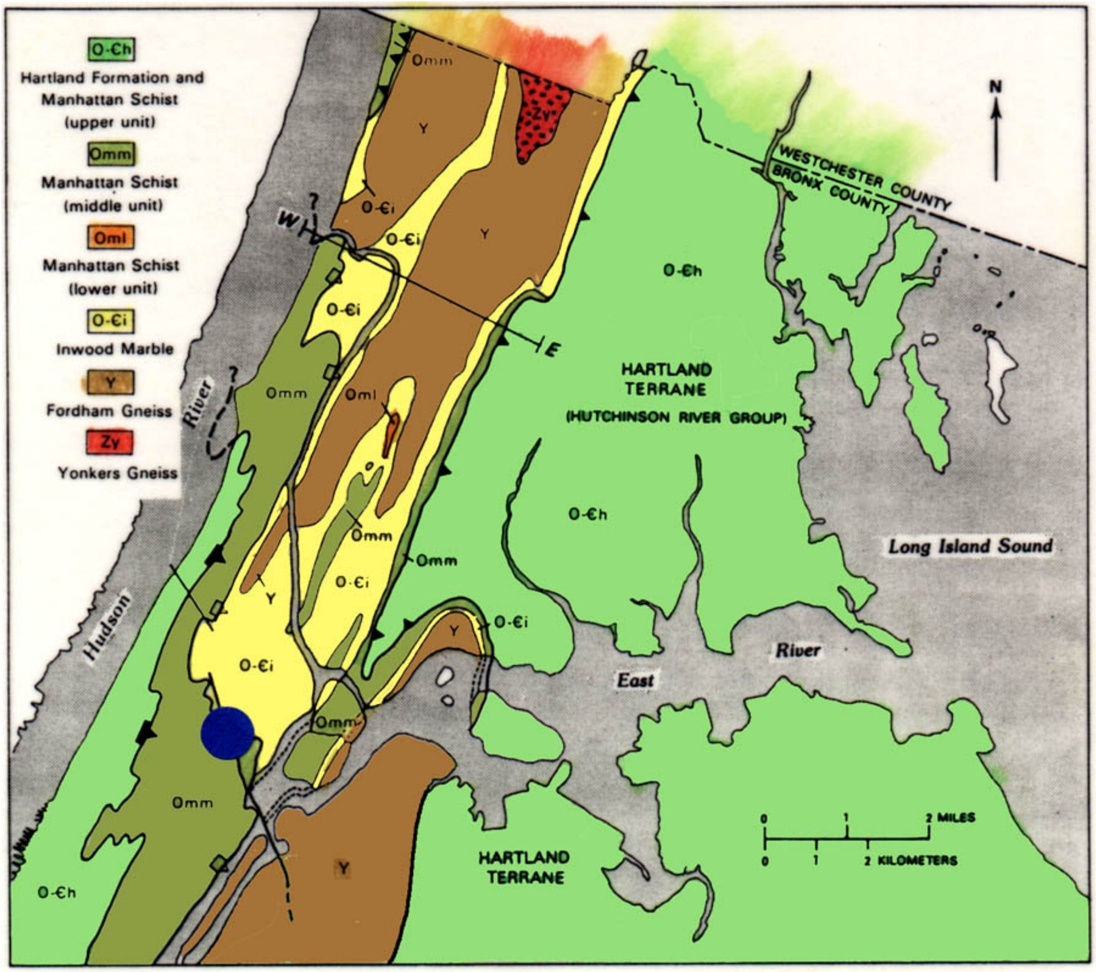

Figure 15 – Geologic map of New York City showing the generalized structural geology of the region. Blue dot shows the epicenter of the 17 January 2001 magnitude 2.4 earthquake that struck NYC. It is located along the famous 125th Street "Manhattanville" fault. (Adapted from Merguerian and Baskerville, 1987.)

The bedrock geology of New York City can best be described using the concept of sequence stratigraphy. All of the major sequences (Sauk, Taconic, Tippecanoe) are represented there (Figure 16). As such, the various metamorphic rocks found in NYC were formerly deposited across the Cambro-Ordovician shelf edge of embryonic North America. The former shelf (**Sauk Sequence**) is preserved as the Cambro-Ordovician Inwood Marble (Ꞓ-Oi) that is locally interlayered with autochthonous calcite-marble bearing Middle Ordovician Manhattan Schist (Om) of the **Tippecanoe Sequence**.

The Saint Nicholas thrust (Taconic frontal thrust) separates lower-plate Tippecanoe (Om) and Sauk (Ꞓ-Oi) rocks from upper-plate gneiss, schist, and amphibolite of the former Cambro-Ordovician slope- and rise (Manhattan Formation; Ꞓ-Om). The structurally higher ductile fault mapped as Cameron's Line, juxtaposes muscovite-rich schist and gneiss, amphibolite, serpentinite, and coticule of a former deep-water realm (Hartland Terrane; Ꞓ-Oh) with Ꞓ-Om rocks. All combined together as the Manhattan Schist Formation by past workers, the subunits Ꞓ-Om and Ꞓ-Oh are here considered to be metamorphosed and sheared facies of the **Taconic Sequence**. During Ordovician Taconian arc-continent suturing, the Saint Nicholas thrust and Cameron's Line juxtaposed former shelf-, rise-, and deep-water facies in a continentward-facing subduction complex (Merguerian 1986, 1996c; Merguerian and Sanders 1991b, 1991g, 1993d).

