DUKE GEOLOGICAL LABORATORY

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TRIPS ON THE ROCKS

Guide 17: Delaware Water Gap and Vicinity, New Jersey and Pennsylvania

Trip 23: 20 June 1992

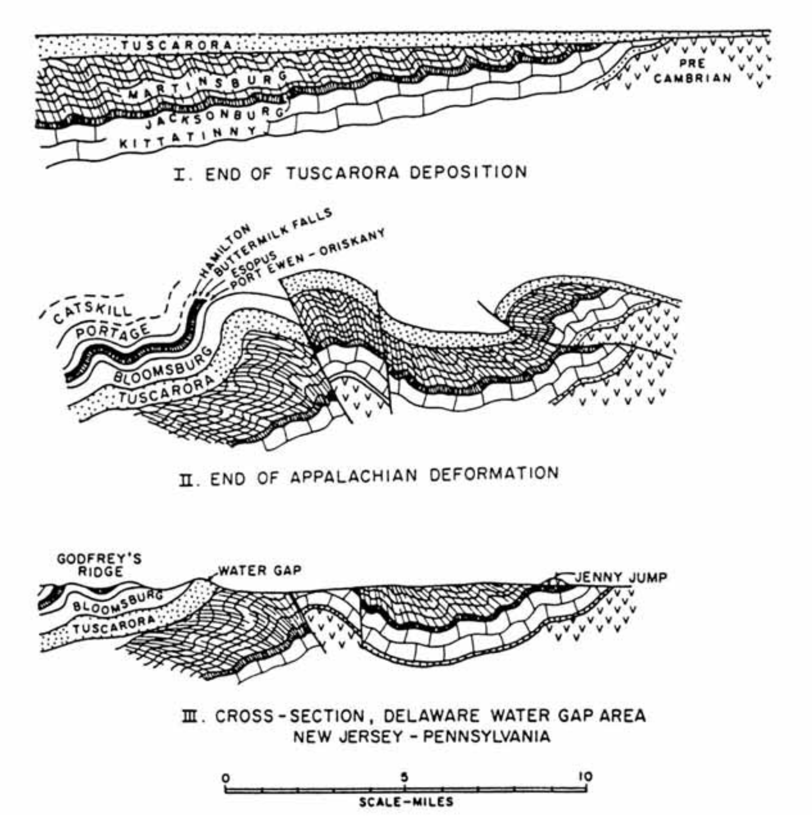

Figure 1 – Schematic tectonic history of the Delaware Water gap area showing the post-Ordovician unconformity between deformed Martinsburg slates and the overlying Tuscarora (Shawangunk) clastics (top section), Appalachian folding and faulting (middle section), and the modern erosion level of orogen. The lack of low-angle thrusts in ther sections is an artifact of Maxwell's (1962) tectonic interpretation.

Field Trip Notes by:

Charles Merguerian and John E. Sanders

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Logistics:
Departure from NYAS: 0830
Return to NYAS: 1800
Bring lunch, including drinking water or other beverages.

INTRODUCTION

When we first visualized what would be the focus of this trip, we did not think about a comparison with our recently completed 2-day Taconic trip of 09-10 May 1992. As we prepared the materials for this guidebook, however, the comparisons between the areas examined on the Taconic trip (No. 22) and to be examined on Trip 23 pressed themselves ever-more-insistently upon us. As a result, we have extracted a few points from the geologic relationships in the two areas that seem not to have been looked at in the same ways as we now view them.

The segment of the Appalachian chain that crosses northwestern New Jersey has been the source of several significant ideas about Appalachian geology that have been widely ignored. We first look at the component parts and then take up some of these "orphaned" ideas.

MORPHOTECTONIC ZONES OF APPALACHIANS, NW NEW JERSEY

Under this heading, we describe the various morphotectonic belts (composed of distinctive rocks and associated morphologic expressions) that trend NE-SW across northwestern New Jersey. Refer to Figure 2 for the following discussion.

From Manhattan on the southeast to the Pocono Plateau on the northwest to its central crystalline core, the Appalachian chain can be subdivided into eight major morphotectonic belts that trend NE-SW. From the NW side to the SE these are: (1) the Pocono Plateau; (2) the Kittatinny monocline-fold belt; (3) the Appalachian Valley and Ridge Province (Wallkill-Kittatinny valleys and vicinity); the Reading Prong, including two belts, (4) the northwestern part of New Jersey Highlands (Wawayanda-Franklin-Pochuck block; Allamuchy Mountain-Jenny Jump Mountain-Musconetcong Mountain ranges underlain by Precambrian basement complex); that are separated by (5) the Green Pond-Bellvale-Schunemunk belt (complexly folded and faulted Silurian-Devonian strata) and (6) the southeastern Jersey Highlands (Ramapo block; Precambrian basement complex); (7) the Newark basin (rocks of Upper Triassic-Lower Jurassic ages); and (8) the Manhattan Prong of the New England Upland. Although on our trip we shall traverse these from the SE to the NW, it will be useful to discuss them from the NW, structurally less-complex side, to the SE, into regions of increasing structural complication.

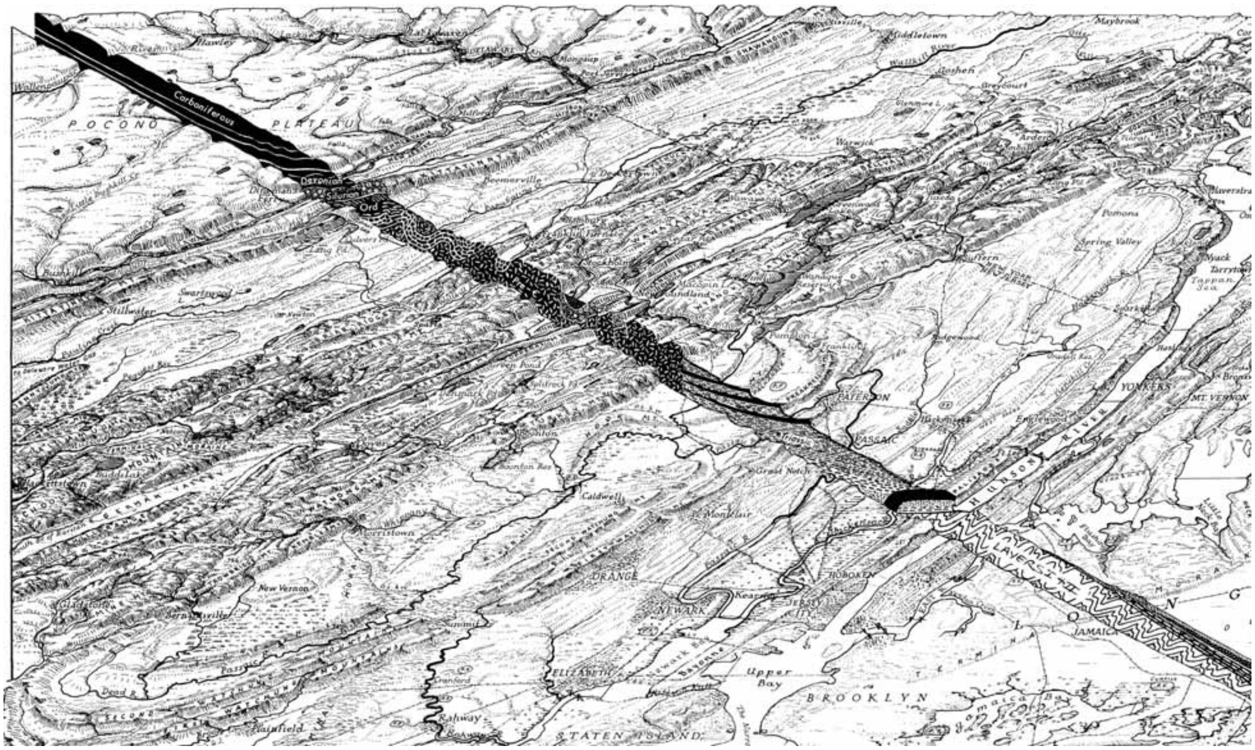


Figure 2 - Oblique bird's-eye-view physiograpghic diagram of the Appalachians, Newark Basin, and Atlantic Coastal Plain [NY, NJ, PA], with vertical slice oriented NW-SE to show geologic structure. (E. Raisz).

(1) The Pocono Plateau

The Pocono Plateau is a rugged area underlain for the most part by nearly flat-lying strata that are of Devonian and Mississippian ages. Locally within this region are the deep, complex synclinal regions that preserve the Pennsylvanian rocks of the anthracite region near Scranton, PA.

(2) Kittatinny monocline-fold belt

This is the belt where we shall spend most of our time today. It coincides with what Rodgers (1970) referred to as the "Blue Mountain front;" it is characterized by NW-dipping strata that dip beneath the Pocono-Catskill plateaus. Several tight folds cross what is generally a monoclinal belt that is so prominent topographically as the Shawangunk-Kittatinny Ridge. We think that the relationships sketched in Figure 3 require a complete rethinking of this belt. We will be discussing the significance of the northwest dips when we reach the Delaware Water Gap.

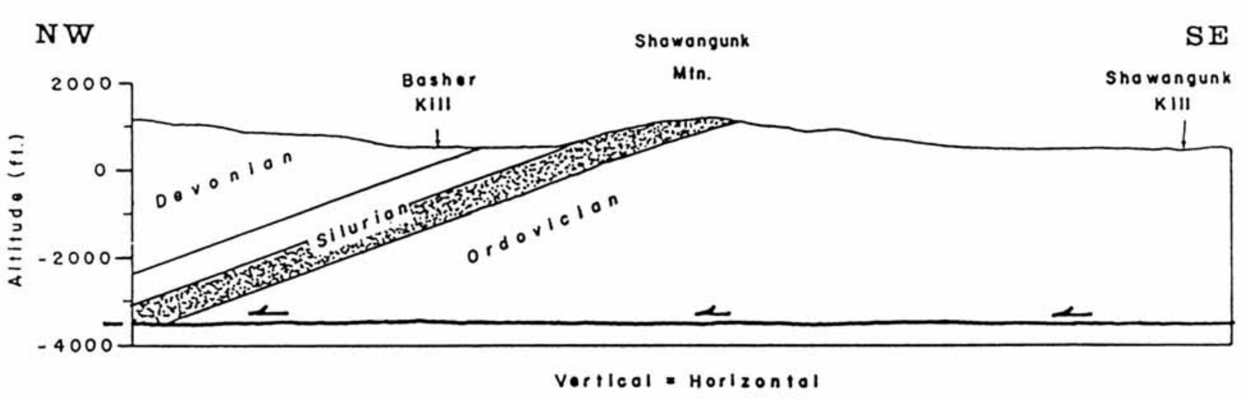


Figure 3 - Profile section based on seismic data across the Shawangunk Ridge showing northwest-dipping strata abruptly truncated against a horizontal surface.

(3) Valley and Ridge province

On first glance we can readily recognize the Appalachian Great Valley, known in New Jersey as Kittatinny Valley. Underlying the Great Valley are the "usual suspects," the Cambro-Ordovician Sauk Sequence carbonates and the overlying Tippecanoe Sequence, with basal limestone (in eastern Pennsylvania and NW New Jersey named the Jacksonburg; somewhat analogous to but thicker and siltier than the Balmville of the central Hudson Valley) and overlying black slate (the Martinsburg Formation in Pennsylvania and NW New Jersey, generally analogous to the "Hudson River shales" of New York State). But where in NW New Jersey is the Taconic Sequence that is so prominent in eastern New York? Keep this question in mind; we shall return to it as we move along.

In NW New Jersey and adjacent Pennsylvania, the Appalachian Great Valley is bounded on the northwest by the feature just described as morphotectonic unit No. 2, a great wall of Tuscarora-Kittatinny Mountain through which the Delaware River flows in such an impressive slot [notch, or water gap (in contrast to a wind gap, which is a notch in a ridge through which no river flows)]. This "Great Wall" of the Appalachians coincides with the tilted edge of a thick, massive, tough, Lower Silurian silica-cemented sandstone named the Tuscarora in Pennsylvania (equivalent of the Shawangunk of southeastern New York) and farther southeast, the Clinch Sandstone.

We take our description of this belt from Rodgers (1970):

"In the southeast part of the Valley and Ridge province, the Great Valley (here the Lebanon, Lehigh, Kittatinny, and Wallkill Valleys), mainly Cambrian and Ordovician rocks are exposed. The northwest part of the Valley, from the Susquehanna to the Hudson, is underlain by a thick sequence of Upper and Middle Ordovician (Martinsburg) shale or slate, [ftn ref: Anomalies in the stratigraphy of the slate sequence are discussed below, p. 89).] with many sandstone (graywacke) beds in the middle part and some thin limestone beds, mainly below, also more local bodies of cherty shale and volcanics. Estimates of the thickness of the shale have ranged from 1000 to 3500 meters (3000 to 12,000 feet); the higher figure is confirmed by the most recent (sic) work (Drake and Epstein, 1967). The southeast part of the Valley is underlain by a thick sequence of Middle Ordovician to Lower Cambrian carbonate rock (Kittatinny group and overlying units), including considerable limestone above but mainly or entirely dolostone below (the shale zone present near the Lower Cambrian-Middle Cambrian contact through the whole Valley and Ridge province to the southwest apparently fades out in eastern Pennsylvania); this carbonate sequence is over (sic) 1000 meters (roughly 4000 feet) thick. Beneath it is a basal Lower Cambrian quartzite unit (Hardyston quartzite), not over (sic) 100 meters (300 feet) thick in this area thought correponding to the thick basal Paleozoic clastic sequence (Chilhowee group) present in the Blue Ridge province to the southwest and in the Piedmont province directly to the south; here it crops out at the southeast edge of the Great Valley or within the Highlands belt to the southeast, resting directly and unconformably on a Precambrian basement complex, mostly gneiss, which forms the Highlands belt, beginning near Reading, Pennsylvania, 80 kilometers (50 miles) east of Harrisburg, and continuing northeast to the Hudson River 50 kilometers (30 miles) below Kingston."

(p.70) "Near the Delaware River, the structure seems more complicated still (Drake, 1970). The Precambrian and Paleozoic rocks form alternate belts, but the Paleozoic belts appear to be antiformal, the Precambrian synformal, and klippen of Precambrian and windows of Paleozoic have been found. Apparently the entire section is here inverted on the overturned limb of the anticlinorium, and the Precambrian with the quartzite at the base of the Paleozoic is thrust northward over the Paleozoic carbonates (Musconetcong nappe of Drake, named for a locality in New Jersey 14 kilometers--9 miles--east of the Delaware where a window was first discovered, but after the thrusting the whole mass was folded again by more nearly upright folds (the present antiforms and synforms) and cut by higher angle (sic) thrust faults.

"The shale or slate belt continues northeastward across New Jersey into southeastern New York, where it widens considerably. In northernmost New Jersey and New York, however, stratigraphic units in both shale and underlying carbonate seem to succeed each other (sic) fairly regularly from southeast (older) to northwest (younger) without overturning or even excessively tight folding (sic) (Offield, 1967). Here, however, we are probably entirely on the upper upright limb of the recumbent anticlinorium, so that the structure is deceptively simple (Drake, 1970, p. 288)."

(p.69) "The northwestern limit of pronounced Taconic deformation can also be located just west of Albany, where it lies a little west of the western limit of strong post-Devonian deformation; between this point and the vaguer limit east of the Susquehanna River, it is hidden beneath the later rocks of the Catskill Mountains and the Pocono Plateau. A line connecting these points would trend about N40°E, nearly along or a bit east of the axis of the anthracite depression; if it were somewhat concave to the west it would approximate the eastern limit of strong folding (sic) in the Carboniferous rocks north of the Blue Mountain structural front.

"To the north, between the Precambrian masses of the Highlands and the Silurian unconformity at the Delaware Water Gap, the Ordovician shale shows evidence of the same two deformations, of which the older produced major recumbent folds (Northampton nappe of Sherwood, 1964, p. 24 ff; see also Ryan and others, 1961, p. 21 ff,. 41-43, 61ff.; Drake, 1970, p.

286) and excellent slaty cleavage (Maxwell, 1962)--slate has been quarried commercially from certain favorable beds--and the younger produced more upright folds and 'fracture' cleavage. What appears to be the younger deformation can be found in the Silurian and Devonian rocks to the north, but the older one, during which the Lebanon Valley synclinorium and the Highlands anticlinorium were formed, is probably Taconic (Drake, Davis, and Alvord, 1960; for a contrary view, see Epstein and Epstein, 1969, p. 165-170.)"

"The shale or slate belt continues northeastward across New Jersey into southeastern New York, where it widens considerably. In northernmost New Jersey and New York, however, stratigraphic units in both shale and underlying carbonate seem to succeed each other (sic) fairly regularly from southeast (older) to northwest (younger) without overturning or even excessively tight folding (sic) (Offield, 1967). Here, however, we are probably entirely on the upper upright limb of the recumbent anticlinorium, so that the structure is deceptively simple (Drake, 1970, p. 288).

(4) Northwestern Part of New Jersey Highlands (Wawayanda-Franklin-Pochuck block; Allamuchy-Jenny Jump-Musconetcong mountains block; Proterozoic basement complex)

Quoting from Rodgers (1970):

"The exposed Precambrian on the southeast (reference is to a position southeast of the Valley and Ridge Province, our belt No. 3) similarly widens northeastward as the edge of the Triassic receds to the east; the overall trend of the anticlinorium seems to be about N50°E across New Jersey and into New York, but individual (commonly faulted) upfolds of Precambrian gneiss and downfolds of younger rock trend about N35°E. Two of three major (faulted and compound) upfolds in the belt of maximum complexity in northern New Jersey plunge down northeastward into the Great Valley just north of the New York state line, and only the third, the southeasternmost, continues to the Hudson, which breaks through it in a scenic fjord."

(5) Green Pond-Bellvale-Schunemunk belt (complexly folded and faulted Silurian-Devonian strata)

The territory in the NW New Jersey Appalachians that includes Green Pond Mountain and vicinity, is underlain by a thick succession of Silurian and Devonian strata. Rodgers (1970) considered that the structure of this belt is only synclinal. By contrast, on our On-The-Rocks Trip 09, we showed that the strata in this downfaulted outlier have been closely folded and that at least one overthrust fault cuts across one of the overturned limbs of the folds (Figure 4). To quote from Rodgers (1970):

"On its northwest flank, in northeastern New Jersey and southeastern New York (west of the Hudson), a narrow, locally isoclinal but nearly upright faulted syncline, the Green Pond syncline (named for a locality 25 kilometers--15 miles--southwest of the state// (p.71) line) preserves a belt of Silurian and Devonian strata 80 kilometers (50 miles) long and up to 6 kilometers (4 miles) wide, lying more than 25 kilometers (15 miles) from the Silurian rocks along the Blue Mountain front northwest of the Great Valley. The basal Silurian formation

(Green Pond conglomerate) in this syncline, again a competent ridge-forming unit, rests unconformably on all the older units from Ordovician shale and limestone at the ends of the belt to Preambrian gneiss along parts of its sides (Finks, 1968); thus here again there were at least two quite separate orogenic episodes. The N35°E trend of the syncline, evidently produced in the later orogeny (late Devonian or younger), suggests that the individual upfolds in the Highlands belt likewise result from the superposition of later folding (sic) and faulting (sic) at an angle across the main anticlinorial axis, presumably established in the Taconic orogeny late in the Ordovician. The apparently steep faults associated with the upfolds and with the Green Pond syncline have (sic) the same strike, roughly N35°E, but this is also the strike of part of the Triassic border fault on the east side of the Highlands; hence the faults may be as late as Triassic, or else both they and the border fault may first have formed at the time of the later folding and then been reactivated in the Triassic."

