DUKE GEOLOGICAL LABORATORY

Web: www.dukelabs.com
E-Mail: CharlesM@dukelabs.com

TRIPS ON THE ROCKS

Guide 10: Little Appalachians and the Catskills, NY

Trip 11: 26/27 May 1990; Trip 32: 24/25 September 1994

Figure 1 – Physiographic diagram of the Hudson Valley showing the Little Appalachians and the Catskills. (From E. Raisz.)

Field Trip Notes by:

Charles Merguerian and John E. Sanders

CONTENTS

TRIPS ON THE ROCKS

Guide 10: Little Appalachians and the Catskills, New York

Trip 11: 26/27 May 1990
Trip 32: 24/25 September 1994

INTRODUCTION

On-The-Rocks Trip 32 will enable participants to examine many geologic features on scale that are small enough so that they can be seen easily and fully comprehended. The centerpiece of this trip is an area that William Morris Davis (1882, 1883) referred to as the "Little Mountains east of the Catskills." Davis enthusiastically championed this area (Figure 1, cover) as a place where one could become familiar with all the kinds of geologic features found in the typical Appalachians, as in central Pennsylvania, for example, but on a miniature scale. Everything is small: formations are thin, distinctive, and many of them are full of marine-invertebrate fossils. Exposures are numerous and strategically situated. The relationships between geologic structure and landscape features are easy to visualize. In short, this trip should enable participants to acquire a thorough "feel" for what much of geology is all about.

Table 1 is a geologic time chart for the names of the geologic eras and periods, the estimated times of their boundaries, and selected events in the greater New York City region. Our attention will be centered on the rocks that we have organized into Layer III in Table 2, Generalized descriptions of major geologic "layers," southeastern New York State and vicinity. On somewhat larger scales, we shall be viewing the contrasting kinds of strata deposited in a shallow tropical sea with those that accumulated farther offshore in deeper water, and with those deposited in non-marine environments. We shall examine the relationships between changes of sea level and the kinds of strata that result from these changes.

We shall be contemplating the geologic characteristics of mountains as contrasted with plateaus. The term "mountains" conjures up the notion of a rugged region having high relief. In geologic usage, relief is only one of the attributes of a mountain chain. High relief is a function of recent uplift and can be present no matter what kind of area has been elevated. A key factor in the geologic definition of mountains is distinctive geologic structure resulting from regional compression (as where two lithosphere plates come together). Such structures include folds and great overthrusts (some of which may include slices of ocean-floor crust in the form of ophiolite sequences), belts of strata that have been metamorphosed on a regional scale, and granitoid batholiths. The general term orogeny designates the complex of processes involved in creating folds, overthrusts, intrusions, and related geologic features that characterize mountain chains (the terms orogenic belt and orogen are sometimes used to refer to places displaying these characteristic "mountain" features without regard to topographic relief).

In contrast to a mountain belt is a plateau, where the relief may be great, but where the strata are essentially horizontal. In the area of this field trip, the Catskill "Mountains" will be seen to be underlain by essentially horizontal strata, and thus are correctly assigned to the geologic category of plateau. By contrast, the Hudson Valley, which now lacks much topographic relief, will be seen to be underlain by diagnostic "mountain"-type geologic structures (folds and overthrusts), and thus is correctly considered to be an orogenic belt (mountain-type structures, negligible modern topographic relief). The whole point is that mountain-type geologic fabric exists in many places in the modern world where no high relief is present (some mountain fabric exists in rocks buried under the coastal plain, for example, and are not even visible at the present-day land surface, but are still classified as orogens). Conversely, many areas displaying high modern topographic relief, are strictly speaking, plateaus.

One of the satisfying topics of Trip 32 is the proof of the burial of the Ordovician-age Taconic orogen by the Silurian strata. The great decrease in the thickness of the Silurian strata toward the northeast proves that these strata were deposited on a surface that originally was inclined toward the southwest. For example, at the Delaware Water Gap, the thickness of the Silurian strata is 1150 m (about 3800 feet). At Catskill, NY, 190 km (about 120 miles) to the NE, the thickness of the Silurian is only 2 m. (about 6 feet) (Figure 2). The average slope to the SW of the base of the Silurian, then is 1150 m in 190 km or 6 m per km (30 feet per mile). This is about 50 percent greater than the regional southward slope on the crest of the Palisades Ridge, which is 20 feet per mile (4 m per km). A dramatic change in the sizes of the folds takes place north of the point where the massive Lower Silurian sandstone laps out against what was a higher part of the former sea floor. Where this sandstone is thick, the folds are "big;" where this sandstone is not present, the folds are "little."

Although we do not expect to emphasize the glacial geology, we cannot escape noticing excellent examples of features made by the now-vanished Pleistocene continental glaciers. The Catskills demonstrate a few key points about the glacial history. According to J. L. Rich (1935) the latest glacier (the Woodfordian) did not completely bury the Catskills. Rich inferred that the uppermost 300 feet of Slide Mountain, the highest peak in the Catskills, had not been covered by Woodfordian ice. However, Chadwick (1928) reported finding glacial striae on the bedrock beneath the regolith dug at elev. +4205 ft. on the crest of Slide Mountain. This finding destroyed Rich's early conclusion that parts of the Catskills had never been glaciated. Rich argued that the striae found by Chadwick had been made by an older (pre-Woodfordian) glacier. JES has not yet climbed Slide Mountain to check on this, but thinks that Chadwick's results are consistent with the regional evidence that the pre-Woodfordian glaciers were thicker than the Woodfordian. Be that as it may, during the meltdown phase of the Woodfordian glacier, local ice caps became established on the Catskills. Among other things, these small ice masses eroded cirques, blocked valleys, and flowed in various directions, some just exactly the opposite from the earlier regional flow to the SSW.

The remaining parts of this guidebook are organized under first-order headings as follows: GEOLOGIC BACKGROUND (including bedrock units to be encountered on the trip route; geologic structure; some tectonic arm waving; glacial history; drainage history; and bedrock units to be examined during the trip); OBJECTIVES; LIST OF LOCALITIES TO BE VISITED; ROAD LOG AND DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS"); ACKNOWLEDGEMENTS; AND REFERENCES. All tables and illustrations are assembled in the pages following the REFERENCES.

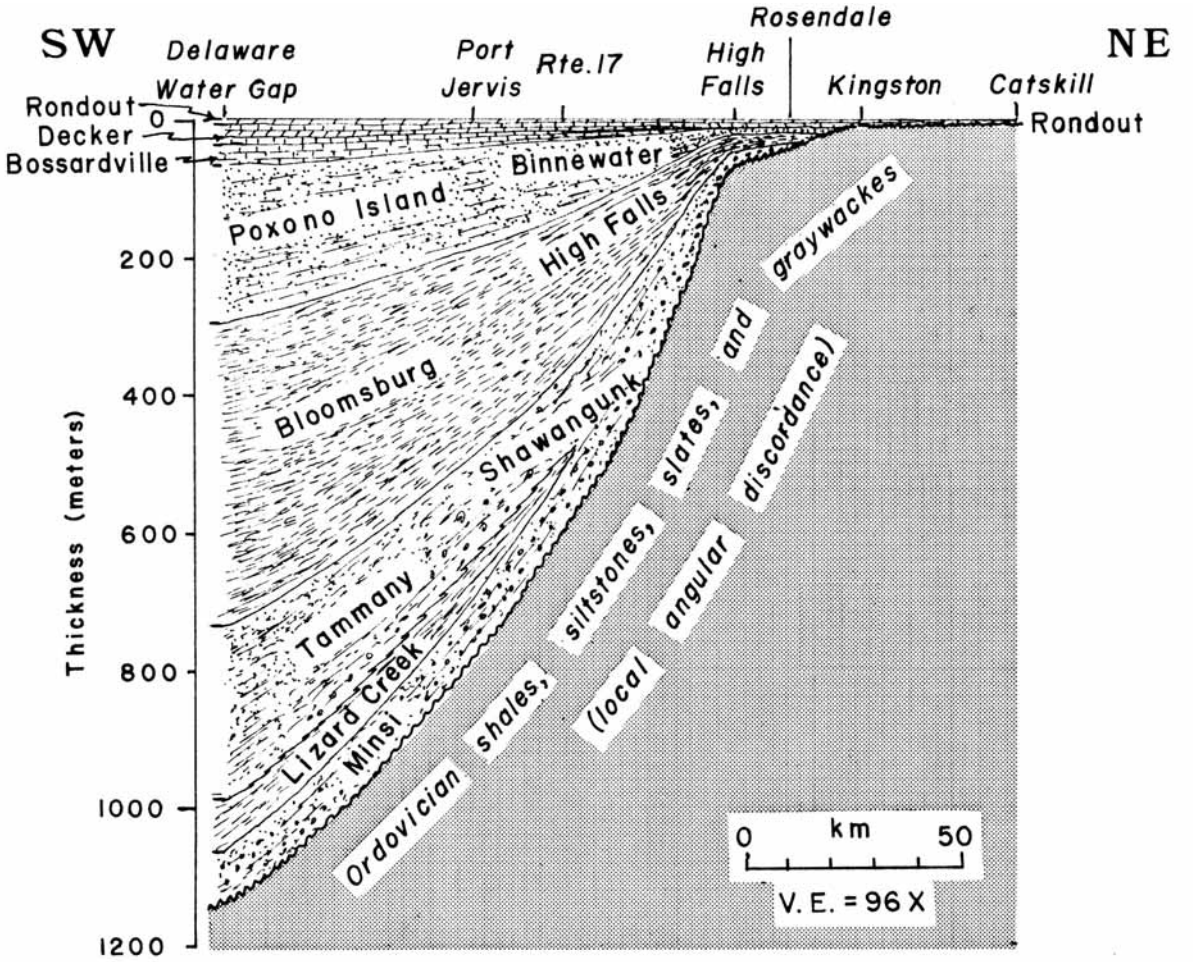


Figure 2 - Diagrammatic section showing the northeasterly along-strike thinning of Silurian strata, Kittatinny-Shawangunk mountain belt. The capping carbonates are shown as horizontal. From Freidman, Sanders, Martini, and others, 1982.

GEOLOGIC BACKGROUND

Under this heading, we discuss the bedrock units enountered on our trip route, geologic structure, some tectonic arm waving, glacial history, drainage history, and bedrock units to be examined during our fieldtrip.

BEDROCK UNITS ENCOUNTERED ON OUR TRIP ROUTE

Layer I "Basement Complex" (Proterozoic Z and Y)

"Precambrian" rocks are now subdivided, by decree of the United States Geological Survey, into the older Archean (4.5 - 2.5 Ga) and younger Proterozoic (2.5 Ga - 575 Ma). Both Archean gneiss terranes and crosscutting rocks of the Proterozoic mobile belts crop out to form the surface of the deeply eroded Canadian Shield of North America. The shield areas (or cratons) contain the oldest rocks on Earth and form the essential "seed crystal" which eventually, through the effects of plate tectonics, localized the development of fringing Phanerozoic mobile belts. In this way, the continents have grown through time, enabling them to push back the oceans and eventually, to cover 29% of the Earth's surface. The eroded remnants of past mountain-building episodes are thus preserved as the cratonic nucleii of our modern continents. North America is no exception.

The Canadian Shield is underlain by highly deformed metamorphic-, metaigneous-, and igneous rocks. The eroded surface cut across these rocks dips southward and becomes buried beneath the Paleozoic and younger strata of the central United States. These basement rocks do crop out in places where tectonic movements have elevated them in upwarps, along faults, and in elongate tracts along the core zones of the Cordilleran and Appalachian mountain belts. The extent of crystalline basement rock in the vicinity of New York State is shown in a depth-to-basement map (Figure 3). This is essentially a negative contour map, produced by geophysical studies, that shows contours on the plunging surface at the top of crystalline "basement". Isachsen's (1964) diagram shows that crystalline rocks trend east-west through most of New York State. The surface eroded on these rocks and dips south- to southeastward from the Canadian Shield beneath the Appalachian Basin (marked as the Allegheny Synclinorium). The ancient North American craton is phenomenally exposed in the Adirondack Mountains and along fault-bounded basement massifs to the east and southeast and in isolated areas such as Stissing Mountain (Knopf, 1962), Snake Hill, and the Ghent block (Ratcliffe and Bahrami, 1975). Proterozoic rocks are also exposed along the Hudson Highland-Reading Prong and in the adjacent Manhattan Prong.

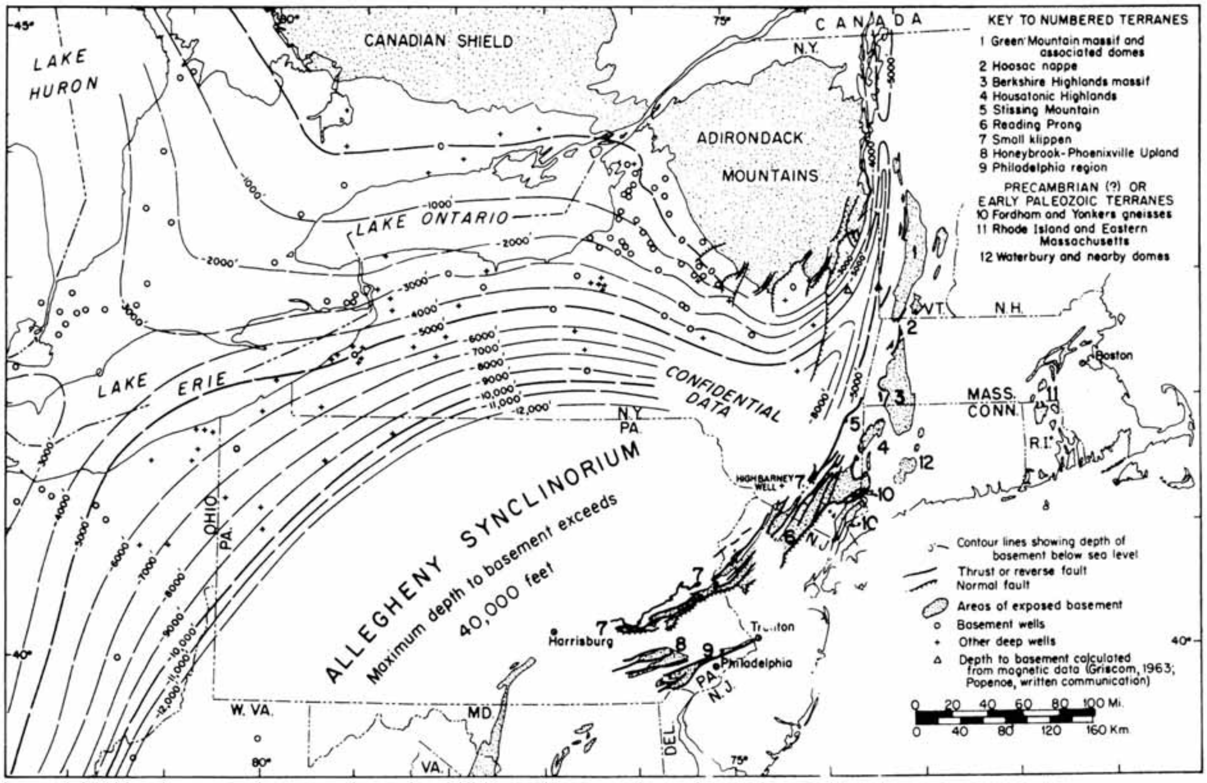


Figure 3 - Configuration of Precambrian surface and areas of exposed basement (Isachsen, 1964).

The oldest recognized strata in southeastern New York include the Fordham Gneiss in the Manhattan Prong of Westchester County and the New York City area and the Hudson Highlands gneisses (Figure 4). The Highlands Gneisses are composed of complexly deformed layered feldspathic gneiss, schist, amphibolite, calc-silicate rocks, and massive granitoid gneiss of uncertain stratigraphic relationships which together form an impressive cratonic sequence.

In the Pound Ridge area (PR in Figure 5) the Proterozoic Y gneisses of the Fordham (a 1.1 Ga U/Pb age on zircons by Grauert and Hall, 1973) is cut by Proterozoic Z granitic gneiss (the Pound Ridge Gneiss and correlative Yonkers Gneiss [Y in Figure 5] farther south). Using Rb-Sr, Mose and Hayes, (1975) have dated the Pound Ridge gneiss as latest Proterozoic (579+21 Ma). This gneiss shows an intrusive, or possibly an unconformable relationship (Patrick Brock, personal communication) with the Grenvillian basement sequence. The Yonkers Granitic Gneiss has yielded ages of 563+30 Ma (Long, 1969) 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.

Recent work by Pamela Brock (1989, 1993 ms.) in the vicinity of the Peach Lake quadrangle, New York and Connecticut, shows the presence of 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) that rest unconformably on the Fordham basement rocks. As such, Brock has identified an easterly, metamorphosed volcaniclastic facies of Proterozoic Z igneous activity whose probable vent area is now marked by the Yonkers and Pound Ridge gneisses. Together, the Proterozoic Y and Z terranes represent the ancient continental crust of proto-North America that was involved in both the Grenville orogeny and post-Grenville, pre-Iapetus extensional tectonic activity. Keep in mind that these ancient rocks were involved in intense compressional deformation and metamorphism during Paleozoic orogenesis.

The rifting of the Proterozoic Y craton in latest Proterozoic time thus sets the stage for the first of the trailing-edge continental margins of eastern North America. This trailing edge of the Iapetus Ocean, (or passive margin I) was to receive clastic, then carbonate sediments of Layer IIA (see Tables 1 and 2). Thus, early into the Paleozoic Era, this part of the Appalachian mountain belt region became the trailing edge of a continental plate, a passive continental margin (Figure 6) adjacent to the ancestral Atlantic Ocean (Iapetus). This tectonic setting persisted until the Taconic orogeny, late in the Ordovician Period (Figure 7). Interestingly, the current plate-tectonic passive-continental-margin setting of eastern North America [deformed Paleozoic and older basement covered by essentially nondeformed Mesozoic and younger sediments that were (and continue to be) deposited as the margin subsides toward an ocean basin to the east] more or less duplicates that of Early Paleozoic time!

We will not stop to see the Fordham Gneiss today, but on our fieldtrip route, north of the Manhattan Prong, we will briefly examine the Hudson Highlands gneisses and find them to consist of a sequence of migmatitic, highly deformed, interlayered quartzofeldspathic and pegmatitic granitoid gneiss, amphibolite gneiss, and calc-silicate rocks harboring dominantly flat-lying penetrative structural fabrics.

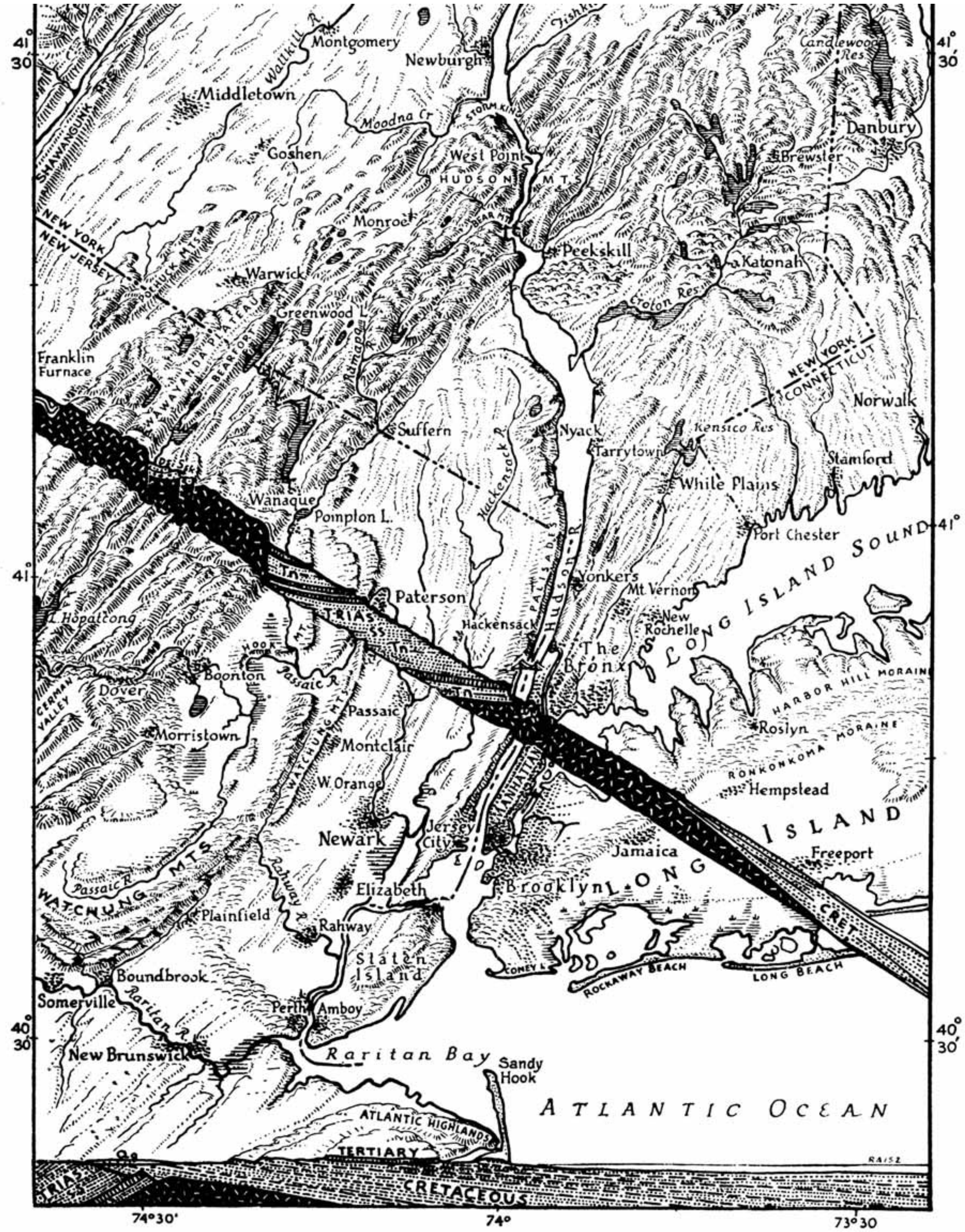


Figure 4 - Oblique, aerial physiographic diagram of a part of the Manhattan Prong, Newark Basin, Hudson-Reading Prong, and Atlantic Coastal Plain of the Appalachians (E. Raisz). The vertical slice is oriented NW-SE to illustrate the generalized across-strike structural relations among major geologic "Layers" as outlined in Table 2.

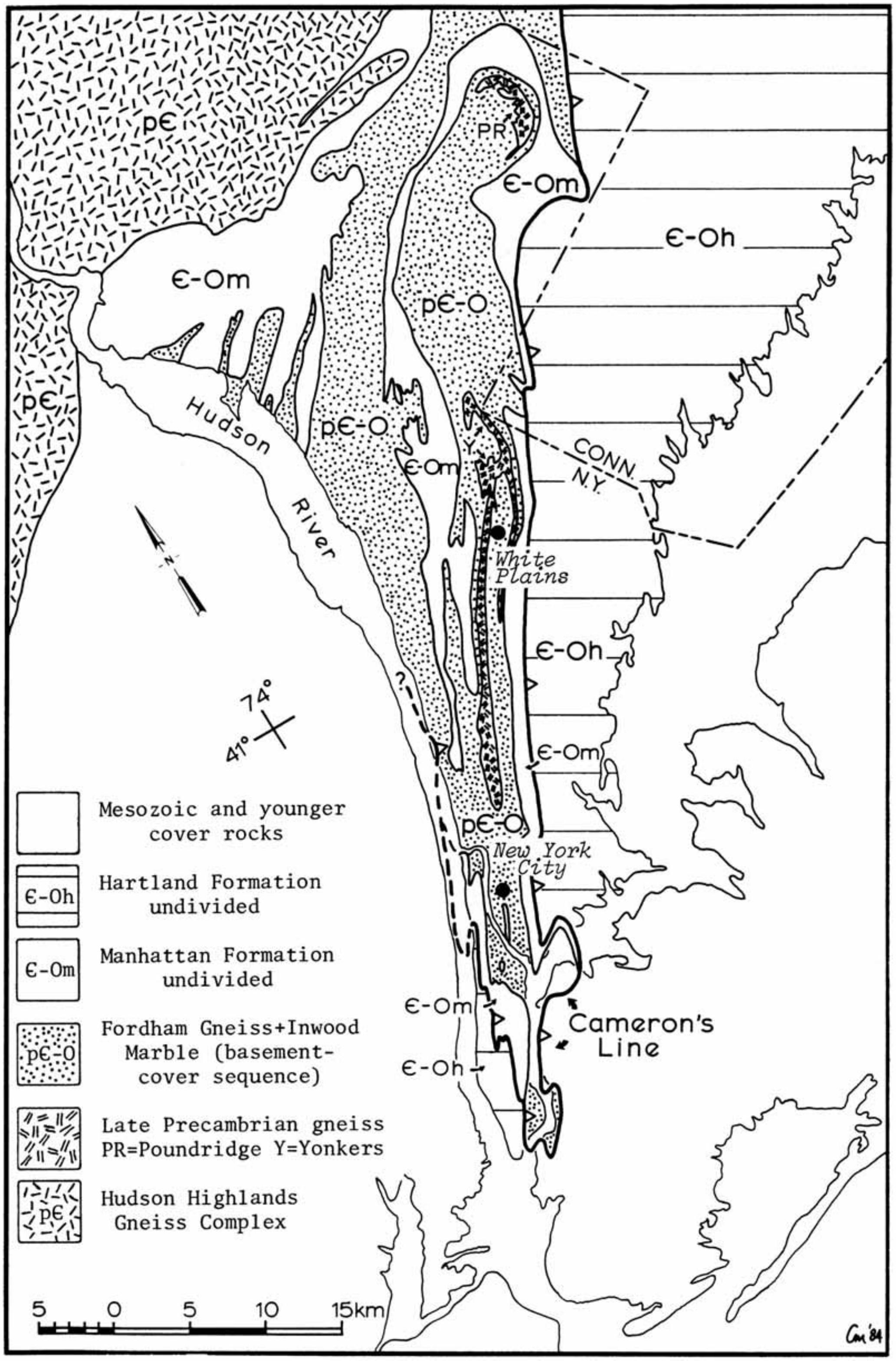


Figure 5 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted (Mose and Merguerian, 1985).

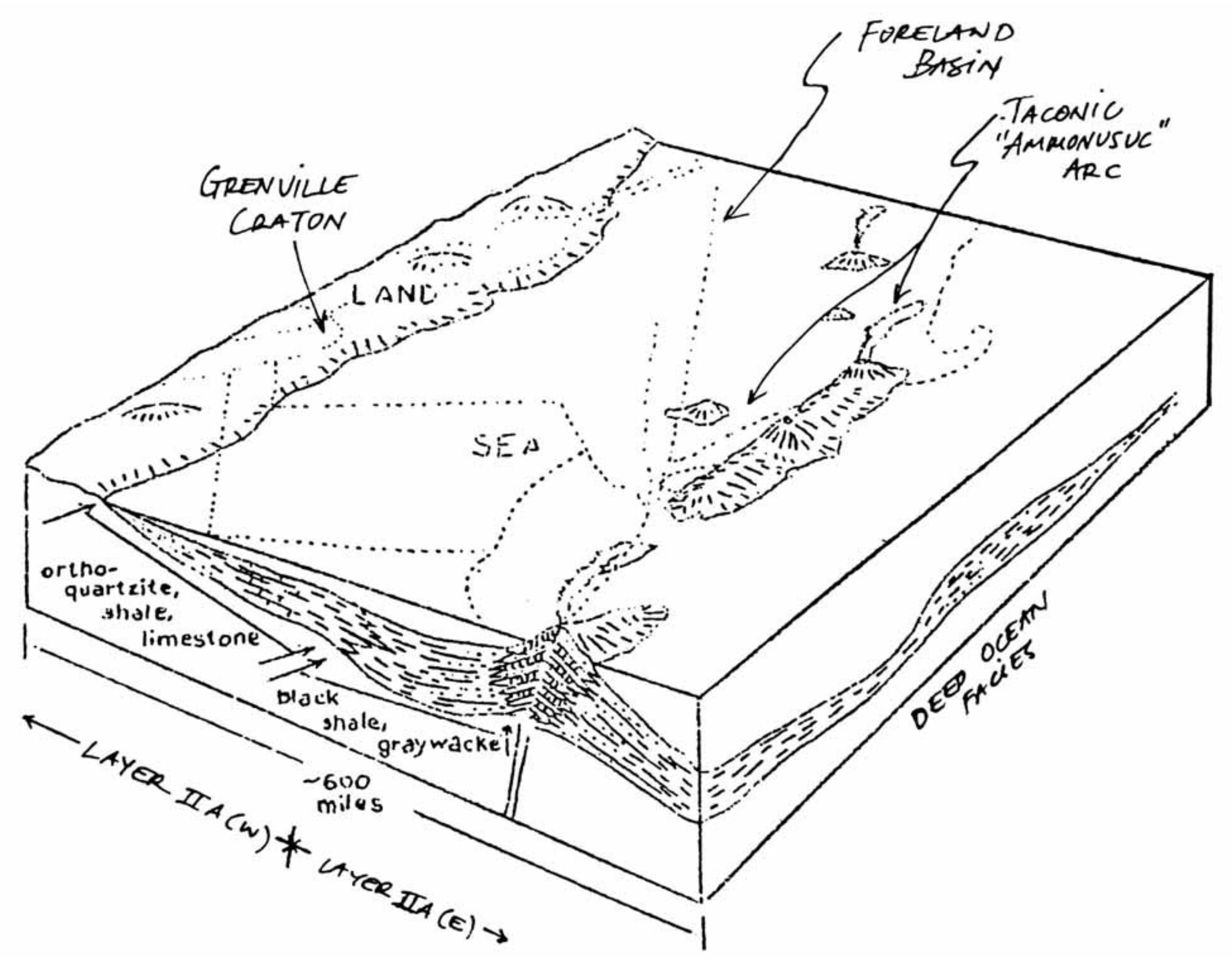


Figure 6 - Block diagram showing the embryonic Lower Paleozoic continental shelf edge of cratonic North America immediately before the deposition of Layer IIB (Tippecanoe Sequence). Current state outlines are dotted. The depositional areas for Layers IIA(W) of the Sauk Sequence and IIA(E) of the Taconic Sequence (in part), and the position of the Taconic "Ammonusuc" arc and foreland basin are shown.