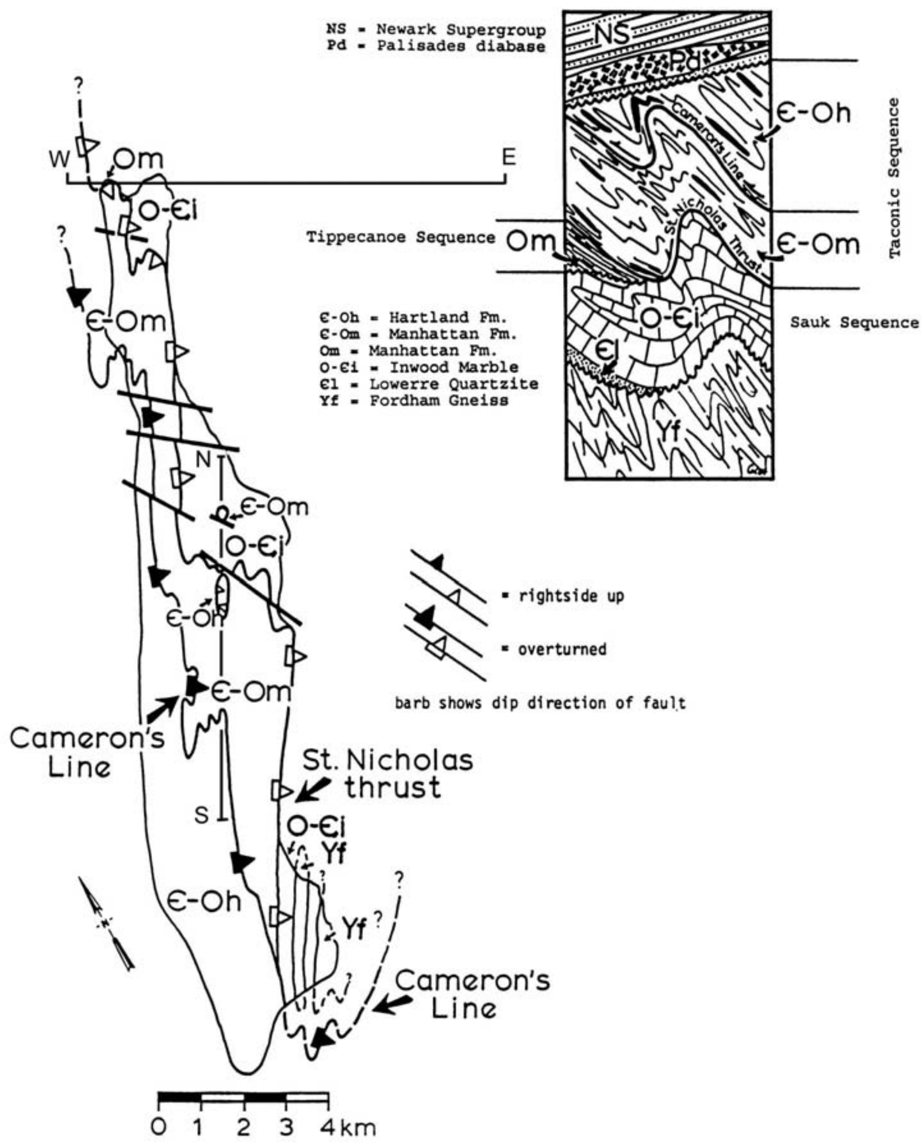

Figure 16 - Geologic map of Manhattan Island showing a new interpretation of the stratigraphy and structure of Manhattan Island. Drawn and mapped by C. Merguerian (unpublished data).

Two cross-sections (Figure 17) show a simplified view of the geologic structure of Manhattan Island. The larger section cuts across northern Manhattan from the Hudson River to the Bronx. The W-E section shows the general structure of New York City and how the St. Nicholas thrust and Cameron's Line place the middle unit of the Manhattan Schist, and the Hartland Formation respectively, above the Fordham-Inwood-lower schist unit basement-cover sequence. The major F_3 folds produce digitations of the structural- and lithostratigraphic contacts that dip gently south, downward out of the page toward the viewer. The N-S section, along Fifth Avenue in Manhattan, illustrates the southward topping of lithostratigraphic units and the effects of the late NW-trending upright folds.

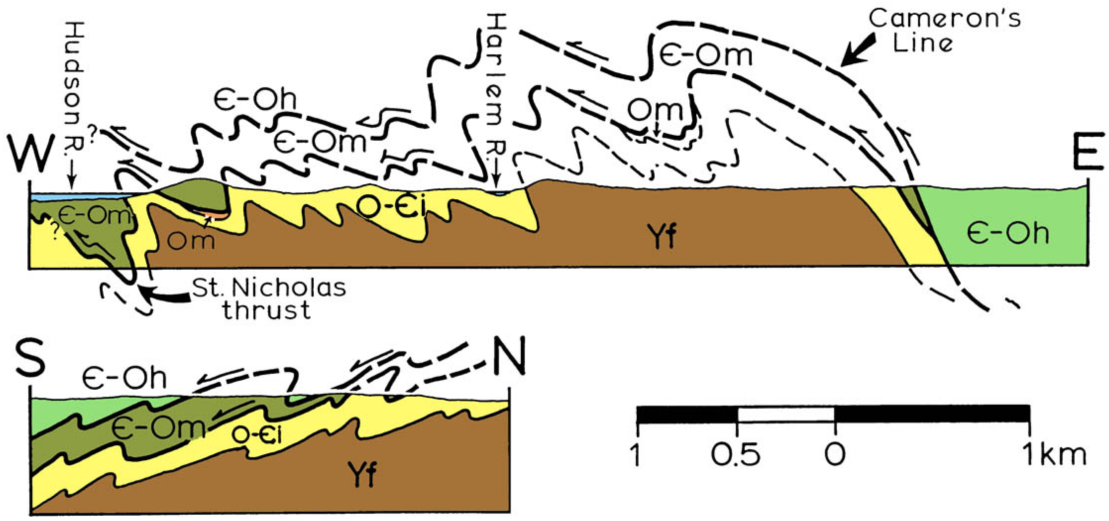

Figure 17 - Geologic cross-sections, keyed to Figures 15 and 16, showing an interpretive west-east and north-south structure sections across northern Manhattan and the Bronx. Drawn by C. Merguerian.

Metamorphic index minerals such as garnet, sillimanite, and kyanite are found throughout the metamorphic rocks of New York City and the Bronx indicating deep conditions (~30 km or more) during their metamorphism. Dr. Ratcliffe has performed important research on the mineral kyanite. Copies of his publications are available in all public areas on campus or can be sought at all Geology Club meetings on Wednesdays during the Common Hour in Gittleson 135.

Enough Geological Background for one day. Lots of additional information is available by visiting the Geology Department webpage, visiting our links, and by downloading our publications. On to our Road Log and description of individual field trip localities (stops).

ROAD LOG AND DESCRIPTIONS OF STOPS

Leg 1 - Hofstra Campus west across Long Island, and the Bronx, to Pelham Bay Park

Heading westward from Hofstra on the Long Island Expressway, the extraordinary lack of topographic relief is because of the thin layers of glacial deposits (called outwash) that were shed southward during post-glacial retreat. These sandy deposits were deposited southward from Connecticut, lapping onto the glacial moraines and thus together form the surface units of Long Island. Keep an eye out for our first turnoff from the LIE. Note how the relief has changed from veritable flatlands to a hilly terrain. We are now encountering areas of Queens underlain by the glacial ridges of Long Island and cut by tongues of advancing glacial ice and meltwater channels. Farther to the west on the LIE near Kissena Boulevard (not passed on this trip), Queens College is perched on the intersection point of the two terminal moraines described earlier. Heading northward on the Whitestone Expressway toward the Throgs Neck Bridge we pass across glacial outwash deposits which terminate along the northern border of Queens on the rubbly north shore of Long Island.

Passing over the Throgs Neck Bridge we pass through a time portal separating us from the Pleistocene strata and older, underlying Cretaceous deposits of the Coastal Plain onto Proterozoic and Paleozoic crystalline rocks exposed in the Bronx. A diagrammatic sketch illustrating the structure of these rocks is shown in Figure 18. Note how the Mesozoic sedimentary rocks dip toward the south above an erosional surface developed on the crystalline rocks. This depositional contact is known as a nonconformity, the first of three major ones we will cross today, as it separates rocks of vastly different age and lithology.