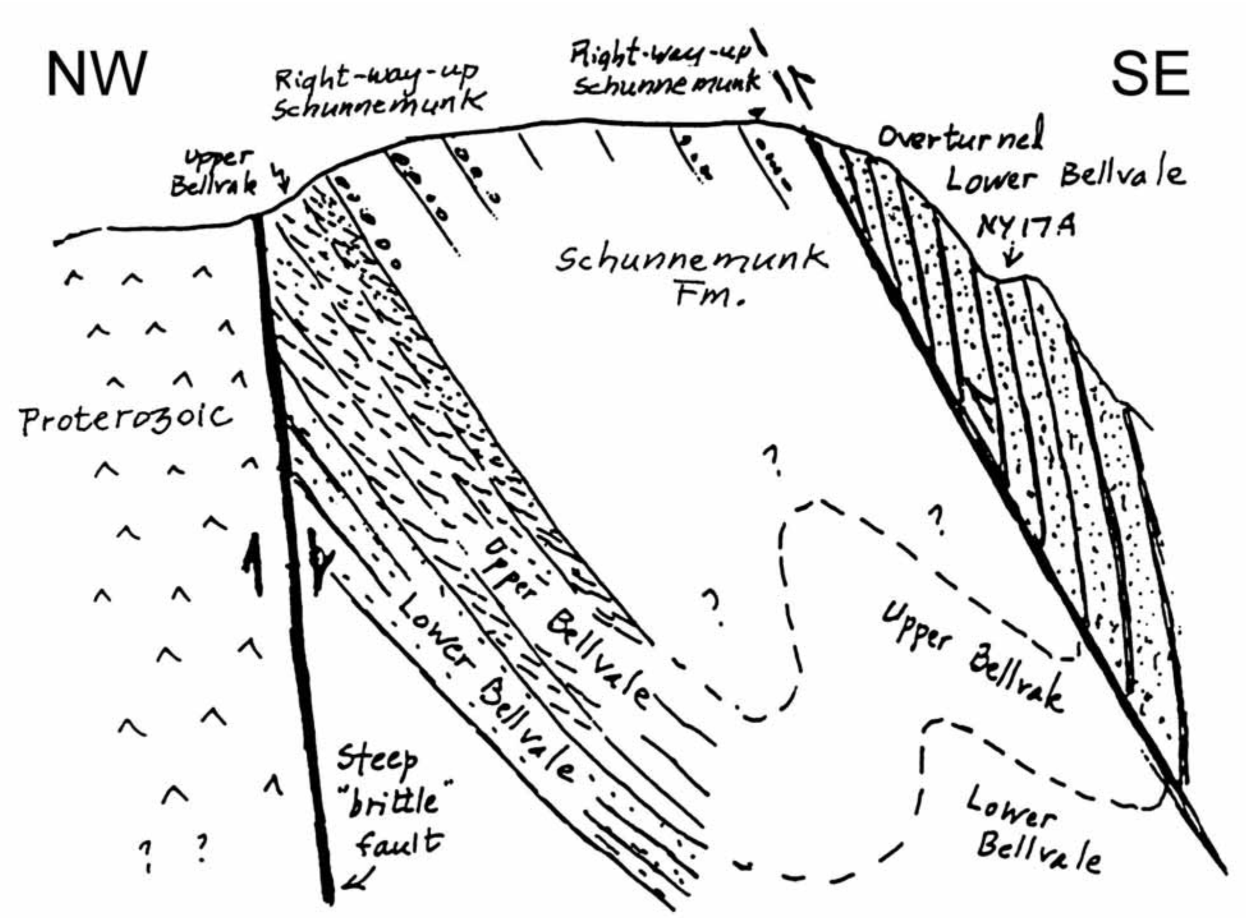


Figure 4 - Schematic profile-section through Bellvale Mountain along NY Route 17A, showing inferred thrust fault breaking across the fold axis and displacing the overturned limb against the normal limb. (JES, based on results of student mapping in August 1981 in the "ad-hoc" Barnard summer field camp based in Monroe, NY.)

As mentioned, we think that the strata in this belt have been much deformed by folding and overthrusting (and with the tilted edges of the two ridge-making units, the Lower Silurian Green Pond Conglomerate at the base and the Devonian Schunemunk Conglomerate at the top, forming a true valley-and-ridge landscape, as seen during On-The-Rocks Trips 09 and 17), have been preserved as a result of late-stage steep brittle faults. Two somewhat-comparable features in the Hudson Valley are Becraft Mountain and Mount Ida, where the Upper Silurian-Lower Devonian strata, mostly carbonates and siltstones, overlie the Cambro-Ordovician strata along a surface of angular unconformity.

(6) Southeastern part of New Jersey Highlands

This belt of Precambrian rocks includes many kinds of rocks and has been complexly faulted. To the northeast, it disappears by plunging under the Lower Cambrian strata in the crests of several anticlines. JES thinks these folds mark underlying tectonic ramps on major overthrusts. The whole question of how possibly overthrust Precambrian basement rocks are related to the Paleozoic strata needs restudy. To quote again from Rodgers (1970): "Isachsen (1964, p. 821-826) has marshalled the reasons for believing that the entire Highlands anticlinorium, at least as far east as the eastern border of New York State, is floating above the Valley and Ridge rocks, as in eastern Pennsylvania" (Figures 5 and 6).

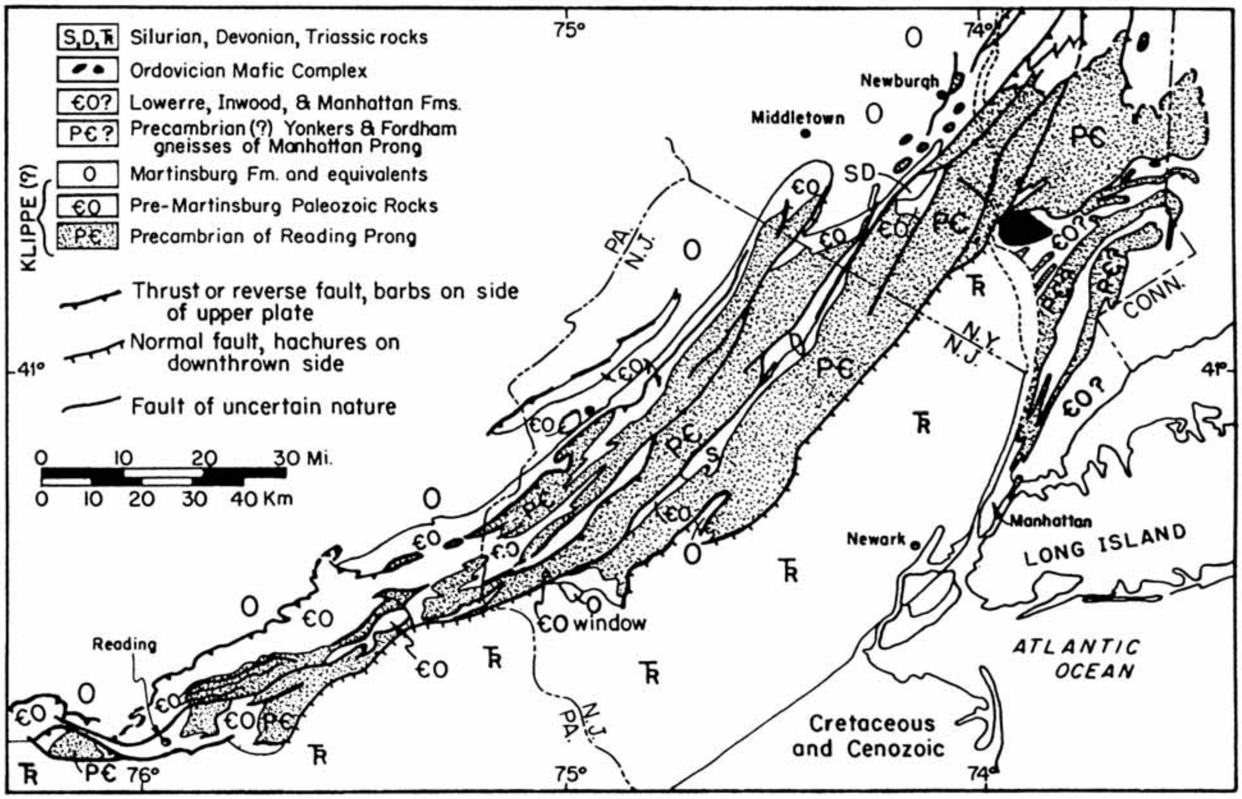


Figure 5 - Sketch map showing extent of Reading Prong klippe stippled areas). (Isachsen, 1964).

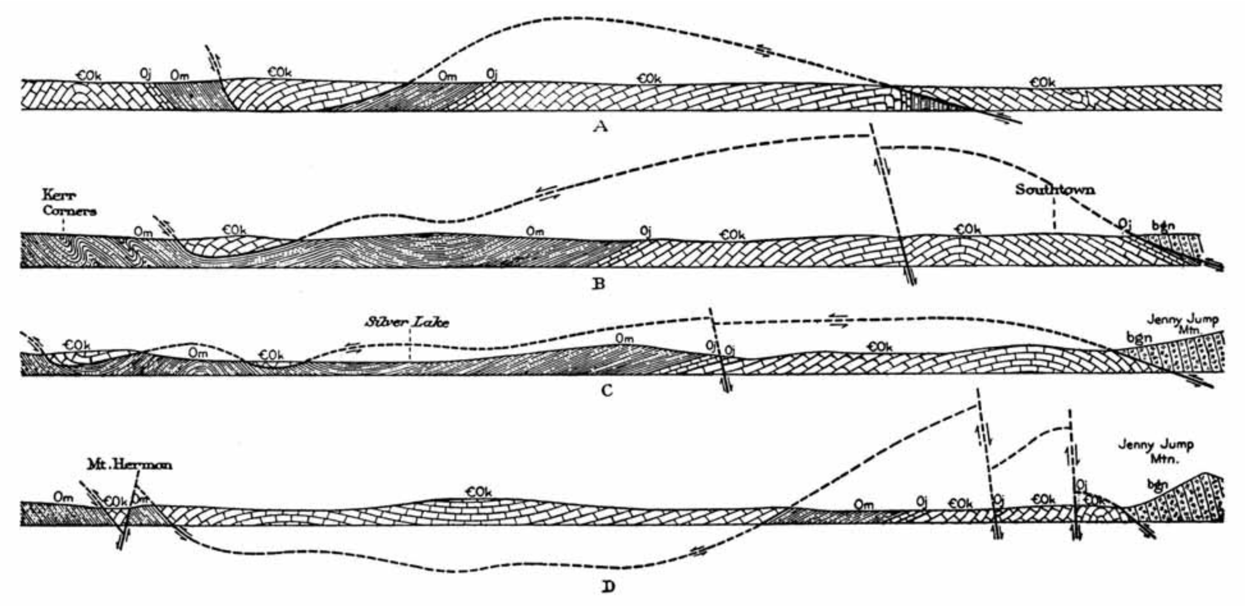


Figure 6 - Geologic sections illustrating the vast overthrusts of Cambro-Ordovician strata in the Kittatinny Valley and Precambrian klippe of Jenny Jump Mountain (Lewis and Kümmel, 1915).

Given the distinct likelihood that this overthrust interpretation is corrct, then our understanding of the relationships of the Precambrian rocks to the Paleozoic strata may be in for some topsy-turvy action. Rather than marking structural highs (such as horst blocks) because of the ages of the rocks involved, as is now universally supposed, if the Precambrian rocks are part of an overthrust block, they may not be so high after all. Instead, they may be preserved because they occupy downdropped graben blocks. In that case, more Paleozoic strata lie below.

(7) The Newark Basin

The rocks underlying what has been named the Newark basin (See Figure 2.) form what we can approximate as a regional homocline dipping toward the northwest into the basin-marginal fault (Ramapo fault along the SE side of the Ramapo block). Viewed more closely, however, the Newark strata and their interbedded sheets of igneous rocks (intrusive Palisades sheet near the base; three extrusive sheets of the Watchungs much higher in the succession) have been folded into a major NW-plunging syncline with subordinate anticlines and synclines at Hook Mountain.

According to the JES analysis (Sanders, 1962, 1963), significant tectonic activity of mid-Jurassic age destroyed the Newark basin and complexly deformed the Newark basin-filling strata. The distinctive aspects of this mid-Jurassic deformation resulted from application of three short-lived strike-slip couples, each of which is inferred to have created strike-slip faults, normal faults, and folds. A major problem yet to be resolved is whether the kind(s) of structural features that involve the Newark strata are present in the pre-Newark rocks lying NW of the Ramapo fault.

(8) The Manhattan Prong

The crystalline bedrock of New York City is part of a physiographic province known as the Manhattan Prong (Figures 7, 8) that widens northward into the New England Upland physiographic province of the Appalachian mountain belt. The Manhattan Prong is underlain by an important sequence of metamorphosed Precambrian to Lower Paleozoic rocks. Originally, the New York City strata of Early Paleozoic ages were, in part, deposited on the complexly deformed sequence of layered feldspathic and massive granitoid gneiss, amphibolite, and calc-silicate rocks of uncertain stratigraphic relationships known as the Fordham and Yonkers Gneiss (Layer I). These complexly deformed rocks are of Precambrian age, but can be assigned to the alphabetical-letter scheme of Precambrian rocks designated as Proterozoic by the U. S. Geological Survey. Present in SE New York are representatives of Proterozoic Y and Z. These are inferred to represent the ancient continental crust of proto-North America.

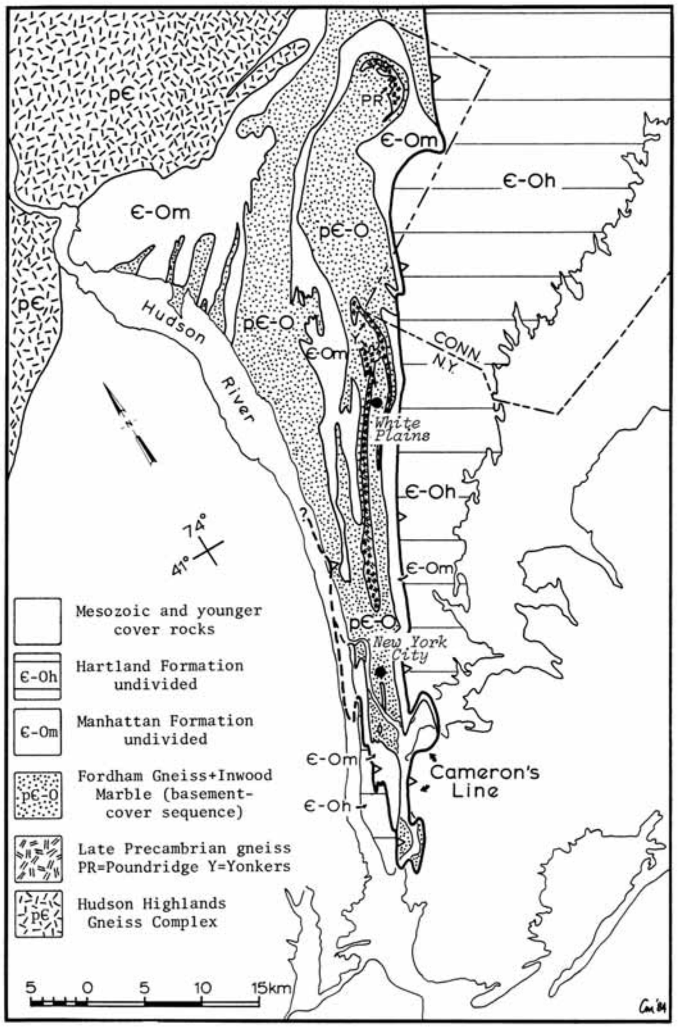


Figure 7 - Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted (Mose and Merguerian, 1985).

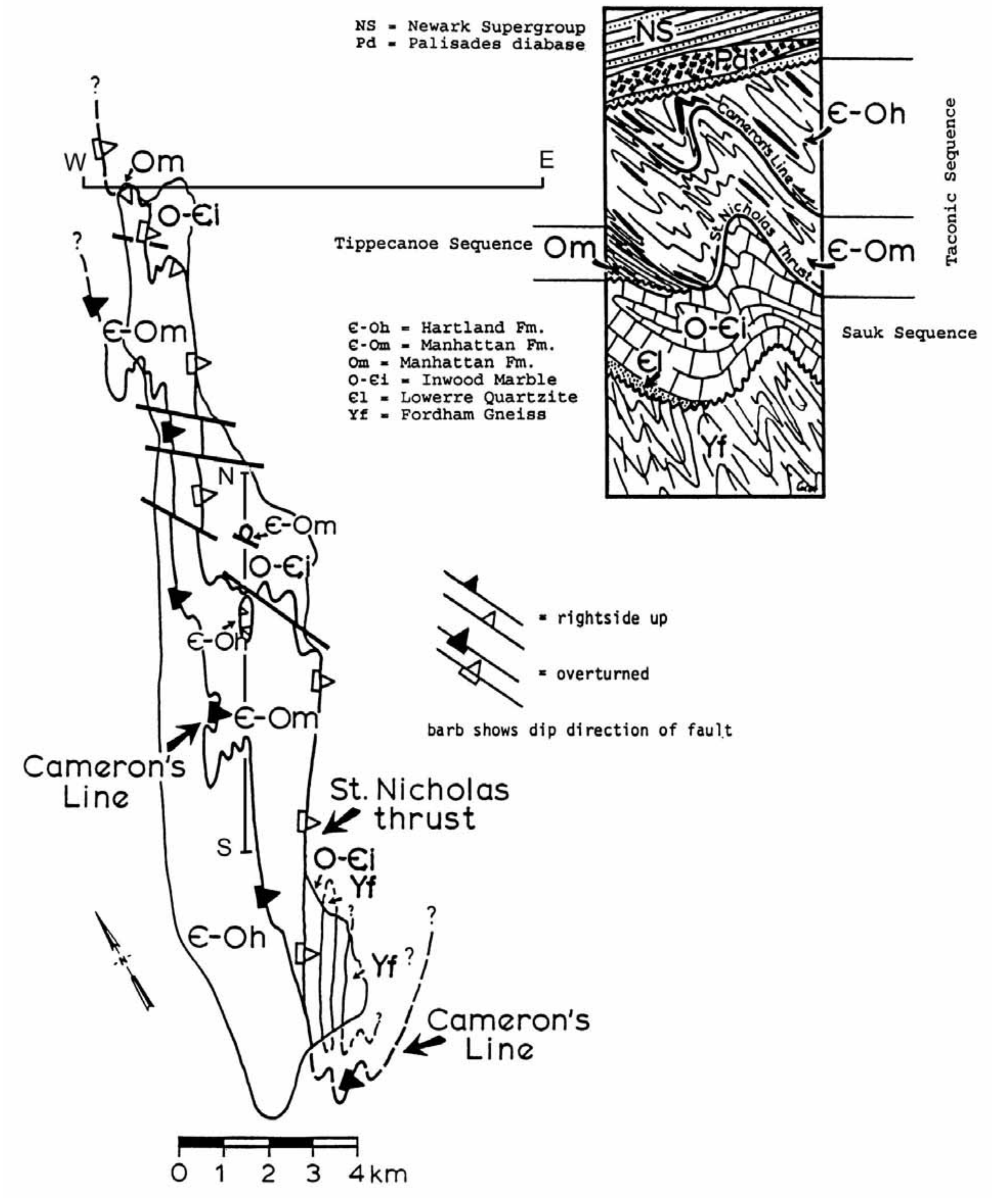


Figure 8 - Geologic map of Manhattan Island showing a new interpretation of the stratigraphy and structure of the Manhattan Schist. Drawn and mapped by C. Merguerian.