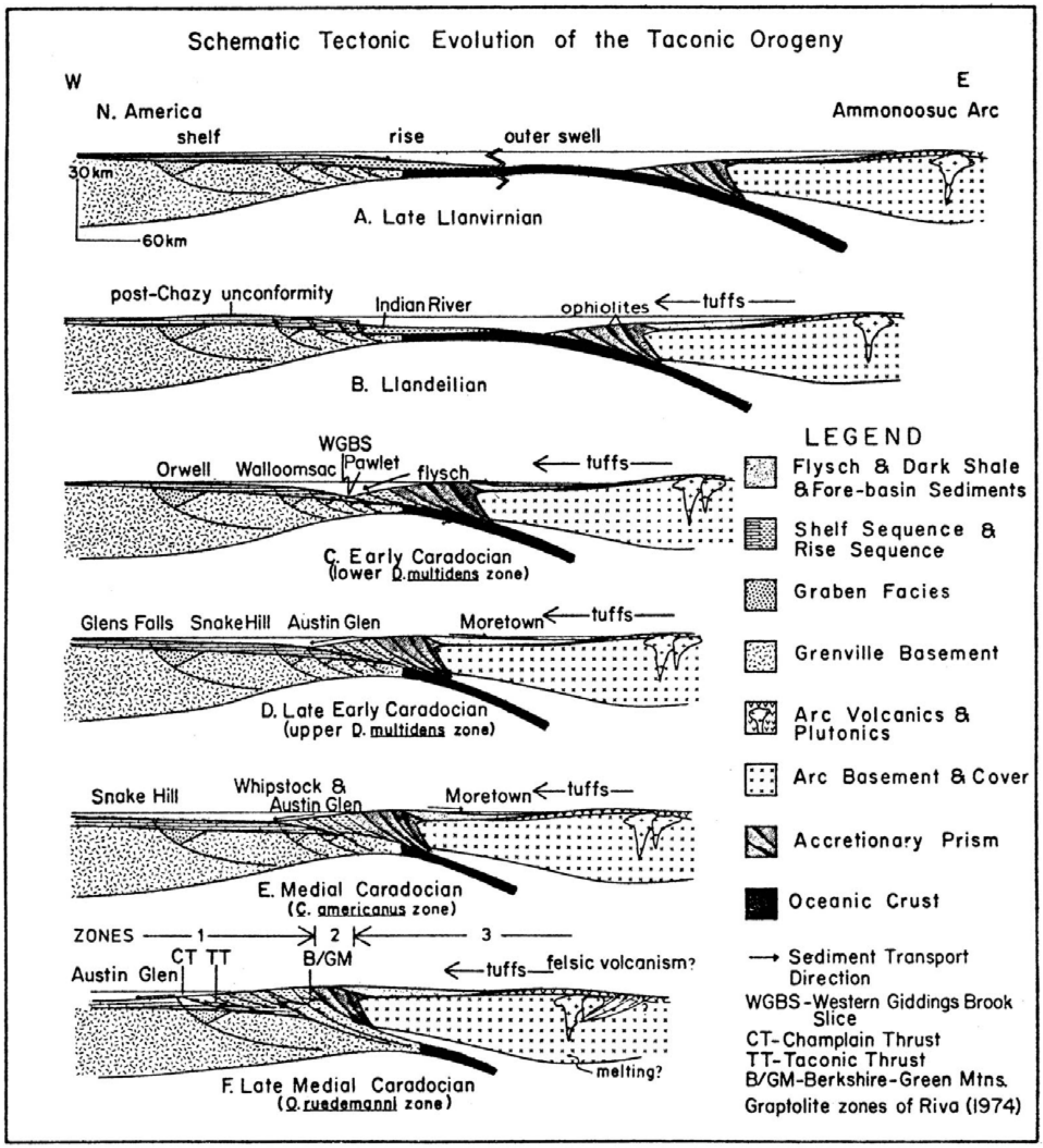


Figure 7 - Sequential tectonic cross-sections for the Taconic orogeny in New England. From Rowley and Kidd (1981).

Layers IIA and IIB: Cambro-Ordovician Strata

As we drive across the Manhattan Prong this morning, on our way to the Little Appalachians, we will skirt across the metamorphosed products of two contrasting paleogeographic-paleotectonic regimes: (1) sediments deposited on an ancient passive continental margin, which lasted from early in the Cambrian Period until the middle Ordovician Period (See Figure 6.) and which featured a carbonate-platform interior on which the Sauk Sequence was deposited and that was bordered on the east by a continental-rise prism of fine-textured terrigenous sediment, the Taconic Sequence, and an oceanward volcanic source [Layers IIA(W) and (E)]; and (2) products of a foreland basin [Layer IIB, the lower parat of the Tippecanoe Sequence], which appeared inboard of the former shelf edge when the continental margin started to its actively convergent phase which continuned throughout the later parts of the Ordovician Period and extended through at least the Silurian Period. The Tippecanoe Sequence holds the eroded products of important mountain-building event(s) (the Taconic and Acadian orogenies), which featured mountains that were elevated where formerly the sea stood and that shed coarse sediments westward toward the interior of the continent.

The important change from a passive continental margin to a convergent margin involved slope reversal and geographic rearrangements. The subsidence of the foreland basin was first event in this changed tectonic situation. The evidence for this change consists of a karst landscape at the top of the carbonate succession and the eventual covering of this karst surface with graptolite-bearing shales (Figure 8).

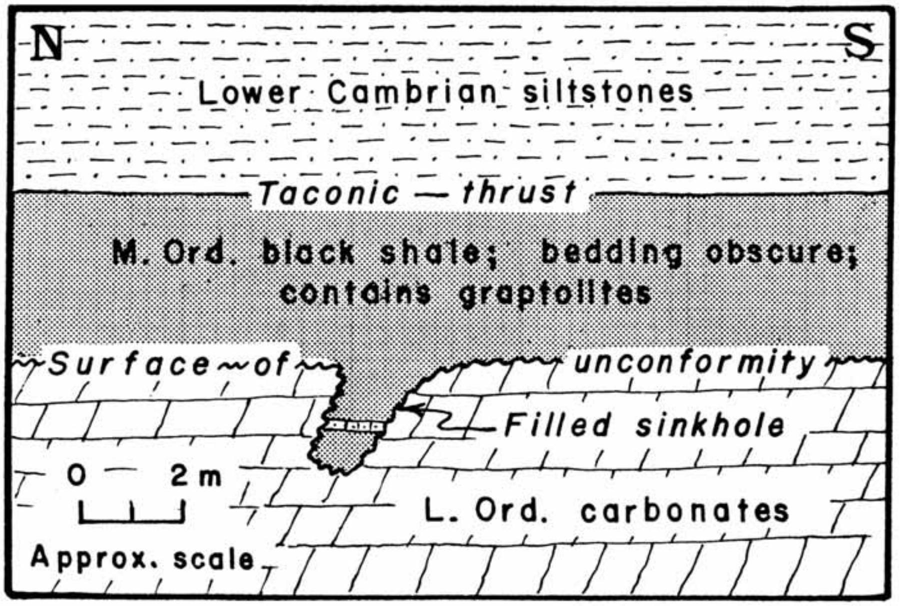


Figure 8 - West face of Bald Mountain, Washington County, New York, showing the three major units of the "Taconic Problem" in contact. The surface of unconformity proves that some terrigenous sediments do not have to be in thrust contact with the Cambro-Ordovician carbonate succession. The Taconic thrust of Cambrian siltstones against Middle Ordovician shales took place on the sea floor. Thus, locally, there is no major indication of thrusting (no mylonite, no contrast in minor structures above and below the thrust - thus nothing to show the presence of a thrust to investigators who do not pay attention to the fossils). Based on Sanders, Platt, and Powers (1961). Sketch by JES.

The turbidites that we shall examine on this trip (Stop 3, in particular) were deposited in this foreland basin. Next came some massive overthrusts which broke loose inboard of the former shelf edge and thrust the Sauk Sequence (with or without slices of the underlying Proterozoic basement rocks) structurally above the Tippecanoe Sequence. Then, the Taconic allochthons were emplaced. On these allochthons, the fine-textured terrigenous sediments of Layer IIA(E), the Taconic Sequence, deposited in the vicinity of the ancient continental rise, were displaced westward to positions over the duplicated slices of the Sauk Sequence [Layers IIA(W) and IIB]. A complicating factor is that the overthrusts, including the Taconic allochthons, moved along the sea floor where the foreland-basin fill was accumulating. Modern hypotheses contend that the loading of the continental margin by the overthrusts probably caused the foreland basin to subside.

In terms of large stratigraphic units, the Cambro-Ordovician Sauk Sequence (Layer IIA(W)), deposited on the former continental platform (Figure 9), is collectively designated as the Wappinger Group (local name taken from Wappinger Creek, SE of Poughkeepsie) or Kittatinny Group (New Jersey name), and their metamorphosed equivalents (From Connecticut northward the Woodville, Vermont, Stockbridge, and Woodbridge marbles; in the New York City region, the Inwood Marble). This vast sheet of Sauk Sequence carbonates is known elsewhere by other names. It is the famous oil-bearing Arbuckle Group of Oklahoma and Kansas; the Ellenburger Group of Texas; and the Knox Group of the southern Appalachians. In general, it consists of dolomite rocks of Cambrian and Early Ordovician ages. A continent-wide surface of unconformity formed on the predominantly dolomitic rocks. During the next episode of marine submergence, starting in the Middle Ordovician Epoch, the Tippecanoe Sequence began to accumulate. The first-deposited layers of this sequence consist predominantly of limestones. The Taconic Sequence refers to the predominantly fine-textured terrigenous strata (Layer IIA(E)) that were deposited seaward of, and in much deeper water than were the carbonates of the Cambro-Ordovician Sauk Sequence.

Layer III: Silurian and Devonian Strata

In the aftermath of the Taconic orogeny which involved an arc-continent collision and resulted in continent-scale overthrusting of the Sauk Sequence over the Tippecanoe Sequence and the Taconic Sequence over both of these already-overthrust sequences, folding, deep-seated regional metamorphism, mafic (alkalic) intrusive igneous activity, uplift, and erosion took place. Eventually, a planation surface was formed. When this surface eventually subsided, Silurian and Devonian strata were deposited on it. On Day Two (at Stops 9, 10, and 15), we will visit his surface of unconformity, and get to see for ourselves how it separates deformed Taconic slates below from subhorizontal- to gently tilted Silurian- and younger carbonate- and clastic rocks above. We will examine this same unconformity (at Becraft Mountain on the east side of the Hudson River) at Stop 17.

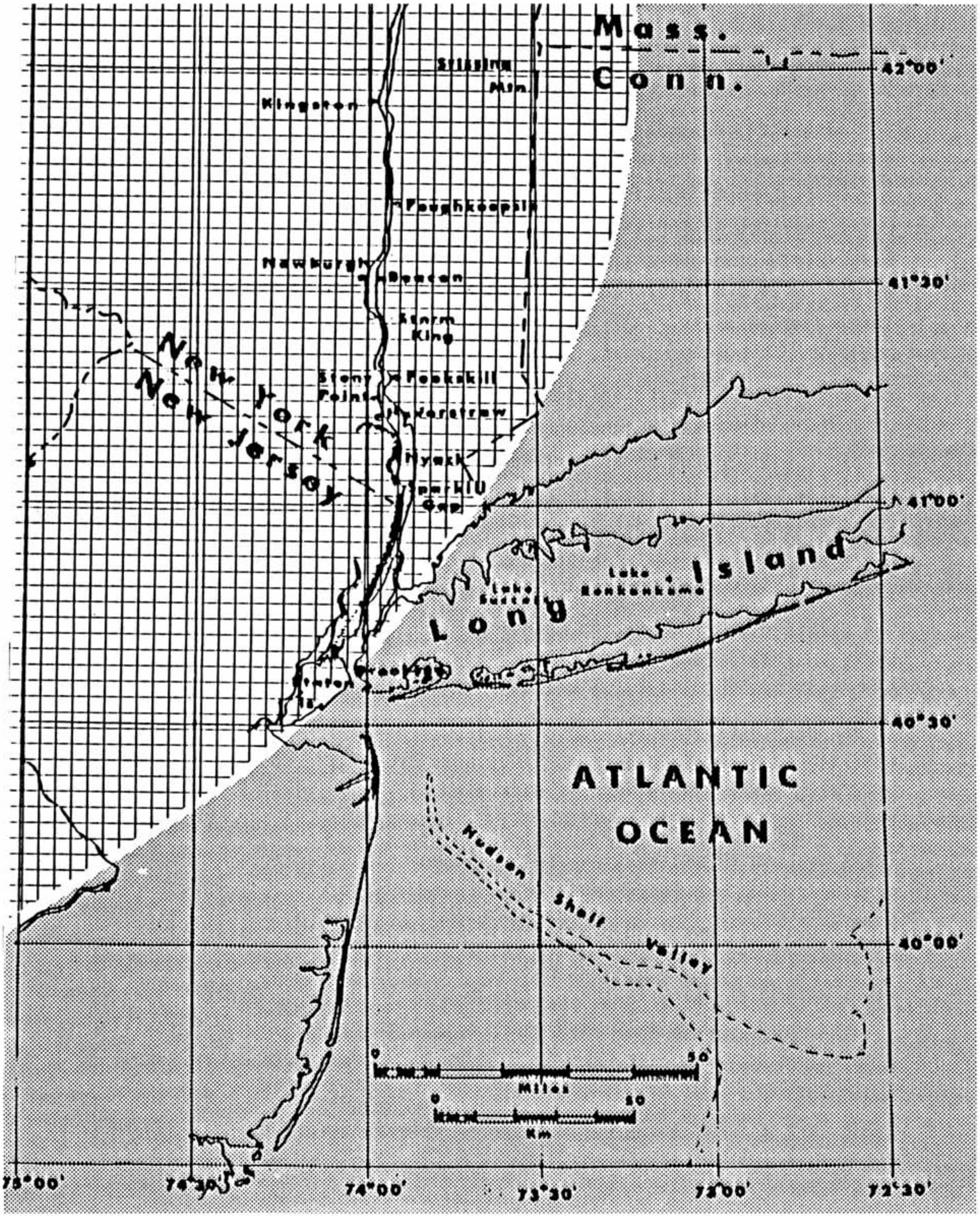


Figure 9 - Boundary between the Sauk carbonate platform (pattern of squares) and deeper-water area to the east where terrigenous sediments were deposited (shaded), during the Cambrian and early part of the Ordovician periods. JES diagram.

The Silurian and Devonian strata of eastern New York State are the products of a major marine transgression. These strata begin with basal terrigenous clastics (including the Shawangunk Formation, High Falls Shale, and Binnewater Sandstone). These are overlain by waterlimes of the Rondout and Manlius formations. These, in turn, grade upward into a magnificent collection of dominantly biohermal carbonates of the Helderberg Group of Latest Silurian-Early Devonian ages. (See Tables 2, 3, and 4.) Tables 3 and 4 list the local names of Silurian and Devonian formations of Layer III and their thicknesses throughout our field trip route for your reference. The carbonates, together, must have formed an impressive carbonate bank analagous to the present-day Bahama Banks off the southeastern United States.

Gradually, the carbonate succession was replaced by conglomerate, chert, siltstone, shale, and eventually coarse clastics that grade upward into the famous Catskill redbeds or "Old Red Sandstone". Thus, the Catskill fan- and delta complex was built upon the carbonate bank as uplift and erosion of the Acadian orogenic belt (in New England) shed coarse clastics continentward and eventually, but not without occasional marine incursions, built up an intracontinental delta. So the next time your friends invite you to go to "the Catskill Mountains" be sure to correct your friends, resolutely, by informing them that "they're not mountains, they are a dissected, uplifted fan-delta complex!".

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

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 intrusive 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.

The Newark sedimentary strata were deposited in a fault-bounded basin bounded on the northwest by the Ramapo fault (Figure 4) to which the sea never gained access. In this basin, the filling strata were deposited in various nonmarine environments, including subaerial fans, streams, and shallow- and deep lakes. Lake levels varied according to changes in climate.

After the Newark strata had been deeply buried, they were elevated and tilted, probably during a period of mid-Jurassic tectonic activities. They were then eroded and truncated to form a surface upon which the Upper Cretaceous and younger coastal-plain strata were deposited.

GEOLOGIC STRUCTURE - A PRIMER

Geologists use terminology to confuse the layman and to enable them to amass a huge library of terms that are undeniably useless in most social situations. Luckily, our On-The-Rocks trips are an exception. We will not try to bury you in a mountain (how about a deeply eroded mountain range?) of terms to help you understand the major types of structures and geologic features that you will read- and hear about today. But, if you are to understand what we are talking about, you need to know some important definitions. In the following section, we describe folds, faults, surfaces of unconformity, sedimentary structures, and structures in sedimentary- vs. metamorphic rocks.

We begin with some concepts and definitions based on the engineering discipline known as strength of materials. Given today's sophisticated laboratory apparatus, it is possible to subject rocks to temperatures- and pressures comparable to those found deep inside the Earth.

Imagine taking a cylinder of rock out of the Earth and torturing it in a tri-axial compression machine to see what happens. Some geologists get a big charge out of this and tell us (the field geologists) that they really understand how rocks behave under stress. [CM thinks they need to perform these experiments over a longer time frame than a few generations of siblings will allow and thus relies more on field observation and inference than from rock-squeezing data to gain a feel for the complex nature of how rocks are deformed in nature.]

Despite the limitations of the experimental work, measurements in the laboratory on specimens being deformed provide some fundamental definitions. One key definition is the elastic limit, which is the point at which a test specimen no longer returns to its initial shape after the load has been released. Below the elastic limit, the change of shape and/or volume (which is known as strain) is proportional to the stress inside the specimen. Above the elastic limit, the specimen acquires some permanent strain. In other words, the specimen has "failed" internally. Irrecoverable strain manifests itself in the distorsion of crystal lattices, grain-boundary adjustments between minerals composing the rock, and minute motions along cleavage- or twin planes.

When differential force is applied slowly (or, according to CM, over long periods of time), rocks fail by flowing. This condition is defined as behaving in a ductile fashion (toothpaste being squeezed out of a tube is an example of ductile behavior). Folds are the result of such behavior. If the force is applied under low confining pressure or is applied rapidly (high strain rates), rocks do not flow, but fracture. This kind of failure is referred to as rocks behaving in a brittle fashion (as in peanut brittle). The result is faults or joints. Once a brittle failure (fracture) has begun, it will propagate, produce offset, and form a fault surface.

In some cases, during deformation, rocks not only undergo simple strain, but also recrystallize. New metamorphic minerals form and newly formed metamorphic minerals acquire a parallel arrangement. More on metamorphic textures later. From the laboratory studies of rock deformation, a few simple relationships are generally agreed upon regarding brittle- and ductile faulting and these are discussed below.

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. Geologists try to sort out the effects of deformation by working out the order in which these surfaces or linear features formed using a relative nomenclature based on four letters of the alphabet: D, F, S, and M. Episodes of deformation are abbreviated by (Dn), of folding by (Fn), of the origin of surfaces (such as bedding or foliation) by (Sn), and of metamorphism by (Mn), where n is a whole number starting with 1 (or in some cases, with zero). 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 history of an area, for example, one might write: "During the second deformation (D_2), F_2 folds formed; under progressive M_1 metamorphic conditions, an axial-planar S_2 foliation developed."

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 sediments in the earliest stage of the formation of sedimentary rock. Imagine how such strata, buried by the weight of overlying strata and laterally compressed by the advance of lithospheric plates, are subjected to the differential force necessary for folds to form. Contrary to older ideas, we now realize that vertical burial cannot cause regional folds (although small-scale slumping and stratal disharmony are possible). Rather, tangential force must be applied to provide the driving force to create folds and faults.

It's 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.

Folds

If layers are folded into convex-upward forms we call them anticlines. Convex-downward fold forms are called synclines. In Figure 10, note the geometric relationship of anticlines and synclines. Axial planes (or axial surfaces) physically divide folds in half. Note that in Figure 10, the fold is deformed about a vertical axial surface and is cylindrical about a linear fold axis which 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 parallel to the fold axis). This is geometry folks; we have to keep it simple so geologists can understand it.

In eroded anticlines, strata forming the limbs of the fold dip away from the central hinge area or core (axis) of the structure. In synclines, the layers forming the limbs dip toward the hinge area. Given these arrangements, we expect that in the arches of eroded anticlines, older stratigraphic layers will peek through whereas in the eroded troughs of synclines, younger strata will be preserved.

In metamorphic terranes, field geologists are not always sure of the correct age relationships of the metamorphosed strata. Therefore, it is helpful to make use of the general terms antiform and synform which describe the folds by whether they are convex upward (antiform) or concave upward (synform) but do not imply anything about the relative ages of the strata within them.

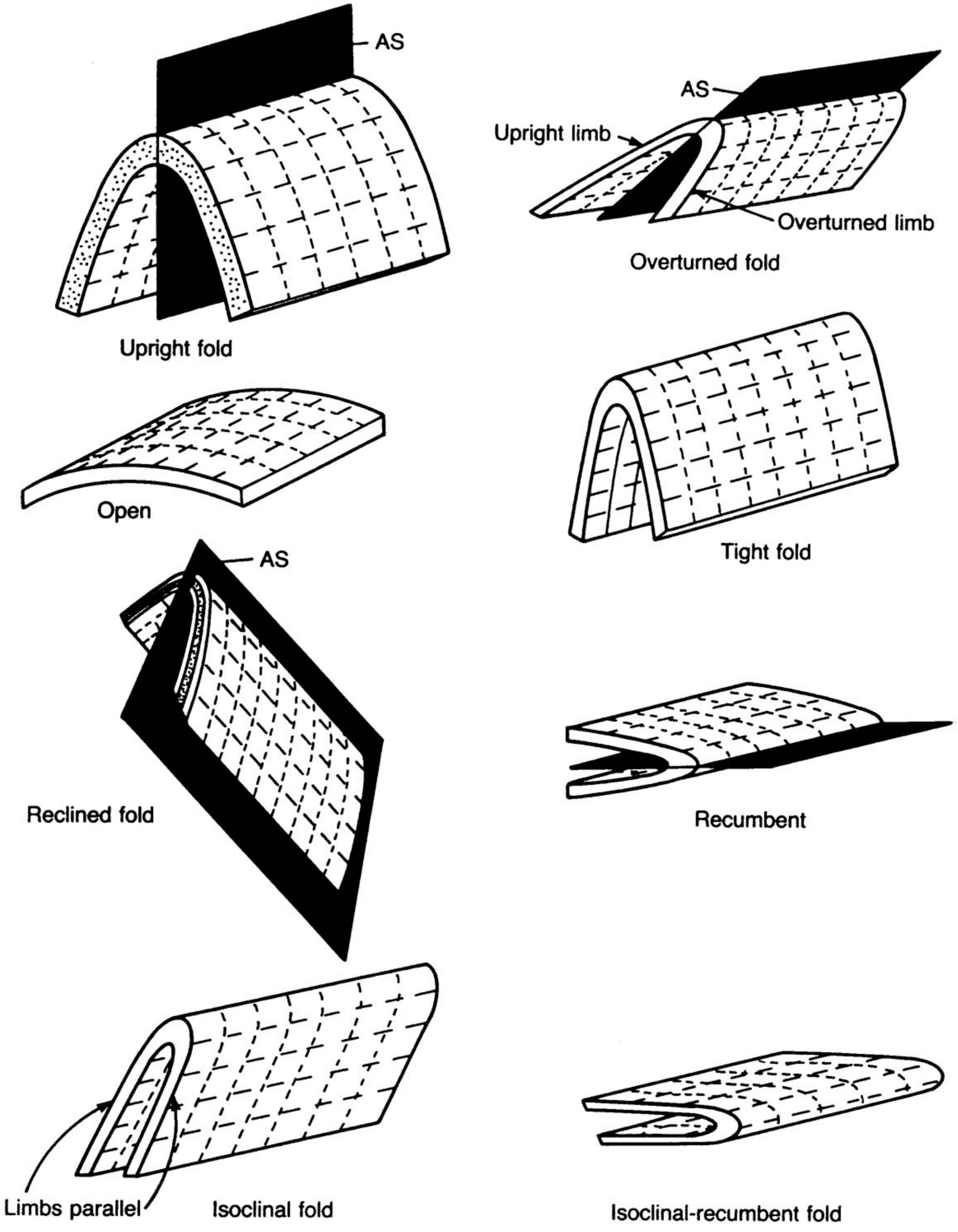


Figure 10 - Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the text.

Realize that in the upright folds shown in Figure 10, 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) 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. 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 re-oriented remnants of stratification (except of course in the hinge areas of folds). Thus, in highly deformed terranes, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they tend to mark regional fold-hinge areas.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine that axial surfaces can be tilted, to form inclined or overturned folds. Or the axial surfaces may be sub-horizontal, in which case the term recumbent folds is used. In both overturned folds and recumbent folds, the fold axes may remain subhorizontal. (See Figure 10.) It is also possible for an axial surface to be vertical but for the orientation of the fold axis to range from horizontal to some angle other than 0° (thus to acquire a plunge and to produce a plunging fold). Possible configurations include plunging anticlines (or -antiforms) or plunging synclines (or -synforms). Vertical folds (plunging 90°) are also known; in them, the terms anticline and syncline are not meaningful. In reclined folds, quite common in ductile fault zones (See below.), the fold axes plunge directly down the dip of the axial surface.

In complexly deformed mountain ranges, most folds show the effects of more than one superposed episode of deformation. As a result of multiple episodes of deformation, the ultimate configuration of folds can be quite complex (i e., plunging folds with inclined axial surfaces and overturned limbs).

We need to mention one other point about the alphabet soup of structural geology. Seen in cross section, folds fall into one of three groups, the S's, M's, and the Z's. Usually only one variety of small folds will be found on a given limb of a larger fold. Therefore, if one notices a change in the pattern from S folds to Z folds (or vice versa), one should be on the lookout for a fold axis. The hinge area is dominated by M-folds (no sense of asymmetry).

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the main forces that produced the fold. Therefore, the orientation of the folds give some hint as to the direction of application of the active forces (often a regional indicator of relative 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. In these instances, simple analysis is often not possible. Rather, a range of possible explanations for a given structural event is commonly presented.

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) that may possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides (Figure 11).

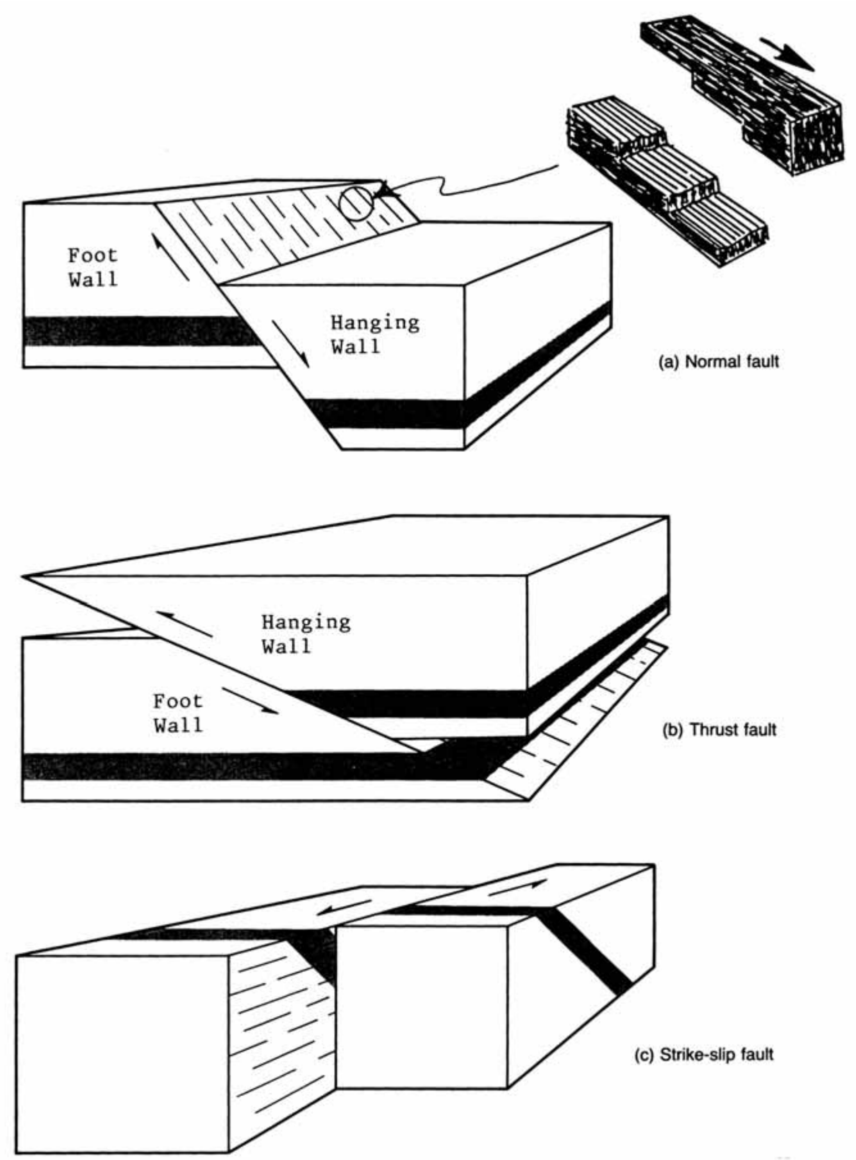


Figure 11 - The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (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 tension fractures) can be used to infer sense of relative motion. [(a), (b), (c), Composite diagram from introductory texts; (d), J. E. Sanders, 1981, fig. 16.11 (b), p. 397.]

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 11 (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 11 (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. 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 11 (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.