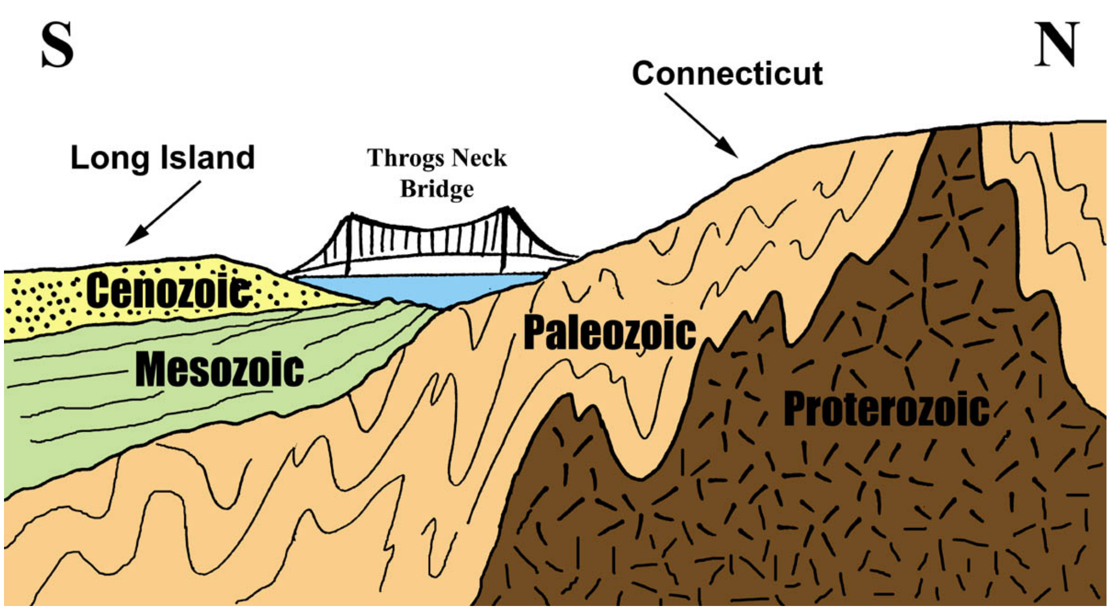

Figure 18 – Diagrammatic north-south sketch of the nonconformity beneath the Throgs Neck Bridge and the disconformity of Long Island found along our first driving leg. (Drawing by C. Merguerian.)

Driving northward from the Throgs Neck Bridge on Route 95 we do not see much exposed bedrock due to a deep weathering profile. The rocks we are driving on through (Layer IIA(E) in Table 2) are a sequence of highly deformed and metamorphosed rocks mapped as the Hutchinson River Group (Baskerville, 1982). Continuous and correlative with rocks of the Hartland Formation (See Figures 15 and 16), the Hutchinson River Group is interpreted as a former oceanic sequence deposited adjacent to the early Paleozoic shelf edge of eastern North America.

Together, the crystalline metamorphic rocks of Manhattan and the Bronx comprise another physiographic province known as the Manhattan Prong. As shown in the cover figure and in Figure 4, the Manhattan Prong consists of a northeast-trending, deeply-eroded sequence of metamorphosed Proterozoic to Lower Paleozoic rocks, including quartzite, marble, and schist, that plunge southward beneath unconformable Cretaceous sedimentary rocks and overlying Recent (glacial) sediments in New York City.

By contrast to coeval (age equivalent) metamorphic rocks cropping out in New York City (Layer IIA(W) in Table 2), the Hutchinson River Group contains abundant amphibolite (metabasalt) and feldspathic gneiss and does not contain appreciable quartzite (metamorphosed sandstone) or marble (metamorphosed limestone) that is so typical of the shallow water depositional environment. As such, compared to the dominantly miogeosynclinal (shallow water shelf deposits) character of the Manhattan Prong west of Cameron's Line, the Hutchinson River Group is decidedly eugeosynclinal (deep-water oceanic parentage). Thus, on either side of Cameron's Line, an important structural boundary in the New England Appalachians, we have disparate sequence of juxtaposed metamorphic rocks of roughly equivalent age.

In summary, the rocks exposed along I-95 form a sequence of highly metamorphosed metasedimentary and metavolcanic rocks of Early Paleozoic age [Layer IIA(E)] which trend northeasterly through Orchard Beach (STOP 1) and City Island into western Connecticut where they are mapped as the Hartland Formation (Є-Oh in Figures 10 and 15). Together with their northward extensions into Massachusetts, Vermont, and New Hampshire this largely metavolcanic rock sequence marks a former oceanic terrane that collided with North America during the medial Ordovician Taconic orogeny or mountain building event (Figure 13). Imagine the Japanese volcanic islands colliding with China and you may picture a modern analog of the Taconic orogeny. A diagram illustrating the pre-Taconic paleogeography of the Early Paleozoic shelf edge of eastern North America is shown in Figure 11. The depositional sites for Layers IIA(W) and IIA(E) are shown.

STOP 1 - Hutchinson River Group - North and South Twin Islands, near Orchard Beach, Pelham Bay Park, Bronx. (UTM Coordinates: 602.4E/4525.0N, Flushing quadrangle.)

Rocks of the Hutchinson River Group occur in highly glaciated exposures (look for glacial striae, till, and erratics) on South and North Twin Islands to the north of Orchard Beach in the Bronx. Described by Leveson and Seyfert (1969), and Seyfert and Leveson (1968, 1969), these high- to medium- grade metamorphic rocks include gneiss, schist, and amphibolite all showing ample evidence for partial melting (fusion) into mixed igneous and metamorphic rocks known as **migmatites**. In addition, many **pegmatites** and veins of quartz occur. A geologic map of the region is reproduced in Figure 19. Try to identify some of the major folds on the ground.

The glacial features of South Twin Island are remarkable and take the form of glacial striae oriented N32°W, glacial polish, and roche moutonnée structure. In addition to these features, a thin red-brown till, consisting of rounded boulders set in a reddish-brown matrix of poorly sorted sand, silt, and clay, has been unearthed (dug out) at the northern part of South Twin Island. Beneath the till the NW-trending glacial grooves are quite obvious on the glaciated bedrock surface (Figure 20). Glacial rounding has produced what Sanders and Merguerian (1994b) describe as a roche moutonnée structure on the bedrock at the extreme north end of South Twin Island. Here, the bedrock shows evidence of being sculpted from both the NW- and NNE- directions. Two important indicator stones (large boulders of ultramafic rock) occur on the striated bedrock surface. They are derived from an exposure of identical plutonic rocks from the Cortlandt Complex found to the NNW in the vicinity of Peekskill, New York. As such, they are the products of a glacial advance from the NW (Glacier II or III in Table 3). The NW to SE trending striae are also the products of our Glaciers II and/or III (Table 3). An older glacier (Glacier IV in Table 3) is responsible for NNE initial sculpting of the roche moutonnée structure at the north end of South Twin Island. Here, we find no evidence for our youngest glacier (I).

Seyfert and Leveson (1968) have subdivided the metamorphosed bedrock into two major units for the purposes of mapping. The "Felsic Unit" includes 95% feldspathic gneiss and 5% sillimanite schist and underlies roughly 50% of North Twin Island and most of South Twin Island. Contacts between the felsic gneiss and schist are gradational over distances of several mm to 10s of cm. The gneisses consist of quartz, plagioclase (An_{33}), and biotite with minor garnet, muscovite, microcline, sillimanite, magnetite, and apatite. The schist unit, although of volumetrically minor importance, consist of plagioclase, quartz, biotite, sillimanite, microcline, and garnet with subordinate magnetite and muscovite. The calculated chemical composition of the felsic unit suggests that their protoliths were interlayered graywackes and shales although CM would not discount the possibility that they are largely of volcaniclastic origin.

The "Mafic Unit" includes amphibolite, diopside-epidote amphibolite, and plagioclase-biotite gneiss together with subordinate calcite- and plagioclase- rich layers. The amphibolites consist of medium-grained hornblende and plagioclase (An_{37}) together with minor biotite, quartz, magnetite, and apatite. Garnet occurs locally as porphyroblasts in layers parallel to the hornblende-plagioclase foliation. On South Twin Island, the "Mafic Unit" occurs as amphibolite, however, the lithologies on North Twin Island include diopside-epidote amphibolite, plagioclase-biotite gneiss and calcite- and plagioclase- rich layers. Contacts between the felsic and mafic units are interpreted as original stratification (bedding) that has been strongly modified by folds and faults. The calculated chemical composition of the mafic unit suggests that they are similar to olivine basalt and thus, they are interpreted as mafic lava flows, sills, and/or tuffs prior to metamorphism with the bounding units.