Early in the Paleozoic Era, this region became the trailing edge of a continental plate, a passive continental margin. This tectonic setting persisted until the Taconic orogeny late in the Ordovician Period. 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.

The Cambrian and Ordovician bedrock units (Layer II) underlying the Manhattan Prong and adjacent parts of western Connecticut consist of sedimentary and igneous rocks that formed near the Earth's surface. They began their geologic lives approximately 550 million years ago as thick accumulations of both shallow- and deep-water sediments adjacent to the Early Paleozoic shores of proto-North America (Figure 9).

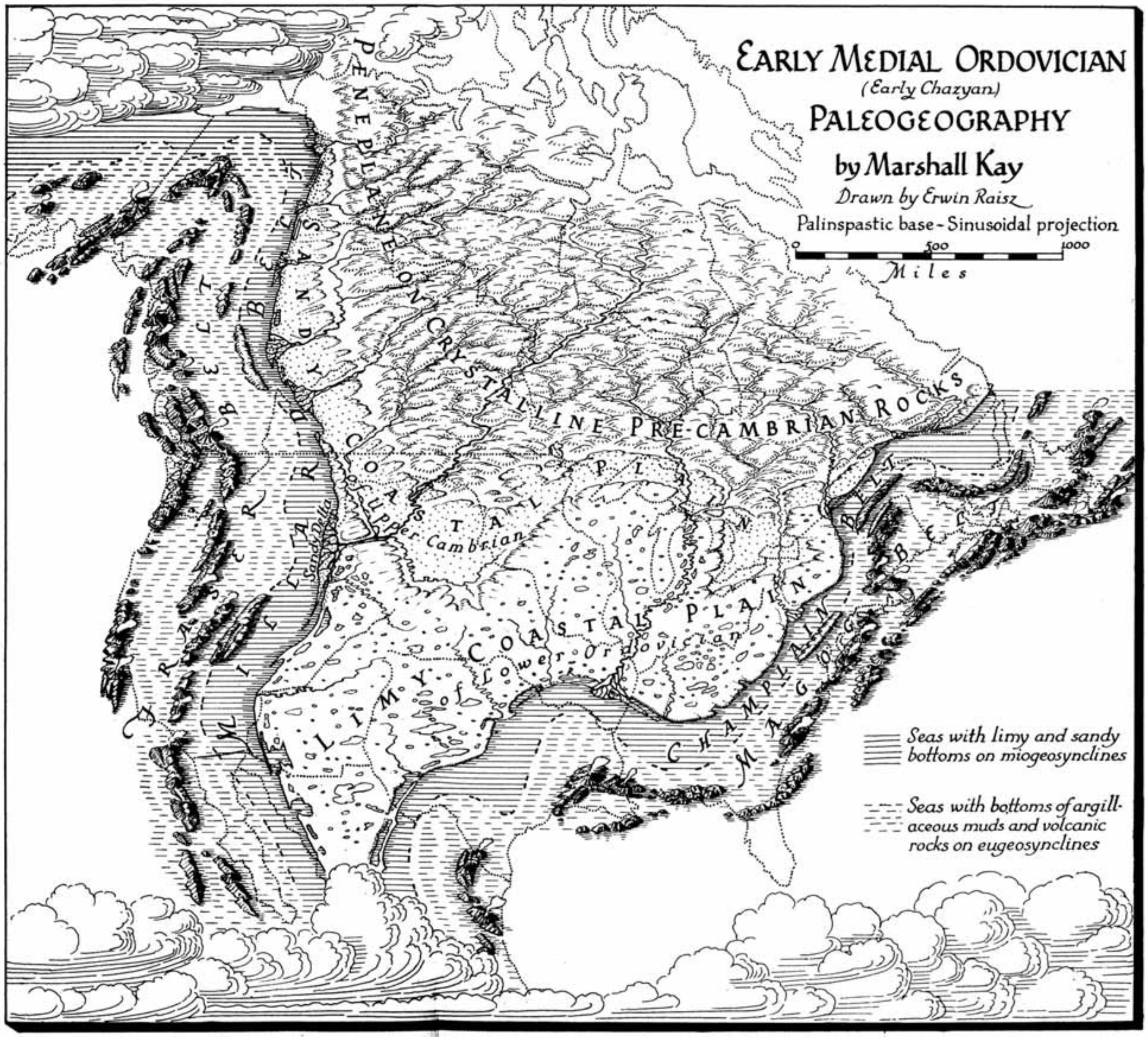


Figure 9 - Paleogeographic map of North America in Early Paleozoic time (Kay, 1951).

Layer II can be divided into two sub-layers, IIA and IIB. The older of these, IIA, represents the ancient passive-margin sequence of the proto-Atlantic (Iapetus) ocean. In turn, these rocks can be subdivided into two facies that differ in their original geographic positions with respect to the shoreline and shelf. A nearshore-shelf facies [Layer IIA(W)] was deposited in shallow water and is now represented by the Cambrian Lowerre Quartzite and Cambro-Ordovician Inwood Marble in New York City (Cheshire Quartzite and Stockbridge Marble in western Connecticut and Massachusetts). These strata were deposited as sandy and limey sediments in an environment closely similar to that of the present-day Bahama Banks. The chief difference is that the salinity of the Paleozoic seas exceeded that of normal seawater (inferred from the features of the dolostones).

Farther offshore, fine-grained terrigenous time-stratigraphic equivalents of the shallow-water strata (shelf sequence) were evidently deposited under deep water on oceanic crust [Layer IIA(E)]. This sequence is also of Cambrian to Ordovician age and is known as the Taconic sequence in upstate New York, as units Ꞓ-Ot and Ꞓ-Oh of the Manhattan Schist(s). (See Figure 8.)

Layer IIB consists of younger, mostly terrigenous, strata that were deposited unconformably above the products of the western shallow-water platform [Layer IIA(W)]. In eastern New York State, the metamorphosed equivalents of these terrigenous rocks are mapped as the Waloomsac Schist and Manhattan Formation.

The schists originally named as the Manhattan Schist were thought to be entirely younger than the Inwood Marble (Layer IIB). As a result of CM's mapping, large parts of this body of schist are now recognized as rock units that are the same age or older than Manhattan Schist unit Om and the Inwood Marble. According to CM, at Inwood Hill Park in Manhattan (NYAS On-The-Rocks Trip #16), this Manhattan schist Unit Om is demonstrably interlayered with the Inwood Marble and at its base, contains thin layers of calcite marble (Balmville equivalent). Such field evidence is used to indicate that unit Om of the Manhattan Schist is in place where found and is therefore younger, or the same age as, Manhattan units Ꞓ-Ot and Ꞓ-Oh.

During medial Ordovician time, roughly 450 million years ago, and prior to the main events of the Taconic orogeny, these older eastern, deep-water formations [Layer IIA(E)], were overthrust into a position above the Inwood Marble and the younger overlying schist (all of the Manhattan Schist as originally conceived, but only Manhattan Schist unit Om, according to CM). In other words, the Taconic allochthon (On-the-Rocks Field Trip 22), extends into New York City.

After this great overthrust took place, the New York City rocks were complexly folded together and metamorphosed under amphibolite-facies conditions. This can be inferred from the presence of such "indicator" minerals as kyanite, sillimanite, and garnet.

The overthrusts imply that much of the bedrock in New York City is allochthonous. The root zone of the thrusts is thought to be Cameron's Line, a feature widely known in western Connecticut. CM interprets Cameron's line as a fundamental plate-tectonic boundary along which rocks belonging in place on the North American continent were overridden by materials from the former continental margin when the plate-tectonic regime changed from a passive margin to a convergent margin featuring an active subduction zone (Figure 10).

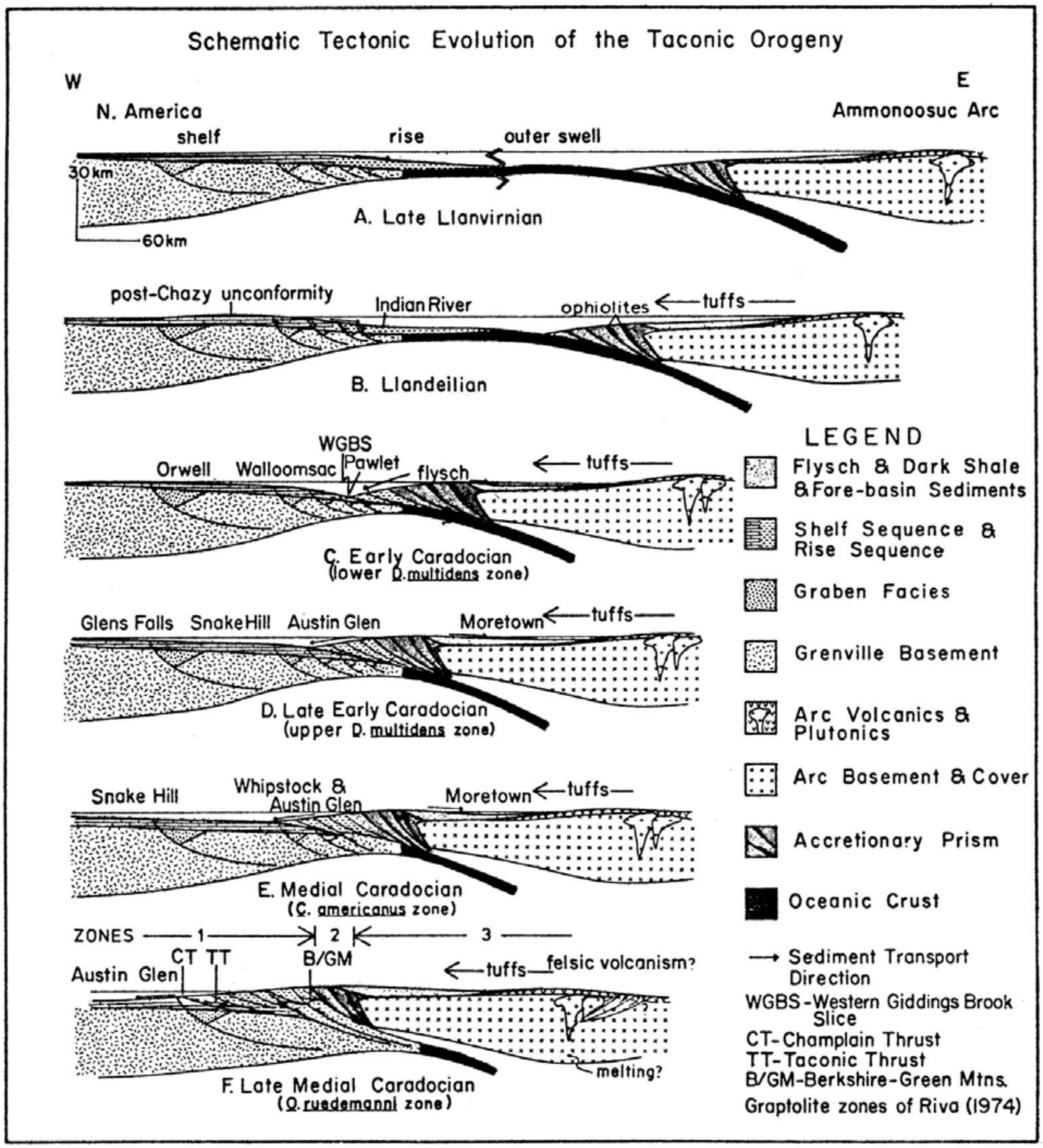


Figure 10 - Sequential tectonic cross sections for the Taconic orogeny in New England. From Rowley and Kidd (1981).

The presence of the diagnostic metamorphic minerals mentioned above suggests that rocks now exposed at the present land surface of New York City formerly were at depths of 20 to

25 km. If this is correct, it indicates that enormous uplift and vast erosion took place between the middle of the Paleozoic Era, the time of the last great metamorphism, and late in the Triassic Period, when these metamorphic rocks began to be covered by the sedimentary strata filling the Newark basin. A simplified geologic section showing the relationships between the folded New York City rocks, at the former land surface, and the Newark Supergroup drawn along an east-west at the George Washington Bridge (GWB) is shown in Figure 11. The overturned anticlines and synclines of the New York City metamorphic rocks are unconformably overlain by the west-dipping strata of the Newark Supergroup (Layer V, Table 2) . The unconformity surface projects out of the Hudson River over Manhattan. On the W side of the Hudson River, this surface dips westward at the same angle as the overlying strata of the Newark Supergroup.

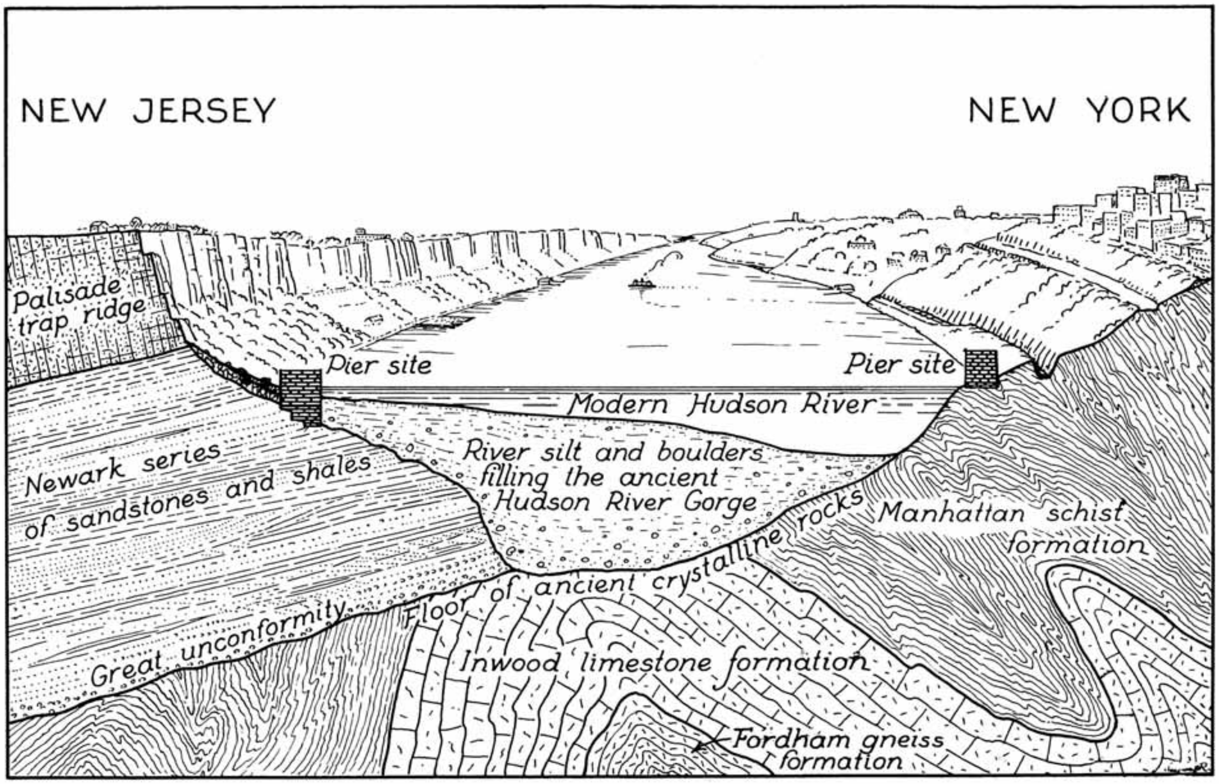


Figure 11 - Diagrammatic cross-section showing the change in bedrock between New York City and New Jersey beneath the George Washington Bridge. From Berkey (1948).

FOUR DISTINCTIVE FEATURES OF APPALACHIANS IN NW NEW JERSEY AND SOME "ORPHANED" GEOLOGIC IDEAS ASSOCIATED WITH THEM

Distinctive Features of Appalachians in New Jersey

Four peculiarly distinctive features of the New Jersey segment of the Appalachians lie southeast of the Great Valley. (1) In many other parts of the Appalachians, the Great Valley is bounded on the southeast by an extensive high region, such as the Blue Ridge. By contrast, in northwestern New Jersey are several stretches of rugged but not exactly precipitous territory that have been assigned to the Reading Prong (one of the two continuations to the SW of the New England Uplands, the other being the Manhattan Prong). The Reading Prong includes areas that are underlain by Precambrian rocks. Although such areas stand higher than their surroundings and are named mountains, they do not constitute such a mighty, nearly continuous topographic barrier as does the Blue Ridge, for example.

(2) The Proterozoic rocks of the Reading Prong are known in at least two places to lie above the Paleozoic rocks along one or more overthrust faults. These two places are (a) the Musconetcong tunnel built by the Lehigh Railroad through Musconetacong Mountain in the mid-19th century and (b) Jenny Jump Mountain. Before we discuss these places, we digress on the general subject of overthrusts.

The Appalachians were the first mountains in which major geologic structures known as folds (anticlines and synclines) were demonstrated (by the Rogers brothers, H. D., and W. B., in the middle of the nineteenth century from their studies in Pennsylvania). To be sure, small folds had been recognized where seen in coastal exposures in numerous localities in western Europe. But, it was a giant step (and anything but an intuitively obvious leap) from seeing small folds in cross section to the reconstruction of very large-scale folds based on working out the stratigraphic relationships of Paleozoic strata, thousands of meters thick, underlying strike ridges that extend for tens, even hundreds of kilometers.

The large-scale repetition of strata by low-angle faults now known as overthrusts was first shown in the Scottish Highlands. Soon thereafter, spectacular examples were found in the Alps and, indeed, in nearly all mountain chains. Studies in the Appalachians made possible new understanding between thrusts and folds. Examples were found illustrating all gradations from small breaks across the axes of overturned folds (Figure 12) to what are known as imbricate thrusts in which the deformed strata and the overthrusts dip southeastward at about the same angles; during deformation, the right-way-up strata of the northwest (normal) limbs of two synclines have been brought together and the southeastern (overturned) limbs and the central parts of the intervening anticlines have vanished (Figure 13).