Two basic kinds of shearing couples and/or strike-slip motion are possible: left lateral and right lateral. These are defined as follows. Imagine yourself 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 11 (c)]. If the block across the fault appears to have moved to the right, the motion is right lateral. Convince yourself that no matter which block you can choose to observe the fault from, 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 fault breccias and cataclasites (including fault gouge, fault breccia, and others). Starting at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallizing during flow. These unique metamorphic conditions prompt the development of highly strained (ribboned) quartz, feldspar porphyroclasts (augen), and frayed micas, among other changes, and results in highly laminated 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, a recrystallized ductile shear zone showing post-tectonic brittle reactivation, is an original ductile fault zone (mylonite) having a complex geologic history.

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 12), such surfaces represent mysterious intervals of geologic time where we really do not have a clue as to what went on! By looking elsewhere, the effects of a surface of unconformity of regional extent can be recognized and piecemeal explanations of evidence for filling in the missing interval may be found.

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.

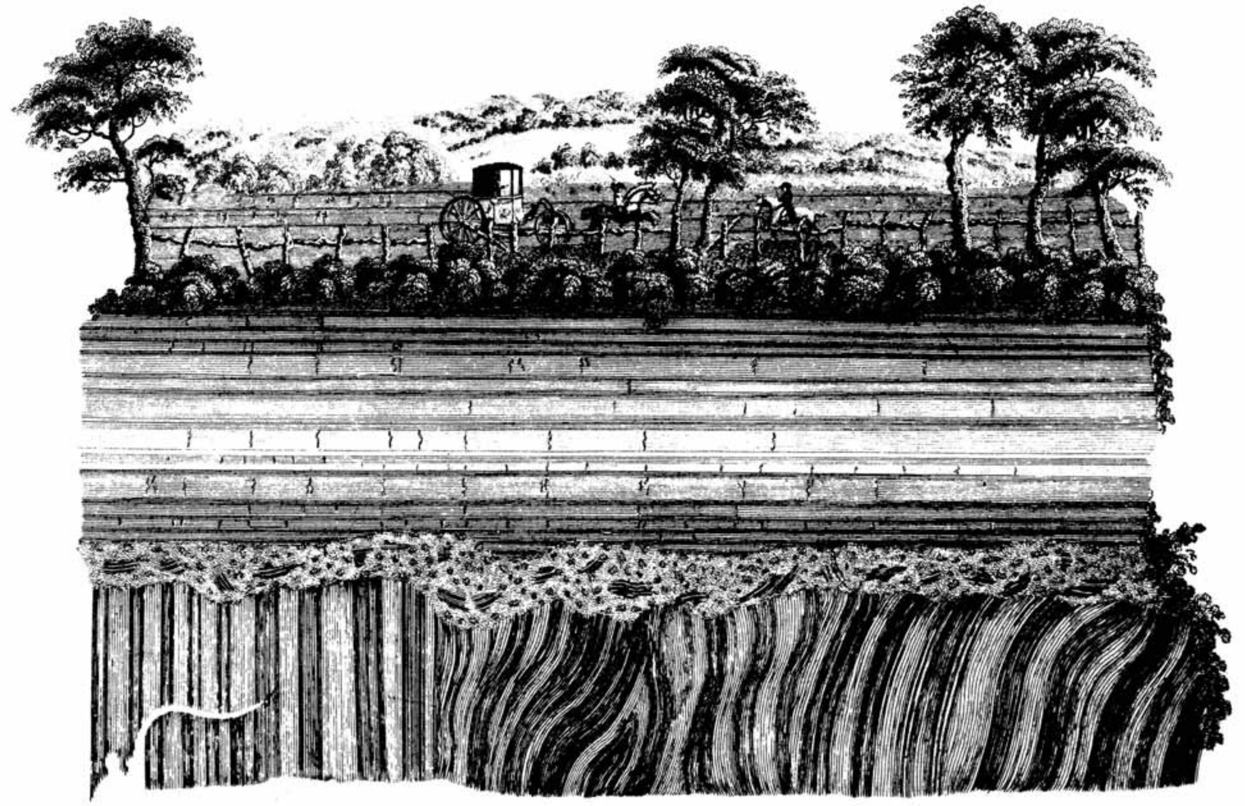


Figure 12 - Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's Theory of the Earth, (1795).

Sedimentary Structures

During deposition in a variety of environments, primary- and secondary sedimentary structures can develop above-, below-, and within strata. During normal deposition, or settling from a fluid in a rainfall of particles, massive, essentially poorly stratified successions may result. The presence of strata implies a change in deposition and as a result most geologists appreciate the significance of layering in sedimentary rocks as marking CHANGE in big letters, be it a change in parent area of the sediment, particle size, or style of deposition. Thus, bedding can best be viewed as marking the presence of mini-surfaces of unconformity (diastems). During high-energy transport of particles, features such as cross beds, hummocky strata, asymmetric current ripple marks, or graded beds result. Cross- and hummocky bedding, and asymmetric current ripple marks are deposited by moving currents and help us unravel the paleocurrent directions during their formation. Graded beds result from a kind of a "lump-sum distribution" of a wide range of particles all at once (usually in a gravity-induced turbidity flow). Thus, graded beds show larger particle sizes at the base of a particular layer "grading" upward into finer particles.

Secondary sedimentary features are developed on already deposited strata and include mud (or desiccation) cracks, rain- drop impressions, sole marks, load-flow structures, flame structures, and rip-up clasts. The last three categorize effects produced by a moving body of sediment on strata already in place below. A composite diagram illustrating these common structures is reproduced in Figure 13.

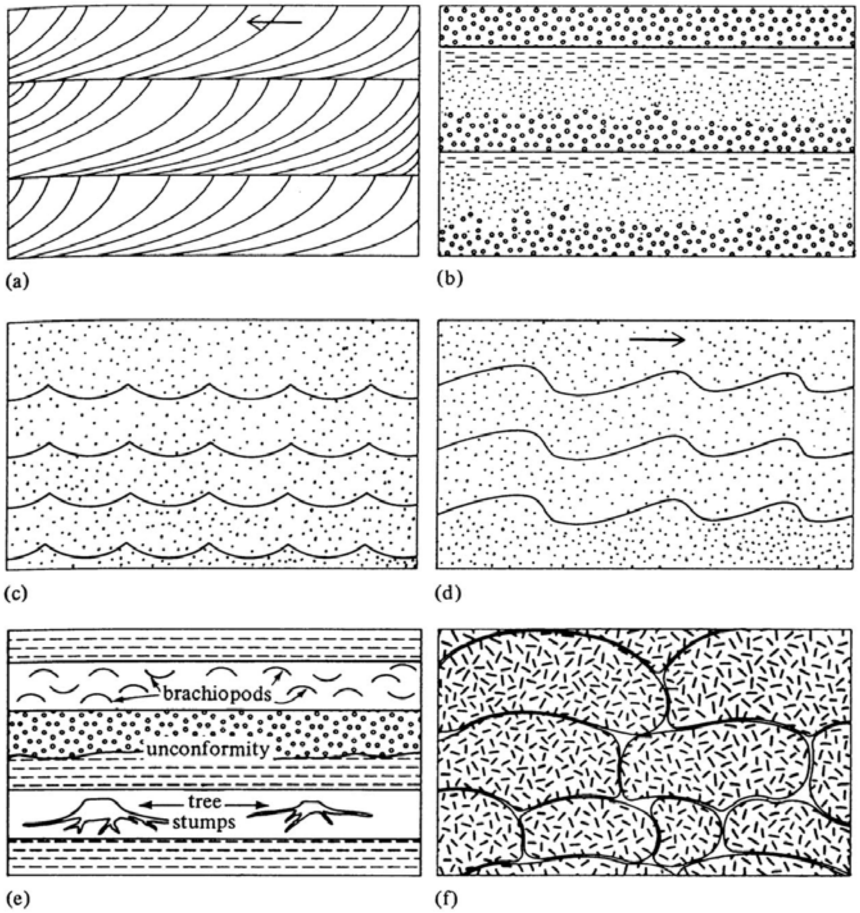


Figure 13 - Diagrammatic sketches of primary sedimentary structures used in determining topping (younging) directions.

Together, these primary- and secondary sedimentary structures help the soft-rock structural geologist unravel the oft-asked field questions - namely.... Which way is up? and Which way to the package store? The direction of younging of the strata seems obvious in horizontal- or gently tilted strata using Steno's principle of superposition. But steeply tilted-, vertical-, or overturned beds can be confidently unravelled and interpreted structurally only after the true topping (stratigraphic younging) direction has been determined. As we may be able to demonstrate on this field trip, simple observations allow the card-carrying geologist to know "Which way is up" at all times.

Structures in Sedimentary- vs. Metamorphic Rocks

For hard-rock geologists working in metamorphic terranes, simple sedimentary observations will not allow the card-carrying geologist to know "Which way is up" at all. Rather, because of intense transposition and flow during ductile deformation, stratification, fossils for age dating, tops and current-direction indicators are largely useless except to identify their hosts as sedimentary protoliths. Thus, according to CM, "at the outcrop scale, metamorphism can best be viewed as the great homogenizer." Commonly during metamorphism, the increase in temperature and -pressure and presence of chemically active fluids severely alter the mineral compositions and textures of pre-existing rocks. As a result, in many instances, typical soft-rock stratigraphic- and sedimentologic analysis of metamorphic rocks is not possible.

SOME GEOLOGIC ARM WAVING

Under this heading we include some remarks about the geologic age of deformation, the sizes of folds, the trends of folds, and structural style with reference to the features we shall see on this trip.

Age of Deformation

No new data have changed the long-established geologic fact that the youngest deformed strata in the Little Mountains are of medial Devonian age. Therefore, the final deformation of the strata in the Hudson Valley could have occurred any time after the middle of the Devonian Period (Schuchert and Longwell, 1932, p. 323; Chadwick and Kay, 1933, p. 7; Rodgers, 1967b, p. 416; and others).

But, as is explained subsequently, certain geologic ideas are like cats (they have 9 lives) or a pendulum (they swing back and forth). The swinging has been back and forth has been between late in the Paleozoic Era (the Appalachian orogeny) and Medial Devonian (the Acadian orogeny).

Starting in the late nineteenth century, geological authors writing about the age of deformation of the strata in the Hudson Valley preferred a late Paleozoic age (W. M. Davis, 1882, 1883; van Ingen and Clark, 1903; Ruedemann, 1942). A reversal began in 1930, when Charles Schuchert, the great promoter of the idea that the Appalachian orogeny was a monumental geologic revolution that brought the Paleozoic Era to a close, began to emphasize the importance of the Acadian orogeny. The ultimate humiliation to the Appalachian orogeny was proposed by Woodward (1957a, b). Because he believed that the effects of the Appalachian orogeny had been overstated, Woodward proposed that the late Paleozoic deformation in the Appalachians cease being known as the "Appalachian orogeny" and henceforth rejoice in the designation of "Alleghanian disturbance."

The current fashion is to base one's belief about this age question on various structural considerations. A few of the possibilities in this department include: (a) sizes of folds, (b) trends of folds, and (c) structural "style." The following paragraphs take up these topics.

Sizes of Folds

Shaler (1877), W. M. Davis (1882, 1883), and Sanders (1969) have expressed the view that the Little Mountains are simply miniature northward extensions of the larger folds of the Valley and Ridge province of Pennsylvania. By contrast, Chadwick (in Goldring, 1943, p. 288) and Woodward (1957a, b) took the position that difference in size means difference in age.

Typical amplitudes of folds serve as an index of size. In the Little Mountains, typical fold amplitudes are 0.4 to 0.75 km (Babcock, 1966 ms.). In the central Appalachians of Pennsylvania, fold amplitudes are in the range of 8 to 16 km (Gwinn, 1964).

The change in sizes of folds takes place southwest of Kingston, New York. As emphasized by JES (Sanders, 1969, p. 19-27), this change coincides with changes in the thickness and characteristics of the Silurian strata. To quote from the JES argument:

> "Where thick competent units are present in the succession, the folds are 'big'; by contrast where thick, competent units are not present in the succession, the folds are 'little.' I think the matter of size of folds resolves itself to this stratigraphic factor. If so, then the contrast in size of folds between 'Little Mountains' and central Pennsylvania is not an argument that supports different times of deformation. Rather, insofar as age of deformation is concerned, size of folds becomes irrelevant and size indicates only a contrast in thickness and competency of units deformed."

As far as we are concerned, nothing that has appeared in the geologic literature in the past 21 years requires any change in the foregoing paragraph.

Trends of Folds

Use of fold trends to determine ages of deformation is based on the proposition that in any single orogeny, only one trend of folds will be formed. If this proposition is resolutely true, then in any given region, the existence of folds of more than one trend implies more than one orogenic event. Woodward (1957a, b) used this two-trend approach to argue that the deformation of the Little Mountains east of the Catskills had been Acadian. He argued that in southern New York, the trend of the Appalachian (his "Alleghanian") folds is E-W. The trend of the folds in the Little Mountains east of the Catskills is N-S. As noted by Rodgers (1967a), some of this change of trend takes place at Kingston, where the folds change in size.

JES argued that this two-trend business is a double-edged sword and that even if the supposed difference in trends is an indicator of discrete orogenic events, the two orogenies involved could have been Appalachian first and mid-Jurassic second (Sanders, 1969, p. 19-28). JES argued that the E-W trend of the Appalachian structures in eastern Pennsylvania is a product of oroclinal bending (Carey, 1953) of the mountain belt and that such bending involves not only the Paleozoic strata but the Newark strata as well. Accordingly, the age of the oroclinal bending must be post-Early Jurassic. Because the Late Cretaceous coastal-plain strata bury this curved part of the Appalachians, the bending must be pre-Late Cretaceous.

Wrote JES (Sanders, 1969, p. 19-28):

> "If two fold trends are really present in the sense of Woodward and if these trends indicate two orogenies, then these fold trends could as well be products of Appalachian and Jurassic orogenies as of Acadian and Appalachian orogenies. In short, the argument based on the supposed two fold trends, even if these two trends really do exist, is not conclusive as Woodward supposed."

Structural Style

The concept that each orogeny is characterized by a distinctive style of deformation is another slippery sort of business that has prompted large amounts of geologic arm waving. The idea seems sound enough but is not always easy to apply. In the case at hand, because no agreement exists on what structures are Acadian and what structures, Appalachian, how can "style" be resolved? JES has no idea what should be considered Acadian style, but the regional evidence amassed from Pennslvania southward and now creeping into New York, is that Appalachian style involves large-scale bedding thrusts (J. L. Rich, 1934). JES discovered such thrusts in the Little Mountains in 1969; they are now popular topics of research (Marshak, 1986; Marshak and Tabor, 1989).

JES argues that even the structural style is not a conclusive kind of argument for age of deformation. CM adds that because deformational style is dependant upon so many elusive factors, including composition, texture, thickness, layering or other anisotropy, relative mechanical strength of adjacent layers, as well as prevailing P-T conditions, that correlations utilizing style alone, in the absence of stratigraphic and geochronologic data, is scientifically indefendable. Pending some new kind of geologic magic, the age question seems likely to remain in the category of geologic "religion" and that firmly held beliefs will continue to fuel more arguments than will well-established geologic evidence.

GLACIAL HISTORY

The subjects of glacial history and drainage are not high on our agenda for this trip, but on trips in New York State are topics that one can scarcely neglect, no matter what other points of emphasis one selects. Under glacial history we discuss the relationship between glacial ice and the Catskills, particularly with reference to thickness of the glacier(s), glacial sediments, and effects of glaciers on the Earth's lithosphere.

Glacial Ice and the Catskills

When geologists were finally convinced that northeastern United States had been covered by one or more now-vanished continental glaciers, they were naturally curious as to how thick the ice had been. In pursuit of this curiosity, they climbed the highest peaks and looked for signs of glacial action. For example, they found glacial striae oriented NNW-SSE on Mount Washington, the highest peak in New England (J. W. Goldthwaite, 1916). These striae displayed resolute parallelism over hill and dale alike. This would have been possible only where the thickness of the glacier had been so huge that the flow direction was determined by the slope of the top of the ice, not by any relief of the land over which the ice eventually flowed.

But, in the Catskills, the relationships between the land and former ice were not so straightforward as at Mount Washington. In order to determine the details of the glacial history of the Catskills, the New York Geological Survey engaged the services of Professor J. L. Rich, from the University of Cincinnati. At the same time, G. H. Chadwick was also employed by the New York State Geological Survey to be their expert on the bedrock of the Catskills. JES has not examined the possible complications of this Rich-invading-Chadwick-territory situation, but one thing is clear: Rich (1915) initially announced a great finding: glacial ice had not covered the top 300 feet or so of Slide Mountain (elev. 4205). G. H. Chadwick (1928) challenged this; he found glacially striated bedrock at the very top of Slide Mountain. Accordingly, in 1935, when his monograph was published, Rich backed off from his earlier position and accepted Chadwick's result. Rich inferred that his earlier conclusions referred to the latest glacier and that what Chadwick had found was evidence for an earlier glaciation from a thicker ice sheet.

Chadwick's brief mention of the glaciation at the top of Slide Mountain did not include any data on the directional orientation of the striae he found. JES thinks Chadwick's result has not been appreciated as much as it should have been. First of all, it implies that the thickness of the earlier glacier had been greater than that of the latest glacier (a conclusion that is supported by evidence from elesewhere, but it would be neat to have some specific numbers). Secondly, what was the flow direction of that thicker, earlier glacier? JES would bet a few beans that the earlier, thicker glacier flowed from NNW to SSE. JES hopes one day to climb to the top of Slide Mountain to check all this out.

Glacial Sediments

We do not expect to see any glacial sediments close up, but will be driving by many drumlins. One can recognize the drumlins from the NYS Thruway by the locations of the apple orchards, illustrations of Millington's (1930) Law (formerly misconstrued as Sanders' Law of

Apple Orchards). Chadwick (1944, p. 188) found a large drumlin, 1.5 mi long on the summit of Bethel ridge in the Catskill 15-minute quadrangle.

Effects of a Glacier on the Earth's Lithosphere

When a continental glacier invades a region, its effects are not limited to the Earth's surface. Indeed, noteworthy changes take place at depths reaching to the base of the lithosphere, in the upper part of the Earth's mantle. The weight of the glacier displaces some of the sub-lithospheric material (within a layer known as the asthenosphere). This causes the top of the lithosphere to subside, invading the territory of the asthenosphere. After the ice has melted, the displaced parts of the asthenosphere flow back again, and the surface of the lithosphere is elevated (Daly, 1934). This kind of activity has been named isostasy, or isostatic compensation. The amount of depression of the surface of the lithosphere is related to the thickness of the continental glacier. Where the glacier was thickest, the amount of lithosphere subsidence is greatest. As a result, after the ice has melted, the greatest amount of so-called glacial rebound likewise takes place where the ice was thickest.

DRAINAGE HISTORY

We confine this brief discussion of the drainage history to the postglacial drainage and divide it into two parts: drainage in the Appalachian Valley and Ridge Province, and drainage in the Catskills. Even a cursory review of what has happened since the last glacier melted indicates that sesveral drainage anomalies are present. In this discussion, we can ignore the possibilities for drainage changes assoiated with earlier glaciations.

Drainage in the Appalachian Valley and Ridge Province

In the Hudson Valley, the major drainage route in the Appalachian Valley and Ridge Province in southeastern New York, isostatic rebound has been demonstrated. The chief points of reference in this demonstration are elevations on shoreline features built by postglacial lakes. These were horizontal initially but now are inclined toward the south. This incination has resulted from greater amounts of rebound in the north, where the glacier was thicker. If nothing else has been going on, then this regional tilting toward the south should have controlled the directions of flow of postglacial rivers. In short, they should all flow to the south.

The Hudson is an example of a river that flows in the expected direction. The Ramapo River is another example. The headwaters of the Ramapo River are in Central Valley, just west of where we shall leave the Thruway for our side trip to Highland Mills. As we drive along the Thruway, it is possible to see the Ramapo River from time to time and to notice that the water flows southward, opposite the direction in which we are driving.

But, at Highland Mills, we encounter Woodbury Creek, which flows northward. Woodbury Creek joins Moodna Creek at Mountainville (Cornwall quadrangle) and the combined flow enters the Hudson just south of Sloop Hill (Cornwall). The Woodbury-Moodna network is one of at least three drainage systems that flow considerable distances northward or northeastward into the Hudson River. The largest such drainage system is the Wallkill. The headwaters of the Wallkill are southwest of Sparta, NJ. The waters flow northeastward from New Jersey into New York and are there augmented by waters from the Shawangunk Kill and other tributaries that flow NE (Figure 14).

East of Rosendale, the Wallkill is joined by Rondout Creek, which drains a network heading in the Catskills. After leaving the Catskills, Rondout Creek flows northeastward in the strike valley formed by the weak Silurian and Devonian strata lying NW of Shawangunk Mountain. A noteworthy tributary of the Rondout with headwaters in the Shawangunk Mountains is the Sanders Kill. The combined Rondout-Wallkill flow drains into the Hudson River at Kingston. There it forms a barbed tributary (a tributary entering a main stream with the acute angle between them on the downstream side, with reference to the flow direction of the main stream). This is unusual, because the downvalley slope of the main stream usually causes entering tributaries to flow downvalley and thus to make an acute angle with the main stream on the upstream side. In the case of the barbed tributaries of the Hudson, the relationship is doubly peculiar because the downvalley slope of the Hudson has been increasing with time as a result of postglacial rebound.

Drainage in the Catskills

A contrasting kind of drainage peculiarity is shown at Haines Falls, in the Catskills. Here, rapid headward erosion in postglacial time has enabled Kaaterskill Creek to erode Kaaterskill Clove. Kaaterskill Creek is a short, steep tributary of the Hudson. At Kaaterskill Falls, just west of South Lake, a branch of Kaaterskill Creek has diverted and captured the drainage from a broad, open valley that trends E-W (Darton, 1896). This same open valley extends westward from Haines Falls and Tannersville. West of Tannersville, the west-flowing drainage of this open valley joins Schoharie Creek, which flows northward out of the Catskills at Middleburg, then continues north to join the Mohawk west of Amsterdam. From there, the water flows eastward to the Hudson just south of Waterford.

Figure 14 - Physiographic diagram showing the Catskills and Little Appalachians with major drainages.

BEDROCK UNITS TO BE EXAMINED DURING THE TRIP

This discussion is organized into two parts, Day 1 and Day 2. A certain amount of overlap and repetition is involved in such an arrangement, but we hope that participants find this plan is one that assists them in becoming familiar with the formations we will examine on our trip.

Bedrock Units to be Seen on Day 1

The bedrock units to be seen on Day 1 begin with the Proterozoic gneisses of the Hudson Highlands, to be studied at Stop 1, and include sedimentary units of Ordovician, Silurian, and Devonian ages. Because the Proterozoic gneisses are not central to the theme of this trip, nothing further is included here. The description of Stop 1 should suffice. Our focus on this trip is on the so-called Taconian unconformity, below which are the Ordovician formations and above which are the Silurian and Devonian units. We first examine some Devonian strata in the Schunnemunk-Green Pond graben (not related to the Taconian unconformity) and then focus on the Ordovician and post-Taconian units.

Devonian strata crop out in the old Highland Mills Railroad Station, Stop 2. The sucession of units in this region has been established by Boucot (1959) and by Boucot, Gauri, and Southard (1970) as shown in Table 3. We will study the Highland Mills member of the Esopus Formation. Later today, on the drive to Kingston after the Williams Lake transect (Stop 7), we will pass exposures of the more-uniform siltstone of the Esopus which typify that formation in the central Hudson valley.

Ordovician strata, along N.Y. Route 213, by Thruway bridge over Wallkill River, Stop 3. We have selected this locality to study the Ordovician strata that are part of the Taconian fold belt that was eroded, submerged, and buried by the Silurian-Devonian carbonates. As some may recall from On-the-Rocks Trips 8 and 22 to the Taconic ranges, the subject of the classification and nomenclature of the Ordovician terrigenous strata in the Hudson Valley is best described as being in a state of flux. The problem name is "Normanskill." Given the chaotic situation surrounding "Normanskill," one seeks other alternatives. We have in the past opted for "Martinsburg," but a veteran student of the Martinsburg of eastern Pennsylvania and northwestern New Jersey, Jack Epstein, of the U. S. Geological Survey, contends that the proposed substitution is not appropriate. Our alternative to returning to the older name of "Hudson River" slates or what have you, is to use the Sloss (1963) term Tippecanoe Sequence. The alternating sandy (graywacke) layers and silty layers exposed at Stop 3 are examples of the deep-water marine deposits that accumulated in the Hudson Valley and vicinity after the former shallow-water area had been subaerially exposed, eroded, and resubmerged, this time to much-greater depths. Brachiopods have been found in some of the sandstones here. Elsewhere, fossils include graptolites and even small eurypterids (New York State's official "State Fossil"--did you know that?).

Silurian conglomerates, sandstones, shales (Stops 4, 5, 6, and 7). One of the main points of emphasis of this trip is the northeastward thinning- and eventual disappearance of the Lower and Middle Silurian conglomerates, sandstones, and shales, here encompassed within the

Shawangunk Conglomerate, High Falls Shale, and Binnewater Sandstone. In the area of this trip, the morphologic expression of the Shawangunk, particularly, contrasts decidedly with that in localities farther southwest. To the SW,the tilted edge of the thick Shawangunk Formation forms a strike ridge that dominates the local landscape (Shawangunk Mountain, Kittatinny Mountain). We will see it forming insignificant local "bumps" at most. A striking feature of the Shawangunk is the abundance of white quartz pebbles and general rarity of pebbles of slates, siltstones, and graywackes, the predominant lithologic constitutents of the Ordovician orogenic belt that the Shawangunk buries. Jack Epstein (in Prave, Alcala, and Epstein, 1989) has found a unit composed of unusual pebbles at the base of the Shawangunk. These pebbles include a wide variety of rock formations other than white quartz; the parent deposits of many of them have not yet been identified. On our trip, we will not see the base of the Shawangunk; hence we do not anticipate finding any comparable pebbles.

The High Falls Shale can be visualized as a fine-textured unit sandwiched between two coarser formations, the Shawangunk below and the Binnewater above. To order one in a deli, one would ask for "red shale on white sandstone, hold the mustard."

Silurian-Devonian ("Helderbergian") carbonates (Stops 4, 5, 6, and 7. The names and general characteristics of the Helderbergian carbonates are shown in Table 4. As a first approximation, we can divide these into four categores: (1) the Rondout Formation of interbedded limestones and silty dolostones (the "cement" rocks); (2) the Manlius Formation (laminated limestones and interbedded layers of algal stromatolites); (3) a lower upward-fining cycle of three units (Coeymans, Kalkberg, and New Scotland); and (4) an upper upward-fining cycle of three units (Becraft-Alsen-Port Ewen). We expect participants to be able to recognize all of these units by noon of Day 2. We will encounter them from base upward, and on Day 1 emphasize the Roundout and Manlius formations. We will use the member names for the Rondout (from base upward, Wilbur Limestone, Rosendale Dolostone, Glasco Limestone, and Whiteport Dolostone), but only the single formation name, Manlius, for what overlies the topmost Rondout.

An important point that we shall address is the evidence bearing on the style of deposition. In particular, we shall try to determine if the successions of various layers imply that the marine water in which they were deposited was becoming deeper with time or just the opposite. In other words, are there upward-deepening successions as contrasted with upward-shallowing- (or -shoaling) successions? An upward-deepening-succession might begin at the base with beach-type sediments and pass upward into nearshore marine deposits laid down seaward of the effects of shoaling waves. An upward-shoaling succession begins with subtidal sediments and ends upward with sediments deposited on an intertidal flat or a supratidal flat. An upward-deepening succession implies that sediments accumulated while a region was being submerged. An upward-shoaling succession implies a rapid submergence, without much sediment accumulation, and then the building of stratigraphic units outward as the shoreline was prograded seaward. The concept of upward-shoaling cycles was first developed in Europe early in the twentieth century and has been "re-discovered" and touted as a fundamental "new" geologic truth by the PACmen Anderson and Goodwin. These investigators have proposed the name PAC (acronym for punctuated aggradational cycle) for upward-shoaling successions of strata deposited as a result of rapid submergence and subsequent seaward progradation. We will be trying to decide if the geologic world of nearshore sedimentary strata consists entirely of PACs or of whatever.

Bedrock Units to be Seen on Day 2

On Day 2, we will continue and refine our studies of the Helderbergian carbonates by studying localities (Stops 9, 10, 16, and 17) where the Rondout rests directly on the deformed Ordovician strata (no Shawangunk, High Falls, or Binnewater) and by including a locality (Stop 12) where we can study the upper fining-upward cycle (Becraft, Alsen, Port Ewen) and compare it with the lower fining-upward cycle (Coeymans, Kalkberg, New Scotland; Stops 11 and 16). We will expand our coverage of the Devonian strata to include the Mount Marion Formation (youngest Devonian marine formation in these parts) and the so-called Catskill "redbeds" (nonmarine strata that prograded westward as the Acadian orogeny took place off to the east).

This ends our discussion of Geologic Background. We continue with our Objectives and the details of the trip.

OBJECTIVES

1) To familiarize you with the variety and depositional history of the Silurian and Devonian strata of Layer III in New York State.

2) To examine and understand the northeasterly stratigraphic thinning and ultimate pinchout of these units in comparison to their temporal equivalents toward the southwest.

3) To get close and personal with anticlines, synclines, faults, and other geologic structures.

4) To examine and use in the determination of topping direction, sedimentary structures such as graded beds, ripple marks, cross beds, etc.

5) To examine and marvel at the Taconic unconformity at a number of places.

6) To observe and hopefully, collect fossils from the Siluro-Devonian strata.

7) To perform a series of exercises in geologic mapping and compass techniques.

8) To test, in the field, the application of the PAC hypothesis in understanding sedimentation.

9) To witness, in a 350-million-year flashback, the depositional history of the Lower Paleozoic strata and to note the change from marine- to non-marine sedimentary successions, and,

10) To visit all of our intended field trip stops (Fat Chance! But 9 out of 10 ain't bad).

ROAD LOG AND DESCRIPTIONS OF LOCALITIES ("STOPS")

NYAS to NYS Thruway (I-87) via the George Washington Bridge (GWB) and Palisades Interstate Parkway (PIP). A detailed roadlog, for your driving and reading pleasure, will begin after Stop 1. Figure 15 is a regional highway map showing our field trip stops. For now, just a few general comments on what you will see between the NYAS and Stop 1 during our morning drive.