Professor Merguerian has mapped much of New York City over the past three decades. Copies of his publications (suitable for wrapping fish and for soaking up oil spills) are available in boutiques at the Roosevelt Field Mall, on the Hofstra Geology webpage, and at all Geology Club meetings, Wednesdays, during the common hour in 135 Gittleson Hall.

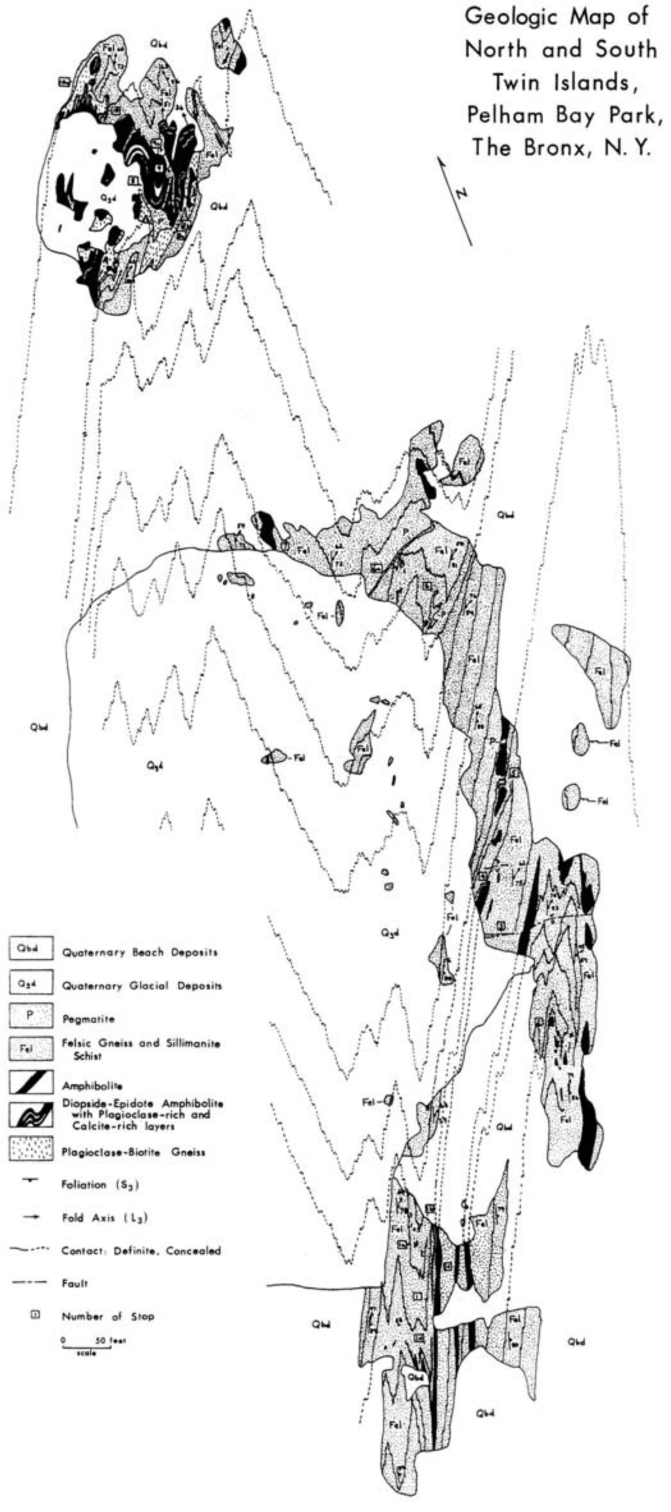

Figure 19 - Geologic map of North and South Twin Islands, Pelham Bay Park, the Bronx, New York. (From Seyfert and Leveson, 1968.)

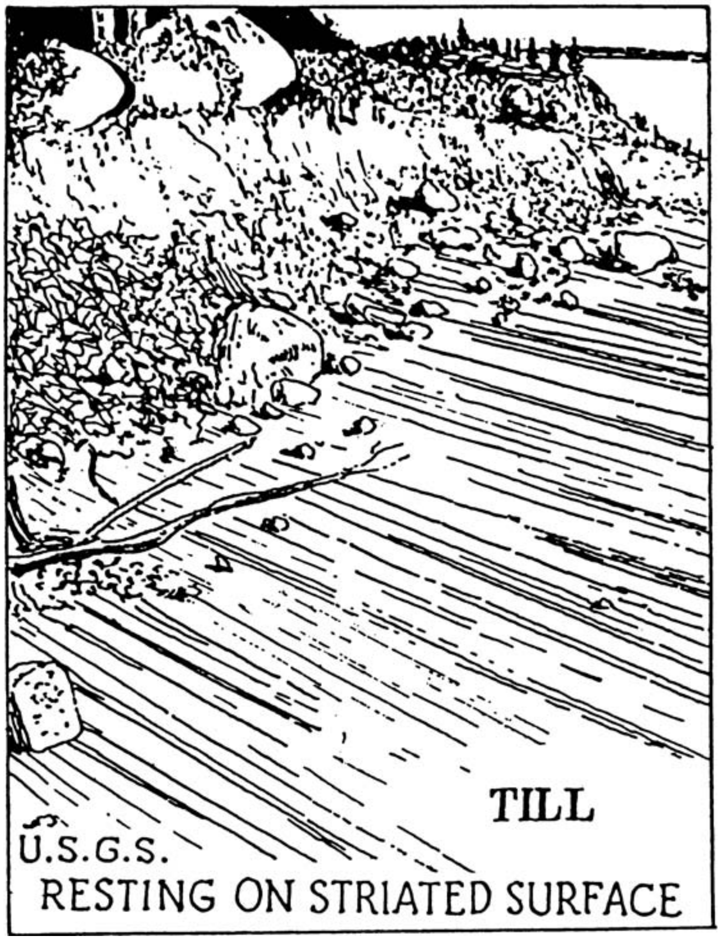

Figure 20 - Sketch of a glaciated bedrock surface exposed by wave action; boulders resting on the linear striae have been eroded out of the bluff of till in the background. This sketch (locality not given in original source) depicts what can be seen along the shore of Long Island Sound at South Twin Island, Pelham Bay Park, New York City. (A. K. Lobeck, 1939, upper right-hand sketch on p. 301, from U. S. Geological Survey.)

Correlative with the Hartland Formation of western Connecticut and southeastern New York, the Hutchinson River Group is strongly deformed under high- to medium- grade metamorphic conditions. Mapping by CM in 1981-83 showed the presence of at least four sets of superposed folds, two early stages of isoclinal folds (F_1 and F_2), followed by tight F_3 folds, and gently warping by open F_4 folds. The F_1 and F_2 fold phases are superposed and probably progressive based on similarities in structural style and orientation compared to sequences mapped in New York City and western Connecticut on either side of Cameron's Line (Merguerian, 1985, 1986). Significant shearing parallel to the axial surfaces of F_1 and F_2 folds has resulted in folds with sheared out limbs and has created beautiful interference patterns. In addition, the generation of pegmatitic sweat-outs and bull quartz veins injected parallel to S_2 is omnipresent which, together, creates local migmatite. The enveloping surface of the composite S_1+S_2 foliation trends roughly N54°W, 60°SW, a bit steeper but of identical strike to older fabrics in coeval rocks mapped in Manhattan by Merguerian (1983b).