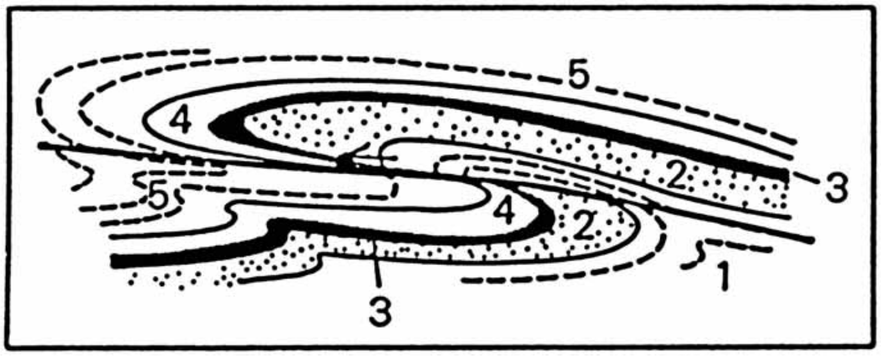
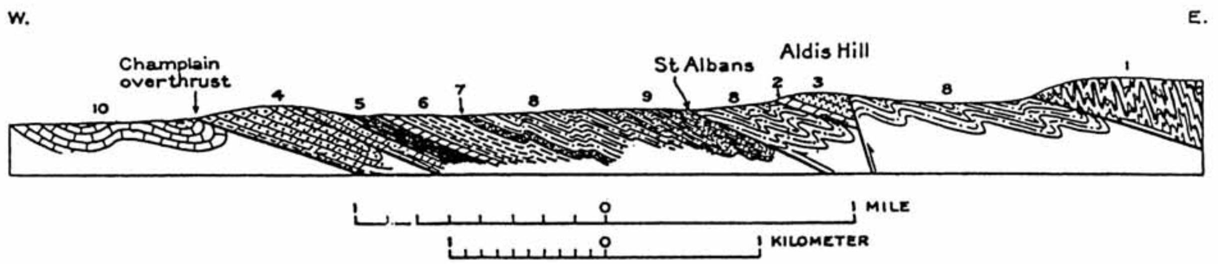


Figure 12 - Overturned fold that has been broken by an overthrust fault, schematic profile section. Units are numbered in order of decreasing age, from 1 (oldest) to 5 (youngest). (J. E. Sanders, 1981, fig. 16.14, p. 398.)



Section from west to east near St. Albans, Vermont, showing the principal thrusts at that latitude and the three sequences of Paleozoic formations separated by the thrusts. 1, Undifferentiated pre-Cambrian and lower Paleozoic; 2, dolomite and schist, probably late pre-Cambrian; 3, Lower Cambrian quartzite (eastern sequence); 4–9, central sequence; 4, Lower Cambrian dolomite; 5, Lower Cambrian slate and dolomite; 6, Middle Cambrian slate; 7, conglomerate, base of Upper Cambrian (thickness exaggerated); 8, Upper Cambrian slate; 9, Lower Ordovician slate; 10, Ordovician of the western sequence. The coarse conglomerate at the base of the Ordovician in the central sequence (No. 9) is not exposed in the vicinity of this section

Figure 13 - Imbricate thrusts that are essentially parallel to the strata that have been duplicated; example from Paleozoic strata in northwestern Vermont. (C. R. Longwell, 1933, fig. 14, p. 63)

Studies in the Appalachians led John L. Rich (1934) to propose the concept of "bedding thrusts." By this term, he referred to overthrusts along which two contrasting segments can be recognized: (1) segments that are parallel to the bedding; and (2) segments that cut across bedding at steep angles (Figure 14). (These segments that cut bedding at steep angles have subsequently been named ramps.) What was totally different about Rich's analysis is the relationship between thrusts and folds. Because of the geometric arrangement of the ramps and the beds, any forward displacement causes the strata of the upper block to be folded. As the strata are pushed against the ramp, they become parallel to it, forming one limb of a ramp-related anticline. Where the strata that have been displaced past the ramp return to the next bedding-parallel segment of the thrust surface, they dip downward toward this surface, thus forming the second limb of the ramp-related anticline. Where later deformation has not obscured the relationships, Rich's mechanism creates flat-topped anticlines whose widths are direct functions of the amount of displacement on the overthrust and and intervening flat-bottom synclines whose widths are determined by the spacing between adjacent ramps.

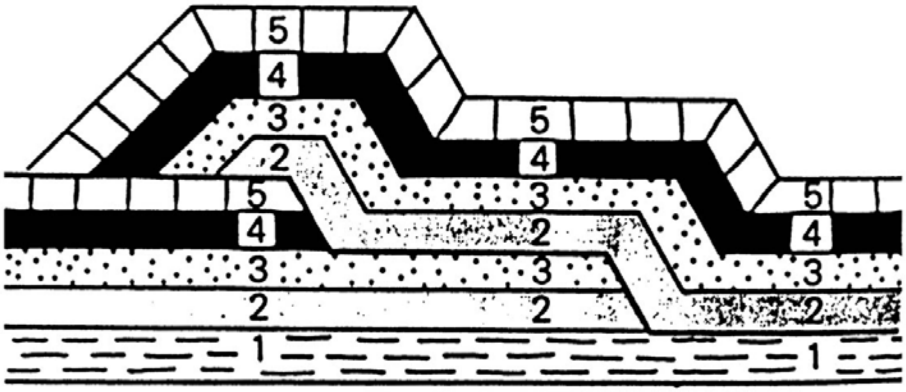


Figure 14 - Folds formed by movement from right to left on a bedding-plane thrust according to the mechanism proposed by J. L. Rich; schematic profile section with units numbered in order of decreasing age from 1 (oldest) to 5 (youngest). (J. E. Sanders, 1981, fig. 16.1 e, p. 390.)

For about 35 years, the only person who seems to have understood the fundamental new point that John L. Rich was trying to make was John Rodgers. In numerous important papers, Rodgers (1949, 1950, 1953, 1963, 1964, 1970) established what he referred to as the "thin-skinned" mechanism of Appalachian deformation. A synonym of the "thin-skinned" style of Appalachian deformation was the term "no-basement" style. That is, the deformation of the strata took place independently of the basement. Therefore, in between the deformed strata and the non-involved basement was a surface of detachment, or decollement. Where the basement was involved, the term "thick-skinned" style was applied. These two styles were thought to be mutually exclusive.

Major new understanding of the importance of John L. Rich's insights have resulted from the discovery of large reserves of petroleum in the Rocky Mountains. For many years, searchers for petroleum avoided drilling in places where the strata had been overthrust. They believed that deformation on a scale that creates overthrusts would destroy any petroleum present in the strata. Therefore, overthrust belts ranked high on the list of places to avoid. Much to everybody's surprise, major discoveries were made by drilling through overthrusts to petroleum traps formed in the strata on the lower block (Gries, 1983). After several giant gas fields had been discovered, "overthrust belts" were stricken from the "no-no" list and quietly moved to the head of the list of places to be explored. As a result, seismic profiles were shot across mountain chains and deep holes were drilled through complex geologic structures. The result has been the acquisition of great quantities of new subsurface information from places that probably would have remained "terra incognita" forever had it not been for petroleum exploration.

All of which brings us back to the Appalachians. The next major point about Appalachian overthrusts is the displacement of basement rocks over the strata. In other words, the basement becomes "involved." (What's that story about ham and eggs? The hen is "involved" but the pig is "committed.") In this respect, northwestern New Jersey and adjacent southeastern New York provides some critical evidence that has been overlooked. In the discussions about "thin-skinned" vs. "thick-skinned" deformation, this part of the Appalachians seems to have been studiously avoided The evidence pointing to basement involvement in the northern Appalachian overthrusts was presented by Isachsen (1964). Isachsen argued that on a regional scale, the Precambrian basement had been thrust over the strata. (See Figure 5.) He inferred that this displacement has taken place during the Late Ordovician Taconian orogeny. (We discuss the subject of age of deformation in a following section.)

A critical locality demonstrating the displacement of Precambrian rocks over Paleozoic strata is the Musconetcong tunnel built by the Lehigh Railroad more than 100 years ago. (See Figure 6.) As far as JES has been able to determine, the significant geologic relationship of Precambrian thrust over Paleozoic, disclosed by tunnel construction, never made its way directly into the geologic literature. Its only mention has been somewhat incidentally in two places: (a) Lewis and Kümmel (1914); and (b) Isachsen (1964). Isachsen (1964, p. 822) cited Kümmel (1940) as his source of the information about this tunnel. As we pointed out in our On-The-Rocks Guidebook for Trip 12 to Franklin Furnace (17 June 1990), however, the correct citation is not Kümmel (1940) but rather Lewis and Kümmel (1915; See Figure 6.).

As far as we have been able to determine, the first published reference in the geologic literature to overthrusting of Appalachian Precambrian rocks over Appalachian Paleozoic strata is by L. G. Westgate (1896). For his doctoral dissertation at Harvard under Professor J. E. Wolff, Westgate mapped the klippe of Precambrian rocks above Paleozoic rocks at Jenny Jump Mountain, New Jersey. This dissertation was published in the Annual Report of the New Jersey State Geologist for 1895 and nowhere else. [Others have subsequently referred to Jenny Jump Mountain as a klippe but have not mentioned Westgate's splendid work (for example, Broughton, 1946; Maxwell, 1962; Drake and Lyttle, 1980)]. During his a recent visit (in January 1992) to Delaware, Ohio, home of JES's alma mater, Ohio Wesleyan University, where Westgate was Professor of Geology for 40 years, JES discussed Westgate's doctoral dissertation with Paul R. Shaffer, retired geology professor from OWU who taught JES beginning geology in 1944. Shaffer succeeded Westgate as Professor of geology at OWU and got to know Westgate very well in the few years they overlapped before Westgate died in 1947. Shaffer said he could never remember Westgate ever mentioning Jenny Jump Mountain (which had been his doctoral dissertation at Harvard). The only place where Westgate's work on Jenny Jump Mountain has been published is in the Annual Report of the New Jersey State Geologist for 1895 (1896 date of publication). However, Professor John Tillman (current chairman of Geology at Ohio Wesleyan) and JES did find a copy of this annual report in the Westgate Library. In light of Shaffer's remarks, JES wonders if Westgate might have presented his ideas at some geological meeting or other and was raked over the coals by some senior "big shot" and being thus intimidated, walked away from his dissertation on Jenny Jump Mountain. If such a thing happened, it must have been traumatic. Westgate was a very assertive individual and at least in his mature years would have been classified much more as a potential intimidator than intimidatee. The reason for Westgate's silence about his doctoral dissertation remains a mystery.

JES wonders what "Uncle Louie" would be thinking if he knew that one of his almost-protoges (namely JES) is now busy resurrecting Westgate's long-lost geological gem about the overthrusting at Jenny Jump Mountain. No doubt LGW would be amused. (As an example of LGW's humor, consider the title he gave himself in the 1940's, when Ohio Wesleyan pressed him back into teaching service after granting him the rank of Professor Emeritus when he had retired after 40 years of distinguished service. LGW said his new title would be "Professor Emeritus Resurrectus.")

In 1980, JES began to wonder about the geologic circumstances under which the gas had been trapped at the Middletown gas well in Orange County, New York. Not far SE of this well are a series of klippe in which Precambrian rocks had been thrust over the Paleozoic strata (usually, but not exclusively, the Ordovician shales; Figure 15). Despite these clear examples of basement involvement with the Paleozoic strata, the authors who were writing about the "basement" vs. the "no-basement" style of Appalachian deformation seemed to be avoiding any discussion of the relationships in northwestern New Jersey and southeastern New York. JES (Sanders, Friedman, and Sternbach, 1981) concluded that the emphasis on the John L. Rich mechanism as a basis for the distinctness of "thin-skinned" deformation was omitting an important point, namely, that the Rich-style mechanism need not be confined to the strata. Deep seismic profiles were showing what appeared to be strata beneath outcropping basement. Therefore, JES suggested that the Rich-style overthrusts were a general phenomenon, and that the depths of their horizontal segments could be the basis for classifying mountain belts into three longitudinal zones: (A) a distal zone in which strata were thrust over strata (the happy home of the "thin-skinned" style); (B) a median zone in which basement was thrust over strata (the habitat of the so-called "thick-skinned" style where basement was clearly "involved"); and (C) a proximal zone in which basement was thrust over basement (Figure 16).

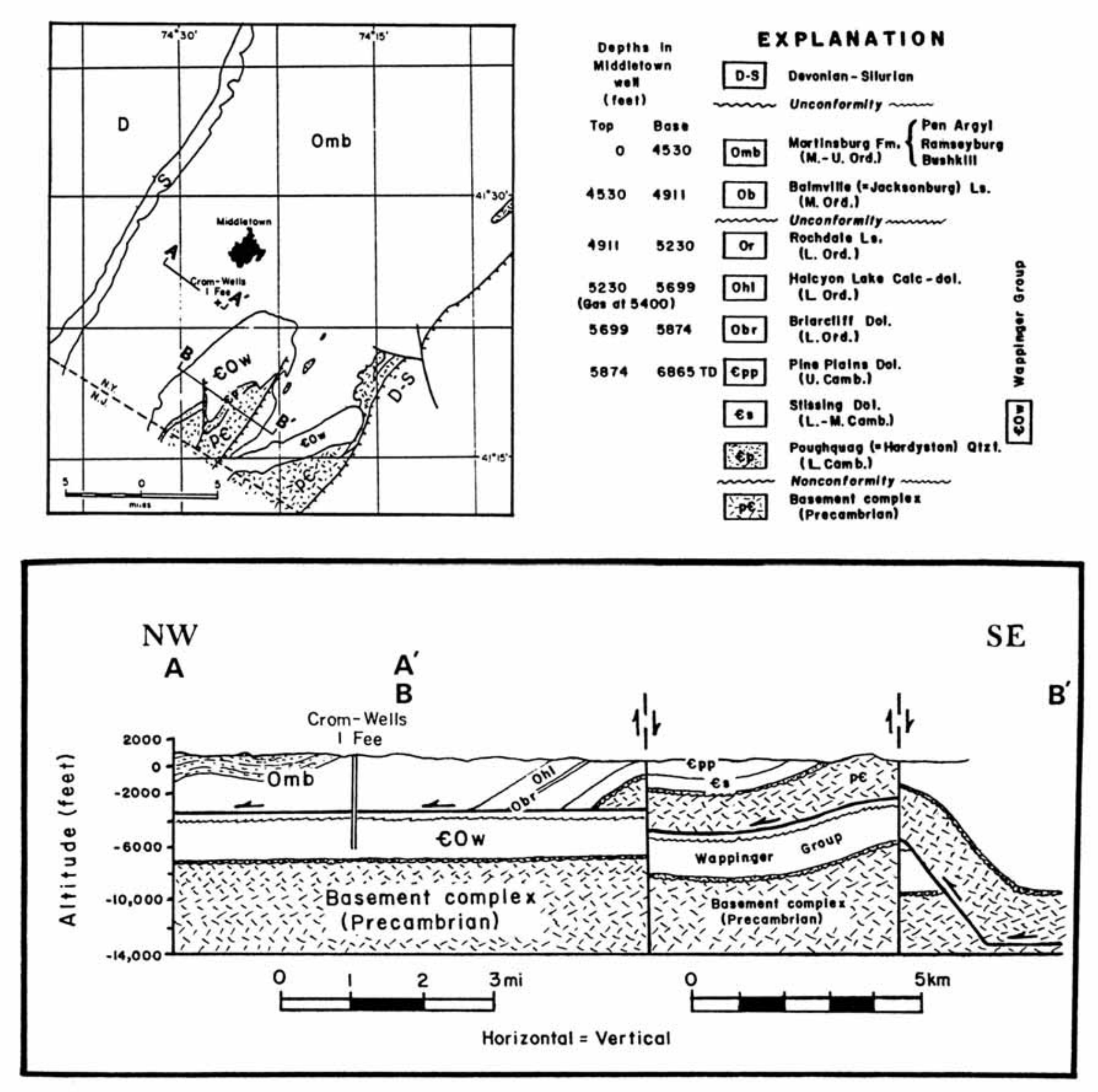


Figure 15 - Geologic setting of Middletown gas well (Crom-Wells 1 Fee), Orange County, NY (Sanders, 1983).

a. Simplified geologic map showing locations of lines of sections AA' and BB' (modified from New York State Geologic Map, 1970, Lower Hudson Sheet).

b. EXPLANATION of geologic map and sections including depths of formation boundaries in Midletown well (depths from Warathin and Pakc, 1956 ms., in Offield, 1967).

c. JES interpretation of structure along lines AA' and BB.' Contacts of formations at surface from Offield (1967), but with subsurface relationships changed to show one possible arrangement according to overthrust interpretation (Sanders, 1983, Fig. 8).

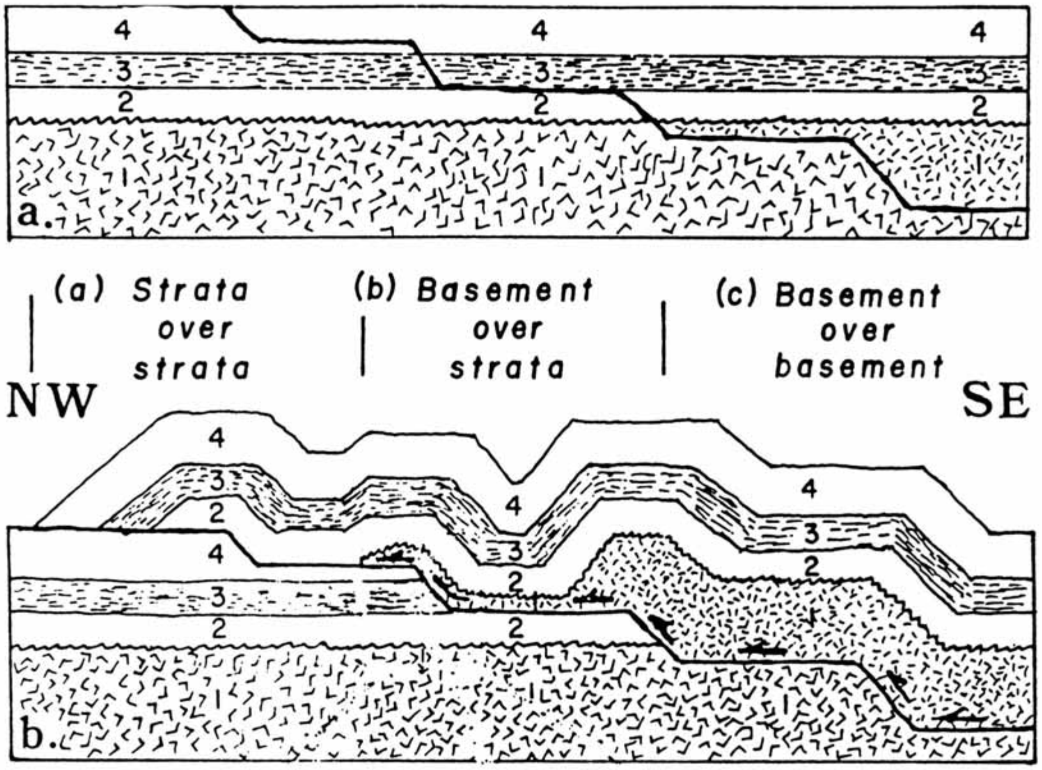


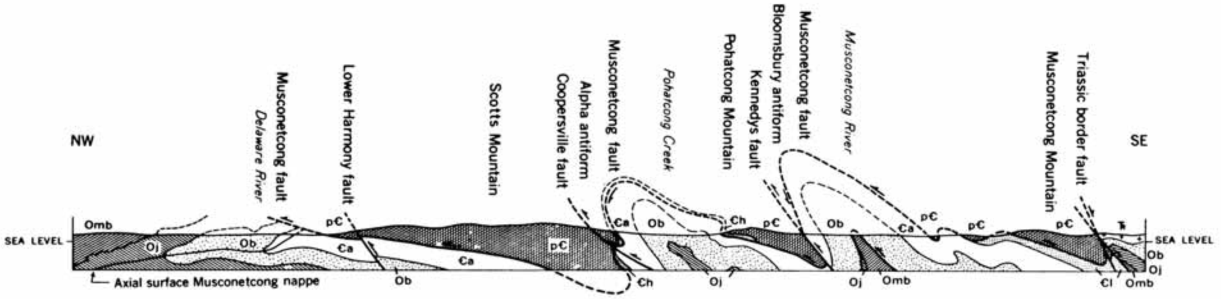
Figure 16 - "Bedding thrusts" as described by J. L. Rich (1934), but extended downward so as to includes sheets of basement rock, schematic profile-section with no erosion. Where basement rocks move over other basement rocks, the cause of the separation is probably thermal, as argued by Armstrong and Dick (1974).

a. Reference sketch before movement on multi-level thrust (thick line).

b. Result of motion forward and up the footwall ramps has created anticlines above each ramp. Three thrust zones: (a), (b), and (c), are based on the relationships of the overthrust strata to other strata, of overthrust basement to strata, and of overthrust basement to other basement (Sanders, Friedman, and Sternbach, 1981, Fig. 15, p. 218).