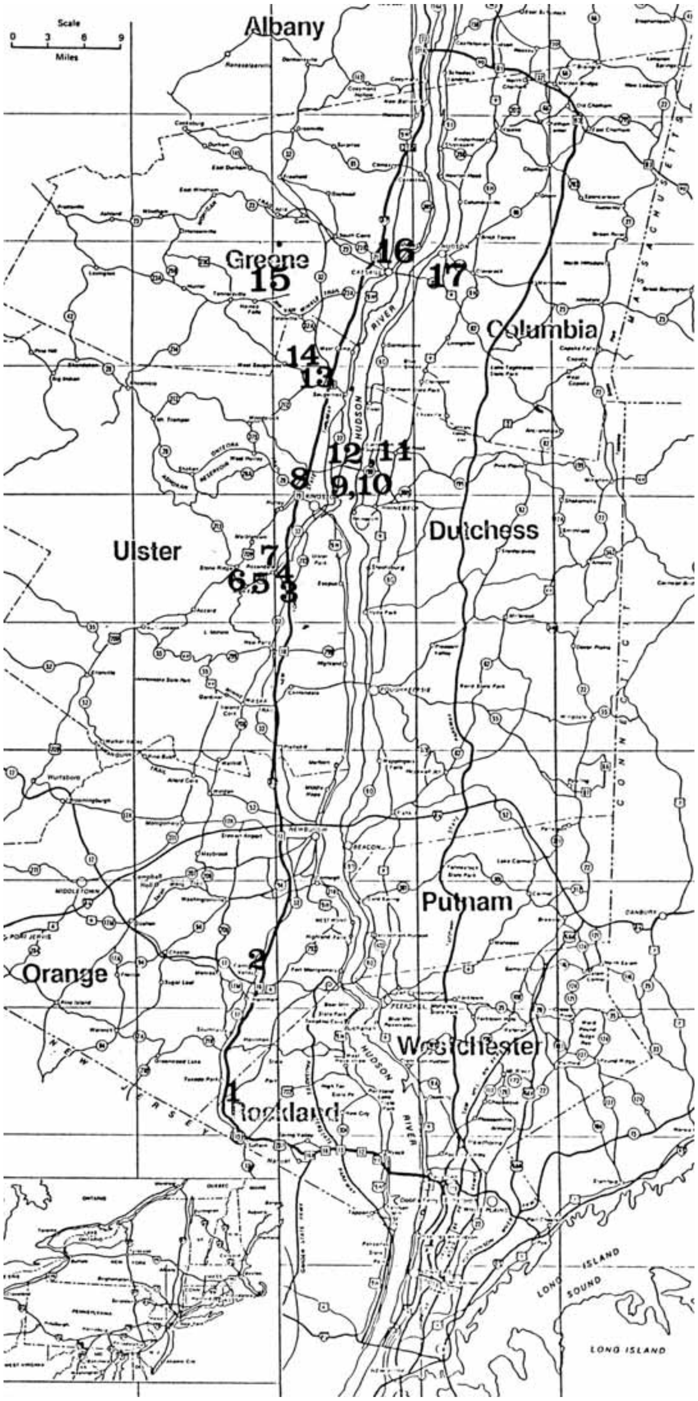


Figure 15 - Roadmap of our field trip route showing our Stop numbers 1-17.

Driving northward from the NYAS we travel upon the deeply eroded roots of the Appalachian mountain belt. In New York City, the southern terminus of the Manhattan Prong (See Figure 5), the bedrock consists of the Proterozoic Y Fordham Gneiss, overlain by the Cambro-Ordovician Inwood Marble, various tectonostratigraphic units of the Manhattan Schist, and allochthonous rocks of the Hartland Formation. Figure 16 is a geologic map of Manhattan and Figure 17 is an east-west structure section across the Manhattan-Bronx border. Together, they illustrate the structure and stratigraphy of New York City as mapped by CM. On our current trip, we will examine less-metamorphosed correlatives of the crystalline rocks that are beneath us here on Manhattan.

Driving across the George Washington Bridge, we pass from the Lower Paleozoic rocks of New York into the Mesozoic rock strata of New Jersey. Figure 18 is a diagrammatic cross section showing the folded rocks of New York City unconformably overlain by gently west-dipping, red-colored sediments and intercalated Palisades intrusive sheet of the Newark Basin. Driving northward on the PIP, all of the roadside cuts are mafic rocks (diabase) of the Palisades intrusive sheet.

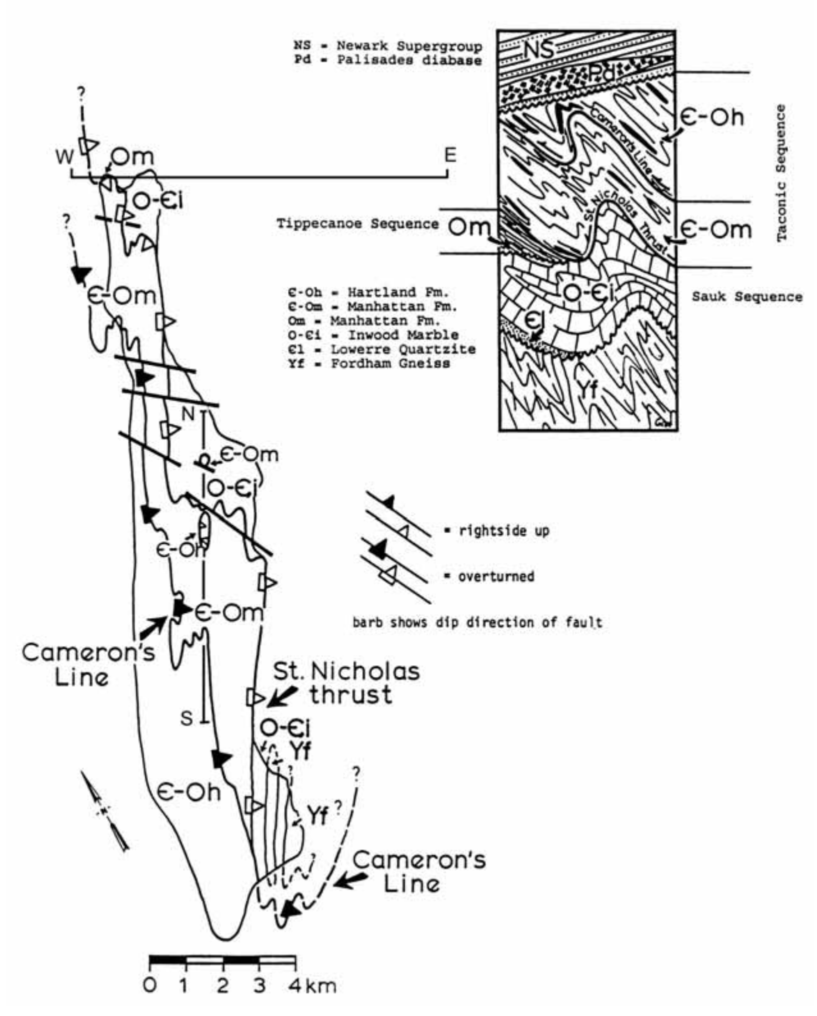


Figure 16 - Geologic map of Manhattan Island showing a new interpretation of the stratigraphy and structure of the Manhattan Schist. Drawn and mapped by C. Merguerian.

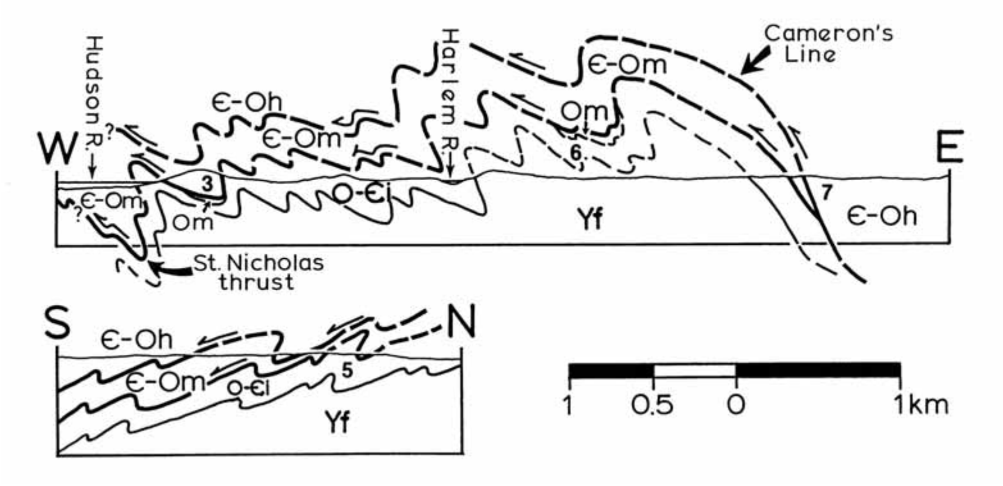


Figure 17 - Geologic cross section across northern Manhattan and the Bronx showing folded overthrusts (Cameron's Line and the St. Nicholas thrust), New York City. Symbols defined on Figure 16. (C. Merguerian).

Starting at the cloverleaf where we exit from the PIP to I-87, note the Newark conglomerate in cuts on right. Followed in 3.7 and 6.7 miles by more Newark conglomerate and sandstone in cuts on the right. We pass over the Ramapo fault at 8.7 miles just before Exit 15 (NY Route 17). Note the newly exposed high cut of Proterozoic rocks from Ramapo Mountains block on right. At 12.1 miles from the PIP-Route I-87 intersection, pull into the Sloatsburg service area for Stop 1. We will meet additional field-trip participants at this rest stop.

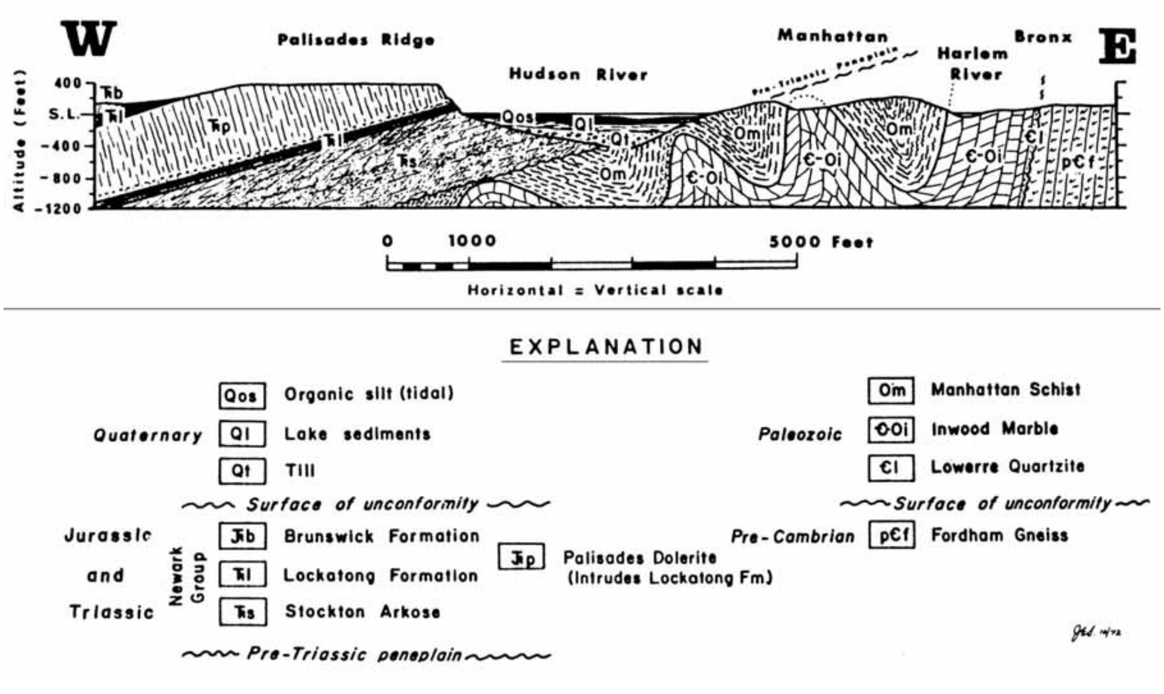


Figure 18 - Profile-section across Hudson River at George Washington Bridge. Topography from U. S. Geological Survey Central Park 7.5-minute quadrangle. (J. E. Sanders, 1974, Figure 3, p. 11).

STOP 1a - Proterozoic metasedimentary, granitic-, and dioritic gneiss of the Hudson Highlands, Sloatsburg Service area, I-87N. [UTM Coordinates: 568.1E / 4556.05N, Sloatsburg quadrangle.]

Grenville-aged (1.1 Billion year old) granitoid gneisses of the Hudson Highlands complex form the basal cratonic layer (Layer I in Table 2) in the New York area. In the vicinity of New York City, we call equivalents of these rocks the Fordham Gneiss (as discussed above). Here, the Grenville basement is well exposed along the east wall of the Sloatsburg Service area of I-87N as hornblende-bearing granitic gneisses that are locally migmatitic (show evidence of partial melting) and cut by numerous faults (with at least three different orientations), as well as a series of joints. Obvious, gently plunging slickensides suggest right-lateral, normal oblique-slip faulting. The intersection of joints and faults create blocks that are generally rust colored because of the weathering of iron-bearing sulfide minerals such as pyrite, which form thin coatings on the surfaces adjacent to the fractures. The faults are distinguished from joints in that they show visible offset and often show slickensides (mineralized gouge developed along the bounding rock surfaces). The joints are often tight (and, by definition, show little or no displacement) but commonly have been mineralized by fine intergrowths of mica, zeolite minerals, epidote, calcite, quartz, and pyrite, or mixtures of the above.

Interlayered within the main mass of the granitic gneiss are layers and lenses of dark-colored amphibolite and light green diopsidic calc-silicate rock. The probable parent rock (protolith) of the granitic gneisses are granite plutons, and/or quite possibly volcanic ash deposits and/or feldspar-rich graywackes. The calc-silicate rocks began life as carbonate-rich sediments and amphibolites are probably metamorphosed basaltic extrusives or calcareous, iron-rich (ferruginous) shales. As such, the overall stratigraphic sequence idealizes our concept of pre-metamorphic continental crustal rock and overlying shallow- water sediment of the cratonic realm. On the north part of the exposure, gabbroic rocks are found to be weakly foliated.

The parallelism of the gneissic layering among the granitic gneiss, amphibolite, and calc-silicates suggests that these units were deformed together during an episode of ductile deformation. Such deformation occurs beneath the ductile-brittle transition or at depths equal to, or greater than 10 to 15 km. The generally low dips of the gneissic layering is typical of the exposures of Grenville-aged basement rock in this part of southeastern New York. Later, as we drive northward, note the sub-horizontal attitude of the gneissic layering in most exposures of Proterozoic gneiss.

These observations lend support to modern contentions that basement rocks deform in huge subterranean overthrusts along shallow-dipping thrust surfaces with ductile metamorphic fabrics developed parallel to the movement surfaces. Also note how, locally, the gneissic layering has been folded by open to crenulate folds fostered by changing motions along the thrusts or entirely younger deformation. Do not confuse the ductile fabrics (metamorphic fabrics) with the younger, superimposed brittle fabrics (faults and joints) which chop the outcrop at typically high angles to form blocky, jagged surfaces. This part of the Appalachians experienced numerous phases of steep, brittle faulting and jointing after the development of metamorphic (ductile) fabric elements.

Locally, the highly deformed gneissic layering has been cut by granitic- and dioritic to gabbroic plutonic rocks that are themselves foliated to a lesser degree. These appear in many places along the outcrop and show dominantly discordant relationships with the gneissic layering. What is more, these late granitoids show very coarse phaneritic to pegmatitic textures with enormous (up to 10 cm) crystals of hornblende and include xenoliths (foreign rocks) of foliated gneiss.

In the center of the exposure note the 30 cm thick, steep post-Grenville mafic dike oriented N45°E, 80°NW that contains no vestige of metamorphic fabric found in the adjacent Proterozoic rocks but is cut by the same brittle features found throughout the exposure. Note the highly laminated margin and weakly foliated interior suggesting cooling of the mafic magma during crystallization and emplacement. Based on regional mapping, these mafic dikes are either lamprophyres of Ordovician age (related to the Taconic Orogeny) or basaltic dikes of Mesozoic age (related to rifting and development of the Newark Basin). At the north end of the exposure note the increase in graffiti! Clearly this is an example of how country rock begins its transition into city rock!

The following road log is meant to be read while we drive between stops. To help you in the event you attempt this trip on your own, actual mileages from the Thruway overpass over Johnstown Road begins our road log at mileage [0.0] below. This overpass is located 0.8 miles north of the Sloatsburg service building immediately beyond Thruway Milepost 34.

From this point on, the roadlog will list mileages in boldface type.

Mileage	**Remarks**
[0.0]	Thruway on bridge over Johnstown Road, MP 34.
[0.4]	Large cut of Proterozoic rocks on R.
[0.5]	End of cut.
[1.0]	More Proterozoic country-rock gneisses with low foliation dips.
[1.4]	County boundary; leave Rockland County, enter Orange County.
[2.5]	More Proterozoic gneisses in low cut.
[3.1]	Proterozoic mafic gneisses; glacial sculpting of rock at left of road.
[3.5]	Foliation in gneiss dips about 45°.
[3.8]	Proterozoic rocks exposed on both sides of Thruway; granitic sills (with pink feldspar) crosscut mafic gneisses.
[4.2]	Thruway passes through open valley; no roadcuts here.
[4.4]	Proterozoic rock on R. Ramapo River on L.
[4.5]	Thruway crossing bridge over Greenwood Lake Road.
[5.3]	No cuts for a stretch.
[6.4]	Thruway passes beneath bridge of local road above.
[6.5]	Leave Sloatsburg quadrangle; enter Monroe quadrangle.
[7.1]	Low cut on R; dark-colored Proterozoic gneiss.
[7.8]	Thruway passing beneath bridge for local road and for Appalachian Trail passing above.
[7.9]	Cut on R newly fenced from highway; dip of foliation is steep to E.

[8.4] House on R in open, rolling fields. The bedrock consists of Paleozoic carbonates in a feature named the Thruway graben by Jaffe and Jaffe, (1973). See also: (Dodd, 1965 and Offield, 1967).
[9.1] Cuts on R. (Pull-over Stop #1) display Paleozoic carbonate rocks (protoliths of the Inwood Marble).

Pull-Over STOP 1b - Carbonate rocks of the Sauk Sequence cut by mafic dikes on Route I-87N (10.2 miles north of STOP 1). [UTM Coordinates: 571.8E / 4570.3N, Monroe quadrangle.]

State law precludes stopping to look at rocks on I-87 so this pull-over stop will be discussed in the van - eyes right! After numerous miles of Proterozoic gneiss exposure on I-87N, we have now passed into a major graben [down-dropped block with normal (gravity) faults on each side] that exposes Cambrian to Ordovician limestone and dolostone. Here the well-layered, whitish to tan-weathering dolostone dips to the east with a strike parallel to the highway (same as the foliation in the Proterozoic gneiss!). Of additional interest here is the tan-weathering ferroan dolomite with algal laminae, and at least three mafic dikes that cut across the bedding of the carbonate rock at a high angle and include angular xenoliths of the carbonate host rock. This discordant relationship and isotopic data (Ratcliffe and others, 1983) suggest that the mafic dike in this outcrop may be post-Ordovician in age. At the north end of the exposure a low angle, top to the north, thrust fault displaces two vertical dikes.

[9.3] Cambro-Ordovician Sauk carbonates, in down-faulted block (the Thruway graben of Jaffe and Jaffe, 1973), form a more-open countryside that has been cleared; the slopes are gentler and the soil more fertile than in areas underlain by the Proterozoic rocks.
[10.1] Low ledge of Cambro-Ordovician carbonates exposed in field on R. (outcrop is covered by graffiti). This is another vain attempt of the country rock trying to look like city rock!
[10.9] Thruway passing under bridge for road to Arden House (former Harriman estate; now Columbia University conference center).

[11.6] Exit on R for US Route 6 and NY 17 before tollgate at Exit 16, Harriman.
[12.5] Tollgate, keep R for exit to NY 32
[12.6] Exit ramp.
[12.8] Turn R on NY 32. Leave Monroe quadrangle; enter Popolopen Lake quadrangle.
[13.7] Central Valley.
[14.0] Blinker light.
[14.4] Re-enter Monroe quadrangle.
[14.8] Highland Mills sign on R.
[15.2] Opposite Exxon station on L, turn R on Park Avenue (before blinker light). Stones in fence on R consist of Devonian Schunnemunk Conglomerate.
[15.4] Re-enter Popolopen Lake quadrangle.
[15.5] Road bends R.; go onto gravel road at L uphill to Highland Mills RR Station.
[15.6] Pull over for Stop 2.

STOP 2 - Devonian Sandstones at Highland Mills (former) Railroad Station. [UTM Coordinates: 573.5E / 4577.3N, Popolopen Lake quadrangle.]

Watch for trains here as they do come by! The belt of outcrop here is the NW-dipping southeast limb of a syncline consisting of steeply dipping Devonian clastic strata of the Highland Mills Member of the Esopus Formation (Table 3). The same strata are exposed in Thruway cuts that we will see when we have gone back onto Thruway. Note the view to the north of Schunnemunk Mountain which occupies the core of a large synclinal structure. The topographic map shows evidence of strike ridge with a NE strike and vertical to very steep NW dip. The ridge is underlain by lower Silurian, here the Green Pond Conglomerate, overlain by redbeds (Longwood Shale = equivalent of High Falls Shale to be seen later). The things we would like to do here is show you how to measure strike and dip, identify tops and bottoms of beds, hummocky strata, and to find some representative Devonian fossils.

The rocks here consist of interbedded highly laminated sandstones and shales with individual layers 0.5 to 1.0 m thick. Local 3-4 cm layers of black shale are present. The laminated texture of the sandstones suggest that deposition took place under the influence of moderate to strong currents. The interbedded shales indicate periods of quiescent deposition. The bedding is oriented N32°E, 61°NW and is strongly jointed showing concentric leached iron oxide deposits known as leisegang. Tension gashes, perhaps due to folding, are mineralized and oriented N5°W, 17°NE.

Hummocky strata are inferred to be products of deposition during the waning stages of storms when the pattern of eddies in the water was comparable to that which forms "interference ripples" but on a slightly larger scale. An example is illustrated in an article by Dott and Bourgeois (1982) (Figure 19).

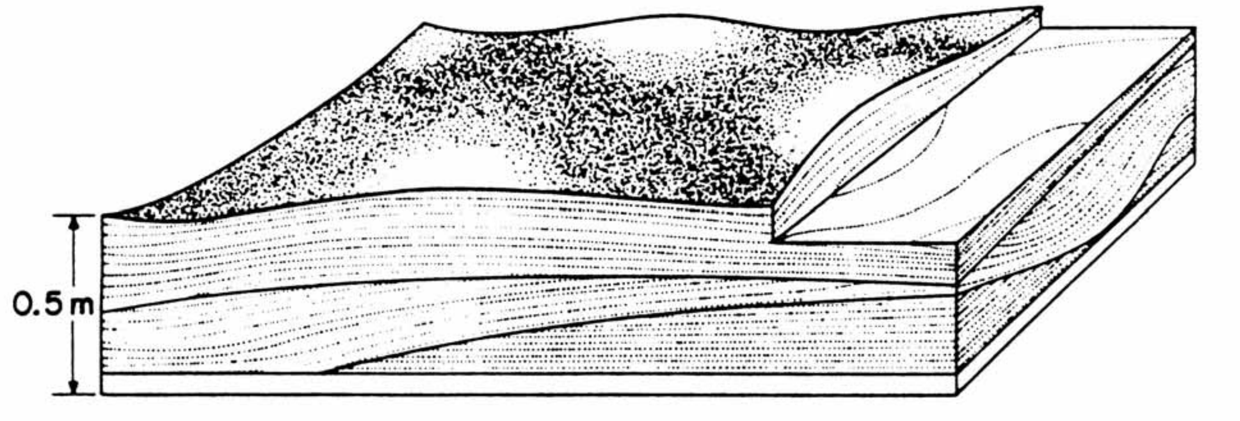


Figure 19 - Block diagram showing the internal structure of hummocky cross strata (Dott and Bourgeois, 1982).

The base of a hummock is flat and the top is concave up, forming mini-domes with strata conforming to the top of the dome. After the deposit has been built, slow sedimentation follows, with shale, etc., covering the hummocks. Burrowing organisms then become very active and riddled the strata with burrow marks. An example of such things here is at the N end of the exposure, where a top surface of a bed shows many of the kinds of marks that early NY State paleontologists referred to as Taonurus caudi-galli (and supposedly were plants or seaweeds). They are now interpreted as the results of some organism that was probing into the bottom in all directions looking for food. (Comparable to what goes on in a modern offshore drilling platform, where from one central spot, many holes are drilled outward and downward to drain the reservoir from as large an areas as is possible). The modern term for these trace fossils is Zoophycus which means "animal-plant".

The fossils found here include various types of brachiopods, gastropods, pelecypods, and trilobites, preserved as molds and casts; original skeletal carbonate has generally been dissolved. The layers show shell hash, probably concentrated during storms. Loose slab shows symmetrical wave-generated ripples; look to see if these can be found in situ. At the N end of exposure, where the burrow marks are so prominent, the overlying massive sandstone shows spheroidal weathering as a result of weathering along right-angle corners of joint intersections.

Sections that show a simple syncline from here to top of Schunnemunk Mountain are probably not correct as the diagrams show too much strata. Instead, the structure is complex, possibly including several folds and/or thrusts, as in our interpreted geologic section of Bellvale Mountain (See our OTR guide for the Shawangunks and Bellvale Mountain.).

[15.6] Retrace route to Thruway.
[16.1] Junction with NY 32; turn L.
[18.3] Traffic light by Monroe-Woodbury Middle School. Move L for upcoming L Turn.
[18.5] Traffic light; turn L to re-enter Thruway.
[18.9] Toll Barrier at Thruway entrance. Bear L for I-87 N, toward Albany.
[19.8] Toll gate for ticket pickup - ask for a discount.
[20.4] Leave Monroe quadrangle; enter Popolopen Lake quadrangle.
[20.7] Slope on R. underlain by till.
[21.0] Thruway passing under bridge for old US Route 6 at Camp Wildwood (on W side of Thruway). The lowland on the L (W) marks the divide between drainage that flows N and into the Hudson via Woodbury Creek and Moodna Creek, and that which flows S via the Ramapo River. The Ramapo has cut through the rocks of the Hudson Highland and eventually drains into lower New York Harbor. The town of Central Valley occupies the low area of the divide.
[21.9] Thruway passing under bridge for Smiths Clove Road.
[22.0] Cambro-Ordovician carbonates on R dip steeply to the SE. High ridge ahead is Schunnemunk Mountain, held up by conglomerate underlain by Middle Devonian conglomerates.
[22.4] Cambro-Ordovician carbonates on R, just S of bridge.
[22.5] Thruway passing under bridge for Pine Hill Road.
[22.6] Red siltstone on R is part of the Longwood Shale, of Silurian age (probably equivalent to the High Falls Shale of the central Hudson Valley and the Bloomsburg Formation of the central Appalachians). The underlying Green Pond Conglomerate is faulted out of the roadcut exposures, but is present to the northeast. This exposure is very significant in that it is the only place in New York State where the Green Pond Conglomerate is present.

[22.7] Strata dipping steeply NW are of Devonian age (part of the Highland Mills succession described by Boucot, Gauri, and Southard, 1970 - see Table 3). The coarse white sandstone at left is the "Oriskany" of older stratigraphers; in the post-Boucot era, the terms used are Connelly Conglomerate and Central Valley Sandstone.
[22.8] Devonian strata exposed in cuts on both sides of the Thruway.
[23.3] End of cuts in Devonian rocks.
[23.4] Till on right of Thruway; bedrock not visible.
[24.2] Thick till on R.; two half-drumlins ending on the S against a narrow ridge underlain by Lower Silurian Green Pond Conglomerate on SE limb of Idlewild (=Mountainville) syncline.
[24.5] Thruway passes above NY Route 32 (Albany Turnpike). On R, in Town of Woodbury, the belt of Devonian strata ends by being faulted against Proterozoic gneiss. JES thinks this fault contains a strike-slip component and that it may be of post-Newark (mid-Jurassic) age (but no proof exists for this interpretation).
[24.8] Leave Popolopen Lake quadrangle; enter Cornwall quadrangle.
[26.8] To W of Thruway is NE end of Schunnemunk Mountain.
[27.1] Star Manufacturing Co. on R., in town of Mountainville.
[27.4] Thruway passing under bridge for Taylor Road.
[27.6] Thruway bridge crossing Moodna Creek.

The Catskill aqueduct crosses the valley of Moodna Creek with a pressure tunnel. According to Berkey (1933, p. 102):

"Great difficulty was experienced in obtaining the required information in this valley. In no other, except the Hudson gorge itself, was it found so difficult to determine the profile of the rock floor and the underlying structure. The overburden of glacial drift carried unusually large boulders, making the boring program difficult and expensive. For a considerable distance in the bottom of the valley the cover is 300 feet (91 meters) deep, and one of the borings penetrated a single boulder 34 feet (10 meters) through, lying in the drift 100 feet (30 meters) above the floor."

The geologic structure was finally unraveled and the surprising result was the discovery of narrow faulted slices of the Proterozoic gneisses. "The strip of ancient gneiss which had been looked for as a continuation of the Snake Hill ridge was located by exceptionally successful exploratory borings but proved to be surprisingly narrow... Heavy crush zones, indicating displacement, were found on both sides of the strip of gneiss. Both zones stand at comparatively steep angles and are in poor condition, and required timbering. The tunnel actually penetrated only about 500 feet (152 meters) of gneiss or granite..."

"It was shown that displacements of two periods are represented--a thrust fault of Appalachian type and a block fault of Triassic age. The two displacement lines strike so nearly parallel that long slivers of ancient rocks are left stranded out in areas of Paleozoic strata..."
[27.9] Thruway passes beneath bridge for Pleasant Hill Road. This place is notorious because the shoulders of the Thruway can accommodate State Troopers' radar patrol cars and the chaser cars to catch the speeders.