The F_3 folds deform the penetrative S_1+S_2 foliation and as a result are quite obvious in outcrop. They possess axial surfaces trending N30°E, 75°SE to vertical. The plunge of F_3 axes is dominantly south to southeastward at roughly 45°- 60° but variable due to differences in the original orientation of S_1 and S_2 foliations and younger, F_4 warps. The F_3 axes are obvious as mineral streaking on the S_2 foliation and as the long axis of boudins. On North Twin Island, extensive boudinage of the mafic rocks and diopsidic calc-marble into sheared boudins occurs due to ductility contrasts with the surrounding felsic units.

The F_4 folds are larger than outcrop scale but show up as broad open warps of preexisting structures and a slip cleavage oriented roughly N85°E, 80°NW. Again, the similarities in structural sequence and orientation between these rocks and those mapped by CM in New York City are striking with all four-fold phases recognized in both regions. Because the structural geology of both regions are identical, they must share a common plate tectonic history.

The two regions also show similar brittle fault histories. Many excellent examples of brittle faults of contrasting type and offset sense can be found in the bedrock exposures half way up the rock terrace on South Twin Island. See if you can find them. Give up? One of the rock exposures displays a fault oriented N42°E, 76°NW that exhibits 0.4 m of left-lateral strike-slip displacement as measured across an offset quartz vein (Figure 21). The offset vein outlines an older fault that can be traced toward the east where important geological relationships can be observed. Here the rock terrace displays two faults of contrasting type and orientation, indeed a textbook example of relative age determination based on crosscutting relationships. Figure 22 shows an eastward view of two faults. Note how the N70°W-trending strike slip-fault offsets a quartz vein in the background. The vein was injected into a N30°E shear zone (ductile fault) developed parallel to foliation in the bounding Hartland gneiss. Thus, both brittle and ductile faults can be observed in a single exposure.

Elsewhere to the south, another NW-trending fault is exposed. This fault trends N66°W and dips 82°SW and shows roughly 0.5 m of composite offset of an isolated quartz vein. The area around the fault is highly fractured because of a family of joints oriented N67°W, 77°SW. Experienced field geologists look for evidence of decreased joint spacing to localize faults in the field and this location illustrates all of the traits of a fault. Although similar in orientation to the NW-trending fault described above, this fault exhibits right-lateral strike-slip offset. This isolated NW-trending fault may be part of a family of NW-trending faults that are considered active in that they exhibit post-glacial offset and localize new earthquakes. They are similar in orientation and offset sense to the fault along which the 17 January 2001 NYC earthquake was localized. (See Figure 15.) Based on traditional bedrock mapping on the surface and detailed mapping in the NYC Water Tunnels, Merguerian (2002) has demonstrated that the NW-trending faults of NYC are the youngest in the region.

Thus, as described earlier, the rocks of the Hutchinson River Group are interpreted as the remnants of an ocean basin adjacent to the Early Paleozoic shelf edge of North America and fringed by a volcanic arc. While walking on the outcrop surface with your lab instructors see if you can identify the various rock types, folds, faults, joints, deformational structures, and glacial features discussed above.

Figure 21 – A N42°E-trending brittle fault that dips 76°NW with 0.4 m composite left-lateral offset. This younger fault cuts the veined N70°W fault of Figure 22.

Figure 22 – Eastward view of N70°W, 62°NE left-lateral fault (lined by large milky quartz vein). This fault cuts an older NE-trending fault and parallel foliation (N30°E, 80° SE) in the bounding Hartland gneiss.

Leg 2 - From Orchard Beach across the Bronx and Manhattan into New Jersey

Driving westward through the Bronx on the Cross Bronx Expressway (I-95) note the outcrops (and abandoned appliances and cars) on either side of the roadway. The first exposures you see are metamorphic rocks assigned to the Hartland Formation/Hutchinson River Group.

Near the western edge of the New York Botanical Garden and the Bronx Zoo in the Bronx the fault contact of the Hutchinson-Hartland Terrane with the Manhattan Prong is exposed. Mapped from New York City into western Connecticut, this zone of highly sheared metamorphic rocks, known as mylonites, are developed along Cameron's Line. This shear zone (suture) separates rocks of oceanic parentage to the east [Layer IIA(E)] from rocks of continental affinities to the west [Layers I, IIA(W), and IIB] and marks an important geologic boundary for the Appalachian mountain belt through southeastern New York into New England.

The St. Nicholas thrust separates Taconic rocks of the Manhattan Schist from the Walloomsac (Tippecanoe) Schist in the New York Botanical Garden, Boro Hall Park, and Crotona Park and across our trip route. This regionally important shear zone cuts across the Cross Bronx Expressway just before the Third Avenue exit. Westward past Third Avenue occur exposures of the Manhattan Schist and Inwood Marble. Recently, Drs. Patrick and Pamela Brock have found exposures of the late Proterozoic Ned Mountain Formation in numerous places in the Bronx, indicating that imbrication of rock types in the highly sheared core zone of mountain ranges is the rule, not the exception. Look on the northern side of the Cross Bronx Expressway and see if you can spot an anticline (upfold) of amphibolite in the Proterozoic Fordham Gneiss that crops out at an entrance ramp before Jerome Avenue.

Beyond Jerome Avenue, the substrate above which the Manhattan-Inwood sediments were deposited crops out. Originally part of the ancient North American craton these highly folded and metamorphosed rocks are the Proterozoic Fordham Gneiss that, in excellent exposures to the north and south of the expressway, show the typical banded and highly folded appearance of gneiss. Note the abundance of folds and faults in the Fordham in large cliff-like cuts, just before we cross the East River near Highbridge. Passing beneath the apartment complex built atop the expressway we skirt across the northern tip of Manhattan Island, also composed of the Manhattan-Inwood-Fordham metamorphic rocks. (See Figure 15.)

As we cross the Hudson River over the George Washington Bridge we catapult forward in time passing from the Proterozoic and Paleozoic rocks of Manhattan and the Bronx into gently west-dipping red-colored sedimentary rocks of the Newark Basin. Figure 8 is a diagrammatic sketch showing the structure of the bedrock beneath the George Washington Bridge (see Figure on cover also!). The prominent cliffs on the west bank of the Hudson River, the Palisades, are formed by the tilted, resistant edge of the igneous rocks of the Palisades sheet which forms a sill-like intrusive. As you should remember, a sill is a concordant tabular pluton, a sheet-like body of igneous rock that has been intruded parallel to the layers of its surrounding rocks. A diagrammatic cross section of the Palisades sheet is reproduced as Figure 23. The composition of this mafic rock is quite similar to the mafic rocks of the oceanic crust. Mafic rocks are named by the coarseness of their crystals: gabbro is the coarse variety; dolerite, the intermediate variety; and basalt, the fine variety.