Using this approach, JES (Sanders, 1983) reinterpreted the geologic structure at the Middletown well. He inferred that the large anticline south of Middletown in which the basement is exposed is a ramp-related anticine above a tectonic ramp that extended upward from some level within the Precambrian rocks to a higher level in the Ordovician shales. (See Figure 15.) A corollary of this interpretation is that the NW dips of the Silurian strata of Shawangunk Mountain/Kittatinny Mountain and the Devonian strata underlying the adjacent strike valley to the NW should not flatten with depth under the Catskill-Pocono Plateau, as generally presumed, but rather should be as shown, previously, in Figure 3. That is, the NW dips should continue downward to a horizontal segment of a bedding-type thrust beneath which the strata should be horizontal. Since 1983, JES has seen the seismic profile that was shot along N.Y. Route 17. Much to his delight, this profile shows that the dip of the Silurian strata continues downward more or less unchanged from its surface value to a level where these strata are truncated. At greater depth the reflector traces are horizontal. JES takes this to be dramatic confirmation that bedding thrusts on a regional scale are present beneath the Catskill-Pocono Plateau. It establishes on a regional scale the local relationships of NW-dipping bedding thrusts that JES found in the Devonian strata exposed NW of Catskill, New York (Sanders, 1969).

The overthrust interpretation for the Proterozoic rocks has been accepted by A. A. Drake, Jr., of the U. S. Geological Survey, who has completed detailed mapping in many parts of the Appalachians in eastern Pennsylvania and western New Jersey. In addition, Drake and co-workers have inferred that large-scale recumbent folds (nappes) are present (Figure 17). Dallmeyer (1974), emphasizing the importance of steep brittle faults at the boundaries in the northeastern Reading Prong, has argued for an in-situ interpretation. A possiblity favored by us, but not considered by Dallmeyer, is that the areas of Precambrian rocks overlie nearly horizontal overthrusts at depth and that these overthrusts were later displaced by the steep brittle faults.



Geologic section across the Reading Prong in the Delaware Valley modified from Drake (1967b) and Drake and others 1969. Symbols: TR, Triassic rocks; Omb, Martinsburg Formation; Oj Jacksonburg Limestone; Ob, Beekmantown Group; Єa, Allentown Dolomite; Єl, Leithsville Formation; Єh, Hardyston Quartzite; pЄ, Precambrian rocks.

Figure 17 - Geologic section across the Reading Prong and part of the Great Valley in the Delaware Valley (Drake, 1969).

(3) A third feature that seems a bit anomalous in the NW New Jersey Appalachians is the near absence of the Taconic Sequence. The only place in New Jersey known to JES where Taconic rocks are exposed is around the town of Jutland, where a transverse anticline of mid-Jurassic age brings up the pre-Newark rocks in a small area. Typical purple-, red-, and green slates, diagnostic Taconic rocks, are well exposed in new roadcuts and building excavations (Sanders, 1962). From this small area, one can infer that a belt of outcrop of Taconic rocks crosses NW New Jersey, but is mostly concealed because it has been buried beneath the Upper Triassic-Lower Jurassic strata filling the Newark basin.

(4) A final point of contrast between the NW New Jersey Appalachians and in eastern New York State is the Newark basin.
As just mentioned, the Newark basin-filling strata locally but not everywhere overlie the Taconic sequence. At the NE end of the Newark outcrop belt, near Stony Point, NY, the Newark basin-filling strata overlie the metamorphosed Sauk Sequence marbles and lower Tippecanoe Sequence phyllites/schists. Large faults that displace the Newark basin-filling strata offset the basin-marginal Ramapo fault and extend out into the older rocks.

Some Ideas (Some "Orphaned") Based on New Jersey Geology

Because of these relationships in NW New Jersey, at least three basic points about the geology of the New Jersey Appalachians have been established that contrast with points based on the Hudson Valley-Taconic region. (1) The age of the black slates (Martinsburg Formation of the Tippecanoe Sequence) is not in dispute; everyone agrees that this body of slates/graywackes depositionally overlies the Jacksonburg Limestone. Accordingly, no "red herrings" about associating these slates with the Taconic Sequence have ever been dragged across New Jersey geology's path to the truth, the way, and the everlasting light radiating from eternal verities. Moreover, geologists mapping these slates in NW New Jersey (for example, Avery Drake, and J. C. Maxwell), have demonstrated that the large thicknesses inferred by C. H. Behre from his work in the slate belt of eastern Pennsylvania, are correct. This contrasts with the tendency in New York State to consider that the thickness of the analogous and comparable unit is only a few thousand feet.

(2) The geological footprints left behind by the Taconic orogeny in NW New Jersey are less obvious than in eastern New York State. We think that the "big one" from the Taconic orogeny in NW New Jersey was the massive overthrusting to the NW of Precambrian basement rocks over the Paleozoic strata, as inferred by Isachsen (1964). Moreover, the overthrusts sheets must have moved across the floor of the foreland basin in which the Martinsburg strata were accumulating. Thus, the conditions for the origin of the slaty cleavage, as visualized by J. C. Maxwell (1962) can be invoked with confidence and we think, assigned to the Taconian orogeny. (The foregoing remarks are not in any way meant to suggest that we deny the evidence showing that overthrusts also took place during the Late Paleozoic Appalachian orogeny.)

(3) The age of late-stage brittle deformation in NW New Jersey can be demonstrated as post-Newark (possibly in the middle of the Jurassic Period) and its effects can be shown to have been on a large scale rather than on a small scale. Moreover, JES at least, is convinced that significant strike-slip faulting took place. Still not settled are ages of "backfolds" having axial surfaces dipping NW (gentler dips of strata on the NW sides, steeper dips on the SE sides).

The rocks of the Appalachians have experienced at least three Paleozoic orogenic episodes. These were originally named Taconic (Late Ordovician), Acadian (Medial Devonian), and Appalachian (Late Paleozoic). In 1957, H. P. Woodward proposed the interpretation that in the northern Appalachians, the last "significant" deformation had taken place in medial Devonian time. Moreover, Woodward (1957a, b) specifically rejected the "classical" viewpoint that the Appalachian "Revolution" (a supposedly terminal Appalachian event) marked the orogenic climax in the Appalachians. Woodward was convinced that the basis for the Appalachian "Revolution" lay somewhere between trivial and non-existant. Accordingly, he proposed the ultimate trivialization of the "good-old" "Appalachian Revolution:" He supplanted Appalachian with "Alleghenian" and "Revolution" with "disturbance."

Woodward's proposal has been accepted by large numbers of Appalachian geologists. Geologists studying the Appalachians kept on calling themselves Appalachian geologists after the geographic name of the mountain chain. In effect, they restricted their use of "Appalachian" to the name of the mountain chain and followed Woodward in referring to the Late Paleozoic deformation as the Alleghenian "disturbance." (We shall start a new trend by referring to these folks as Alleghenian geologists). What has been happening since Woodward's proposal is that more and more evidence has been compiled to show that the Late Paleozoic deformation was considerably more vigorous than Woodward visualized. In other words, the "Alleghenian" is being upgraded. That situation strikes us as being absurd. If the evidence supports the conclusion that the Late Paleozoic deformation was not a ho-hum affair (as we might paraphrase the Woodward viewpoint), then why not reject the upstart term, Alleghenian "disturbance" and bring back the "good-old" Appalachian orogeny?

No new data have changed the long-established geologic fact that the youngest deformed strata in northwestern New Jersey are of medial Devonian age. Therefore, the final deformation of the strata in the Valley and Ridge province 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 H. P. 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."

Rodgers (1970, p. 64) has summarized the age of the terminal Appalachian deformation: "As Carboniferous rocks (lower Upper Carboniferous in the Southern Appalachians, upper Upper Carboniferous in the Central Appalachians) are obviously involved in typical and intense Valley and Ridge folding (sic) and faulting (sic) in many places from the anthracite coal basin of eastern Pennsylvania to the Cahaba coal basin of central Alabama, the climax of deformation in the province was late or post-Carboniferous. The presence of Lower Permian strata in the Georges Creek syncline just to the west of the province boundary in Maryland confirms this conclusion. Upper Triassic sedimentary rocks lap over deformed Ordovician rocks in eastern Pennsylvania and contain pebbles of Devonian rocks; presumably the deformation was over well before their deposition. This period of deformation, occurring in the Permian or perhaps continuing into the early Triassic, is the Alleghany orogeny of Woodward (1957b); apparently it formed most if not all the major structural features of the province, at least southwest of the Susquehanna River."

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.

Shaler (1877), W. M. Davis (1882, 1883), and Sanders (1969) have expressed the view that the folded Paleozoic rocks of the Hudson valley 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.

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 JES is concerned, nothing that has appeared in the geologic literature in the past 23 years requires any change in the foregoing paragraph.

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."

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; Merguerian and Sanders, 1991).

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 dependent upon so many elusive factors, including duration of deformation, strain rate, rock 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 indefensible. 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.

Students of the plate-tectonic history of the Appalachians have not reached total agreement about the relative effects of and about the circumstances involved in the changes from a given long-established plate-tectonic regimen to a contrasting regimen. What is generally agreed upon, however, is that the passive-margin regimen that became established in the middle of the Jurassic Period, when the Atlantic Ocean began to open, more or less duplicates a previous such regimen that became established during the Cambrian Period and persisted until the middle of the Ordovician Period. One of the points on which we disagree totally with the established "party line" is the relationship between the growth, filling, and destruction of the Newark basins and the opening of the Atlantic Ocean.

We make no claims to having solved some of these Appalachian plate-tectonic puzzles. Our purpose in drawing attention to certain anomalous features will be fulfilled if we convince some readers that these anomalous features should be taken seriously and not simply glossed over.

What we hope to show participants on this trip is how all of the above can be synthesized into a geologic history and how features made in the rocks by various episodes of deformation can reveal insights into this history. Fasten your seat belts!

The remainder of this guidebook is organized under the first-order headings of: GEOLOGIC BACKGROUND, OBJECTIVES, LIST OF LOCALITIES TO BE VISITED, ROAD LOG AND DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS"), ACKNOWLEDGEMENTS, and REFERENCES. The tables and illustrations (figures) referred to in the text follow the reference section.

GEOLOGIC BACKGROUND

Under this heading, we discuss the bedrock units, the glacial deposits, and the drainage history of our field-trip route.

BEDROCK UNITS

As we begin Trip 23 from the New York Academy of Sciences, let us express a few thoughts to the rocks beneath our feet. It may not have occurred to you in these terms, but as you observe outcrops in New York City, you are doing two contrasting things. First, you are vicariously walking backward in time. And second, you are figuratively descending deep within a former mountain zone.

Layer I: "Basement Complex" of the Hudson Highlands-Reading Prong

The rocks of Layer I underlying the Hudson Highlands and Reading Prong contrast with those of Layer I in New York City. This contrast is the basis for our discussing them here under a separate heading. Various felsic- and mafic gneisses, syenites and granites are widespread; schist is not common, but locally, very distinctive, coarsely crystalline marble, graphitic phyllite, and graphitic quartzite are present.

These rocks have been studied in great detail in a few selected localities by researchers interested in learning about the exact mineralogic composition of individual specimens and petrologic interpretations based thereon. They mapped outcrops in great detail and carried out extensive laboratory investigations. Examples include the studies by Dodd (1965) in the Popolopen Lake quadrangle and by Jaffe and Jaffe (1973) in the Monroe area and Puffer (1980) in northern New Jersey. Only Offield (1967) and Drake (1984) have tried to aggregate the outcrop information into mappable formations and thus to infer a stratigraphic succession. Both of these contrasting kinds of investigations are necessary. The greatest progress has always come about when these are carried out by the same investigator.

In a few localities, the Proterozoic rocks clearly are allochthonous. Isolated hills composed of Proterozoic rocks in their high parts display Paleozoic rocks, typically the Martinsburg Formation (Layer IIB, Table 2), in their lower regions. Both the structural relationships and the composition of the Precambrian rocks (commonly graphitic phyllite or graphitic quartzite) demonstrate that these isolated hills are remnants of formerly more-extensive overthrust sheets (klippen, auf Deutsch; see Jaffe and Jaffe, 1973). A few examples include Woodcock Hill klippe, Museum Village klippe, and Goose Pond Mountain, west of Monroe.

Elsewhere, the allochthonous relationship is not particularly obvious from study of the exposed rocks, but is strongly suggested by geophysical surveys, notably from aeromagnetic data (Henderson, Tyson, and Wilson, 1958; Henderson and Smith, 1962; Henderson, Andreasen, and Petty, 1966; Harwood and Zeitz, 1974), from gravity data (Urban, Bromery, Ravetta, and Diment, 1973), and from seismic-reflection profiles (Herman, 1992).

Allochthonous or autochthonous, some of the Proterozoic rocks of the Reading Prong are famous throughout the world. An example is the remarkable suite of minerals uncovered in the zinc mines at Franklin and Sterling Hill, New Jersey (Metsger, 1980; Frondel and Baum, 1974; Frondel, 1972; Baker and Buddington, 1970; Metsger, Tennant, and Rodda, 1958; Hague, Baum, Herrmann, and Pickering, 1956; Palache, 1929, 1935; Spencer, Kümmel, Wolff, Salisbury, and Palache, 1908). (See our On-The-Rocks guidebook for Trip 12 to Franklin, New Jersey and vicinity.)

Layer IIA: Sauk Sequence (Cambro-Ordovician) Carbonates

We have mentioned the rocks of Layer II in the Manhattan Prong, where they have been subjected to Taconic overthrusting and high-grade metamorphism. In the belts northwest of the Hudson Highlands, these rocks have been folded and faulted, but never subjected to the temperatures that thoroughly recrystallize rocks. Moreover, throughout most of the Appalachian Great Valley, no Taconic klippe is present. The same general two-fold subdivision of predominantly carbonates below and predominantly terrigenous rocks above can be recognized. In New Jersey, the names for these formations are, from base upward: Hardyston (Lower Cambrian clastics, equivalent to the Poughquag Quartzite and Lowerre Quartzite), Kittatinny Supergroup (the Cambro-Ordovician carbonates equivalent to the Wappinger of New York and also to the Inwood-Stockbridge marbles), regional unconformity, Jacksonburg Limestone (equivalent to the New York Balmville), and the Martinsburg Formation (equivalent to the Hudson River "Shales," a correlation suggested by faunal-, physical-, and chemical evidence. For an example of chemical data, see Vargas 1976 ms.).

In the region of our field trip, these rocks were folded and eroded several times. Initially, the Cambro-Ordovician dolomitic carbonates were elevated and gently folded. The overlying limestone fills local sinkholes and rests on various units. During the Taconian orogeny, the folding was more intense and, the erosion cut more formations than during the Medial Ordovician. Accordingly, the basal unit of Layer III (Lower Silurian Green Pond or Shawangunk Conglomerate) rests on any of these units, even on the Proterozoic "basement" (Finks and Raffoni, 1989, p. 116-118). (See Figure 1, cover.)

The Cambro-Ordovician carbonate succession displays numerous features produced within a peritidal environment. Present are dolomitic rocks that formed from what were originally calcium-carbonate muds and -sands. The originally sandy layers feature ooids, rounded quartz particles mixed with varying proportions of carbonate sand whose particles included intraclasts of the adjacent muddy sediment. In addition, algal stromatolites are prominent. Chert is abundant. Finally, as a result of deep burial, all layers have been subjected to pressure solution, as is evidenced by the numerous stylolites on several scales. (Tada and Siever, 1989, summarize pressure solution.)

Layer IIB: Tippecanoe Sequence

During the next episode of marine submergence, starting in the Middle Ordovician Epoch, the Tippecanoe Sequence began to accumulate. The initial deposits of the Tippecanoe Sequence consist predominantly of limestones (as contrasted with the generally dolomitic rocks of the underlying Sauk Sequence). These limestones are richly fossiliferous and have been studied extensively and subdivided to the maximum extent possible. A few local names applied to these limestones must be understood. In New York State, the subdivisions of the Middle Ordovician limestones used early in the twentieth century were as follow:

Trenton

Middle Ordovician | Black River [Lowville Limestone in U. pt.]

Chazyan

These Middle Ordovician limestones are overlain by a thick body of terrigenous strata, shales at the base, coarse graywackes in the middle, and shales again at the top that are now considered to represent foreland-basin sediments which accumulated during and after the emplacement of the great overthrusts (the Martinsburg Formation). The name that has been applied to the thick terrigenous strata of the lower part of the Tippecanoe Sequence in the field-trip area is the Martinsburg Formation.

A complication with the terrigenous strata of the Tippecanoe Sequence is their thickness, a difficult problem compounded by lack of large, continuous exposures; lack of a detailed stratigraphic subdivision; and by complex effects of multiple episodes of tectonic deformation.

From time to time, contrasting thickness values have appeared in the literature based on: (1) guesses by those who did not attempt to work out the stratigraphic succession nor geologic structure but whose "sixth geologic sense of how things ought to be" informed them that the number should be small (i.e., no more than a few hundred meters); (2) calculations made after careful mapping; and (3) the results of exploratory borings.