[28.5] Clear-day view of Storm King, Hudson Highlands, on R.

[29.1] Thruway passes beneath bridge for Orrs Mill Road. Ridge on L (west) is underlain by Silurian rocks.

[29.5] Thruway crosses above railroad tracks. On W (left) is the northeast end of the Idlewild (=Mountainville) syncline. Here, the Lower Silurian Conglomerate rests on the Middle Ordovician Martinsburg Formation. The nature of the contact is not known; it could be one of unconformity or a fault.

[30.7] Thruway passes over NY 94, just W of Vails Gate. The New York State Geologic map shows a fault block of Proterozoic rocks, about 500 feet wide, beneath the Thruway here. This mapping is based on the borings for the Catskill Aqueduct (Berkey, 1933, p. 101-105; Plate 12, following p. 98). See Berkey and Holzwasser profile-sections and keyed map (Figures 20, 21, 22) for geologic relationships determined in this vicinity when the Catskill Aqueduct was built and during later mapping.

[30.9] Thruway passes over railroad.

[31.0] Thruway crosses over Catskill Aqueduct.

[31.1] In the straight stretch for the next 1.5 miles, the Thruway parallels a pair of large drumlins on the L. (SW). The long axes of these drumlins trend N20°W - S20°E.

[32.6] Covered contact between Cambro-Ordovician Sauk carbonates and Middle Ordovician Martinsburg Formation.

[33.1] Thruway bridge over NY Route 207.

[33.5] Lake Washington on R. (E).

[33.9] Crossing thrust fault of Cambro-Ordovician Sauk carbonates against Middle Ordovician Martinsburg Formation (Tippecanoe Sequence).

[34.6] Leave Cornwall quadrangle; enter Newburgh quadrangle.

[34.7] Pass exit ramp on R for Exit 17.

[34.8] MP 60 on Thruway. Here the Thruway cuts through Ordovician slates and shales with not many exposures. Any seen will be noted.

[36.5] Bridge over low area; no creek.

[39.7] Ramp on R for Plattekill Service Area; Pit stop here.

[40.0] MP 65.0 back on Thruway again. Cut on L of Ordovician slates which dip gently toward the NE.

[43.8] Outcrop on L of Ordovician slates with dips gentle toward the NE. Slaty cleavage dips steeply SE.

[44.1] Newly planted apple orchard on drumlin on L. Ends on N with another outcrop of Ordovician slates.

[44.5] Slate outcrop; same attitude.

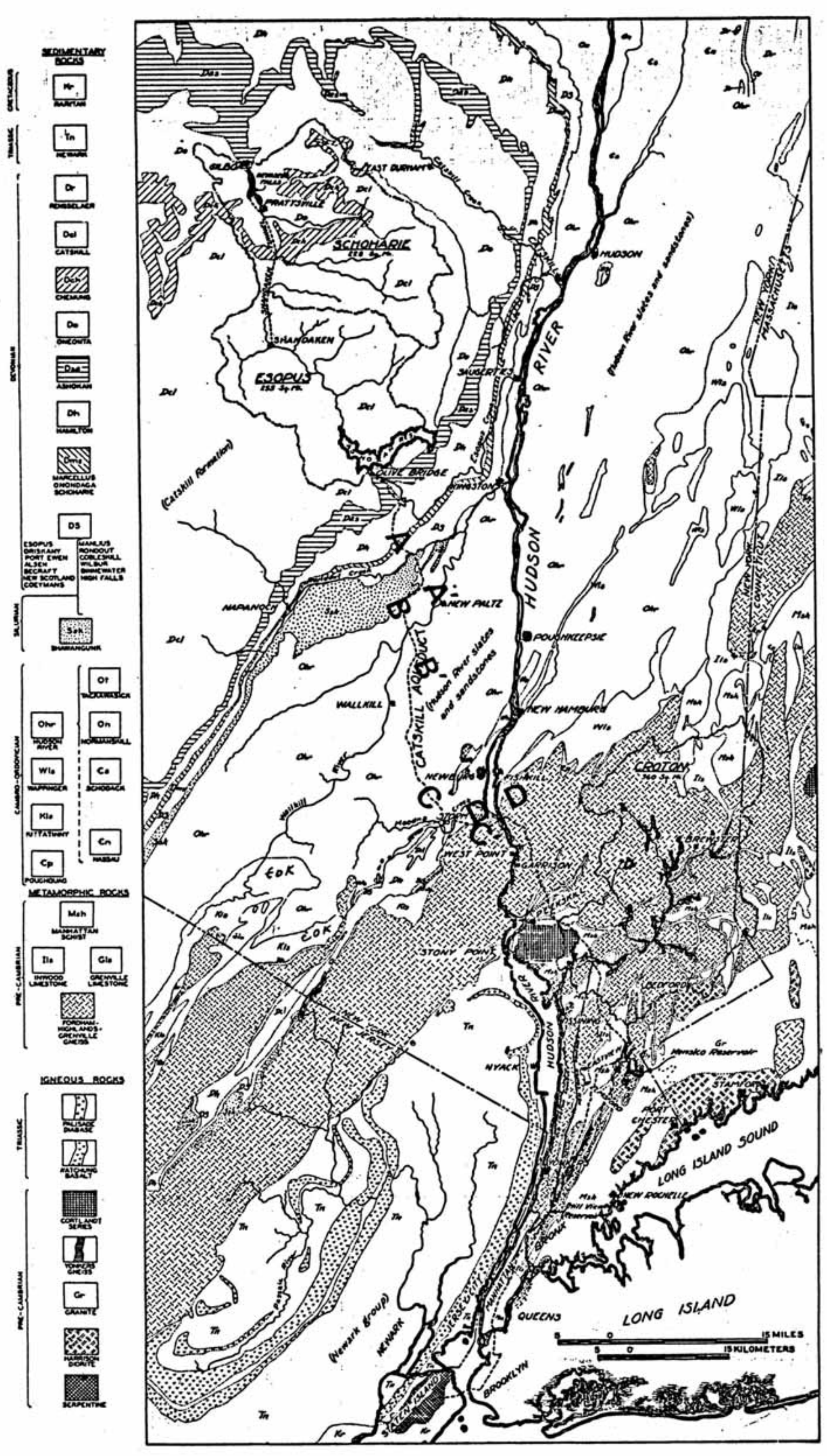


Figure 20 - Geologic sketchmap (from Berkey, Plate 9, 1933) showing the positions of cross sections of Figures 21 and 22.

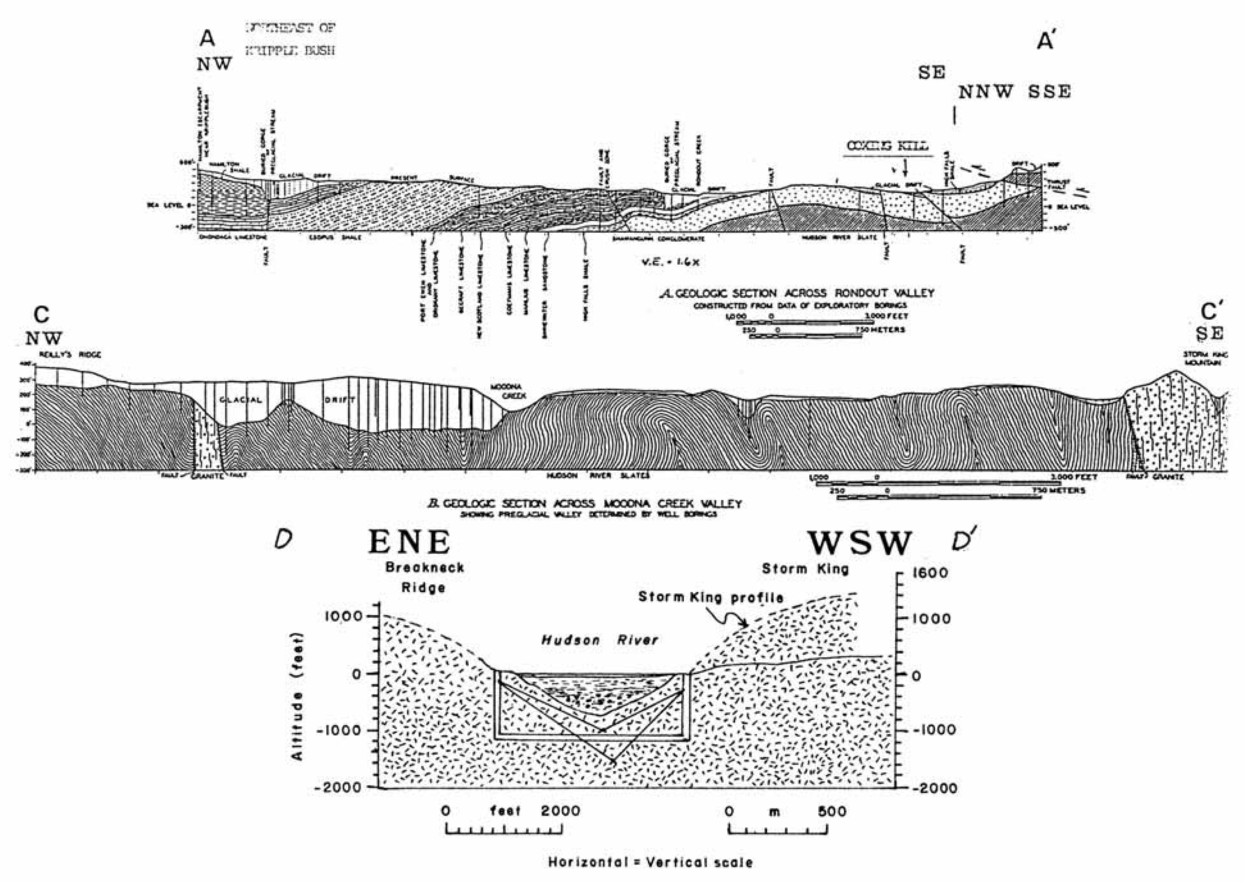


Figure 21 - Geologic cross sections (A-A', C-C', and D-D') of the Hudson Valley, New York (keyed to Figure 20) from Berkey (1933).

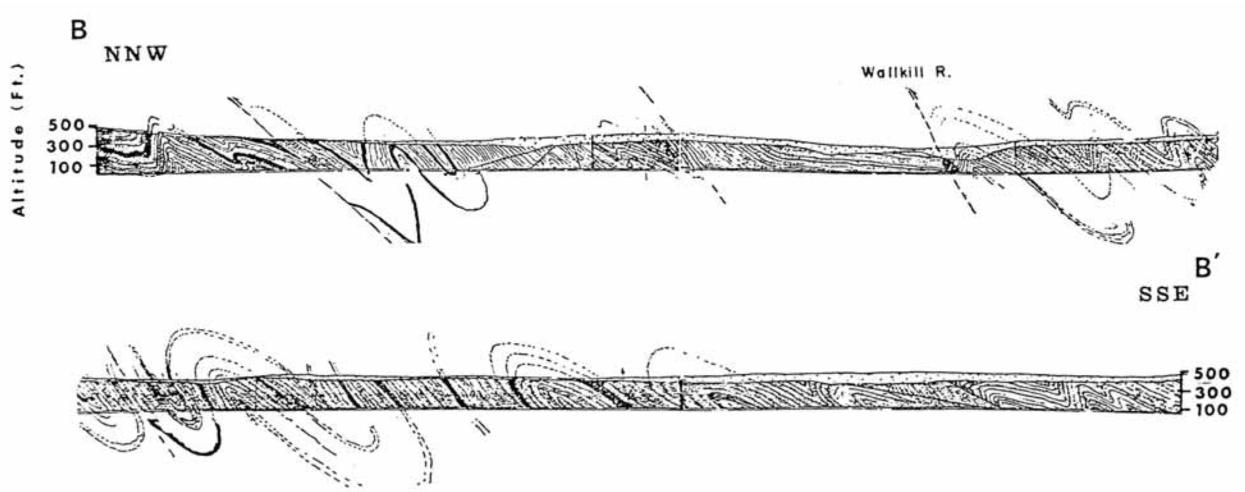


Figure 22 - Geologic cross-section (B-B)' of the Hudson Valley, New York (keyed to Figure 20) from Holzwasser (1926) [as redrawn by JES].

[44.9] More slates on L.
[45.2] More slates on R; same attitudes. Cleavage here is more obvious.
[45.9] Low outcrop of Ordovician on R.
[46.1] More of same.
[48.3] MP 73 on Thruway.
[51.1] Exit ramp on R for New Paltz (Exit 18). Leave Thruway here.
[51.7] Toll gate - Ask for educational discount.
[51.9] Traffic light at NY Route 299; turn L.
[52.0] Crossing above Thruway.
[52.2] Turn R on N. Putt Corners Road.
[52.4] Freihofer's bakery on L; breathe deep cookie lovers!. Leave Clintondale quadrangle; enter Rosendale quadrangle.
[53.5] Powerline crossing overhead.
[53.6] Turn L on Shivertown Road. View toward Shawangunk Mountains ahead (toward W) in distance.
[54.7] Stop sign. Turn R on NY 32. Small exposure in ditch on R is Ordovician slates.
[55.0] Ordovician slates on R.
[55.9] Ordovician slates on R.
[56.0] Ordovician slates on L. View of Shawangunk ridge on L. Notice the decrease in height of ridge toward the N.
[56.2] More Ordovician slates on R.
[57.7] Sign for Town of Esopus on R.
[58.0] Ordovician slates on R.
[58.2] Road Junction. Turn R on NY 213.
[58.6] Bridge over Thruway
[58.7] Pull off to R, park opposite Perrine's Bridge (covered bridge over Wallkill River (Ulster County Historical Site)) for Stop 3.

STOP 3 - Ordovician graywackes of the Tippecanoe Sequence under Thruway Bridge. [UTM Coordinates: 578.21E / 4629.7N, Rosendale quadrangle.]

Exposed under the Thruway overpass are interbedded, cross laminated Ordovician graywacke and black shale and siltstone exposed in an open syncline. Beneath the Thruway bridge, strata are nearly horizontal and wacke layers are over a meter thick. West of the bridge, the average thickness of the wacke layers are 5 to 15 cm and they are internally laminated indicating deposition during strong currents. They strike N25°E, dip 28°SE and exhibit graded bedding, irregular bases, rip-up clasts, flame structure, and sole marks that together indicate that tops are up. Cross strata indicate current flow towards the SW. Locally the wackes contain pebbles of Sauk carbonate and black chert, black argillite, and brachiopod fossils. The brachiopods show up as "holes" in the graywacke layers and as these are grain-flow deposits, the fossils have been transported and would give a maximum age for the layer. Farther W, as a result of folding, the bedding is oriented N34°E, 33°SE and is cut by a steep cleavage suggesting an anticlinal fold or fault toward the north eroded by the Wallkill River. Similar relationships are indicated by Holzwasser (1926). (See section B-B' in Figure 22.)

These rocks are totally different than the Silurian and Devonian strata to be seen at upcoming stops. One point of confusion here - don't get fooled - as road-metal float contains Siluro-Devonian fossils.

Time permitting, we may continue eastward on Route 213 to examine a thick-bedded portion of the Tippecanoe sequence exposed on the above the Dashville hydroelectric plant along the Wallkill river. Here, many spectacular anticlines and synclines expose Tippecanoe rocks. Faulting and imbrication and minor folding of the wacke layers was produced by layer-parallel shortening during large-scale folding when the incompetent shaly interbeds flowed and the sandy beds broke. A steep fault is exposed at the east end of the exposure. Note the calcite and quartz veining and the abrupt change in orientation east of the fault. Glacial scratches here are oriented N5°W and an erratic of Helderbergian limestone looms on the hillside above the fault.

[58.7] Go back to NY 32.
[58.9] Turn R on NY 32
[59.0] Bridge over Wallkill River.
[59.2] Town of Rosendale sign.
[59.4] Town of Tillson sign.
[59.7] Four corners, Tillson Road.
[60.0] Rowley Building Center Sign on R before steep grade sign and curve to L.
[60.4] Driveway on R to The Heins.
[60.45] Town of Rosendale sign.
[61.0] Park at trail entrance into woods to old cement mine for Stop 4.

STOP 4 - Siluro-Devonian Section and Rosendale Quarry at Tillson. [UTM Coordinates: 576.7E / 4631.7N, Rosendale quadrangle.]

The strata exposed here are quite thin but consist of a northward-topping sequence of Shawangunk Conglomerate (L. Sil.), overlain by the High Falls Shale, Binnewater Sandstone, and overlying cementstone carbonates. See Figure 23 for a stratigraphic column. Farther ahead in the woods, the Siluro-Devonian succession crops out.

From the base upward, the units trend N55°E, 22°NW and include the Shawangunk Conglomerate near the Taconic unconformity. The actual contact is not visible here (we might dig a little during the trip). The Shawangunk consists here of white quartz pebbles 1 to 2 cm in diameter and coarse, sandy interlayers. The sandy layers are laminated and cross laminated, as shown by intercalated black- and gray coarse sands. The cross strata indicate downdip transport direction and that the sequence is right way up. The thickness of the conglomerate is about 4 meters. (See Figure 23.)

The Shawangunk Conglomerate is in sharp contact at top with an overlying silty unit, the High Falls "Shale". The High Falls is not too well exposed and is about 6 m thick behind the bushes. Some reddish layers occur but bedding is obscure as the siltstone breaks into irregular chips. Farther along the road, is a good exposure of the top of the High Falls and base of the overlying Binnewater Sandstone.

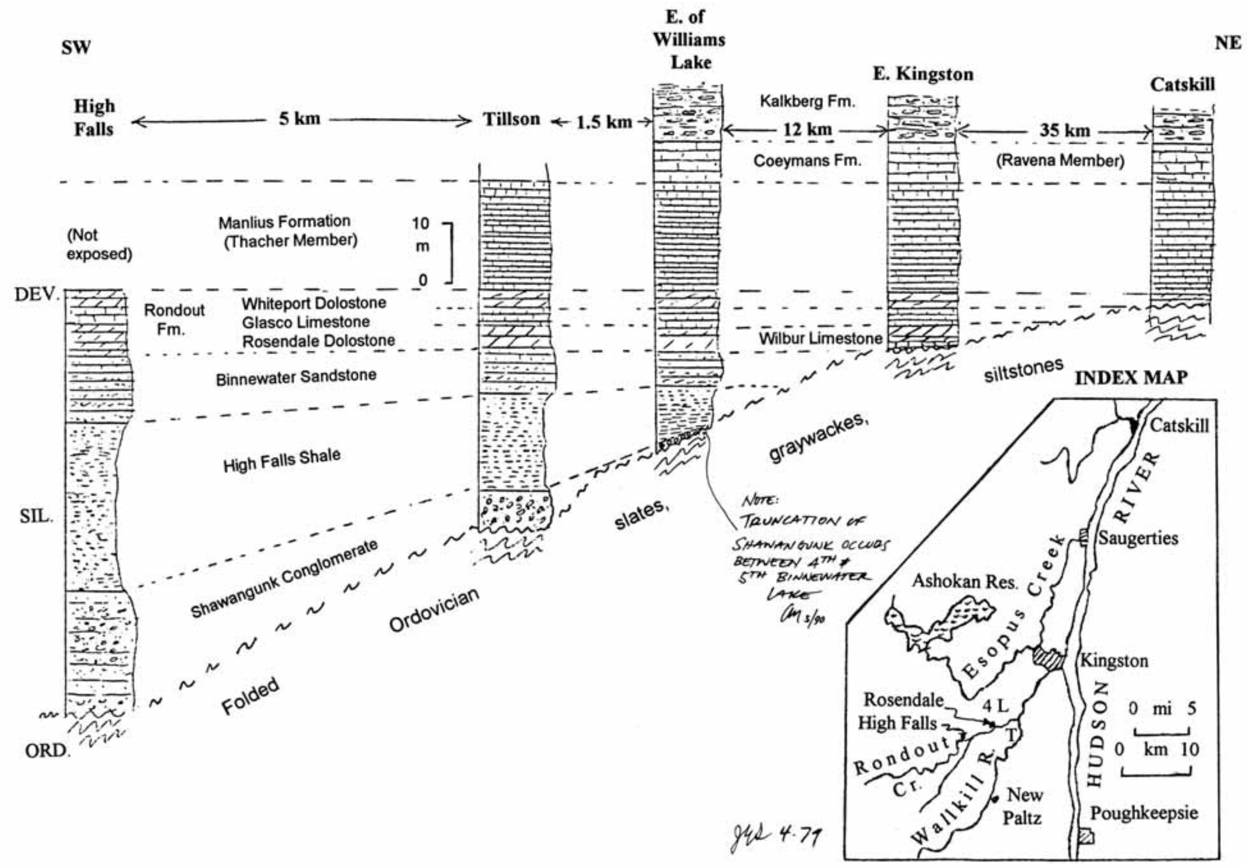


Figure 23 - Restored stratigraphic section showing northeastward thinning and overstep of Silurian strata against high area underlain by folded Ordovician strata, central Hudson Valley and vicinity, New York. JES diagram.

The Binnewater consists of interlayerd dolomitic carbonates and gray quartzose sandstones, in layers 10 to 15 cm thick. In the sandstones, are wave-generated oscillatory ripples, ripple cross strata, and possible hummocks. Trend of ripples on top of one bed in middle is N55°W, bedding here strikes N55°E; dip is 22°NW. The ripple axes are parallel to old shore with bottom sloping to SW (direction in which Silurian strata thicken). The sandstones resemble sandstones in underlying Shawangunk, but there are no pebbles in the Binnewater, beds in the Binnewater are thinner, and it contains prominent brownish-weathering dolomitic layers. In addition, ripples and ripple cross laminae more abundant in the Binnewater compared to the Shawangunk.

Walk to end of exposure; find trail on R at start of metal guard rail. Continue along trail to exposure in woods to R and beware of poison ivy. Look for two pillars and entrance to former cement mine, now flooded (Figure 24). There is a slight gap in section as dip slope at R is formed on top of the Binnewater Sandstone. It is possible that the Wilbur Limestone occurs in this covered interval. The next rock unit exposed is the Rosendale Dolostone, the brownish-weathering rock found in the bottoms of the pillars. Cementstones were quarried because the dolomitic layers contain just the right amount of quartz silt to make a cement when roasted. These formed the basis of the Rosendale cement business of the 19th century (see historical marker in village of Rosendale).

The thickness of the Rosendale Dolostone here is about 4 m and it is overlain by about 1 m of Glasco Limestone with corals, followed by the Whiteport Dolostone (about 2 m thick), up to the roof of the mine. Above the roof of the mine, the cliff continues, and within it one can see vertical strata at the nose of a recumbent fold (Figure 24).

This fold overlies a detachment zone, which coincides with a bedding-plane thrust. The rock above the detachment is the Devonian Manlius Formation (Thacher member), the next unit overlying the Whiteport Dolomite member of the Rondout Formation. In most localities hereabouts, a bedding-plane thrust is found at or near the Siluro-Devonian boundary (Rondout-Manlius contact).

An important point to emphasize is the thickness of strata exposed between the base of the Whiteport Dolomite and the Ordovician. Here, that thickness is about 20 m, and present are 3 members of the Rondout, the Binnewater, the High Falls, and the Shawangunk. Reboard the happy vans.

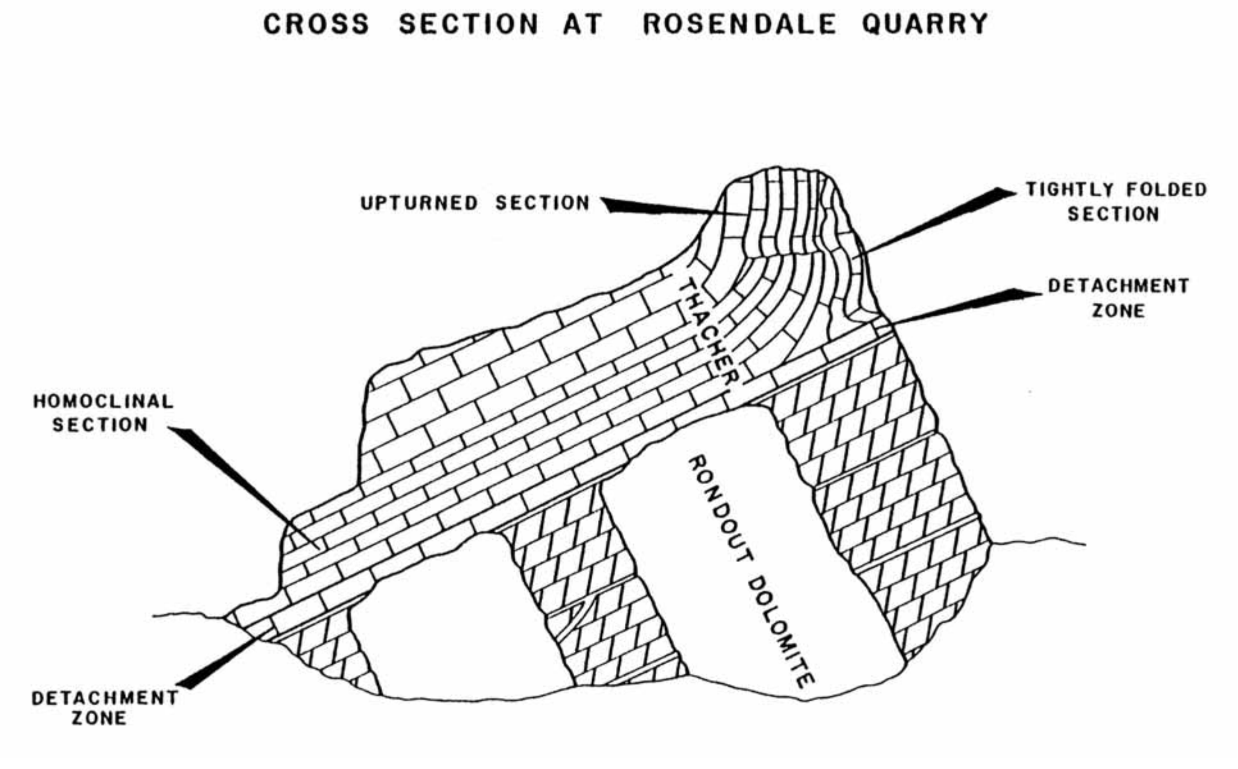


Figure 24 - Diagrammatic sketch of Rosendale cement quarry showing the room and pillar method of mining.

[61.0] Continue N on NY Routes 32 and 213.
[61.5] Turn L into James Street just before bridge over Rondout Creek.
[62.1] Opposite road junction, turn R (Keator Road is the cross street).
[62.2] Cross Rondout Creek.
[62.3] Dead end; turn L onto NY 213 in Rosendale.
[62.4] Curve in road to L beneath overhead trestle for old RR.
[62.5] Binnewater Road on R.
[62.9] Entrance on R to old cement mine; now used to grow mushrooms.
[63.6] Bridge over Rondout Creek.
[63.7] Cliff on R is New Scotland Formation (L. Dev.).
[63.9] Bruceville Road on R.
[64.4] Old Route 213-2 on R.
[64.7] Sign on R for High Falls.
[65.1] Pull over on R for Stop 5.

STOP 5 - Faulted Shawangunk Conglomerate in High Falls village. [UTM Coordinates: 572.6E / 4630.65N, Rosendale quadrangle.]

This stop is in two parts separated by a buried (inferred) fault. Part 1 is found to the E, opposite the High Falls Motel (CM, but not George Washington, slept here on the eve of his first undergraduate field trip with Drs. Jack Fagan and Sy Schaffel of CCNY in 1968). Here occurs Shawangunk, about 6 m thick, with no top or bottom exposed. The conglomerate and silica-cemented sandstone dips 13°E. Planar cross strata show updip transport direction. Two sets of slickensides are found at the western edge of the exposure: (1) parallel to bedding, and (2) steep, with sense of motion E side up.

Part 2 to the W is across a fault with overlying red High Falls Shale preserved on top of the Shawangunk. The conglomerate here is about 8 to 10 m thick with base not exposed, in the crest of a broad anticline that trends N-S. The features here include shale interbeds, possible hummocks, and cross beds.

It is unusual to find this much Shawangunk without high relief. A possible explanation is that this is the crest of an anticline only recently exposed and not yet elevated with respect to surrounding rocks. Between the two outcrops is a fault, trending NS and with E side up to bring Shawangunk up to level of High Falls Shale Formation. In the covered interval, Ordovician shale may be faulted against High Falls Formation.

[65.1] Drive on and continue W on 213. Leave Rosendale quadrangle; enter Mohonk Lake quadrangle.
[65.2] Old Route 213-3.
[65.3] Four corner intersection by center of High Falls village.
[65.35] Sign for Old Stone Aqueduct; part of canal used in heyday of Rosendale cement business.
[65.7] On curve going uphill, turn R into powerplant. Pull into parking lot for Stop 6.

STOP 6 - Binnewater Sandstone and High Falls Shale in east-vergent monoclinal flexure, High Falls hydroelectric station. [UTM Coordinates: 571.91E / 4630.95N, Mohonk Lake quadrangle.]

Walk through fence maze to the fence nearest the falls. This area has been restored and made available by Central Hudson Gas and Electric Corp and the High Falls Civic Association.

At the upper Falls, the lip is composed of the Rosendale Dolostone with Binnewater Sandstone just below, both dipping NW (upstream). Beneath the Binnewater is the High Falls Shale with cuts here on the N side of creek marking the type locality. Walk down blacktop path to lower level. Exposed on R is cliff of Binnewater Sandstone, with dip to NW. Near the bottom is the contact with the High Falls Shale. Pay attention here. On-The-Rocks Geology Merit Badges to be awarded for those who can figure out the structure without looking across the river.

Continue along footpath to edge of creek by lower falls, held up, again, by the Rosendale Dolostone with thin underlying Binnewater Sandstone and High Falls Shale exposed downstream. Still farther downstream, out of view, is the Shawangunk Conglomerate (as seen at Stops 4 and 5).