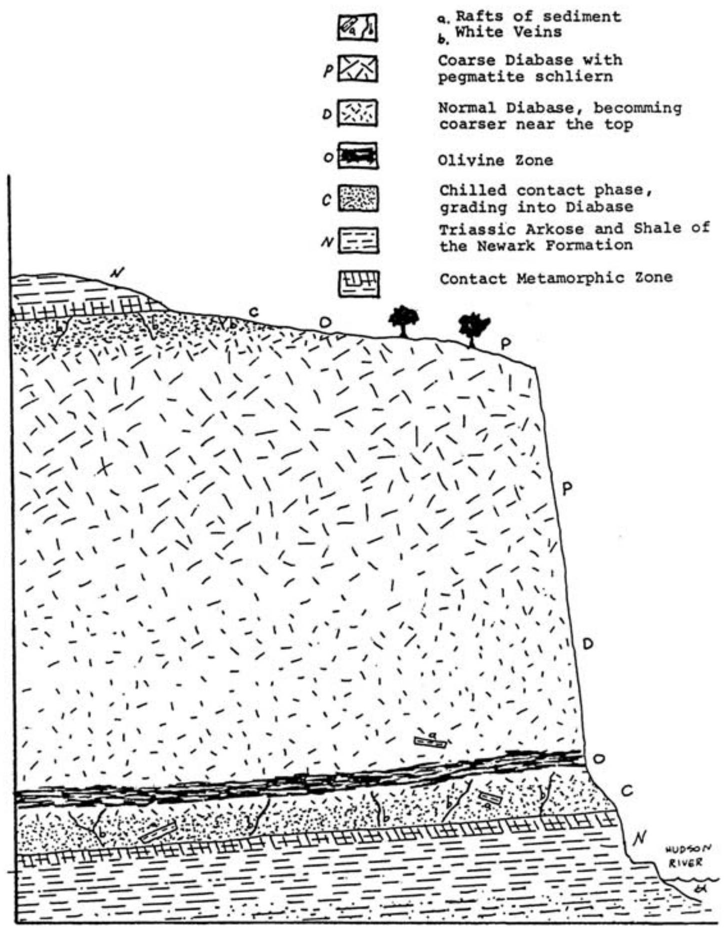

Figure 23 - Schematic cross-section of the Palisades intrusive sheet, New Jersey. (Drawn by M. Sichko.)

Because of the prevailing northwest dip in the central part of Newark Basin, as we drive northwestward during the remainder of today's trip, we will encounter successively younger strata among the Newark basin-filling strata. Geologists refer to traverses across the strike of strata starting with older strata and encountering successively younger strata as "traversing up section" (the "section" referring to the succession of strata, and the "up" to the progression from older strata to younger). By contrast, they refer to the reverse, that is, a traverse progressing from younger strata to older, as "traversing down section"). Try to locate the top of the Palisades sheet and look for outcrops of Layer V (red shale, sandstone, and conglomerate) on both sides of Route 80 in New Jersey as we drive westward towards Stops 2 and 3.

After crossing the outcrop belt of the Palisades intrusive sheet, and across red-colored sedimentary rocks of Layer V, we will eventually view high-standing ridges of the First, Second, and Third Watchung Mountains. (See Figures 4 and 8.) Thus, from the upper contact of the Palisades sheet, we will drive past west-dipping sedimentary rocks of the Newark Supergroup on our way to stops to examine the first of three sheets of extrusive mafic igneous rock constituting the Orange Mountain Formation ("First Watchung basalt" of older usage), the Preakness

Formation (former "Second Watchung basalt"), and Hook Mountain Formation (formerly "Third Watchung basalt"; each "basalt" named after one of the Watchung mountains that were numbered from east to west). These curvilinear mountain ridges are truncated on the northwest by the Ramapo fault, a normal (gravity) fault that juxtaposes the Hudson Highlands block (footwall) on the NW and the Newark Basin (hanging wall) on the SE.

The **Newark Supergroup** is a thick sequence of Late Triassic to Early Jurassic (Mesozoic) sedimentary strata and interbedded sheets of mafic volcanic rocks whose basal part was intruded by a thick sheet of mafic magma that cooled to form the Palisades Intrusive sheet. The Newark Supergroup (Layer V in Table 2) rests with profound angular unconformity atop folded and faulted units of Layers I and II, the pre-Newark complex of Paleozoic and older metamorphic rocks that underlies the Manhattan Prong of the New England Uplands. (See Figure 4.) Rocks of Layer I crop out immediately west of the Ramapo fault zone. Here, they underlie the Ramapo Mountains, a tract of hilly, highly glaciated crystalline rocks. These rocks lie along strike and are correlative with Proterozoic rocks of the Hudson Highlands. The tilted and eroded edges of the Newark strata were overlapped and covered by the strata of Layer VI, the coastal-plain strata. Recent work by many geologists has defined the stratigraphy of the Watchung basalts and intercalated sedimentary strata (Figure 24). The outcrop pattern of these various formations in New Jersey are shown in Figure 25 based on a proposed flood-diversion tunnel as discussed below.

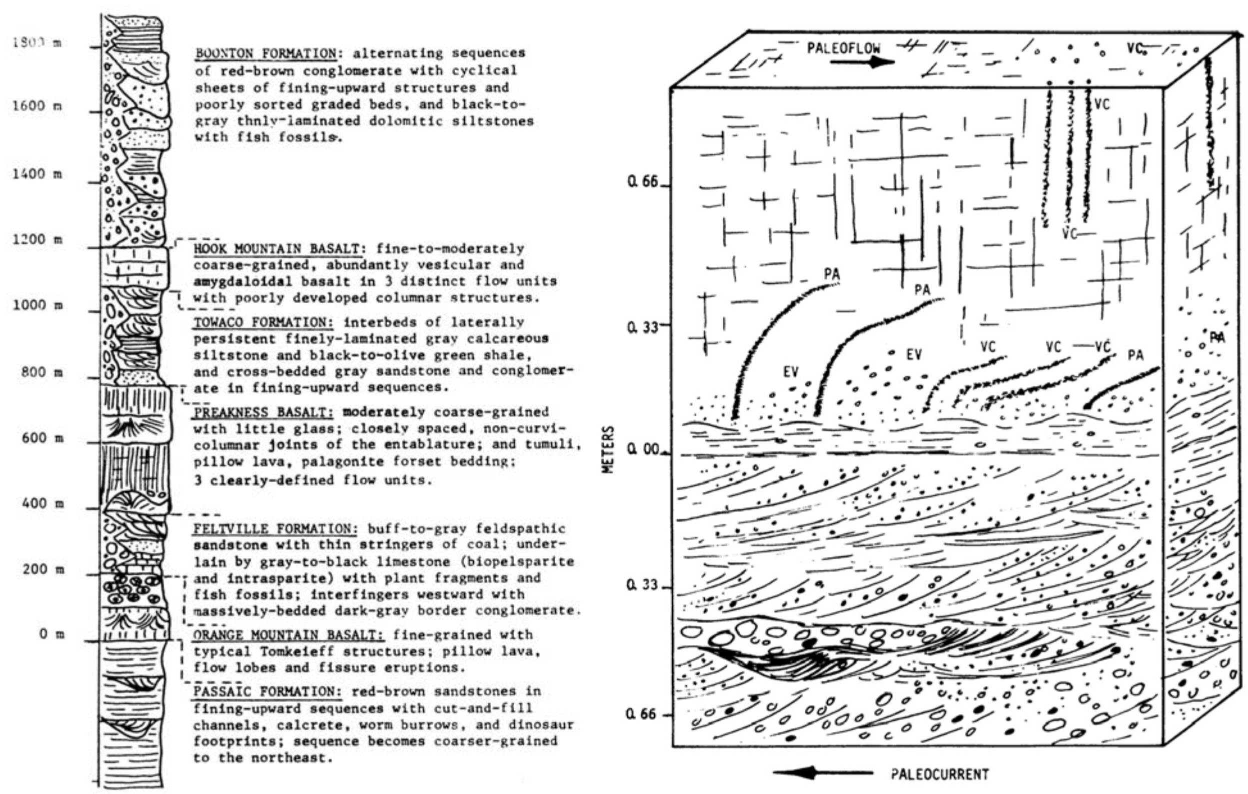

Figure 24 - Columnar section of Newark Supergroup from upper part of Passaic Formation to Boonton Formation. Block diagram showing the downflow bending of pipe amygdules found at the base of the Watching basalts flows. (From Manspeizer, 1980.)