Ruedemann pioneered the category (1) "thick-small" version of the thickness of these shales. Ruedemann based his conclusions on his mapping of the region around Saratoga Springs and study of a well at Mechanicville that cut 1400 feet of shale where the dip was about 70° and the beds were repeated on overturned folds. He concluded (in Cushing and Ruedemann, 1914, p. 91) that: "the thickness of the shale in the well is clearly no indication of a corresponding thickness of shale beds." Ruedemann arrived at his preferred estimate of 1000 feet from studying exposed strata on the west face of Willard Mountain.

Table 3 shows various subdivisions of the Martinsburg Formation made by geologists who studied this formation in eastern Pennsylvania and adjacent New Jersey. Two examples of category (2) results are those by Behre (1927, 1933) from the slate belt of eastern Pennsylvania and by Drake and Epstein (1967) based on detailed mapping in New Jersey.

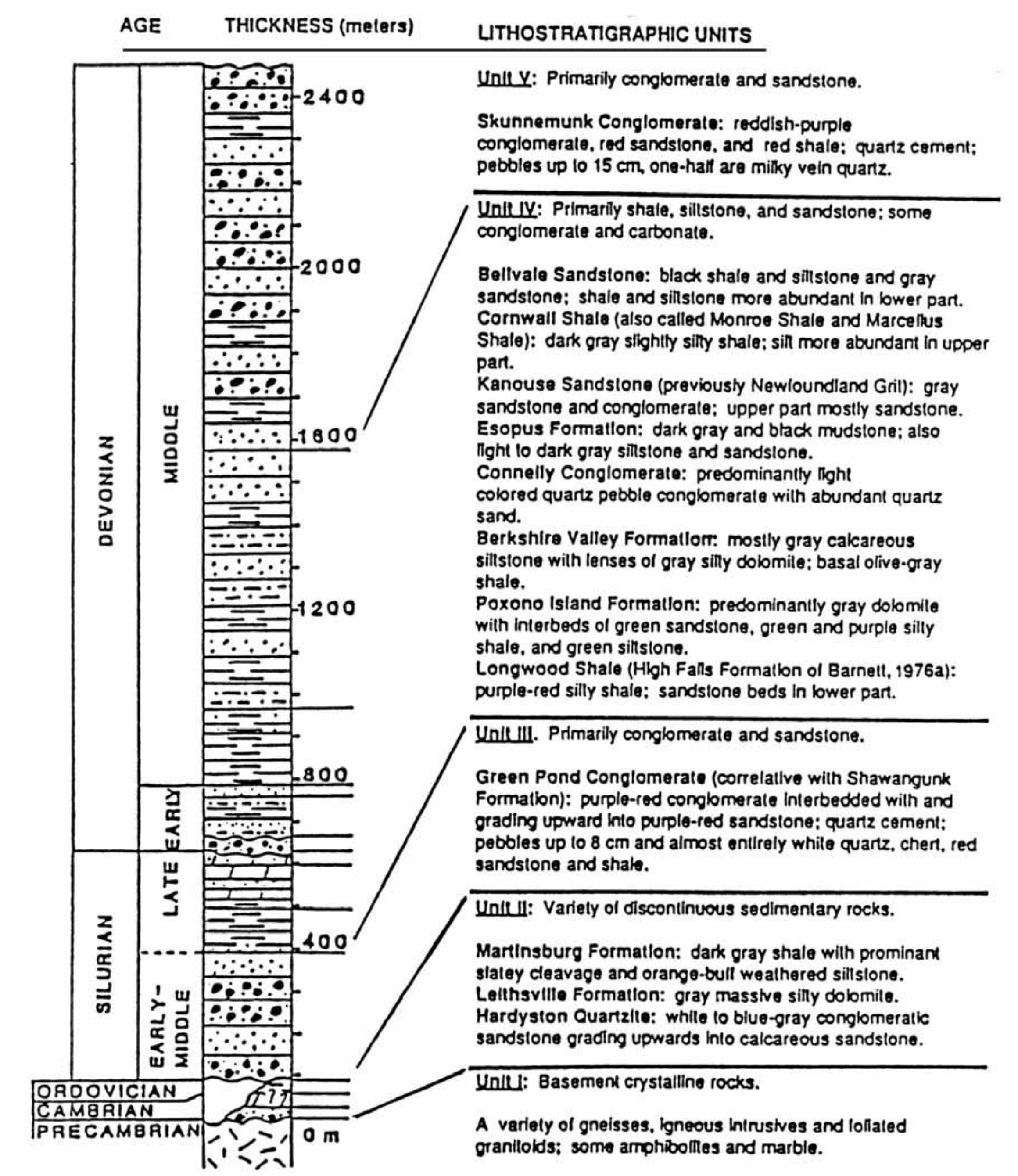
Exploratory borings in the Hudson Valley have supported these large thickness determinations. At least three exploratory borings have been drilled in locations where the hole penetrated 8000 feet or more of shale, probably much more than the operators had imagined would be present. The Senigon boring, Quebec, cut 4000 feet of shale. The Columbia Gas No. 1 D. J. Finnegan boring in southern Washington Co., NY, penetrated 2760 feet of Taconic strata and 2000 feet of mid-Ordovician (presumably Utica) shale. The Crom-Wells No. 1 Fee, SW of Middletown, Orange Co., NY drilled through 4700 feet of shale.

Layer III: Silurian and Devonian Strata

The rocks of Layer III are at center stage on this trip. We will examine them in their western outcrop belt. The stratigraphic succession that has been established in the eastern belt (Layer IIIE, Table 2) begins with the Lower Silurian Green Pond Conglomerate and ends with the Middle Devonian Schunemunk Conglomerate. A recent version of the succession at the southwestern end near Green Pond Mountain, NJ is shown in Figure 18.

A renewed interest in the structural geology of the eastern belt of Layer III has developed on the part of investigators studying the features made as the rocks were deformed (i. e., strained). The latest wrinkle is that "flower structures" are present along the SE side of the Reservoir fault zone, which forms the border of the western belt of the Green Pond outlier in NW New Jersey and which has been inferred to display significant right-lateral strike-slip movement. Latest movement on the Reservoir Fault has been inferred to be of Late Paleozoic age, although the constraints listed range from post-Medial Devonian to Triassic (Malizzi and Gates, 1989, p. 84-86). JES finds this evidence for right-lateral strike-slip movement of more than casual interest in view of the JES "minority-of-one" interpretation of the strike-slip offsets on the Hopewell and Flemington faults that cut the Newark and associated strata in the Delaware River Valley and adjacent areas (Sanders, 1962b). Not much straining of geologic credulity is required to connect the Flemington fault (with its JES-inferred 19 km of right-lateral strike-slip displacement accompanying a dip-slip shift of approximately 3 km) and the Reservoir fault. If this intuitive leap by JES proves to be correct, then the age of the deformation on the Reservoir fault becomes Medial Jurassic. And the combined Hopewell-Reservoir fault assumes a big-league status not heretofore imagined.

The most-prominent unit of Layer IIIW is the ridge-making Shawangunk Formation (conglomerate and sandstone), of Early Silurian age. Along the northwest side of the Appalachian Great Valley, this formation forms a wall-like ridge in which the strata dip to the NW. The younger strata share this direction of dip, but upward, the dip becomes less and less. Beneath the Catskill and Pocono plateaus, the strata are essentially horizontal. This NW dip grading northwest into horizontal strata has been taken to mean that the strike ridge marks the NW limit of deformation in the Appalachian chain. Granted the possibility of large-scale overthrusts of Late Paleozoic age, then this NW dip may result from a ramp-related anticline and be the NW limb of such a structure. (See Figure 15.) JES has seen a seismic-reflection profile shot along NY Route 17 in which the NW dips of the Shawangunk Formation terminate abruptly downward and at greater depth, the reflectors are horizontal. (See Figure 3.) JES thinks that this profile confirms the existence of overthrusts and that the interpretation of the NW dips as part of a ramp-related anticline is correct. For a contrasting view see Herman, 1992.



LITHOSTRATIGRAPHIC UNITS

Unit V: Primarily conglomerate and sandstone.

Skunnemunk Conglomerate: reddish-purple conglomerate, red sandstone, and red shale; quartz cement; pebbles up to 15 cm, one-half are milky vein quartz.

Unit IV: Primarily shale, siltstone, and sandstone; some conglomerate and carbonate.

Bellvale Sandstone: black shale and siltstone and gray sandstone; shale and siltstone more abundant in lower part.
Cornwall Shale (also called Monroe Shale and Marcellus Shale): dark gray slightly silty shale; silt more abundant in upper part.
Kanouse Sandstone (previously Newfoundland Grit): gray sandstone and conglomerate; upper part mostly sandstone.
Esopus Formation: dark gray and black mudstone; also light to dark gray siltstone and sandstone.
Connelly Conglomerate: predominantly light colored quartz pebble conglomerate with abundant quartz sand.
Berkshire Valley Formation: mostly gray calcareous siltstone with lenses of gray silty dolomite; basal olive-gray shale.
Poxono Island Formation: predominantly gray dolomite with interbeds of green sandstone, green and purple silty shale, and green siltstone.
Longwood Shale (High Falls Formation of Barnett, 1976a): purple-red silty shale; sandstone beds in lower part.

Unit III. Primarily conglomerate and sandstone.

Green Pond Conglomerate (correlative with Shawangunk Formation): purple-red conglomerate interbedded with and grading upward into purple-red sandstone; quartz cement; pebbles up to 8 cm and almost entirely white quartz, chert, red sandstone and shale.

Unit II: Variety of discontinuous sedimentary rocks.

Martinsburg Formation: dark gray shale with prominant slatey cleavage and orange-buff weathered siltstone.
Leithsville Formation: gray massive silty dolomite.
Hardyston Quartzite: white to blue-gray conglomeratic sandstone grading upwards into calcareous sandstone.

Unit I: Basement crystalline rocks.

A variety of gneisses, igneous intrusives and foliated granitoids; some amphibolites and marble.

Figure 18 - Stratigraphic column in the Green Pond outlier, NW New Jersey, according to Mitchell and Forsythe, 1989, their Figure 2, p. 53, slightly modified.

A notable feature of the terrigenous sediment, especially during the Early and Medial parts of the Silurian Period, was an enormous abundance of quartz, ranging in size from pebbles to silt. Although deep burial doubtless contributed to the dissolution of easily dissolved minerals, such as feldspar, it is still remarkable that so much sand-size and coarser quartz was spread throughout such a vast area and to the thickness of many tens of meters. The sheet of Silurian sand extends unbroken from New York to Tennessee and has been found in the subsurface as far west as eastern Ohio.

The Silurian strata also include dolomitic carbonates (a re-appearance of such rocks after the predominance of limestone during the Ordovician Period) and evaporites, notably halite rock (in the Salina Group). The details of the pattern of Silurian and Devonian environments of deposition are active subjects on ongoing research.

Layer IV: Coal Measures and Related Strata

On this trip, we will not be examining any of the rocks of Layer IV. We mention them briefly because they are significant factors in the debates about the age(s) of the episodes of deformation. The important points about the rocks of Layer IV are that they are thick and coarse; possibly the conglomerates mark episodes of Late Paleozoic deformation. In addition, they contain coal beds that have been metamorphosed to anthracite grade. The anthracite district is near Scranton, Pennsylvania. After about a century of extensive mining, the district's reserves have been exhausted.

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 2, 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 Sill 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 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

What geologists refer to as "structures" are features in rocks that have resulted from deformation. The precepts of plate tectonics imply that deformation results from one of only three kinds of plate motions: (1) plates diverging or spreading; (2) plates converging or coming together; and (3) plates moving laterally against each other (Figure 19).

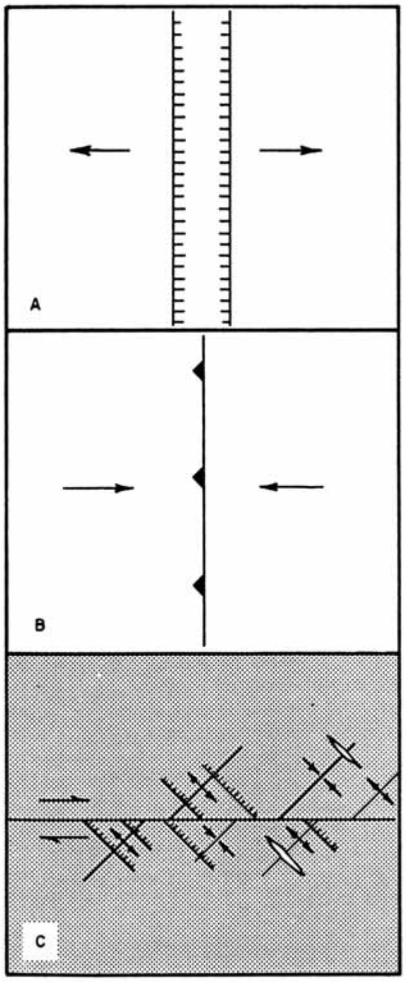


Figure 19 - Kinds of forces that deform strata as related to major kinds of inferred plate motions, schematic sketch maps.

A) Plates moving apart creating tension with development of graben bounded by normal faults.

B) Converging plates create compression.

C) Translational motion produces major shearing couple.

These plate motions impose deforming forces on bodies of rock. In turn, the deforming forces establish systematic patterns of internal stresses within the rocks being deformed. And, if these internal stresses exceed certain levels, the body of rock may be permanently deformed or strained and thus display changes from its initial shapes and/or volumes. One of the major goals of studying geologic structures is to describe the strained rocks and to try to relate them to former stresses and these, in turn, to deforming forces and plate motions. Before we take up some examples, it will be helpful to review the relationships between strain, stresses, and deforming forces.

The most-obvious effect of deformation on sedimentary strata is change of attitude: originally horizontal strata are no longer horizontal. Apart from such changes, other indicators of deformation include displacement of strata, disruption of strata, and rock cleavage. In regions where several episodes of deformation intense enough to form rock cleavage have been superimposed, it may be very difficult to unravel the relative ages of cleavage. If deformation has beem along subparallel trends, tlhis problem may become acute. Normally, cleavage direction parallels the axial surface of folds. That is, the layer-type minerals whose parallelism causes the cleavage are oriented parallel to the plane of maximum compression. Where two or more sets of cleavage have been superimposed upon one another, the rocks tend to break into wedge-like, triangular shapes or into long, slender faceted "pencils." This property of shape is further promoted if the deformed rocks contain a planar parting parallel to bedding.

In the vicinity of our field trip, slaty rocks of Layer IIB show evidence that at least five structural fabrics have been superimposed on one another. The oldest fabric resulted from an eastnortheast-trending fold set with attendant penetrative slaty cleavage. These early folds and related cleavage are cut by a younger, northeast- to east-trending set of later folds (Drake, 1978). These early structures have been cut by low-angle thrust faults involving bedding-parallel, continentward displacement of strata over strata, basement over strata, as well as basement over basement. Local folds accompany these low-angle structures; they have been cut by two additional sets of regional folds trending northeast and east (Drake, 1978).

Except for the oldest cleavage, the geologic ages of these various structures are not well constrained. The earliest cleavage in the Martinsburg is definitely of Taconian age. This is proved by the finding within the Upper Ordovician intrusive rocks of the Beemerville Complex in northern New Jersey of xenoliths of the Martinsburg slate displaying cleavage [David Rowlands and Nick Ratcliffe, 1979 and 1980, respectively, personal communications to Avery A. Drake]. No such geological good fortune is available for resolving the ages of the subsequent deformational fabrics. Based on the regional studies presented in Drake and Lyttle (1980) the low-angle thrusts and younger cleavages are probably of Late Paleozoic "Alleghanian" age.

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 reoriented remnants of stratification (except of course in the hinge area of folds). Thus, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they mark regional fold hinge areas.

Most folds in complexly deformed mountain ranges show the effects of more than one episode of deformation and as such their ultimate configuration can be quite complex (i. e., plunging folds with inclined axial surfaces and overturned limbs).

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

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. Our On-The-Rocks trips are an exception, luckily, and we can now 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 hear about today.

In the following section, we describe folds, faults, surfaces of unconformity, sedimentary structures, and structures in sedimentary- vs. metamorphic rocks.

Folds

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. In dealing with the structural geology of 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 behind the creation of folds and faults. At crustal levels below 10 km, rocks behave in a ductile fashion. Folds and faults are accompanied by recrystallization and reorientation of newly formed metamorphic minerals. More on metamorphic textures later. For now let's discuss some geometric aspects of structural geology.

If layers are folded into convex-upward forms we call them anticlines. Convex-downward fold forms are called synclines. In Figure 20, note the geometric relationship of anticlines and synclines. In eroded anticlines, strata forming the limbs of the fold dip away from the central hinge area or core (axis) of the structure. In synclines, the layers forming the limbs dip toward the hinge area. Given these arrangements, we expect that older stratigraphic layers will peek through in the arches of eroded anticlines whereas younger strata will be preserved in the eroded troughs of synclines. 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 terms "antiform" and "synform" which describe the shapes of folds but do not imply anything about the ages of the strata within them.

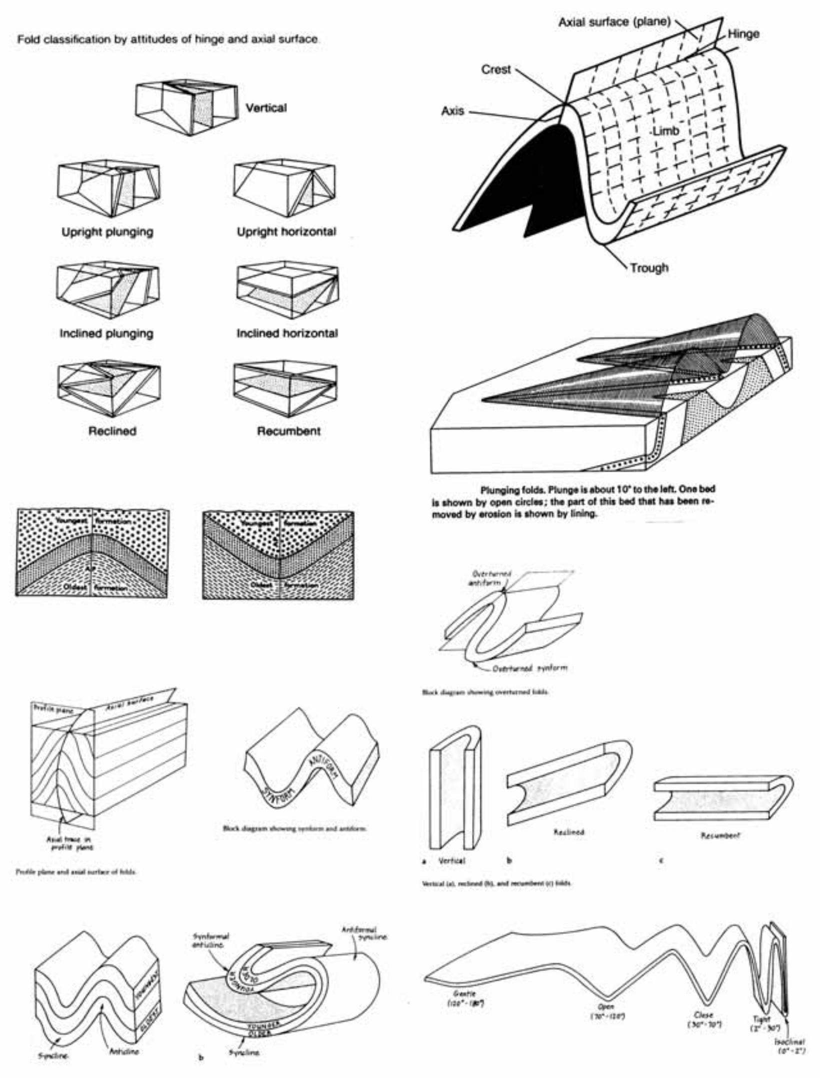


Figure 20 - Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the text.