A noteworthy feature of the asymmetric fold on opposite bank of creek is that the fold axial surface dips NW (opposite to the SE dip of most Appalachian folds). CM and JES suggest that this anticline has developed over a ramp up to a bedding-plane thrust that duplicates the Rosendale-Binnewater-High Falls succession here (Figure 25). Such an interpretation would allow low-angle thrusting from the west, an unusual sense of overthrusting per the local sources. Jack Epstein, of the United States Geological Survey, suggests that a low-angle thrust is not necessary and views the lower carbonate layer as a part of the High Falls shale (the Powerhouse Limestone). Clearly, this area needs to be investigated after JES and CM are set loose with his brush clippers on the north side of the creek.

[65.7] Make a quick, difficult L turn onto NY 213 eastbound (please beware of speeding cars in both directions).
[66.2] Town of Rosendale sign near Stop 5. Leave Mohonk Lake quadrangle; enter Rosendale quadrangle.
[67.7] Bridge over Rondout Creek just past sign for Town of Rosendale.
[67.9] Road to L optional entry to Williams Lake.
[68.8] Turn L onto Binnewater Road by start of curve to R in 213.
[69.2] On R and L; ruins of old cement-roasting ovens.
[69.8] Intersection at center of hamlet of Binnewater with Ulster County Road 7.
[70.0] Road junction with County Road 7 to L.; straight ahead to Williams Lake Hotel.
[70.3] Road on R is a gravel lane parallel to paved road. It is an old railroad bed marking the start of our traverse.
[70.6] Park at far side of parking lot opposite office, Williams Lake Hotel. Traverse along old RR track.

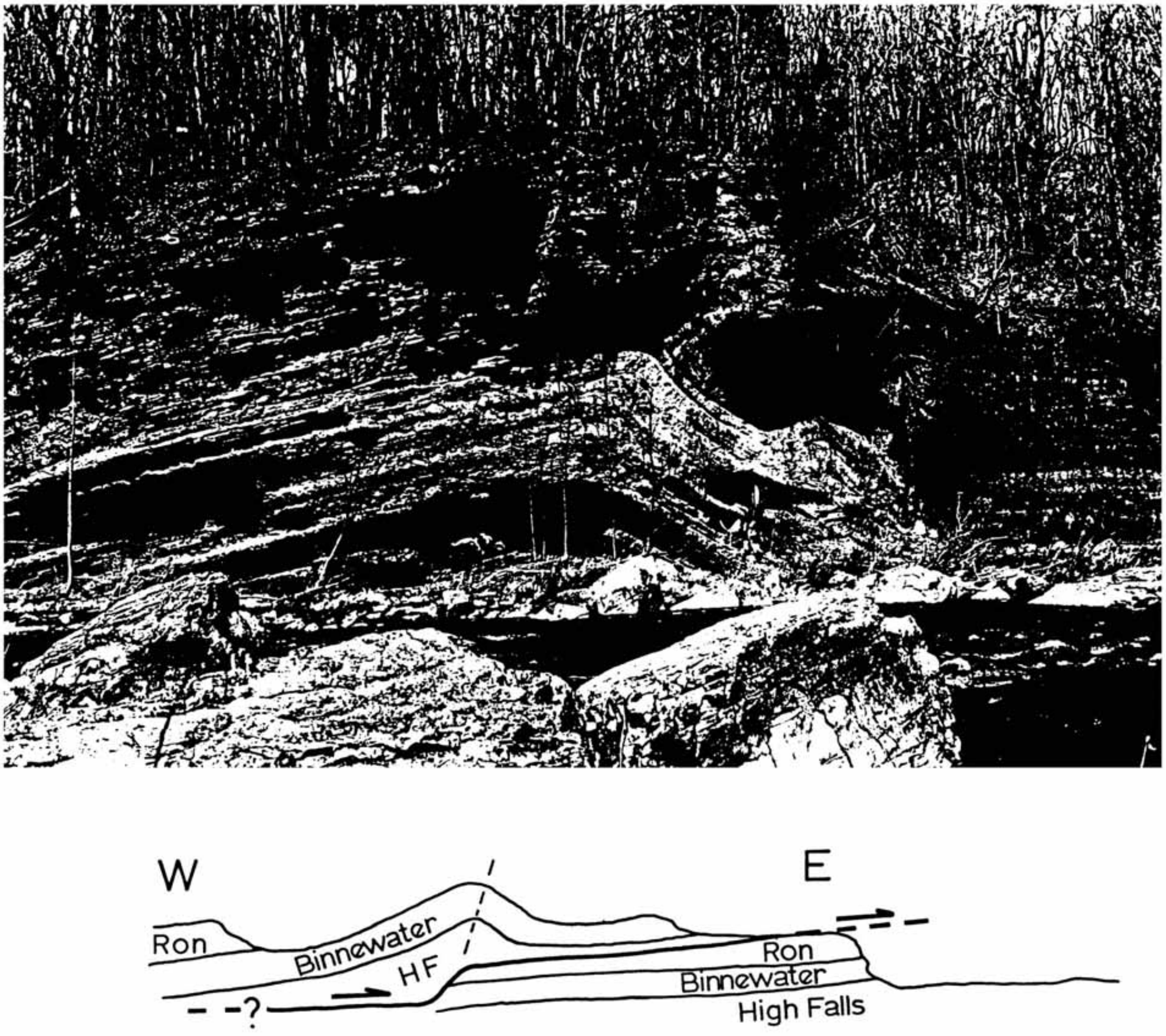


Figure 25 - Photograph of SE-vergent monoclinal flexure exposed on the north side of Rondout Creek at High Falls hydroelectric station (Stop 6). Inset shows our prefered interpretation of the structure. JES photo; CM sketch.

STOP 7 - Williams Lake Hotel transect through plunging folds. [UTM Coordinates: 576.3E / 4535.0N, Rosendale quadrangle.]

This is a free-form stop with no notes, but we will traverse the old railroad bed to map the lithology and structure of the rocks exposed here. The section starts with Shawangunk Conglomerate and proceeds upward through the High Falls Shale, Binnewater Sandstone, Rosendale Dolostone, Glasco Limestone, Whiteport Dolostone, and Manlius Formation. Note that this area marks the northernmost exposure of the Shawangunk which pinches out somewhere between the Fifth and Fourth Binnewater Lakes. (See Figure 23.) We will examine many geologic features, including sedimentary structures, bedding-plane thrusts, bedding-cleavage relationships, and folds and you will be rewarded with a lovely trip through the plunging folds (literally). We will walk up section into the Helderbergian limestones which you will see in more detail tomorrow. Refreshing cold air comes up from the old dolostone mines; possibly even some ice still there. Definitely the resting place of Jimmy Hoffa and other buddies who have fallen out of favor with the non-existent Mafia.

Glacial striae on the Shawangunk conglomerate and High Falls Shale (new 1994 exposure near archery range) vary greatly from N18°W to N16°E indicating generally southward flow directions.

[70.9] Stop sign at County Road 7. Continue straight.
[71.1] Road junction with Breezy Hill Road. Turn L onto Ulster County Road 26.
[72.0] Curve to the R on Co. Rd. 26 at Kallops Corner onto Hickory Bush Rd.
[72.2] T-intersection. Turn L onto road not marked. Sign on tree opposite for Familys Market to L on NY Route 32, 0.5 mi.
[72.7] Kallops Road and NY 32. Turn L on NY 32. Beware fast traffic. This junction is named Maple Hill.
[73.1] Bridge over NY Thruway.
[73.5] Leave Rosendale quadrangle; enter Kingston West quadrangle.
[73.9] Sign for Bloomington on R. Outcrop of carbonates on L; big outcrop beyond shows vertical beds.
[74.4] Cuts both sides.
[74.6] Esopus black siltstone in cut on L. Begin Fly Mountain section.
[74.8] Esopus steep cleavage, gentle NW dip of bedding.
[75.3] More cuts on L.
[75.5] More Esopus in cuts on R.
[76.9] Old railroad at boundary of Kingston City limits.
[77.1] Blinking yellow light.
[77.4] More Esopus with steep cleavage on R in S-bend of road.
[77.6] Golden Hill Road on L.
[77.9] After end of curve to R, on straight stretch on downhill grade, turn L abruptly near Thruway sign onto Washington Ave. ATI gas station ahead one l block. Tricky turn here!
[77.95] Blinker light at Greenkill Road.
[78.3] Traffic light for Linderman Avenue.
[78.5] Pearl Street. Watch for wild-eyed woman driver in black car darting out from L.
[78.6] Main Street.
[78.8] Traffic light at Lucas Ave. Go straight.
[79.0] Bus Station on R before Hurley Ave.
[79.05] Traffic light for Hurley Avenue.
[79.2] Turn L. into entrance to Holiday Inn (our motel for this evening).

End of Day 1

DAY TWO

[0.0] Out of Motel driveway.
[0.05] Turn L onto Washington Avenue.
[0.1] Bridge over Esopus Creek.
[0.2] Traffic light, Ulster County Road 31.
[0.4] Stop sign at start of traffic circle. Keep L for NY 28 West toward Pine Hill.
[0.5] Turn R on NY 28.
[0.6] Cross over NY Thruway.
[0.75] Traffic light.
[0.85] Turn R onto US Route 209 Northbound.
[1.1] On US Route 209, note deep cuts both sides in Mount Marion Formation the Devonian equivalent of the Ordovician Martinsburg Formation. Here these deep-water terrigenous strata are dipping very gently toward the NW.
[1.9] Under powerline; large cut on L.
[2.3] More large cuts in Mount Marion Formation.
[2.9] Large cut on R before Sawkill Road exit sign. Pull over on R shoulder before sign for Stop 8.

STOP 8 - Mount Marion Formation on US Route 209, near Sawkill Road. [UTM Coordinates: 581.25E / 4647.15N, Kingston West quadrangle.]

The Mount Marion Formation is exposed here and consists of turbidites with individual beds 20 to 30 cm thick. They are interspersed in a predominantly black siltstone/shale succession. A spectacular repetition of an individual bed, over 30 times, in slices 2 m long, occurs as stacked, imbricate slices, sandwiched between horizontal beds. CM noticed this at 55 MPH! Let's pace the current horizontal distance between the 30 slices and calculate the percent of layer-parallel shortening. We estimate roughly 300% shortening just within this one obvious thrust zone.

The main slip surface is subhorizontal and disappears within bedding. Slabs are sheared along individual imbricate thrusts which trend N4°W and dip 44°NE. Many of the slabs terminate in lenticular tips which we view as "tectonic" with a capital T. Earlier investigators have suggested soft-sediment deformation for this exposure. Rather we view the lenticular ends the result of mechanical slivering. Many angular shards of wacke floating in the weaker shaly matrix originated from the larger slabs of wacke. Overall, the movement sense is right-lateral slip with travel toward the west. As such, this small exposure is a microcosm of the entire Valley and Ridge Province as deformed during the terminal stage of the Appalachian orogeny. The age of the formation is via marine brachiopods (Middle Devonian - Marcellus age). We cannot be sure whether the structures resulted from Acadian or late-stage Appalachian orogenesis. CM and JES both lean toward the latter. What is more, we view this exposure as evidence that the overlying sequence (Catskills) have been nudged to the west during Appalachian orogenesis. We wonder whether the huge stratigraphic thickness (~800' in Table 4) may be, in part, the result of tectonic overthickening and how many similar west over east slip surfaces have not been identified.

The Mount Marion is equivalent to the Lower Bellvale Formation of the Monroe area of New York. It is the highest marine unit in the Appalachian Devonian and also the highest marine formation in Devonian. From here on up section there are no more carbonates. You might say we have made a sudden withdrawal from the carbonate bank.

[2.9] Continue on US Route 209 toward Kingstone-Rhinecliff Bridge.
[3.4] Re-crossing over Thruway.
[3.8] Bridge over Esopus Creek again.
[4.0] Leave Kingston W quadrangle; enter Kingston East quadrangle.
[4.6] Passing exit on R for 9W N to Saugerties (site of the Mudstock '94 Festival).
[4.8] Cuts both side are the Schoharie formation in a gentle open syncline with axis at 4.9 mi.
[5.2-5.4] Cuts in anticline with Becraft in core; overlying Alsen and Port and Port Ewen. (We will stop here later - Stop 12).
[5.5] Limestone outcrops on R; dip steep to NW.
[5.7] Turn R for NY 32. Outcrops of Ordovician graywakces on L. (We will stop here later - Stop 11).
[6.0] Turn L on NY 32 in direction of Kingston.
[6.4] Start of long outcrop on R (We will see it later - Stop 10).
[6.6] End of outcrop on R.
[6.7] Start of outcrop on R opposite Nick Roberts Marine boating shop.
[6.9] Make a U-turn at Ulster Landing Road. Go back to the N on NY 32.
[6.95] Park on R opposite trail on L for Stop 9.

STOP 9 - Taconic Unconformity with Silurian Rondout Formation on Ordovician (Tippecanoe) Siltsone, NY 32, East Kingston. [UTM Coordinates: 585.1E / 4646.2N, Kingston East quadrangle.]

The two main features to be seen here are the Taconian unconformity and the Binnewater and Rondout strata that immediately overlie it. Notice the characteristics and attitude of the Ordovician strata (dominantly siltstones) which dip more gently than the overlying Rondout strata. Although obscured by the steep cleavage(s), bedding in the Ordovician strata trends N22°W, 29°SW and is defined by a sandy interlayer immediately beneath the unconformity. The Binnewater and Rondout strata are oriented N15°W, 34°SW. Here the Binnewater is only 0.25 m thick and the High Falls and Shawangunk formations are totally missing.

The rocks are tilted due to folding and although we do not see obvious folds a prominent pressure solution cleavage, oriented N10°E, 65°SE, is developed in the Silurian strata. It passes through and beneath the unconformity and is sub-parallel to the Ordovician slaty cleavage which trends N10°W, 77°NE. Thus, the Ordovician strata are cut by two cleavages (note the wedge-like appearance of the cleavage fragments) but the Silurian only possesses one obvious deformational fabric. If the Rondout strata are rotated back to their initial horizontal positions, the attitude of the Ordovician strata would be subhorizontal. Note that the pre-Silurian (Taconic) Ordovician cleavage (after unfolding of the Silurian strata) would dip moderately steep toward the SW! Thus, we must be at the hinge area of an eroded Ordovician fold and, as such, the unconformity here might be a disconformity.

Overlying a 15-cm-thick layer of the Binnewater sandstone, here the lowest member of the Rondout Formation is the Wilbur Limestone (refer to Column 10, Figure 23). This is our first opportunity to examine this unit. Its thickness is only about 2 m. Notice its composition. Does a "basal conglomerate" exist? What about fossils? The next unit above is the Rosendale Dolostone. We have seen this formation several times previously. Look for fossils.

According to a popular modern interpretation, dolostones are products of intertidal settings, possibly even supratidal settings. Supratidal deposits are verified by finding shrinkage cracks and other evidence of subaerial exposure. Algal stromatolites abound in modern dry tropical peritidal settings. Their distribution is controlled by the salinity effect on the distribution of gastropods. In waters of normal salinity, gastropods flourish and tend to gobble up the algal mats which are the building blocks of the stromatolites. A succession that begins with a marine limestone and ends upward with a mud-cracked dolostone containing algal stromatolites is a classic PAC (Punctuated Aggradational Cycle). Do you think the Wilbur-Rosendale combination should be interpreted as a PAC?

Next above the Rosendale Dolostone is the Glasco Limestone with abundant marine fauna, especially colonies of chain corals of the genus Halysites, stromatoporoids (not the same as algal stromatolites), bryozoa, other corals, and brachiopods. Overlying it is the Whiteport Dolostone. Does the Glasco-Whiteport pair mimic the Wilbur-Rosendale pair? What are the similarities? The differences? Is the Glasco-Whiteport combination a PAC?

[6.95] Continue N on NY 32.
[7.3] Just after last driveway on R, pull-over for Stop 10.

STOP 10 - Taconic Unconformity and bedding-plane thrusts in Helderbergian carbonates, NY 32, East Kingston. [UTM Coordinates: 585.1E / 4646.82N, Kingston East quadrangle.]

At Stop 10, we see all parts of the Rondout Formation, with base resting on the Taconian unconformity, as at Stop 9, but with the added factor of repetition of the Siluro-Devonian strata along a number of bedding-plane thrusts. We will work our way along the large rock face beginning at the N end with the Ordovician strata. Then come Wilbur, Rosendale, Glasco, and Whiteport and the first of many bedding thrusts (Figure 26). Continue S, passing several more bedding-plane thrusts. Eventually find an undisturbed contact between the top of the Whiteport (of the Rondout) and the base of the overlying Manlius (Thacher Member). The next-higher unit is the Coeymans (Ravena Member, shown only as Ravena on Figure 26), which is the basal part of the lower fining-upward cycle of three units (Coeymans-Kalkberg-New Scotland). Steeply north-dipping extension fractures (related to the ramp-like thrusts) are lined with calcite. We note minor normal reactivation of some of the bedding plane thrusts based on left-lateral offset of steep, post-thrust calcite veins.

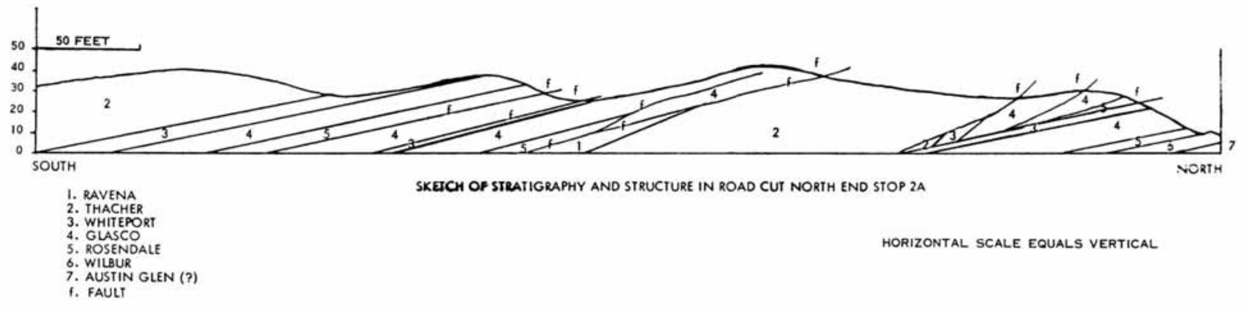


Figure 26 - Structure section of Stop 10 from Waines and Hoar (1967).

[7.3] Continue ahead to sign for Rhinecliff Bridge.
[7.8] Pass under NY 199.
[7.9] Turn into ramp on R for NY 199 Westbound.
[8.0] Passing Ordovician graywackes in cuts on ramp.
[8.1] Enter NY 199 westbound.
[8.3] Pull over to R for Stop 11.

STOP 11 - Helderberg Strata on N side NY Route 199, on W approach to Kingston-Rhinecliff Bridge. [UTM Coordinates: 585.05E / 4647.5N, Kingston East quadrangle.]

At this stop, the bottom of the Helderberg carbonates is not visible, but we can see the upper part of the Manlius (Thacher Member) and all three units of the lower fining-upward cycle of Coeymans (Ravena Member)-Kalkberg (lower Hannacroix and upper Broncks Lake members)-New Scotland. Instead of a single deepening sequence, the PACmen interpret this succession as shown in Figure 27, with two PAC sequences within the Coeymans-Kalkberg beds. Their argument presupposes that the silty beds in the upper part of the Hannacroix member of the Kalkberg are not deeper-water deposits, but shallower-water deposits, and that the brachiopods forming the Docoelosia bed represent a deepening. JES finds the PAC argument here less than compelling.

See what you can find in the way of fossils here. The best specimens may not be in the fresh bedrock, that breaks so irregularly, but in the weathered blocks at the top of the ridge. Study of the molds and casts in fine-textured rocks can yield nearly as much detail as study of fossils in which the original skeletal material is intact.

[8.3] Continue W on NY 199.
[8.5] Pull over to R for Stop 12.

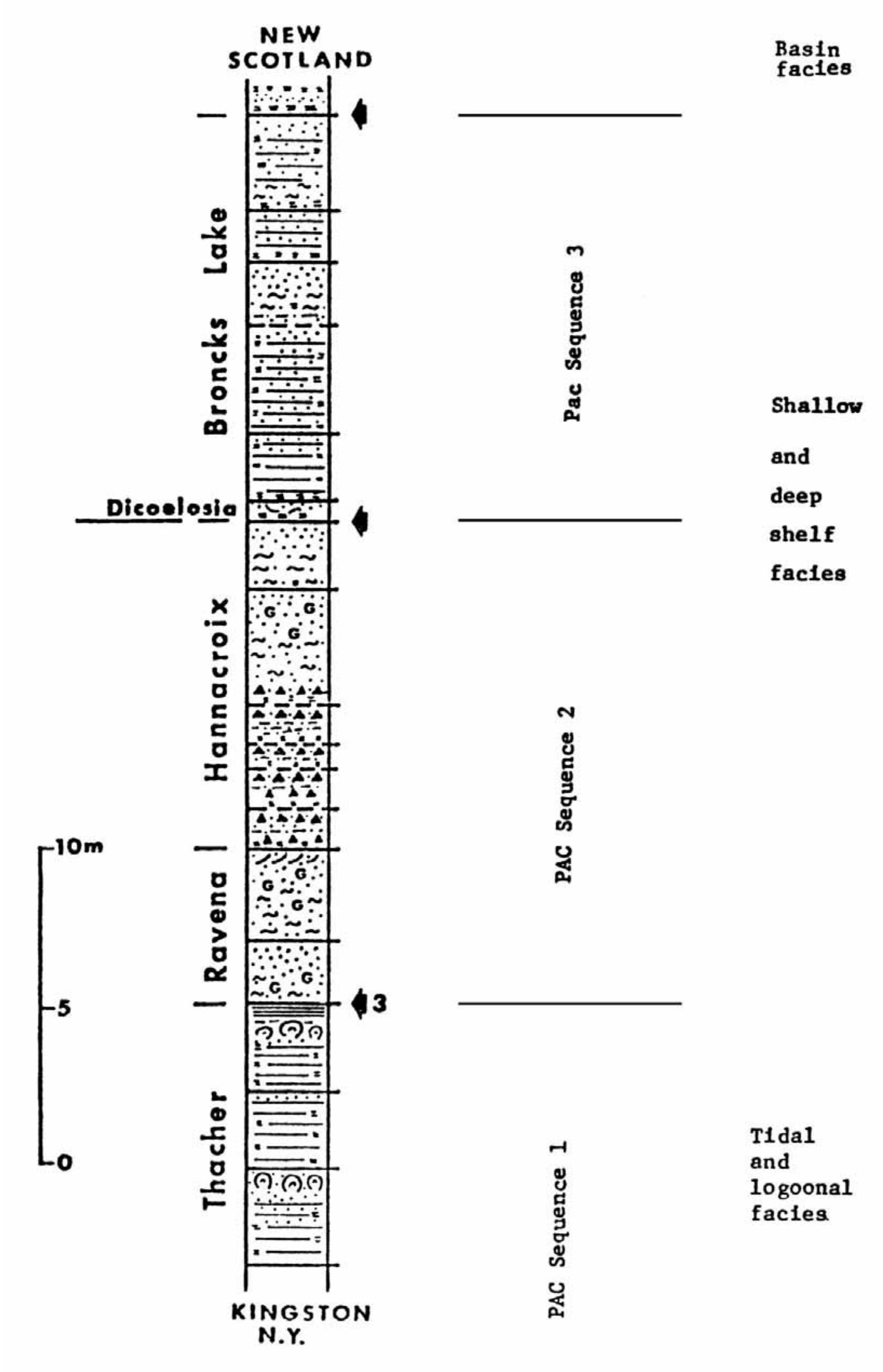


Figure 27 - Stratigraphic column for Stop 11 (Friedman et al., 1982).

STOP 12 - Anticlinal Fold of Helderberg Strata, on N side of NY Route 199, W approach to Kingston-Rhinecliff Bridge. [UTM Coordinates: 584.75E / 4647.38N, Kingston East quadrangle.]

This small anticline brings up the strata of the upper fining-upward cycle, the Becraft-Alsen-Port Ewen beds. The anticline is separated from the strata at Stop 11 by a fault that follows the low covered interval between the two ridges where rock is exposed along the highway. Notice the comparable relationships of a coarse, gray, skeletal limestone without much silt and lacking chert in the basal unit (Coeymans and Becraft). This grades upward into a siltier rock containing chert (Kalkberg and Alsen). At the top, the chert vanishes and the rock is a shaly calcareous siltstone (New Scotland-Port Ewen).

[8.5] Continue W on N. Y. 199.
[8.8] Large cuts on both sides expose the Esopus, the overlying Schoharie Formation, and at the W end, the Onondaga Limestone (a very cherty limestone; the youngest widespread Devonian limestone).
[9.0] Bear R into ramp for US Route 9W northbound.
[9.2] Entering US Route 9W northbound.
[10.9] Leave Kingston East quadrangle, enter Saugerties quadrangle. The highway follows a strike valley at the base of the Esopus Formation.
[12.2] Entering town of Saugerties.
[12.4] Esopus Creek forms Glenerie Falls to the W and turns N to follow the strike valley toward Saugerties. For the next mile, the low ledges on the E that dip W are the Glenerie Formation, a thin unit overlying the Port Ewen and underlying the Esopus. The Glenerie here is full of fossils. They have been silicified and weather out in the dirt formed by the dissolution of the carbonate matrix. The steep bluff on the W side of Esopus Creek is underlain by the Esopus Formation. The parting that dips steeply to the E is the cleavage; bedding dips gently W.
[13.6] US Route 9W bends R and cuts across the strike.
[14.6] US Route 9W bends L.
[14.9] US Route 9W bends R, entering Saugerties on flat surface, altitude 150 feet, underlain by Pleistocene deposits or postglacial lake clays, with Ordovician bedrock below.
[15.9] 90° L turn at blinking light.
[16.2] 90° R turn. View of Hudson River to R.
[16.3] 90° L turn.
[16.55] Bridge over Esopus Creek; view to R shows thick graywacke beds in Ordovician strata. Just beyond bridge, another 90° turn to the R.
[16.7] Going uphill, then 60° turn to L.
[17.0] Major intersection; US Route 9W goes R; follow NY 32 to L.
[17.1] At light, 90° turn to R. Follow Thruway sign.
[17.15] Sharp turn to L onto Ulster Avenue.
[17.8] Crossing over RR tracks. Cut in Esopus Shale.
[18.2] Crossing over NY State Thruway. At traffic light the Helderbergian limestones dip south. View of Catskills ahead.
[18.3] NY 32 makes 90° R turn.
[18.5] Thruway entrance - Interchange 20.

[18.8] Onondaga Limestone on R.
[19.1] Onondaga Limestone on R.
[19.2] Blinker light.
[19.8] Jointed Onondaga Limestone dips to R.
[19.9] Road curves L just S of hamlet of Katsbaan.
[20.2] Onondage dips west. Valley in distance underlain by Bakeoven Shale.
[20.3] End of large curve.
[20.9] Pull up on R for Stop 13.

STOP 13 - Mount Marion Formation, New Cut on NY Route 32, Quarryville (N of Mt. Airy). [UTM Coordinates: 584.0E / 4363.15N, Saugerties quadrangle.]

This cut exposes the same formation we examined at Stop 8, a deep-water marine deposit consisting of dark gray to black shale, siltstone, and sandstone somewhat resembling the Ordovician flysch. Very little shale is exposed at the W end of the exposure. Rather, non-graded and non-laminated massive sandstone and siltstone occurs. The bedding is oriented N12°W, 16°SW with a strong jointing oriented N28°E, 75°SE. Note the rounded, dense concretions which consist of pyrite, siderite, and possibly barite. Look for Devonian brachiopods in the sandy layers. Check closely to see if any bedding-plane thrust faults repeat any layers, as observed at Stop 8.

[20.9] Continue W on NY 32. Going uphill on curve to R past Quarryville.
[21.5] Mt. Airy Road on R.
[21.6] Cross road.
[21.8] Pull up on R for Stop 14.

STOP 14 - Ashokan Formation, NY Route 32, W of Quarryville. [UTM Coordinates: 583.13E / 4663.6N, Saugerties quadrangle.]

The Ashokan Formation is the formation quarried as New York blue stone and is used for paving slabs on sidewalks. Notice the well-developed large-scale cross strata that show stream flow toward the west. JES thinks that the Mount Marion-Ashokan combination is equivalent to the Bellvale Formation of the Schunnemunk-Green Pond belt, with lower Bellvale equal to Mount Marion and upper Bellvale, to the Ashokan.

[21.8] Continue NW on NY 32.
[22.0] Leave Saugerties quadrangle, enter Cementon quadrangle.
[22.3] Fawn Road on L. Catskill Mountains in distance.
[22.6] Leave Cementon quadrangle, enter Kaaterskill quadrangle.
[22.8] Road curves to R, heading north.
[23.2] Road bends L. Ashokan Formation both sides of road.
[23.5] Junction NY 32 and 32A. Continue northward.
[24.1] Leave Kaaterskill quadrangle, re-enter Cementon quadrangle.
[24.3] Blinker Light. NY 32 bends R; NY 32A goes straight; take NY 32A.

[24.4] Road curves L.
[24.7] Leave Cementon quadrangle, re-enter Kaaterskill quadrangle.
[25.15] Greene County boundary.
[25.35] Palenville sign on R.
[25.6] NY 32A curves R toward center of Palenville.
[26.2] At T-intersection, join NY 23A and turn L (23A West) toward Haines Falls and Tannersville. Cliffs en route expose nonmarine Devonian strata deposited by ancient rivers.
[27.1] Kaaterskill Creek; a post-glacial valley.
[28.0] Cuts on L and R are shale and siltstone redbeds of Catskills.
[29.6] Hairpin curve; tributary to R flows into Kaaterskill Creek. Note cross-bedded outcrops on R.
[29.9] Redbeds on R.
[30.0] Note channels in crop on R.
[30.7] Haines Falls sign.
[31.1] In Haines Falls, turn R for road to North Lake.
[31.2] Turn R again at General Store.
[32.9] Road on R.
[33.4] Park Entrance and Toll Gate.
[33.5] Turn L.
[34.65] Cross-bedded sandstones.
[35.0] North Lake Park; park in SE corner and walk north on escarpment trail (Blue Markers) to Artists Rock (north of former Mountain House) to Stop 15.

STOP 15a - Catskill Redbeds and Conglomerate along North Lake Escarpment, Haines Falls, New York. [UTM Coordinates: 580.02E / 4672.92N, Kaaterskill quadrangle.]