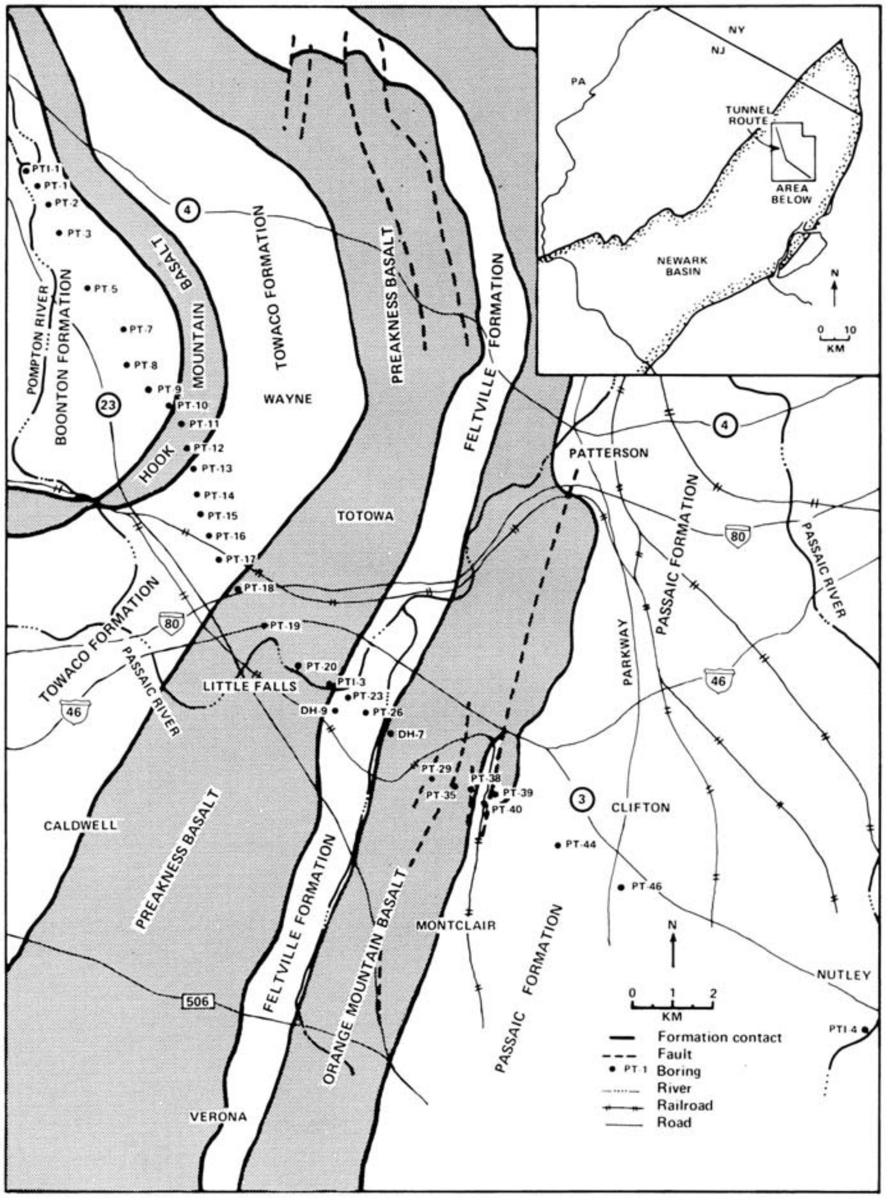

Figure 25 - Geologic map in the vicinity of proposed flood-diversion tunnel. Dots mark sites of core borings made in 1985 and 1986. (From Fedosh and Smoot, 1988.)

Our second stop today will be in Paterson, New Jersey where extrusive basalts (Orange Mountain formation) of the First Watchung Mountain are exposed in a spectacular setting known as Paterson Falls. To get there from Stop 1, after crossing the George Washington Bridge, take Route 80 West and take the Express Lanes. Continue west on Route 80 to Exit 56 (Squirrelwood Road - West Paterson and Paterson, New Jersey) and bear R at fork at end of exit ramp. Make first L onto Glover Avenue and take Glover down to McBride Avenue along the east side of the Passaic River. Turn R on McBride and travel for 0.7 mi. past a spectacular exposure of basaltic pillow lavas on east side of McBride Ave. Continue north on McBride Ave for 0.3 mi. At traffic light, turn R and take the first L past the Paterson Visitor's Center. After 0.2 mi. turn L and park.

STOP 2 - The Great Falls of Paterson; Orange Mountain and Passaic formations. (UTM Coordinates: 568.9E/4529.5N for hillside exposures E and N of stadium, 569.05E/4529.75 N for basal contact, 569.15E/4529.85N for cliff face near dog pound, and glacial erratic at 568.95E - 4529.65 N. Paterson quadrangle.)

Here, at the Great Falls of Paterson, New Jersey, (former home of Lou Costello), the Passaic River cuts through extrusive sheets of the Orange Mountain (First Watchung) lava flow. Professor Sichko has performed petrologic research comparing the Palisades intrusive sheet to parts of the First Watchung lava (Sichko, 1970 ms., 1975). Autographed copies of his papers are available at newsstands across the country and at Geology Club meetings, Wednesdays, during the common hour in Gittleson 135! As discussed earlier, recent studies suggest that the Palisades magma was intruded over a protracted time period spanning the interval from the first to the second Watchung lava outpourings.

The waterfall here drops about 75 feet (from the 120-foot contour at the lip to about 45 feet below). The Passaic River, flowing northeastward (more or less parallel to the strike of the tilted strata), pours into a fracture that trends N-S. The water tumbles over the lip on the rock forming the W side of the fracture, and then flows southward along the fracture, then makes a U-turn and continues flowing NE. No gorge has formed downstream, as has been eroded, for example, by the upstream retreat of the lip of Niagara Falls. In its flow along a fracture and absence of a gorge, Great Falls are a miniature version of the mighty Victoria Falls on the Zambezi River in southeastern Africa (Zambia/Zimbabwe).

The view downstream from the footbridge (made famous in the TV series "The Sopranos") shows that igneous rock extends all the way to the water's edge on the lower level (altitude about 45 feet). Keep this fact in mind as we move northward past the stadium. Notice, also, that you are all wet from standing in the mist too long. Luckily, the quantity of water flowing over Great Falls has been lower than normal lately because of the withdrawls allowed to various upriver communities (they drink this stuff -- after treatment, of course).