Axial surfaces of folds physically divide the fold in half. Note that in Figure 20 the fold is deformed about a vertical axial surface and is cylindrical about a linear fold axis which lies within the axial surface. Realize that in the upright folds shown in Figure 20, axial surfaces are vertical and fold axes, horizontal. 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.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine tilting of the axial surface, to form inclined or overturned folds, or a sub-horizontal axial surface, to form recumbent folds, all accomplished by keeping the fold axis horizontal. (See Figure 12.) In addition, we can keep the axial surface vertical and alter the plunge of the axis from horizontal to some angle other than 0° to produce a plunging fold. Such folds can be plunging anticlines (antiforms) or plunging synclines (synforms). Vertical folds (plunging 90°) also occur, in which case the terms anticline and syncline are not meaningful.

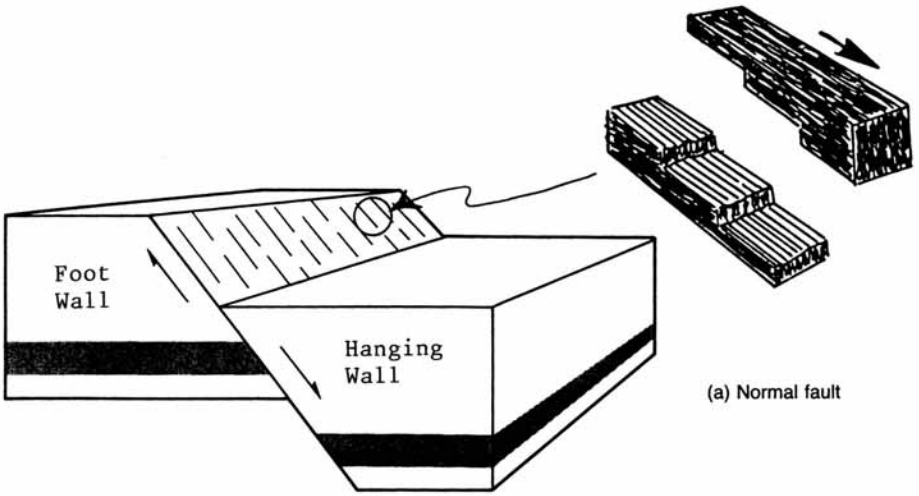
Another point about the alphabet soup of structural geology. Seen in cross section, folds fall into one of three groups, the S's, the Z's, and the M's. Usually only one variety of small folds will be found on a given limb of a larger fold. Therefore, if one notices a change in the pattern from S folds to Z folds (or vice versa), for example, one should be on the lookout for a fold axis.

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the direction of maximum compressive 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.

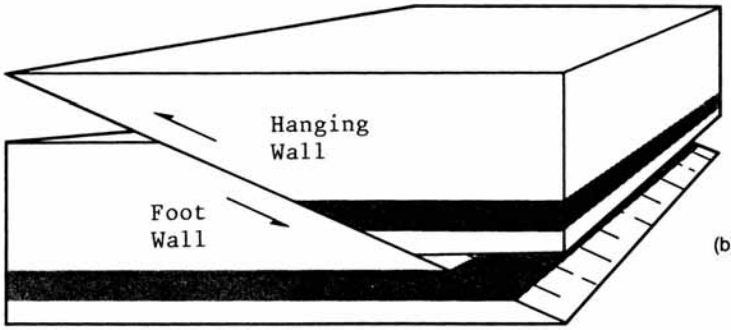
Faults

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 stressed rocks behave. 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 inferences than from rock-squeezing data to gain a feel for the complex nature of ductile vs. brittle folding and -faulting. In any case, a few simple relationships are generally agreed upon regarding brittle- and ductile faulting and these are discussed below.

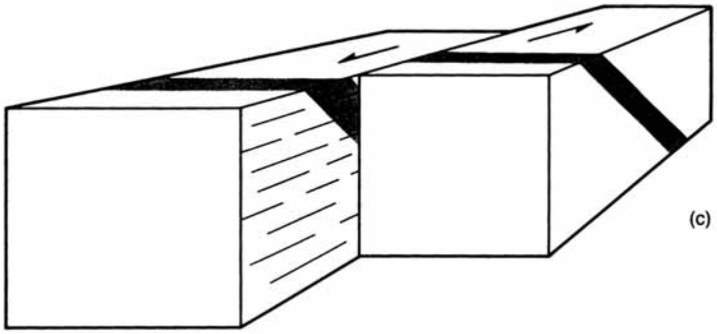
Start with a block of rock and assume that the elastic limit to intracrystalline glide and lattice deformation have been exceeded to the point where the rock begins to behave in a brittle (as in peanut brittle) solid rather than in a plastic (as in toothpaste) manner. Once a failure begins (fracture) it will propagate, produce offset and form a fault surface that will show elongate gouges (called slickensides) that may possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides. The fault block situated below the fault plane is called the footwall and that situated above the fault plane, the hanging wall (Figure 21). With extensional force acting on the sides of the block, the hanging wall will slide down the fault plane producing a normal fault. If the forces are compressive, the hanging wall slides up the fault plane and results in a reverse fault. A reverse fault with a low angle (<30°) is called a thrust fault. In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane. These, therefore, illustrate dip-slip motion.



(a) Normal fault



(b) Thrust fault



(c) Strike-slip fault

Figure 21 - Composite diagram from introductory texts showing the three main types of faults.

Rather than apply extension or compression imagine shearing the block along its sides (i.e., attempt to rotate the block about a vertical axis but do not allow the block to rotate). This type of force will generate a strike-slip fault (See Figure 21.) with the fault plane showing slickensides oriented subhorizontally. Left-lateral and right-lateral motion directions are possible and the trick is to imagine standing on one block facing across the fault plane to the other block. If the other block appears to move to the left, fault is left-lateral and vice versa. Convince yourself that it matters not which block you choose to observe from! 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 km, is accompanied by seismicity and the development of highly crushed and granulated rocks called 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. Our field trip will clearly show you deformed middle Ordovician slates of the Taconic autochthon overlain by essentially flat-lying to gently tilted Siluro-Devonian carbonate rocks of Layer III. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure 22), such surfaces represent mysterious intervals of geologic time (usually ascribed to uplift and erosion) 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.

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 sequences of essentially poorly stratified sequences result. The presence of stratification 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 source area, 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.

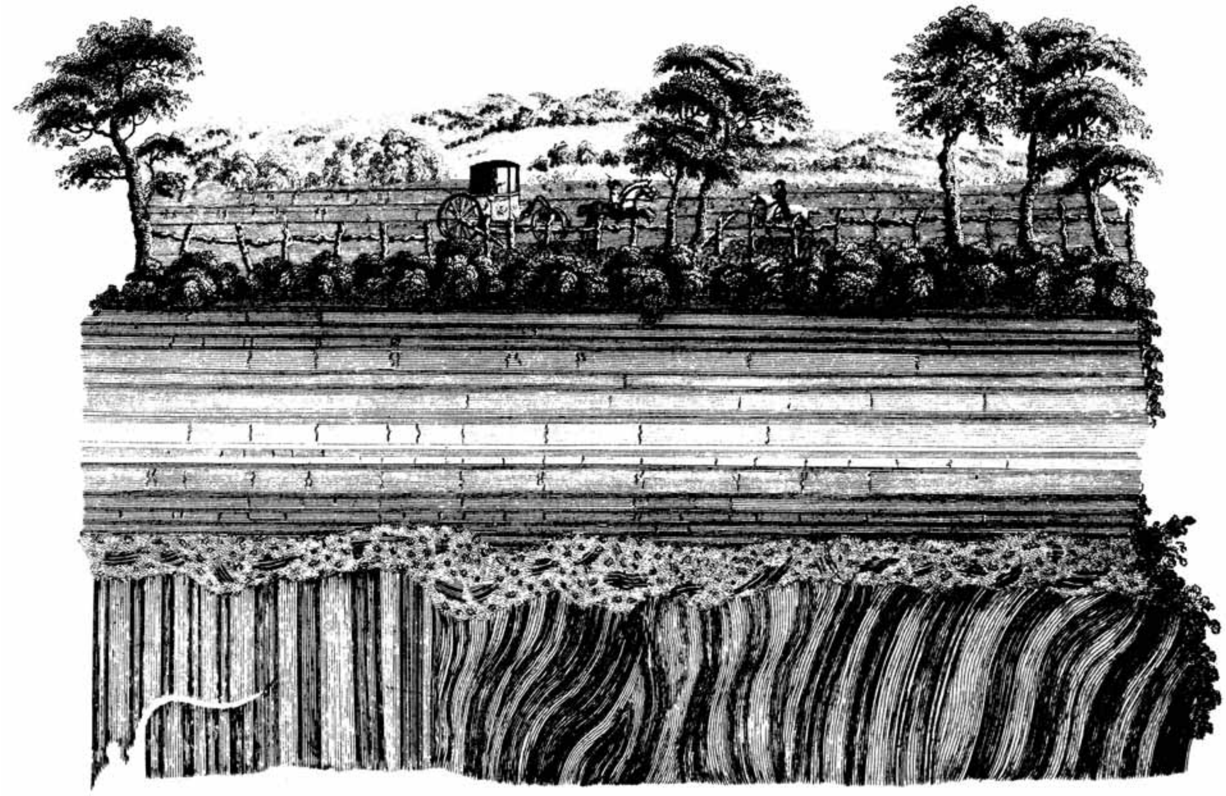


Figure 22 - Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's "Theory of the Earth", (1795).

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 23.

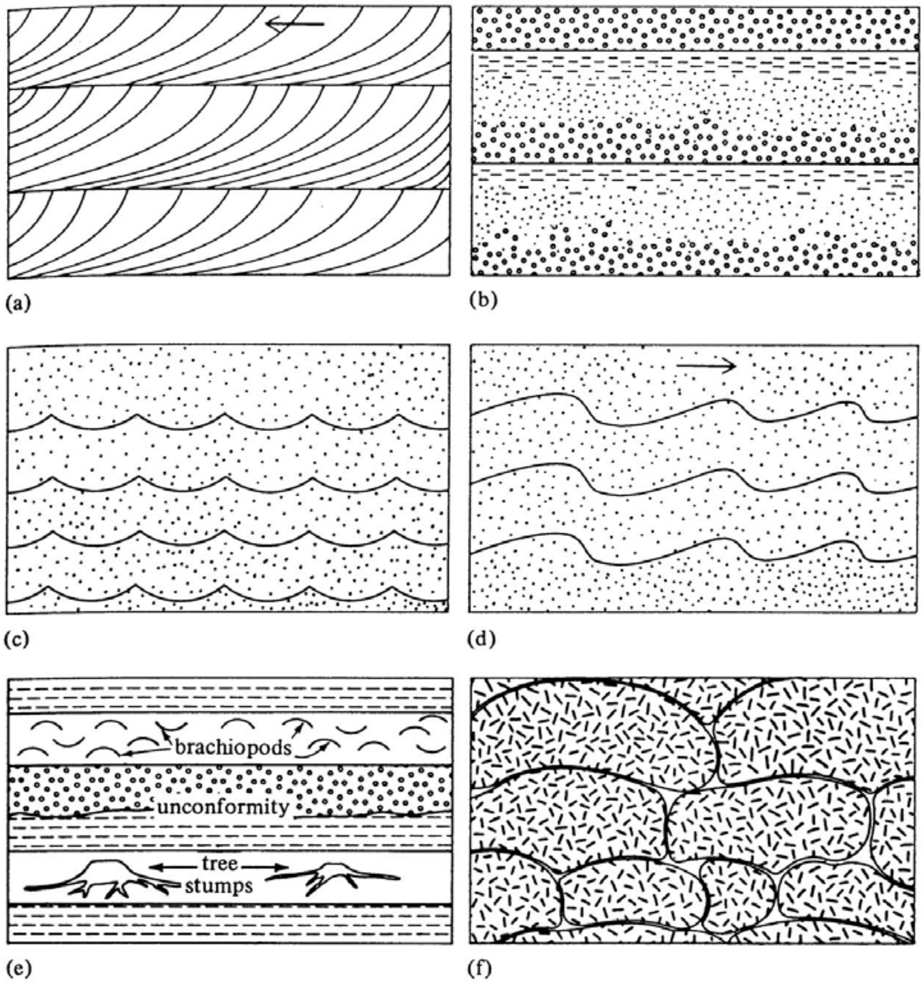


Figure 23 - Diagrammatic sketches of primary sedimentary structures used in determining topping (younging) directions in stratified rocks.

Together, these primary- and secondary sedimentary structures help the structural geologist unravel the oft-asked field questions - namely.... Which way is up? and Which way to the package store? The direction of younging 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 when the true topping (stratigraphic younging) direction is known. As we will demonstrate on this field trip, simple observations allow the card-carrying geologist to know "Which way is up" at all times.

LAYER VII: QUATERNARY SEDIMENTS

In our discussion of Quaternary sediments we include only the Pleistocene deposits made by continental glaciers that formerly flowed across the region and various bodies of outwash that were deposited when the glaciers melted.

Pleistocene Deposits

The Pleistocene sediments consist of several contrasting varieties deposited either directly by now-vanished continental glaciers or as a consequence of the melting of these glaciers. We will be especially interested in the characteristics of till and asymmetric features created by glaciers, and outwash.

Till And Asymmetric Features Created By Glaciers

Till is a general name for any sediment deposited directly by the flowing ice of a glacier. Typically, till is not stratified and contains a wide range of particle sizes, from boulders to clay. Outwash is a general term for any sediment deposited by water melted from a glacier. Outwash includes such contrasting sediments as stream sands and lake clays. The key point about recognizing outwash is the stratification that resulted from the action of water. We discuss these two kinds of deposits at greater length in the following paragraphs.

An important point to be determined in studying a glacial deposit is which way the glacier flowed. Because glaciers create scratches and even large grooves on solid bedrock, it is usually a straightforward matter to infer ice-flow direction. It is along the trend of the linear grooves, striae, and other elongate features.

In some places, the ice created various crescentic marks (Flint, 1971, p. 95; G. K. Gilbert, 1906; S. E. Harris, 1943; P. MacClintock, 1953). The use of crescentic marks for inferring the direction of ice flow is based on the asymmetric longitudinal profiles through the centers of the crescents. The ice came from the gently dipping side. The direction of concavity is not reliable. Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the direction of flow (Figure 24).

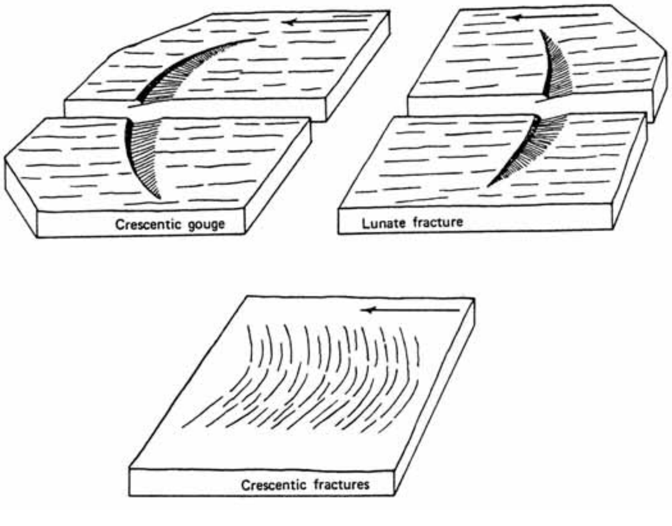


Figure 24 - Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

Glaciers also sculpt larger-scale asymmetric relief features in the bedrock known as roche moutonnées. These are smooth, broadly rounded and gently dipping on the side from which the ice flowed (a result of the glacier's grinding on an obstruction to flow), but jagged, irregular, and steep on the side toward which the ice flowed (a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction).

Another kind of asymmetric feature fashioned by a glacier is an elongate streamlined hill known as a drumlin. The long axis of a drumlin is parallel to the flow direction of the ice; the steeper side is toward the direction from which the ice came. Drumlins consist of till, of bedrock, or of some combination of till and bedrock. The term used by itself implies a feature composed of till. A rock-cored drumlin is one that consisting of both till and of bedrock. A rock drumlin consists only of bedrock. (We do not know why a glacier forms a rock drumlin instead of a roche moutonnée or vice versa.)

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

Study of the hundreds of engineering borings made in connection with bridges and tunnels crossing the Hudson Valley and for highways and other structures in the Hackensack Valley to the west supported the conclusion that the Pleistocene history included only one glacial advance. A fresh-looking till was found to be resting on bedrock and to be overlain by pro-glacial lake sediments, typically varved. These lake sediments in turn are overlain by gray organic silts and/or peats related to the encroachment of the modern sea.

Striae, crescentic marks, directions of asymmetry of roche moutonnées, long axes of drumlins, and indicator stones all show that more than one glacier flowed across the New York region; flow indicators prove that the ice came from not one but rather from several directions.

Figure 25 shows a map of North America with what was for a long time the standard view of how the Pleistocene ice covered Canada and northern United States. Notice that New York is within the flow pattern shown for the Labrador Ice Sheet.

Given the concept that ice from the Labrador center should have been present in New York City, then the expected direction of such glacier flow is from the NNE to the SSW, a direction that is parallel to the Hudson River. However, in Manhattan and on the top of the Palisades Ridge, striae are oriented from about N20°W to S20°E, or even more toward the NW-SE direction. A previous generation of glacial geologists adopted the view of deviated flow from a central lobate glacier (Figure 26).

According to this concept, the main flow of the latest (and, according to many, the only Wisconsinan) glacier was concentrated down the Hackensack lowland, but the ice deviated to its left and crossed the Palisades ridge and New York City on a NW-to-SE course. This concept of a single glacier flowing in a direction that is parallel to the Hudson Valley was reinforced by the results of thousands of engineering borings through the thick bodies of sediment underlying the Hudson, Hackensack, and other valleys that trend NE-SW. These borings show bedrock overlain by a fresh till that is in turn overlain by outwash (sands/gravels and/or lake clays and -silts) that is overlain by estuarine deposits. By contrast, the borings from valleys that trend NW-SW display a more-complicated succession of sediments. JES infers that these complex sediments in the fillings of valleys that trend NW-SE are products of glaciers that flowed from NW to SE that that would tend to deepen valleys having orientations parallel to their direction of flow. Any sediments that were deposited in valleys trending NW-SE would tend to be preserved from destruction by ice flowing from NE to SW. By contrast, any such complex deposits that may have been deposited in valleys trending NE-SW would have been especially vulnerable to total removal by a glacier flowing from NE to SW.

Figure 25 - Reconstruction of North American Pleistocene Ice Sheets with Keewatin center and Labrador center shown as attaining simultaneous maxima. Further explanation in text. (U. S. Geological Survey).