The Catskills are a thick sequence of fan- and delta deposits that show sedimentary structures indicating an eastward source. The horizontal layering of the Catskills are quite obvious (even from a distance) and the rocks vary from red shales to siltstones and sandstones to very coarse conglomerates. The red color may make you think of the Newark Series but, in fact, these rocks are much older (middle Devonian) despite the fact that they appear similar. We hope you noted the impressive thickness of the Catskill sequence as we drove up the Catskill Front from Stop 14.

The Catskill Mountains are mountains because they are composed of resistant strata containing sandstone and conglomerate. These are much more difficult to erode than the soft shales and limestones in the Hudson Valley. The section of strata along Route 23A consists of 2,000 feet of coarse river deposits and also contains successive intervals of fine grained floodplain deposits (red siltstone and mudstone) - all characteristics of the non-marine portion of the Catskill Delta (Figure 28). The source area for the cobbles is clearly toward the east - any ideas on where they came from? Try to imagine the ancient landscape as mirror image of the modern Rockies and Great Plains with mountains to the east (now eroded hills of the Taconics and Berkshires) with an alluvial apron sloping westward as far as present day Ohio. The continentally-derived fans gave way westward to shallow marine seas into western Pennsylvania and Ohio where thinner Devonian marine facies are found. The shoreline prograded toward the west as the abundance of sediment pushed the seas toward the interior of Devonian North America.

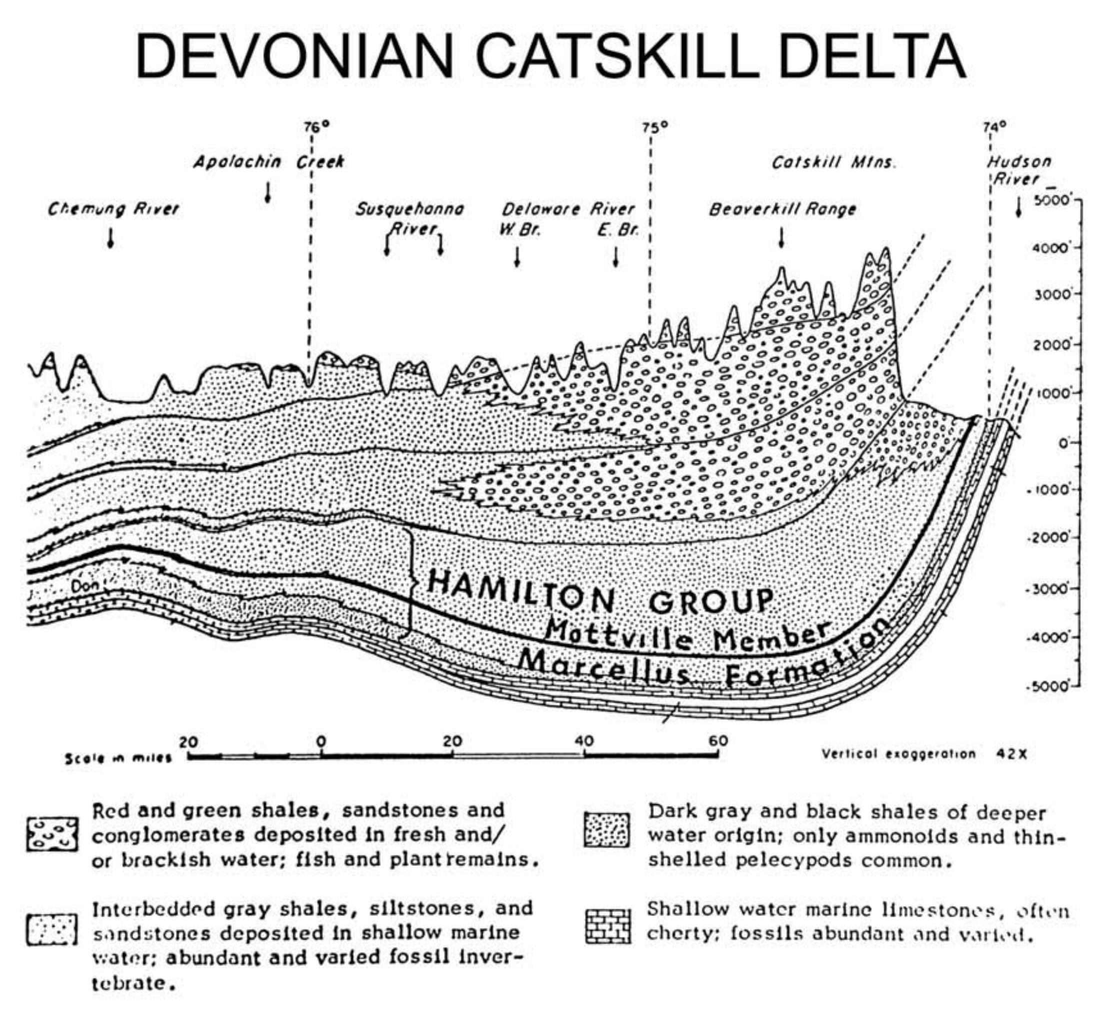


Figure 28 - Diagrammatic section of the Catskills showing the westward thinning of the Catskill fan- and delta facies. Sketch by M. P. Wolff.

Although there are no marine fossils in the Catskills, plant fragments are common (twigs and branches of Devonian trees). This is the first evidence of trees in North America! The river currents produced successive sequences of sand bars containing ripple marks and cross bedding, still preserved in the Catskill red beds. The deepest parts of the wide river channels produced extensive "lag" deposits of gravel. These strata now form the highest peaks of the Catskill Mountains from New York into Maryland and Pennsylvania (Pocono Mountains - see Figures 1, 14). We will walk along the eastern escarpment of the Catskills here and feast our eyes on the spectacular view of the Hudson Valley and the Taconics and Berkshire massif in the distance. The glacially sculpted landscape in front of you was strongly modifed during the Pleistocene with the dominant flow direction down the Hudson Valley. The escarpment is steep because of regional jointing.

Glacial striae on the escarpment are oriented N50°E with flow toward the NE suggesting the presence of a glacial ice cap on top of the Catskills here. We know this because two chattermarks (asymmetric crescentic gouges [one concave NE and one convex NE] both with steep steps on the NE side) were observed on the rock ledges near Artists Rock. These are diagnostic glacial features which prove directional ice flow from the SW toward the NE. Near the conglomerate exposure, local chattermarks indicate glacial flow toward the SE! We think that the evidence suggest the former presence of an ice cap at this location with conflicting flow directions due to radial flow from the top of the high ground. Be careful not to walk too close to the edge of the cliff face as its a long walk back to the Academy.

[35.0] Follow exit signs to park exit, retracing route to Palenville.
[36.7] Park exit and toll booth.
[38.8] Cross creek.
[38.9] Turn L at General Store.
[39.0] Turn L onto Route 23A (eastbound).
[43.0] Cross Kaaterskill Creek.
[43.4] Palenville sign.
[43.85] Palenville; turn L on NY 23A toward Catskill.
[43.9] Leave Kaaterskill quadrangle, re-enter Cementon quadrangle.
[45.4] Kiskatom sign.
[45.75] Stony Brook Ext. on L.
[46.1] Intersection with NY 32; continue on NY 23A.
[47.5] Mountain Turnpike on L.
[48.7] Road curves to L. Mt. Marion to R (south).
[49.4] Bridge over Kaaterskill Creek.
[49.8] Old Kings Road.
[49.9] Cross over NY Thruway. Onondaga Limestone on L (west) and Schoharie on R (east) sides of Thruway. There is a fault parallel to Thruway here and obvious folds to the immediate east.

[50.2] **Pull-Over STOP 15b**. [UTM Coordinates: 589.27E / 4672.20N, Cementon quadrangle.]

Note the open anticline on the right (south) side of the road at the end of the unfinished (abandoned?) Thruway exit ramp. Here, The sequence, from top to bottom, is the Esopus Shale, Glenarie Limestone, and Port Ewen Limestone (see Table 4). Note the well developed subvertical slaty cleavage in the Esopus and the intricate folds in the Glenarie within the disrupted bedding. Note the contrast in structural style of the three units, a function of their composition and layering characteristics (anisotropy).
[51.5] Glenarie Limestone on L.
[51.7] Steeply dipping Helderberg limestones.
[52.1] NY 23A ends. Junction with US Route 9W; join it.
[52.6] At light, road junction Routes 385 and 9W. Stay on 9W.
[52.7] Light; follow 9W to L.
[52.9] Leave Cementon quadrangle, enter Hudson South quadrangle.

[53.4] Bridge over Catskill Creek, Catskill.
[54.1] Enter ramp on R for NY 23 West (toward Thruway)
[54.3] Turn R; enter NY 23 westbound.
[54.45] Cross over 9W.
[54.9] Leave Hudson South quadrangle; re-enter Cementon quadrangle.
[55.5] Take exit ramp on R for Jefferson Heights and old NY 23 and direction of Thruway.
[55.6] Park on R for Stop 16.

STOP 16 - Taconic Unconformity and overlying Rondout and Helderbergian carbonates, N side of exit ramp from new location of NY Route 23 from Rip Van Winkle Bridge to old NY Route 23, Jefferson Heights, Catskill. [UTM Coordinates: 591.9E / 4676.6N, Cementon quadrangle.]

Here, the Rondout Formation and Helderbergian carbonate succession are in marked steeply-dipping unconformity with underlying Ordovician graywackes with bedding oriented N7°E, 71°NW. The Rondout Formation consists of about 1 m of Rosendale Dolostone with a thin basal sandstone (Binnewater?) resting on the steeply dipping Ordovician Tippecanoe sequence. Overlying the Rosendale is roughly 10 cm of limestone that is probably the feather edge of the Glasco Limestone, followed by the Whiteport Dolostone. Thrust faults occur above the Whiteport in a chaotic zone with right-lateral shear sense, characterized by intrafolial isoclinal folds and then the chaotic sequence is capped by the highly laminated Manlius (Helderbergian) Limestone follwed by the Coeymans and Kalkberg limestones. Note that the Shawangunk, High Falls, Binnewater, Wilbur sequence is absent (See Figure 23.) and that what is left of the Silurian is exceedingly thin.

Measure the attitude of Ordovician graywackes and Helderbergian carbonates and compare them to our measurements above. Load casts and graded bedding in the wackes indicates tops to the left (NW) but isoclinal folding may have duplicated the sequence. Look for upside-down beds. The unconformity is parallel to bedding in the Silurian strata and overlying Helderbergian limestones and is oriented N35°E, 47°NW. Note the distant SE-dipping limbs of a syncline across the highway. A solution cleavage in the limestones (probably the axial surface of the synclinal fold) at the west end of the outcrop is oriented N30°E, 36°NW. If the carbonates are restored to horizontal, what is the attitude of the Ordovician? Look for graptolites in the Ordovician graywackes. They have been found here, partly because the rocks break parallel to the bedding. From the Manlius, a nearly complete exposure of the lower fining-upward cycle is present. We shall walk through the succession from E to W. Look for fossils.

[55.6] Continue down exit ramp.
[55.7] At end of ramp, turn L, pass under NY 23.
[55.8] Turn L, entrance ramp to NY 23 eastbound, direction of Rip Van Winkle Bridge.
[56.5] Leave Cementon quadrangle, enter Hudson South quadrangle.
[56.9] Cross over US Route 9W.
[57.4] Road junction with NY 385; continue on 23.
[57.8] Toll plaza, Rip Van Winkle Bridge.
[58.8] Road junction to US Route 9G; bear L staying on NY 23.

[59.2] Road junction US Route 9G and NY 23B go left up Mount Merino; stay on NY 23, bearing to R. Big cuts on R side of NY 23 are Mount Merino Chert at N. end of Church's Hill (Olana Historic Site; home of artist Frederick Lewis Church).
[61.4] Road junction US Route 9 at S end of Becraft Mountain. Find parking place for Stop 17.

STOP 17 - Taconic Unconformity at SW corner of Becraft Mountain, S of Hudson, NY. [UTM Coordinates: 599.75E / 4673.42N, Hudson South quadrangle.]

In this exposure, the Silurian Rondout formation rests unconformably, upon Taconic cherts of the Mount Merino formation. The unconformity is of a very low angle and quite irregular, perhaps as a result of minor thrust faulting at the Rondout-Mount Merino contact. Within the base of the brown-weathering Rondout (a silty dolostone), however, clasts of black "Mount Merino" chert and quartz occur. This would be expected if the contact is indeed an unconformity!

The Rondout is overlain by highly laminated, whitish rocks of the Manlius formation, but the Rondout appears again above the Manlius. What gives? Bedding thrusts occur within the Rondout and overlying Manlius. The field sketch (Figure 29 shows the bedding thrusts (the lower one outlined by a calcite vein) which imbricate the Siluro-Devonian carbonates above the unconformity with local folding ("rolling") of the Rondout. Again, clear evidence for significant post-Taconic, low-angle thrusting as seen at Stop 8! Toward the south, the Manlius gives way to calc-arenites of the Coeymans Formation and possibly massive limestones of the Kalkberg and New Scotland formations but there are, again, significant complications.

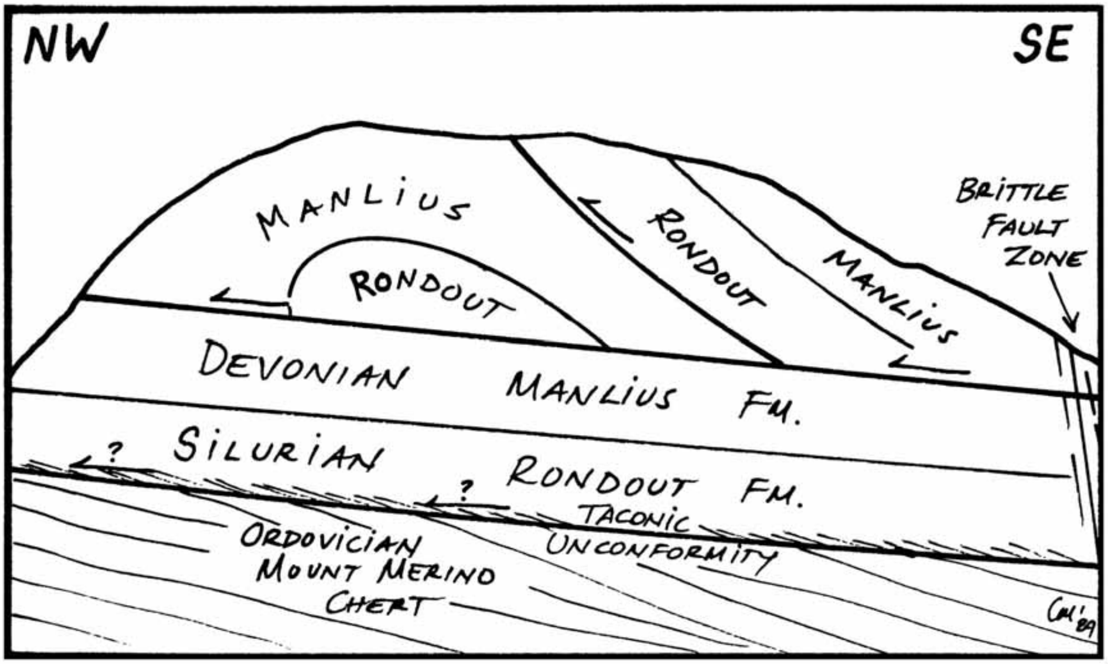


Figure 29 - Diagrammatic sketch of Taconic unconformity and overlying Siluro-Devonian rocks exposed at Becraft Mountain, Stop 17. Sketch by CM.

Walking southward along the exposure note the erosional swale in the outcrop and the NE-trending subvertical jointing in the carbonates. Immediately south of this broken-up area, coarse grained calcarenite of the Becraft Formation crops out. Thus, the Becraft is dropped down along a vertical to steeply NW-dipping fault (or fault zone) against the Coeymans and/or Kalkberg (see Figure 28). Detailed fossil work needs to be done here to complete the true picture of the structure but it would appear that high-angle faults (as well as low-angle thrusts) disrupt the "simple flat-lying" sedimentary picture here.

END OF TRIP - WE HOPE YOU'VE ENJOYED YOURSELVES! ========> :)

Retrace route back across Hudson River via NY Route 23 following signs for New York Thruway. Enter Thruway at Interchange 21. Drive back to NYAS. We will stop at the west branch of the Sloatsburg Service area to allow some of our crew to pick up their cars.

ACKNOWLEDGEMENTS

We would like to thank the management of the Williams Lake Hotel for allowing access to the railroad bed on their property and for permission to park in their lot. Matt Katz and Marcie Brenner of the New York Academy of Sciences and the staff of Duke Geological Laboratory were, as usual, most helpful in the logistical support necessary for such an undertaking. We dedicate this field trip to silicon chips in our computers and to the invention of coffee.

Table 01

GEOLOGIC TIME CHART

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

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

PALEOZOIC	245	
(Permian)		Pre-Newark erosion surface formed.
	260	**Appalachian orogeny.** (Terminal stage.) Folding, overthrusting, and metamorphism of Rhode Island coal basins; granites intruded.
(Carboniferous)		Faulting, folding, and metamorphism in New York City area. Southeastern New York undergoes continued uplift and erosion.
(Devonian)	365	**Acadian orogeny.** Deep burial of sedimentary strata. Faulting, folding, and metamorphism in New York City area. Peekskill Granite and Acadian granites intruded.
(Silurian)		
	440	**Taconic orogeny.** Intense deformation and metamorphism.
	450	Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line and St. Nicholas Thrusr Zone). Arc-continent collision. Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata.
(Ordovician)		Ultramafic rocks (oceanic lithosphere) sliced off and transported structurally above deposits of continental shelf.
(Cambrian)		Shallow-water clastics and carbonates accumulate in west of basin. (= **Sauk Sequence**; protoliths of the Lowerre Quartzite, Inwood 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 SEdirected 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	**Eastern deep-water zone**
(L. Cambrian - M. Ordovician)	(L. Cambrian-M. Ordovician)
Copake Limestone (Stockbridge,	
Rochdale Limestone (Inwood Marble)	
Halcyon Lake Fm.	
Briarcliff Dolostone	(Ꞓ-Oh) Hartland Fm.
Pine Plains Fm.	(Ꞓ-Om) Manhattan Fm.
Stissing Dolostone	
Poughquag Quartzite	
Lowerre Quartzite	
Ned Mtn Fm.	

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

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

LAYER I - PROTEROZOIC BASEMENT ROCKS

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

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

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

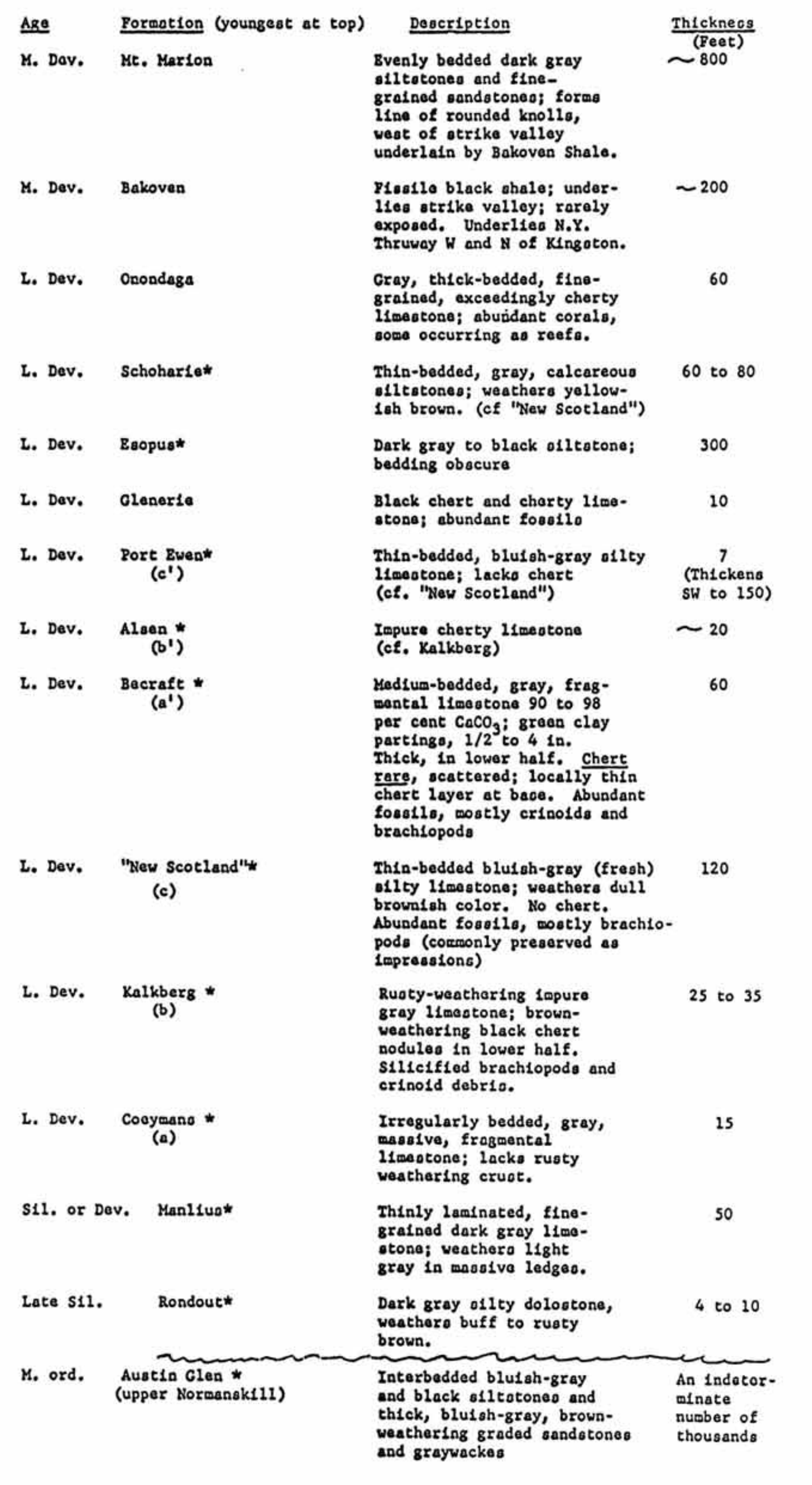
~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~

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

Table 03
Silurian and Devonian formations near Highland Mills, NY
(Boucot, Gauri, and Southard, 1970)

Group	Formation (and Member)	Thickness (feet)
Stone Ridge Group	Bellvale Flags (=Hamilton)	
	Cornwall Shale (=Marcellus)	
	(covered)	
	Pine Hill Formation	
	Kanouse Member	25-150(?)
	Woodbury Creek Member	125
	Esopus Formation	
	Eddyville Member	80
	Highland Mills Member	155
	Quarry Hill Member	165 (max.)
	Mountainville Member	210-110
	Connelly Conglomerate (="Oriskany"?)	40-45
	Central Valley Sandstone	up to 50-60
	(covered)	
Helderberg Group	New Scotland Formation	60
	Kalkberg Limestone	50
	Coeymans Limestone	13
	Rondout Formation	25-40
	Decker Formation	25
	Poxono Island Formation	75
	Longwood Formation	160
	Mudstone member	95
	Sandstone-siltstone mbr.	65; 8-10
	Shawangunk Formation	
	Sandstone member:	
	Evenly bedded sandstone	13
	Cross-bedded sandstone	8
	Red sandstone	2-5
	Quartzitic sandstone	55
	Conglomeratic member	115 (W)-285 (E)

Table 04
Silurian and Devonian Formations, vicinity of Catskill, NY



Age	Formation (youngest at top)	Description	Thickness (Feet)
M. Dev.	Mt. Marion	Evenly bedded dark gray siltstones and fine-grained sandstones; forms line of rounded knolls, west of strike valley underlain by Bakoven Shale.	~800
M. Dev.	Bakoven	Fissile black shale; underlies strike valley; rarely exposed. Underlies N.Y. Thruway W and N of Kingston.	~200
L. Dev.	Onondaga	Gray, thick-bedded, fine-grained, exceedingly cherty limestone; abundant corals, some occurring as reefs.	60
L. Dev.	Schoharie*	Thin-bedded, gray, calcareous siltstones; weathers yellowish brown. (cf "New Scotland")	60 to 80
L. Dev.	Esopus*	Dark gray to black siltstone; bedding obscure	300
L. Dev.	Glenerie	Black chert and cherty limestone; abundant fossils	10
L. Dev.	Port Ewen* (c')	Thin-bedded, bluish-gray silty limestone; lacks chert (cf. "New Scotland")	7 (Thickens SW to 150)
L. Dev.	Alsen * (b')	Impure cherty limestone (cf. Kalkberg)	~20
L. Dev.	Becraft * (a')	Medium-bedded, gray, fragmental limestone 90 to 98 per cent $CaCO_3$; green clay partings, 1/2 to 4 in. Thick, in lower half. Chert rare, scattered; locally thin chert layer at base. Abundant fossils, mostly crinoids and brachiopods	60
L. Dev.	"New Scotland"* (c)	Thin-bedded bluish-gray (fresh) silty limestone; weathers dull brownish color. No chert. Abundant fossils, mostly brachiopods (commonly preserved as impressions)	120
L. Dev.	Kalkberg * (b)	Rusty-weathering impure gray limestone; brown-weathering black chert nodules in lower half. Silicified brachiopods and crinoid debris.	25 to 35
L. Dev.	Coeymans * (a)	Irregularly bedded, gray, massive, fragmental limestone; lacks rusty weathering crust.	15
Sil. or Dev.	Manlius*	Thinly laminated, fine-grained dark gray limestone; weathers light gray in massive ledges.	50
Late Sil.	Rondout*	Dark gray silty dolostone, weathers buff to rusty brown.	4 to 10
M. ord.	Austin Glen * (upper Normanskill)	Interbedded bluish-gray and black siltstones and thick, bluish-gray, brown-weathering graded sandstones and graywackes	An indeterminate number of thousands

REFERENCES CITED

Amsden, T. W., 1955, Lithofacies map of Lower Silurian deposits in central and eastern United States and Canada: American Association of Petroleum Geologists Bulletin, v. 39, no. 1, p. 60-74.

Anderson, E. J., and Goodwin, P. W., 1980, Application of the PAC hypothesis to limestones of the Helderberg Group: Society of Economic Paleontologists and Mineralogists, Eastern Section Field Conference Guidebook, 32 p.

Anderson, E. J.; Goodwin, P. W.; and Cameron, B., 1978, Punctuated aggradational cycles (PACS) in Middle Ordovician and Lower Devonian sequences, p. 204-224 in Merriam, D. F., ed., New York State Geological Association, Annual Meeting, 50th, Syracuse University, 23-24 September 1978, Guidebook, 385 p.

Anderson, E. J., Goodwin, P. W., and Sobieski, T. H., 1984, Episodic accumulation and the origin of formation boundaries in the Helderberg Group of New York State: Geology, v. 12, p. 120-123.

Babcock, E. A., 5th, 1966 ms., Structural aspects of the folded belt near Leeds, New York: Syracuse, New York, Syracuse University, Department of Geology, Master's Thesis, 62 p.

Banino, G. M., and Brown, S. P., 1978, Economic geology of the central Hudson River Valley: Forum on the Geology of Industrial Minerals, Annual Meeting, 14th, Albany, New York, Guidebook to Field Trip.

Banino, G. M., and Cutcliffe, W. E., 1979, Economic geology of the central Hudson River Valley, Trip B-1, p. 292-308 in Friedman, G. M., ed., New England Intercollegiate Geological Conference, Annual Meeting, 71st and New York State Geological Association, Annual Meeting, 51st, Troy, New York, 5-7 October 1979, Guidebook: Troy, New York, Rensselaer Polytechnic Institute and Albany, New York, New York State Geological Survey, 457 p.

Benimoff, A. I., and Sclar, C. B., 1984, Coexisting silicic (sic) and mafic melts resulting from marginal fusion of a xenolith of Lockatong Argillite in the Palisades sill, Graniteville, Staten Island, New York: American Mineralogist, v. 69, nos. 11/12, p. 1005-1014.

Berkey, C. P., 1933, Engineering geology of the City of New York, p. 77-123 in Berkey, C. P., ed., Guidebook 9, New York Excursions, New York City and vicinity: International Geological Congress, 16th, United States, 1933, Washington, D. C., United States Government Printing Office, 151 p.

Boucot, A. J., 1959, Brachiopods of the Lower Devonian rocks at Highland Mills, N. Y.: Journal of Paleontology, v. 33, p. 727- 769.

Boucot, A. J.; Gauri, K. D.; and Southard, John, 1970, Silurian and Lower Devonian brachiopods, structure and stratigraphy of the Green Pond Outlier in southeastern New York: Palaeontographica, Bd. 135, Abt. A, nos. 1-2, p. 1-59.

Brock, P. J. C., 1989, Stratigraphy of the northeastern Manhattan Prong, Peach Lake quadrangle, New York-Connecticut, p. 1-27 in Weiss, Dennis, ed., New York State Geological Association Annual Meeting, 61st, Field trip guidebook: Middletown, NY, Orange County Community College, Department of Science and Engineering, 302 p.

Brock, P. J. C., 1993 ms., Geology of parts of the Peach Lake and Brewster quadrangle, southeastern New York and adjacent Connecticut, and basement blocks of the north-central Appalachians: New York, NY, City University of New York Graduate Faculty in Earth and Environmental Sciences, Ph. D. Dissertation, 494 p., 6 plates.

Broughton, J. G., and others, 1962, The geology of New York State: New York State Museum and Science Service, Geological Survey, Map and Chart Series 5.

Broughton, J. G., Davis, J. F., and Johnsen, J. H., not dated (1964?), Geology land mineral resources of the middle and lower Hudson River valley: New York State Museum and Science Service, Geological Survey, report prepared for State of New York, Hudson River Valley Commission, 103 p.

Brown, S. P., and Cutcliffe, W. E., 1969, Applied geology in the central Hudson Valley, p. 17-1 to 17-9 in Bird, J. M., ed., New England Intercollegiate Geological Conference, Annual Meeting, 61st, Albany, New York, 10-12 October 1969, Guidebook for field trips in New York, Massachusetts, and Vermont: Albany, State University of New York at Albany, Not consecutively paginated.