Walk northward toward the soccer stadium and proceed down the path toward the river. Stop at the first exposure (on S side of a small knoll beneath the d of the label Stadium; enclosed by the 170-foot contour line). Find the contact at the base of the Orange Mountain Formation (or of one of the extrusive sheets within this formation if not the base) and the underlying pebbly sandstone (top of Passaic Formation or a sedimentary member within the Orange Mountain Formation).

Notice the relationship between the landscape and the contact: a small bench at the top of the sandstone; trees growing where they can send roots into the cliff. The altitude of the contact here is about 100 feet, which is about 50 feet higher than the base of the basalt downstream from the falls. About 10 years ago, during a class field trip, Dr. Sanders noticed this relationship and interpreted the offset as being the effect of a fault with displacement of at least 50 feet. CM and

JES think that the northward- and upward shift of the basal contact of the extrusive rock is evidence for two other small faults.

Notice the sequence of columnar joints in the extrusive rock and the chilled margin at the base. The top of the flow unit is not exposed here, but if it were, what features might be present to enable you to distinguish the sheet as an extrusive as contrasted with an intrusive?

Note the features of the Passaic Formation (if that is what these strata are, and not sedimentary members of the Orange Mountain Formation). In your analysis, include bedding characteristics, sizes of channels, composition of pebbles, and coarseness of particles. Note that the average trend of the channels is into a direction S85°W and that the inferred paleoflow of the water in them is from the east! [This is quite in contrast to the accepted view that the Newark Basin filled in with sediment derived from the uplifted highlands (Ramapo Mountains) to the west.]

Note the numbers marked by various methods on the cliff face near the dog pound, an attempt by an unknown geologist(s) to break out individual units. Three channels are especially obvious. The lowest one occurs below unit 5, a second between units 9 and 10, and the third between units 14 and 15. The channels are indicated by sharp contrasts in grain size and by the presence of pebbles in their basal parts. The pebbles are largely (>50%) carbonate with lesser amounts of quartz and recycled red sandstone.

JES and CM suggest that the dominantly structureless, uniform, locally laminated sands and interspersed rudites here are the result of flash floods which produced debris flows on the outer fringes of a subaerial fan as contrasted with the upward-fining cross-stratified point-bar successions formed by the migration of meandering streams; in this regard, the absence of shales is especially significant. Thus, we suggest that the sediment blankets are true time-stratigraphic horizons similar to their interlayered volcanic conterparts.

On the walk back up the trail, notice the large, polished boulder of hornblende-bearing Proterozoic gneiss. It is an erratic weathered out of Pleistocene till and must have come from the west, northwest, or north.

Leg 3 - Paterson Falls to Garrett Mountain Preserve, New Jersey

On leaving Great Falls parking area, turn R and follow over the bridge and turn L onto McBride Avenue heading south. At Glover Avenue traffic light turn L. After a few blocks, turn R onto Squirrelwood Road and continue straight over the overpass of Route 80. Before Mobil station, turn L into the Mid-Atlantic Plaza and bear L through parking area past Mid-Atlantic Bank building. Continue ahead and turn L at stop sign onto New Street. After 0.3 mi. note the famous New Street quarry on R and continue 0.1 mi. to Dixon Avenue. Turn R onto Dixon and follow uphill for 0.25 mi., then turn R onto Garrett Street.

Follow Garrett Street around to L and then bear R past blocks of pillowed basalt on Mountain Avenue (Condos on right of Holocene age!). After 0.35 mi. turn L into Garrett

Mountain Reservation and turn R into park. Follow road (south) past Barbour Pond. At 0.8 mi. from park entrance turn L at stop sign. Follow road for 0.6 mi. past stop sign and park in small lot to left of road across from the tower.

STOP 3 - Upper, glaciated contact of the Orange Mountain Formation ("First Watchung basalt") at Garrett Mountain Reservation. (UTM Coordinates: Location of old house [altitude = 500 feet] 569.50E/4577.75 N, Paterson quadrangle.)

From parking lot, follow trail uphill to the building, and then take the trail along the crest of the ridge. Part way up the hill is a large erratic of hornblende-bearing granitic rock from the Proterozoic of the Hudson Highlands. Does the hornblende mean that it came from west of Hudson?

From the crest of the ridge enjoy the splendid view eastward toward Manhattan (atmospheric conditions permitting). Notice the two clusters of skyscrapers: at the Battery and in midtown Manhattan. This is a function of the depth of bedrock. Where the tall buildings have been built, solid bedrock is close to the surface. In between, where no tall buildings have been built, the depth to bedrock becomes several hundred feet.

Along the trail, look for are vesicles in the basalt (we are near the top of a flow unit where vesicles are to be expected) and the glacial features. Present here are glacial grooves trending N10°E-S10°W (produced by Glacier III or IV in Table 3), about parallel to the trend of Garrett Mountain, and the mini-roche moutonnée.

The recent floods have been another catastrophe to those living near the junction of the Pompton and Passaic rivers but probably have strengthened the arguments for the U. S. Army Corps of Engineers and sundry politicians who have been advocating the construction of the flood-diversion tunnel, the proposed route of which is shown by the dots marking core sites in Figure 25. During 1990-91, other cores have been collected at points selected to extend the stratigraphic coverage from the strata penetrated by the line of cores along the proposed route of the flood-diversion tunnel so as to yield cores through the full thickness of the strata filling the Newark basin. These are housed at Lamont-Doherty Geological Observatory of Columbia University and are being studied by Paul Olsen and associates.

The Garrett Mountain block lies east of a fault that is downthrown on the east. JES suspects that another fault, possibly the one extending northward from the label Orange Mountain Basalt in the lower center of Figure 17, may be upthrown on the east, thus bringing up the Passaic Formation against higher-than-normal parts of the Orange Mountain Formation. JES suspects that this up-on-the-east fault extends NE-SW along the eastern side of the First Watchung Mountain. If so, then this fault defines a horst block with the Garret Mountain block. Under this fault hypothesis, the only places where the full thickness of the Orange Mountain Formation would be exposed are located at the northeast- and southwest ends of the Watchung ridges, where the curvature of the strata on the limbs of the transverse Watchung syncline causes the outcrop belts to curve around to the northwest away from this possible fault.

Leg 4 - Garrett Mountain Preserve back to the Hofstra Campus.

Continue north on Garrett Mountain loop access road to exit. Turn L onto main road and at 0.8 mi. turn L onto Weasel Drift Road. Follow up over crest of Garrett Mountain and then down to Valley Road (aka Mountain Park Road). At Getty station, turn L onto Valley Road (northbound) and bear L to Route 19, taking 19 to Route 80 (eastbound) to Hofstra University.

Here's a chance to see it all again in reverse. We will try to stop for bathroom facilities along the way. Feel free to ask questions of your trip leaders and enjoy the scenery on the way home. We sincerely hope you've enjoyed your fieldtrip to southeastern New York and eastern New Jersey and hope you have a new appreciation of the geology of the region. See you in class!

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)		
	440 450	**Taconic orogeny.** Intense deformation and metamorphism. 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)

Copake Limestone (Stockbridge,
Rochdale Limestone (Inwood Marble)
Halcyon Lake Fm.
Briarcliff Dolostone
Pine Plains Fm.
Stissing Dolostone
Poughquag Quartzite
Lowerre Quartzite
Ned Mtn Fm.

Eastern deep-water zone
(L. Cambrian-M. Ordovician)

(Ꞓ-Oh) Hartland Fm.
(Ꞓ-Om) Manhattan 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 – 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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