Carey, S. W., 1953, The orocline concept in geotectonics: Royal Society of Tasmania, Proceedings, v. 89, p. 255-288.

Chadwick, G. H., 1908, Revision of the "New York Series": Science, new series, v. 28, p. 346-348.

Chadwick, G. H., 1910, Downward overthrust fault at Saugerties, New York: New York State Museum Bulletin 140, p. 157-160.

Chadwick, G. H., 1913, Angular unconformity at Catskill (abstract): Geological Society of America Bulletin, v. 24, p. 676.

Chadwick, G. H., 1917, Hypothesis for the relation (sic) of normal (sic) and thrust-faults (sic) in eastern New York (abstract): Geological Society of America Bulletin, v. 28, p. 160-161.

Chadwick, G. H., 1928, Glacial striae topping the Catskill Mountains, New York (abstract): Geological Society of America Bulletin, v. 39, p. 216 (only).

Chadwick, G. H., 1944, Geology of the Catskill and Kaaterskill quadrangles. Part II, Silurian and Devonian geology, with a chapter on glacial geology: New York State Museum Bulletin 336, 251 p.

Chadwick, G. H., and Kay, G. M., 1933, The Catskill region: International Geological Congress, 16th, United States, Guide Book 9A, New York Excursions.

Clarke, J. M.; and Schuchert, C., 1899, The nomenclature of the New York series of geological formations: Science, new series, v. 10, p. 874-878.

Cook, J. H., 1924, The disappearance of the last glacial ice sheet from eastern New York: New York State Museumk Bulletin 251, p. 158-176.

Cotter, E. C., 1983, Shelf, paralic, and fluvial environments and eustatic sea-level fluctuations in the origin of the Tuscarora Formation (Lower) Silurian) of central Pennsylvania: Journal of Sedimentary Petrology, v. 53, no. 1, p. 25-49.

Cotter, E. C., 1988, Hierarchy of sea-level cycles in the medial (sic) Silurian siliciclastic succession of Pennsylvania: Geology, v. 16, p. 242-243.

Dale, T. N., 1879, The fault at Rondout, New York: American Journal of Science, 3rd series, v. 18, p. 293-295.

Daly, R. A., 1934, The changing world of the ice age: New Haven, CT. Yale University Press, 271 p. Reprinted 1973: New York, NY, Hafner Press.

Darton, N. H., 1894a, Preliminary report on the geology of Ulster County: New York State Geologist, Annual Report, 13th (for 1893), p. 290-372 (also, New York State Museum, 47th Annual Report).

Darton, N. H., 1894b, Report on the relations (sic) of the Helderberg limestones and associated formations in eastern New York: New York State Geological Survey, New York State Geologist, Annual Report, 13th (for 1893), v. 1, p. 197-228; (also New York State Museum, Annual Report, No. 47, p. 393-422).

Darton, N. H., 1894c, Geologic relations (sic) from Green Pond, New Jersey to Skunnemunk Mountain, New York: Geological Society of America Bulletin, v. 5, p. 367-394.

Darton, N. H., 1896, Examples of stream-robbing (sic) in the Catskill Mountains: Geological Society of America Bulletin, v. 7, p. 505-507.

Davis, W. M., 1882, The Little Mountains east of the Catskills: Appalachia, v. 3, p. 20-33.

Davis, W. M., 1883a, The nonconformity at Roundout, New York: American Journal of Science, 3rd series, v. 26, p. 389-395.

Davis, W. M., 1883b, The folded Helderberg limestones east of the Catskills: Harvard College Museum of Comparative Zoology Bulletin, v. 7, p. 311-329.

Drake, A. A., and Lyttle, P. T., 1981, Alleghanian thrust faults in the Kittatinny Valley, New Jersey, p. 92-112 in Manspeizer, Warren, ed., Field studies of New Jersey geology and guide to field trips: New York State Geological Association, 52nd Annual Meeting.

Dott, R. H., Jr.; and Bourgeois, Joanne, 1982, Hummocky stratification: significance of its variable bedding sequences: Geological Society of America Bulletin, v. 93, no. 8, p. 663-680.

Dunn, J. R., and Rickard, L. V., 1961, Silurian and Devonian rocks of the central Hudson Valley, p. C1-C32 in LaFleur, R. G., ed., New York State Geological Association, Annual Meeting, 33rd, Troy, New York, Guidebook to field trips, not consecutively paginated.

Emmons, Ebenezer, 1835, Strontianite in the vicinity of Ball's cave, Schoharie: American Journal of Science, v. 27, p. 182-183.

Epstein, A. G., Epstein, J. B., Spink, W. J., and Jennings, D. S., 1967, Upper Silurian and Lower Devonian stratigraphy of northeastern Pennsylvania, New Jersey, and southeasternmost New York: United States Geological Survey Bulletin 1243, 74 p.

Epstein, J. B., and Epstein, A. G., 1967, Geology in the region of the Delaware to Lehigh water gaps: Pennsylvania Geologists, Field Conference, 32nd, East Stroudsburg, Pennsylvania, Guidebook: Harrisburg, Pennsylvania, Pennsylvania Geological Survey, 89 p.

Epstein, J. B., and Epstein, A. G., 1972, The Shawangunk Formation [Upper Ordovician(?) to Middle Silurian] in eastern Pennsylvania: United States Geological Survey, Professional Paper 744, 45 p.

Epstein, J. B., and Lyttle, P. T., 1987, Structure and stratigraphy above, below and within the Taconic unconformity, southeastern New York, P. C1-C78 in Waines, R. H., ed., New York State Geological Asociation, Annual Meeting, 59th, New Paltz, New York, Guidebook to field trips, not consecutively paginated.

Fenner, Peter, and Hagner, A. F., 1967, Correlation of variations of trace elements and mineralogy (sic) of the Esopus Formation, Kingston, New York: Geochimica et Cosmochimica Acta, v. 31, p. 237-261.

Fessenden, F. W., 1960, A petrologic investigation of the Manlius and Coeymans limestones: New York Academy of Science, Annals, v. 84, p. 287-302.

Fisher, D. W., 1960, Correlation of the Silurian rocks in New York State: New York State Museum and Science Service, Geological Survey, Map and Chart Series, No. 1.

Fletcher, F. W., 1962, Stratigraphy and structure of the "Catskill Group" in southeastern New York, p. D1-D20 in Valentine, W. G., ed., New York State Geological Association, Annual Meeting, 34th, Port Jervis, New York, 4-6 May 1962, Guidebook to field trips, not consecutively paginated.

Fletcher, F. W., 1967, Middle (sic) and Upper Devonian clastics of the Catskill front, New York, Trip C, p. C1-C21 in Waines, R. H., ed., New York State Geological Association, Annual Meeting, 39th, New Paltz, New York, 5-7 May 1967, Guidebook to field trips: New Paltz, New York, State University College at New Paltz, Division of Physical Sciences, not consectively paginated.

Friedman, G. W., and Sanders, J. E., 1967, Origin and occurrence of dolostones, p. 267-348 in Chilingar, G. V., Bissell, H. J., and Fairbridge, R. W., eds., Carbonate rocks: Amsterdam, Elsevier Publishing Company, 471 p.

Friedman, G. M., and Sanders, J. E., 1978, Principles of sedimentology: New York-Chichester-Brisbane-Toronto, John Wiley and Sons, 792 p.

Friedman, G. M., and Sanders, J. E., 1982, Time-temperature-burial significance of Devonian anthracite implies former great (~6.5 km) depth of burial of Catskill Mountains, New York: Geology, v. 10, no. 2, p. 93-96.

Friedman, G. M., and Sanders, J. E., 1983, Reply to discussion of Time-temperature-burial significance of Devonian anthracite implies former great (~6.5 km) depth of burial of Catskill Mountains: Geology, v. 11, p. 123-124.

Friedman, G. M., and Sanders, J. E., 1984, Sedimentary environments in Paleozoic strata of the Appalachian Mountains in eastern New York: The Compass of Sigma Gamma Epsilon, v. 61, no. 4, p. 155-180.

Friedman, G. M., Sanders, J. E., and Kopaska-Merkel, D. C., 1992, Principles of sedimentary deposits. Stratigraphy and sedimentology: New York, NY, Macmillan Publishing Company, 717 p.

Friedman, G. M., Sanders, J. E., Martini, I. P., et al., 1982, Excursion 17A: Sedimentary facies: products of sedimentary environments in a cross section of the classic Appalachian Mountains and adjoining Appalachian basin in New York and Ontario: International Congress on Sedimentology, 11th, 22-27 August 1982, Hamilton, Ontario, Field Excursion Guidebook: International Association of Sedimentologists, not consecutively paginated.

Goldring, Winifred, 1933, Guide to the geology of John Boyd Thacher Park (Indian Ladder region) and vicinity: New York State Museum, Handbook 14, 112 p.

Goldring, Winifred, 1943, Geology of the Coxsackie quadrangle: New York State Museum Bulletin 332, 374 p.

Goldring, Winifred; and Flower, R. H., 1942, Restudy of the Schoharie and Esopus formations in New York State: American Journal of Science, v. 240, p. 673-694.

Goldthwait, J. W., 1913, Following the trail of ice sheet and valley glacier on the Presidential Range [White Mountains, N. H.]: Appalachia, v. 13, p. 1-23.

Goldthwait, J. W., 1916, Glaciation in the White Mountains of New Hampshire: Geological Society of America Bulletin, v. 27, p. 263-294.

Goldthwait, J. W., 1920, Dispersion of stones in the drift in New Hampshire (abstract): Geological Society of America Bulletin, v. 31, no. 1, p. 130-131.

Goldthwait, J. W., 1922, Glaciation of New Hampshire (abstract): Geological Society of America Bulletin, v. 33, p. 86 (only).

Goodwin, P. W., and Anderson, E. J., 1982, Punctuated aggradational cycles and carbonate facies, Helderberg Group (Lower Devonian), New York State, p. A1-A12 in Friedman, G. M., Sanders, J. E., Martini, I. P., et al., Excursion 17A: Sedimentary facies: products of sedimentary environments in a cross section of the classic Appalachian Mountains and adjoining Appalachian basin in New York and Ontario: International Congress on Sedimentology, 11th, Hamilton, Ontario, 22-27 August 1982, International Association of Sedimentologists, variously paginated.

Goodwin, P. W., and Anderson, E. J., 1985, Punctuated aggradational cycles: a general hypothesis of episodic stratigraphic accumulation: Journal of Geology, v. 93, no. 5, p. 515-533.

Grabau, A. W., 1903, Stratigraphy of Becraft Mountain: New York State Museum Bulletin 69, p. 1030-1079.

Grabau, A. W., 1906, Guide to the geology (sic) and paleontology of the Schoharie Valley in eastern New York: New York State Museum Bulletin 92, 386 p.

Guyot, Arnold, 1880, On the physical structure (sic) and hypsometry of the Catskill Mountain region: American Journal of Science, 3rd series, v. 19, p. 429-451.

Gwinn, V. E., 1964, Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge provinces of the central Appalachians: Geological Society of America Bulletin, v. 75, p. 863-900.

Harris, G. D., 1904, The Helderberg invasion of the Manlius: Bulletin of American Paleontology, no. 4, p. 51-77.

Hartnagel, C. A., 1903, Preliminary observations on the Cobleskill ("Coralline') limestone of New York: New York State Museum Bulletin 69, p. 1109-1175.

Hartnagel, C. A.,, 1905, Notes on the Siluric or Ontaric section of eastern New York: New York State Museum Bulletin 80, p. 342-358.

Heyl, G. R.; and Salkind, Morris, 1967, Geologic structure of the Kingston area of the Appalachian fold belt, p. E1-E5 in Waines, R. H., ed., New York State Geological Association, Annual Meeting, 39th, New Paltz, New York, Guidebook to field trips, not consecutively paginated.

Hoar, F. G., and Bowen, Z. P., 1967, Brachiopoda (sic) and stratigraphy of the Rondout Formation in the Rosendale quadrangle, southeastern New York: Journal of Paleontology, v. 41, no. 1, p. 1-36.

Holzwasser, Florrie, 1926, Geology of the Newburgh quadrangle: New York State Museum Bulletin 270, 95 p. (includes colored geologic map on scale of 1:62,500).

Howell, B. F., 1942, Geological studies in Ulster County, New York: New York State Museum Bulletin 327, p. 73-76.

Hutton, James, 1795, Theory (sic) of the Earth with proofs and illustrations: Edinburgh, W. Creech, 2 vols. (Facsimile reprint, 1959, New York, Hafner), 000 p.

Jaffe, H. W., and Jaffe, E. B., 1962, Geology of the Precambrian crystalline rocks, Cambro-Ordovician sediments (sic) and dikes of the southern part of the Monroe quadrangle, Trip B, p. B1-B10 in Valentine, W. G., ed., New York State Geological Association Annual Meeting, 34th, Port Jervis, New York, 4-6 May 1962, Guidebook to field trips: New York, NY, City College, Department of Geology, not consecutively paginated.

Jaffe, H. W., and Jaffe, E. B., 1973, Bedrock geology of the Monroe quadrangle, Orange County, New York: New York State Museum and Science Service Geological Survey Map and Chart Series No. 20, 74 p. (includes colored geologic map on a scale of 1:24,000).

Jaffe, H. W., and Jaffe, E. B., 1989, Structure (sic) and petrology of the Precambrian allochthon, autochthon and Paleozoic sediments of the Monroe area, New York, p. 29-49 in Weiss, Dennis, ed., Field Trip Guidebook: New York State Geological Association Annual Meeting, 61st, Middletown, New York, Orange County Community College, Department of Science and Engineering, 302 p.

Johnsen, J. H., 1958, Preliminary report on the limestone of Albany County, New York: New York State Museum, Handbook No. 19.

Johnsen, J. H., and Schaffel, S., 1967, The economic geology of the mid-Hudson valley region, Trip B, p. B1-B18 in Waines, R. H., ed., New York State Geological Association, Annual Meeting, 39th, New Paltz, New York, 5-7 May 1967, Guidebook to field trips: New Paltz, New York, State University College at New Paltz, Division of Physical Sciences, not consecutively paginated.

Johnsen, J. H., and Southard, J. B., 1962, The Schoharie Formation in southeastern New York, p. A7-A15 in Valentine, W. G., ed., New York State Geological Association, Annual Meeting, 34th, Port Jervis, New York, 4-6 May 1962, Guidebook to field trips, not consecutively paginated.

Johnsen, J. H., and Waines, R. H., 1969, Late Cayugan and Early Helderbergian stratigraphy near Accord, New York (abstract): Geological Society of America Abstracts with Programs for 1969, p. 30.

Johnson, D. W., 1917, Date of local glaciation in the White, Adirondack, and Catskill Mountains: Geological Society of America Bulletin, v. 28, p. 543-552.

Krynine, P. D., 1946, The tourmaline group in sediments: Journal of Geology, v. 54, no. 1, p. 64-87.

Laporte, L. F., 1963, Codiacean algae and algal stromatolites of the Manlius Formation (Devonian) of New York: Journal of Paleontology, v. 37, p. 643-647.

Laporte, L. F., 1964a, Facies of the Manlius Formation (Lower Devonian) of New York State, p. 66-73 in Prucha, J. J., ed., New York State Geological Association, Annual Meeting, 36 the, Syracuse, New York, Guidebook to field trips, 127 p.

Laporte, L. F., 1964b, Supratidal dolomitic horizons within the Manlius Formation (Devonian) of New York, p. 59-66 in Purdy, E. G. and Imbrie, John, eds., Carbonate sediments, Great Bahama Bank: Geological Society of America, Annual Meeting, 77th, Miami Beach, Florida, Guidebook for Field Trip No. 2, 66 p.

Laporte, L. F., 1967, Carbonate deposition near mean sea-level (sic) and resulting facies mosaic: Manlius Formation (Lower Devonian) of New York State: American Association of Petroleum Geologists Bulletin, v. 51, no. 1, p. 73-101.

Laporte, L. F., 1969, Recognition of a transgressive carbonate sequence within an epeiric sea: Helderberg Group (Lower Devonian) of New York State, p. 98-119 in Friedman, G. M., ed., Depositional environments in carbonate rocks. A symposium: Tulsa, Oklahoma, Society of Economic Paleontologists and Mineralogists, Special Publication No. 14, 209 p.

Lindholm, R. C., 1969, Carbonate petrology of the Onondaga limestone (Middle Devonian), New York: a case for calcisiltite: Journal of Sedimentary Petrology, v. 39, p. 268-275.

Long, L. E., 1969, Whole-rock Rb-Sr age of the Yonkers gneiss, Manhattan prong: Geological Society of America Bulletin, v. 80, no. 10, p. 2087-2090.

Marshak, S., 1986, Structure and tectonics of the Hudson Valley fold-thrust belt, eastern New York State: Geological Society of America Bulletin, v. 97, no. 3, p. 354-368.

Marshak, S., and Tabor, J. R., 1989, Structure of the Kingston orocline in the Appalachian fold-thrust belt, New York: Geological Society of America Bulletin, v. 101, no. 5, p. 683-701.

Merguerian, Charles, 1988, Annealed mylonitic textures in polyphase deformed metamorphic terrains (abstract): Geological Society of America Abstracts with Programs, v. 20, no. 7, p. A214 (only).

Merguerian, Charles; and Sanders, J. E., 1990, Trip 11: Geology of the Little Appalachians and the Catskills, 26-27 May 1990: New York Academy of Sciences Section of Geological Sciences 1989-90 Trips on the Rocks Guidebook, 90 p.

Merguerian, Charles; and Sanders, J. E., 1991, Variations in style of Paleozoic fold-fault deformation in the southern New England Appalachian foreland of New York and New Jersey - A case for basement control of structures (abstract): Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 103 (only).

Merguerian, Charles; and Sanders, J. E., 1992, Trip 22, Taconic Range of eastern New York and Massachusetts (revision of Trip 08, 21-22 October 1989), 09-10 May 1992: New York Academy of Sciences Section of Geological Sciences 1991-92 Trips on the Rocks Guidebook, 107 p.

Merguerian, Charles; and Sanders, J. E., 1993, Trip 29, Geology of the northeastern Newark basin, 14 November 1993: New York Academy of Sciences Section of Geological Sciences 1993 Trips on the Rocks Guidebook, 93 p.

Merguerian, Charles; and Sanders, J. E., 1994, Trip 30: Geology of the Hudson Highlands and Bear Mountain: Guidebook for On-The-Rocks 1994 Fieldtrip Series, 21 May 1994, Section of Geological Sciences, New York Academy of Sciences, 112 p.

Millington, B. R., 1930, Glacial topography (sic) and agriculture in central Massachusetts: Economic Geography, v. 6, no. 4, p. 1-8.

Mose, D. G.; and Merguerian, Charles, 1985, Rb-Sr whole-rock age determination on parts of the Manhattan Schist and its bearing on allochthony in the Manhattan Prong, southeastern New York: Northeastern Geology, v. 7, no. 1, p. 20-27.

Oliver, W. A., 1956, Biostromes (sic) and bioherms of the Onondaga limestone in eastern New York: New York State Museum and Science Service, Circular 45, 23 p.

Pedersen, K., Sichko, M., Jr., and Wolff, M. P., 1976, Stratigraphy and structure of Silurian and Devonian rocks in the vicinity of Kingston, N. Y., p. B-4-1 to B-4-27 in Johnsen, J. H., ed., New York State Geological Association, Annual Meeting, 48th, Vassar College, Poughkeepsie, New York, 15-16 October 1979, Guidebook to field trips, not consecutively paginated.

Pepper, J. F., 1934, The Taconic and Appalachian orogenies in the Hudson River region: Science, new series, v. 80, p. 186.

Prave, A. R., Alcala, M. L., and Epstein, J. B., 1989, Stratigraphy (sic) and sedimentology of Middle and Upper Silurian rocks and an enigmatic diamictite, southeastern New York, p. 121-140 in Weiss, Dennis, ed., New York State Geological Association, Annual Meeting, 61st, Middletown, New York, 13-15 October 1989, Guidebook to field trips, 302 p.

Prosser, C. S., 1900, Sections of the formations along the northern end of the Heldergerg plateau, p. 53-56 in New York State Geologist, Annual Report, 18th (for 1898).

Prosser, C. S., 1907, Section of the Manlius limestone at the northern end of the Helderberg Plateau: Journal of Geology, v. 15, no. 1, p. 46-51.

Prosser, C. S., and Rowe, R. B., 1897, Sections of the stratigraphic geology of the eastern Helderbergs, New York State Geologist, 17th Annual Report.

Ramsay, A. C., 1859, On some of the glacial phenomena of Canada and the northeastern provinces of the United States..: Geological Society of London Quarterly Journal, v. 15, p. 200-215.

Rich, J. L., 1906, Local glaciation in the Catskill Mountains: Journal of Geology, v. 14, p. 113-121.

Rich, J. L., 1914, Divergent ice flow on the plateau northeast of the Catskill Mountains as revealed by ice-molded topography (abstract): Geological Society of America Bulletin, v. 25, p. 68-70.

Rich, J. L., 1915, Notes on the physiography (sic) and glacial geology of the northern Catskill Mountains: American Journal of Science, 4th series, v. 39, p. 137-166.

Rich, J. L., 1934, Mechanics of low-angle overthrust faulting as illustrated by the Cumberland overthrust block: American Association of Petroleum Geologists Bulletin, v. 18, p. 1584-1596.

Rich, J. L., 1935, Glacial geology of the Catskills: New York State Museum Bulletin No. 299, 180 p.

Rickard, L. V., 1962, Late (sic) Cayugan (Upper Silurian) and Helderbergian (Lower Devonian) stratigraphy in New York State: New York State Museum and Science Service Bulletin 386, 157 p.

Rickard, L. V., 1964, Correlation of the Devonian rocks in New York State: New York State Museum, Geological Survey, Map and Chart Series, No. 4.

Rickard, L. V., 1975, Correlation of the Silurian and Devonian rocks in New York State: New York State Museum, Map and Chart Series, No. 24.

Rickard, L. V., Oliver, W. A., Jr., and Laporte, L. F., 1963, Stratigraphy, facies changes, and paleoecology of the Lower Devonian Helderberg limestones and the Middle Devonian Onondaga Limestone: Geological Society of America Annual Meeting, 76th, New York City Guidebook to field trip No. 1, 30 p. (L. V. Rickard, The Helderberg Group, p. 1-8; L. F. Laporte, Algae of the Manlius Limestone, p. 9-10; W. A. Oliver, Jr., The Onondaga Limestone, p. 11-16).

Rodgers, John, 1967a, Unusual features of the New York sector of the Appalachian Mountains, p. 1-4 in Waines, R. H., ed., New York State Geological Association, Annual Meeting, 39th, New Paltz, New York, 5-7 May 1967, Guidebook to field trips: New Paltz, New York, State University College at New Paltz, Division of Physical Sciences, not consecutively paginated.

Rodgers, John, 1967b, Chronology of tectonic movements in the Appalachian region of eastern North America: American Journal of Science, v. 265, p. 408-427.

Ruedemann, Rudolf, 1942, Geology of the Catskill and Kaaterskill quadrangles, Part I. Cambrian and Ordovician geology of the Catskill quadrangle: New York State Museum Bulletin 331, 188 p. (Includes colored geologic map on scale of 1/62,500).

Sanders, J. E., 1969, Bedding thrusts and other structural features in cross section through "Little Mountains" along Catskill Creek (Austin Glen and Leeds Gorge), west of Catskill, New York, Trip 19 p. 19-1 to 19-38 in Bird, J. M., ed., New England Intercollegiate Geological Conference, Annual Meeting, 61st, Albany, New York, 10-12 October 1969, Guidebook for field trips in New York, Massachusetts, and Vermont: Albany, State University of New York at Albany, not consecutively paginated.

Sanders, J. E., 1974, Geomorphology of the Hudson Estuary, p. 5-38 in Roels, Oswald, ed., Hudson River Colloquium: New York Academy of Sciences Annals, v. 250, 185 p.

Sanders, J. E., 1981, Principles of physical geology: New York, NY, John Wiley and Sons, 624 p.

Sanders, J. E.; and Merguerian, Charles, 1992, Directional history of Pleistocene glaciers inferred from features eroded on bedrock, New York metropolitan area, SE NY (abstract): Geological Society of America Abstracts with Programs, v. 24, no. 1, p. 72 (only).

Sanders, J. E.; and Merguerian, Charles, 1994a, Fitting newly discovered north-shore Gilbert-type lacustrine deltas into a revised Pleistocene chronology of Long Island (extended abstract), p. 103-113 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Sanders, J. E., and Merguerian, Charles, 1994b, The glacial geology of New York City and vicinity: p. 93-200 in A. I. Benimoff, ed., The Geology of Staten Island, New York, Field guide and proceedings, The Geological Association of New Jersey, XI Annual Meeting, 296 p.

Sanders, J. E.; Merguerian, Charles; and Mills, H. C., 1993, "Port Washington deltas" of Woodworth (1901) revisited: pre-Woodfordian Gilbert-type deltas revealed in storm-eroded coastal bluff, Sands Point, New York (abs.): Geological Society of America Abstracts with Programs, v. 25, no. 6, p. A-308.

Sanders, J. E., Platt, L. B., and Powers, R. W., 1961, Bald Mountain Limestone, New York: new facts and interpretations relative to Taconic geology: Geological Society of America Bulletin, v. 72, no. 3, p. 485-488.

Schuchert, Charles, 1903, On the Manlius formation of New York: American Geologist, v. 31, p. 160-178.

Schuchert, Charles, 1916, Silurian formations of southeastern New York, New Jersey, and Pennsylvania: Geological Society of America Bulletin, v. 27, p. 531-554.

Schuchert, Charles, 1930, Orogenic times of the northern Appalachians: Geological Society of America Bulletin, v. 41, p. 701-724.

Schuchert, Charles; and Longwell, C. R., 1932, Paleozoic deformations of the Hudson valley region, New York: American Journal of Science, v. 233, p. 305-326.

Shaler, N. S., 1877, On the existence of the Allegheny division of the Appalachian range within the Hudson Valley: American Naturalist, v. 11, p. 627-628.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, no. 2, p. 93-114.
Smith, N. D., 1970, The braided stream (sic) depositional environment: comparison of the Platte River with some Silurian clastic rocks, north-central Appalachians: Geological Society of America Bulletin, v. 81, no. 10, p. 2993-3013.

Smock, J. C., 1880, Thickness of the ice sheet at its southern edge (abstract): American Naturalist, v. 14, p. 59-60.

Smock, J. C., 1883, On the surface limit or thickness of the continental glacier in New Jersey and adjacent states: American Journal of Science, 3rd series, v. 25, p. 339-350.

Smock, J. C., 1885, Evidence of local glaciers in the Catskill Mountain region (abstract): American Association Proceedings, v. 33, p. 403-404.

Swartz, C. K., and Swartz, F. M., 1930, The age of the Shawangunk Conglomerate of eastern New York: American Journal of Science, 5th series, v. 20, p. 467-474.

Swartz, C. K., and Swartz, F. M., 1931, Early (sic) Silurian formations of southeastern Pennsylvania: Geological Society of America Bulletin, v. 24, p. 621-662.

Swartz, F. M., 1948, Trenton (sic) and sub-Trenton outcrop areas in New York, Pennsylvania, and West Virginia: American Association of Petroleum Geologists Bulletin, v. 32, no. 8, p. 1493-1595.

Tarr, R. S., 1894, The origin of drumlins: American Geologist, v. 13, p. 393-407.

Titus, Robert, 1993, The Catskills. A geological guide: Fleischmanns, NY, Purple Mountain Press, Ltd., 141 p.

Toots, Heinrich, 1976, Structural geology of the Taconic unconformity, p. B-2-1 to B-2-13 in Johnsen, J. H., ed., New York State Geological Association, Annual Meeting, 48th, Vassar College, Poughkeepsie, New York, 15-16 October 1976, Guidebook to field trips, not consecutively paginated.

Upham, Warren, 1892, Conditions of accumulation of drumlins: American Geologst, v. 10, p. 339-352.

Van Ingen, Gilbert; and Clark, P. E., 1903, Disturbed fossiliferous rocks in the vicinity of Rondout, New York: New York State Paleontologist, Report for 1902, p. 1176-1227 (also New York State Museum Bulletin 69, p. 1176-1227).

Waines, R. H., 1976, Stratigraphy and paleontology of the Binnewater Sandstone from Accord to Wilbur, p. B3-1 to B3-15 in Johnsen, J. H., ed., New York State Geological Association, Annual Meeting, 49th, Vassar College, Poughkeepsie, New York, 15-16 October 1976, Guidebook to field trips, not consecutively paginated.

Waines, R. H., and Hoar, F. G., 1967, Upper Silurian-Lower Devonian stratigraphic sequence, western mid-Hudson valley region, Kingston vicinity to Accord, Ulster County, New York, p. H1 to H3 in Waines, R. H., ed., New York State Geological Association, Annual Meeting, 39th, New Paltz, New York, 5-7 May 1967, Guidebook to field trips: New Paltz, New York, State University College at New Paltz, Division of Physical Sciences, not consecutively paginated.

Whisonant, R. C., 1977, Lower Silurian Tuscarora (Clinch) dispersal patterns in western Virginia: Geological Society of America Bulletin, v. 88, p. 215-220.

Willis, Bailey, 1894, The mechanics of Appalachian structure: United States Geological Survey, Annual Report, 13th (1893), part 2, p. 211-281.

Woodward, H. P., 1957a, Structural features of the northeastern Appalachian basin: American Association of Petroleum Geologists Bulletin, v. 41, p. 1429-1440.

Woodward, H. P., 1957b, Chronology of Appalachian folding: American Association of Petroleum Geologists Bulletin, v. 41, no. 10, p. 2312-2327.

Woodward, H. P., and Drake, C. L., 1963, Appalachian curvature, wrench faulting, and offshore structures: New York Academy of Sciences, Transactions, Series 2, v. 26, p. 48-63.

Yeakel, L S., Jr., 1962, Tuscarora, Juniata, and Bald Eagle paleocurrents and paleogeography in the central Appalachians: Geological Society of America Bulletin, v. 73, p. 1515-1540.

Filename: DL OTR10 Little Appalachians Catskills.doc