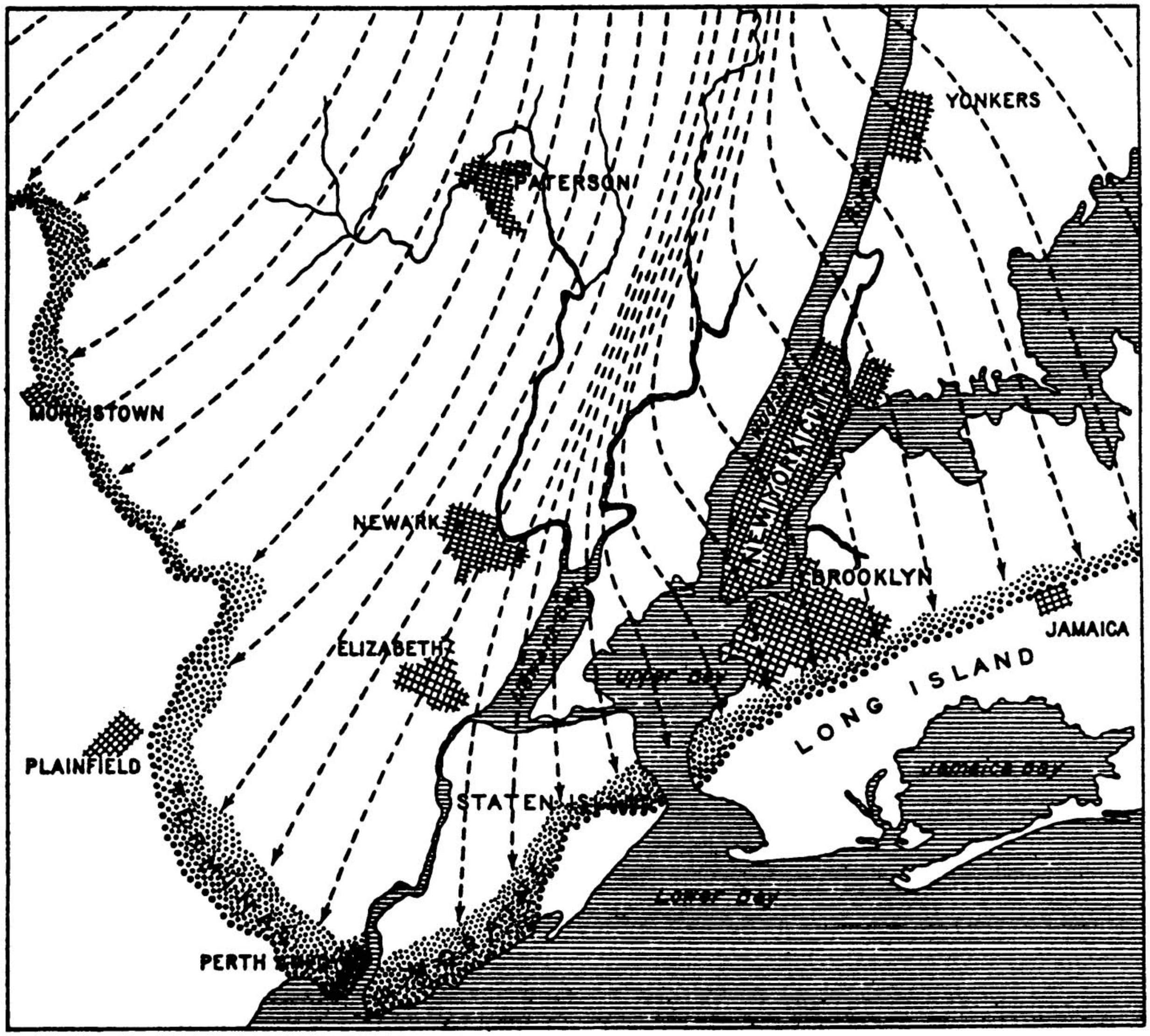


Figure 26 - Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (U. S. Geological Survey, Passaic Folio, No. 157, Figure 11, 1908, rendering of R. D. Salisbury).

From studying the stratigraphic relationships, provenance, grooves and crescentic gouges on bedrock surfaces, directions of asymmetry of roche moutonnées and of drumlins, we propose an alternative view. In our scheme of things, the flow indicated in Figure 26 is not the product of one glacier, but of more than one (two, possibly more). Figures 27 and 28 show how we interpret the glaciers in the same area of Figure 26. In Figure 27, the ice flowed rectilinearly from NW to SE, across the highest ridges and across the Hudson Valley without deflection. This suggests a thick ice sheet whose flow pattern was governed by the gradient on the top of the glacier. Figure 28 shows the flow from NNE to SSE as resulting from a later glacier. According to JES, the two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 27. The latest glacier, shown in Figure 28, did not reach much of Long Island. It covered parts of Queens and Brooklyn, Manhattan, and Staten Island. What its terminal moraine was like is not yet known.

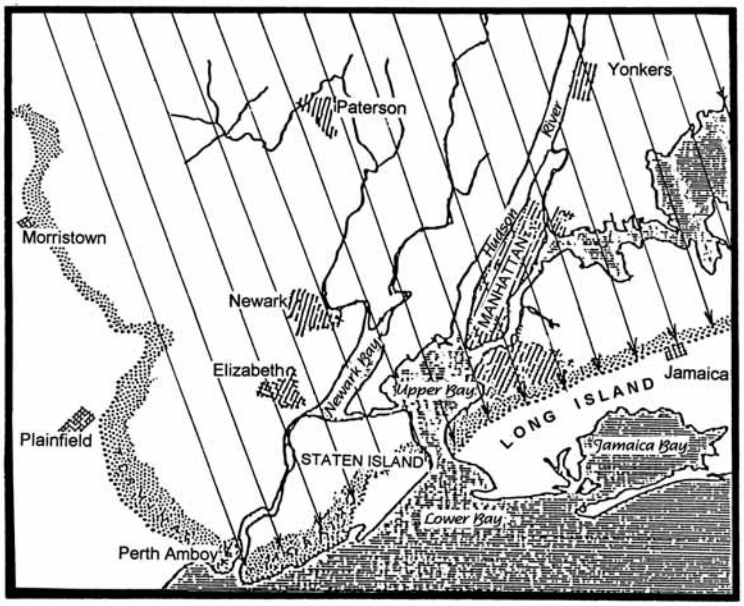


Figure 27 - Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders).

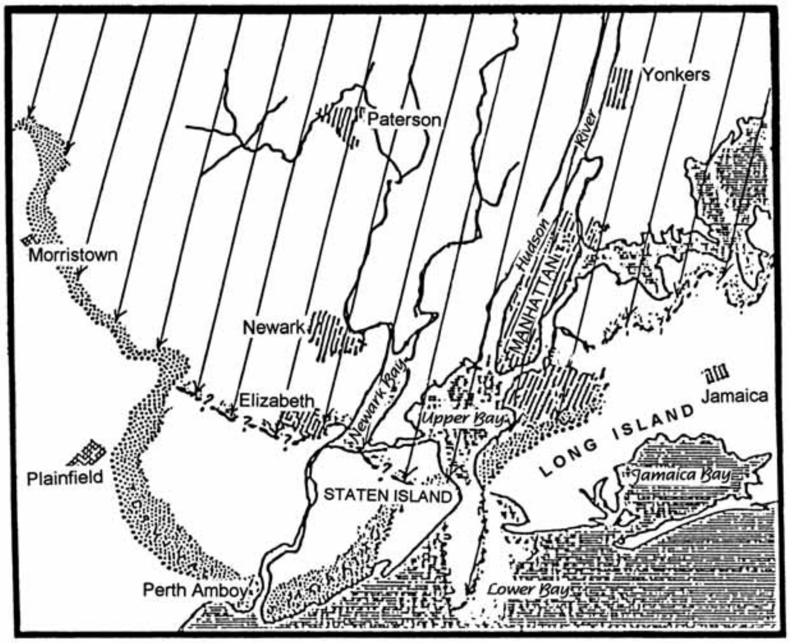


Figure 28 - Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

The distribution of erratics derived from as far away as the anthracite district in eastern Pennsylvania (Figure 29) in the red-brown tills and -outwashes in localities east of the Hudson River (as in New York City and Westchester County, New York) lends strong support to the JES interpretation shown in Figures 27 and 28, as contrasted to Figure 26. The finding by JES of natural erratics of anthracite in the red-brown till in the Hudson Valley suggests that the fossiliferous pieces of Carboniferous material found in the Country Club road excavations in the Bronx are glacial erratics and not indicators of a buried Carboniferous basin, as suggested by Zen and Mamay (1968).

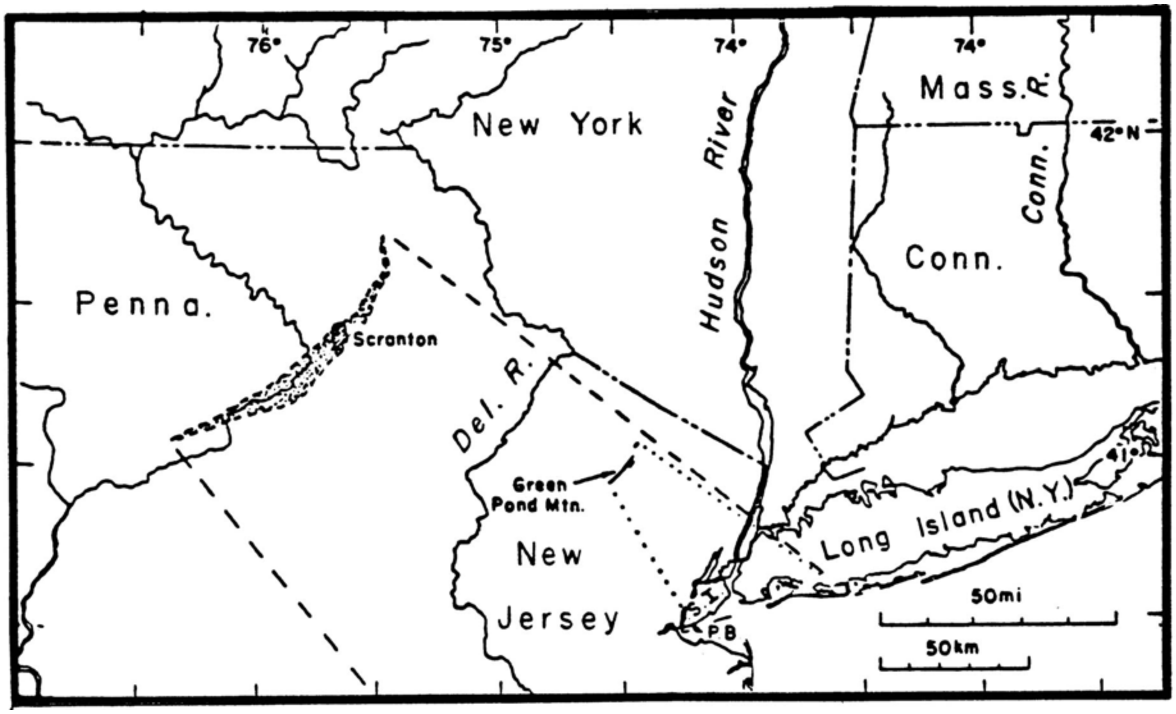


Figure 29 - Distinctive erratics found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten Island; P. B. = Princess Bay. (Friedman and Sanders, 1978, Figure 2-1, p. 27.)

Stratigraphy of Pleistocene Sediments

The stratigraphy of glacial deposits is worked out by noting the relationships among till, outwash, and sediments that have nothing at all to do with a glacier and, in fact, were deposited under a climate regime that is nonglacial. In a coastal area such as New York, glacial deposits are interstratified with marginal-marine deposits. This has resulted from the relationship between growth of continental ice sheets and the volume of water in the ocean basins. Professor R. A. Daly, of Harvard, once described this relationships between glacial ice and the water of the oceans as one of "robbery and restitution." By robbery, he meant the locking up of the water in the glaciers. By restitution, he meant the return of the water to the oceans when glaciers melted.

Although the exact climate settings involved in these changes are not as well known as one might suppose, it is well established that when the glaciers reached their maximum extents, the sea was at its lowest stand, a level around 75 m lower than now.

The most-critical evidence for interstratification of glacial- and nonglacial sediments comes from borings in the general vicinity of Jones Beach. Here, sandy strata interpreted as outwash deposited during times of emergence are interbedded with fossiliferous marginal-marine strata deposited during a submergent episode. (Rampino, 1978 ms.; Rampino and Sanders, 1976, 1980, 1981a, b).

Field studies by JES and CM in connection with preparation of guidebooks for these On-The-Rocks trips have turned up evidence which is completely at odds with the prevailing "one-glacier (or possibly at the most, two)" view of the Pleistocene sediments in New York City and vicinity. We visualize relationships as shown in Table 4. The two most-drastic changes shown in Table 4 as compared with "conventional wisdom" are: (1) based on provenance and thickness of weathering rinds on stones, we infer that the latest glacier, the Woodfordian, which flowed down the Hudson Valley (the second one from the Labrador, flow direction NNE to SSW, thus indicated by LII in Table 4 did not reach most of Long Island, but rather left its end moraines along the south coast of Connecticut (Flint and Gebert, 1974, 1976; situation depicted in Figure 28); (2) An ancient till containing decayed granitic stones (thus matching the descriptions of Fuller's Manetto Gravel) and evidence of flow from NNE to SSW (indicated as LI in Table 4) is present on Long Island (discovered by JES and CM after storm erosion and some digging at Garvies Point), on Staten Island, and at the S end of Tellers Point, Croton Point Park. Elsewhere, the former erosive activities of this inferred early glacier are shown by rock drumlins having long axes oriented NNE-SSW that have been remolded by ice flow from NW to SE (Sanders and Merguerian 1991, 1992).

The two sandy formations in the subsurface of southern Long Island (Merrick below, Bellmore, above) separated by the interglacial Wantagh Formation (= the "20-foot clay" of various authors from the U. S. Geological Survey Water Resources Division) have been interpreted as belonging to the same glacial meltdown episodes during which Long Island's two prominent moraines were fashioned. Thus, Bellmore goes with the Harbor Hill Moraine; Merrick, with the Ronkonkama Moraine. If this coupling of inferred outwash sediments and moraines is correct, then it implies that the age of the Harbor Hill moraine is no younger than medial Wisconsinan and that of the Ronkonkama, probably youngest Illinoian. Such a correlation represents a significant shift of these two moraines downward in the geologic time scale from the position assigned to them by Fuller (and everybody else), namely, the latest Wisconsinan.

How these newly proposed correlations fare in the future will probably depend to a considerable degree on careful sedimentologic study of the samples from the myriad of engineering borings that have been made over the years in New York City and vicinity. From these newly proposed correlations, specific, checkable hypotheses about the provenance and degree of alteration of minerals can be made. The time for testing is at hand.

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

Outwash

As mentioned previously, outwash consists of stratified sediments deposited by the meltwater from a glacier. In the region of today's trip, most of the outwash was spread out near the terminal moraine in the lowland between Kittatinny Mountain and the southeastern margin of the Pocono Plateau (Figure 30).

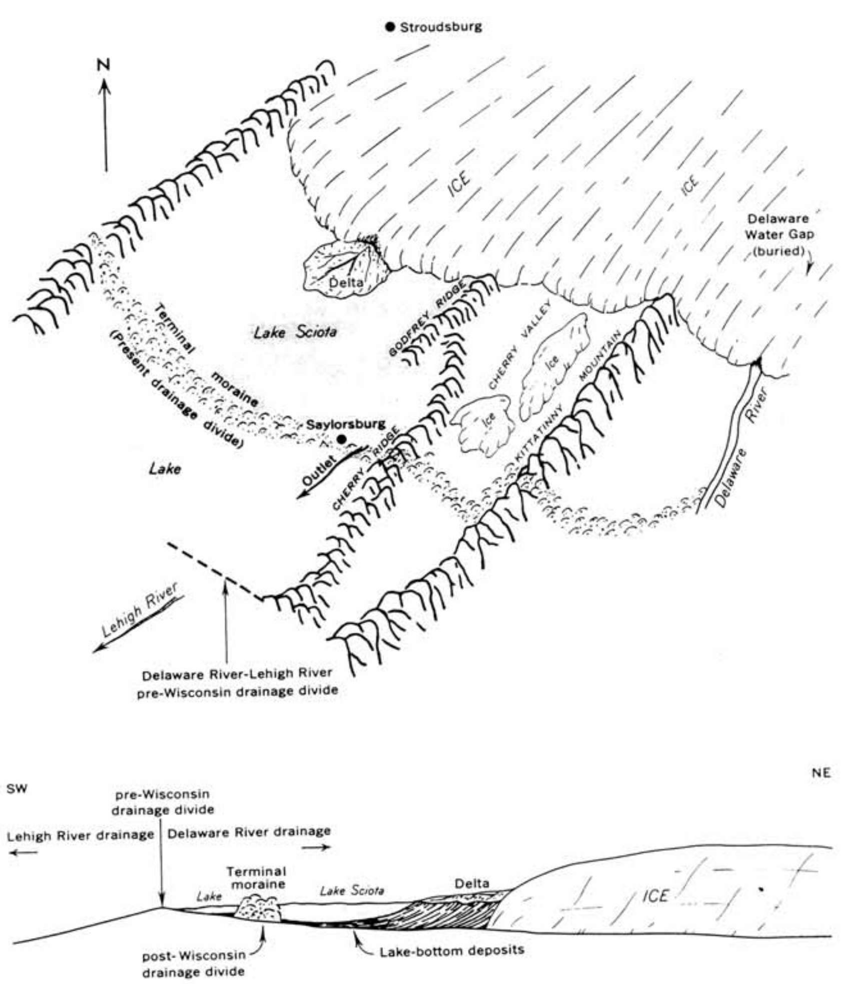


Figure 30 - Bird's eye view of margin of latest Wisconsinan glacier in vicinity of Delaware Water Gap (covered by ice), showing position of Lake Scotia between ice margin and terminal-moraine ridge near Saylorsburg. The modern drainage divide between the Delaware River and the Lehigh River is the terminal moraine. (J. B. Epstein and A. G. Epstein, 1969, Fig. 37, p. 172.)

When the most-recent of the Wisconsinan glaciers (the Woodfordian, reaching a maximum about 14,000 yr ago, and beginning its rapid disappearance starting about 13,000 yr ago), had attained its southernmost limit, it covered the Delaware Water Gap. (See Figure 30.)

Another aspect of glacial deposits dear to the heart of those who are Pleistocene geologists is use of sediments to infer the positions of the margin of a melting, retreating glacier. In many places, records of deglaciation are extensive; numerous ice-margin positions during the retreat can be established. The deglacial record in the Wallkill Valley has recently been revised by Connally, Sirkin, and Cadwell (paper in 1989 New York State Geological Association Guidebook for meeting in Middletown, NY). Several glacial lakes left bottom deposits subsequently covered by peat. The flat areas underlain by peat are used to grow onions on a large scale. Many onion fields are present between Warwick and Pine Island. The digging of the drainage ditches in these flat bottom lands has, on occasion, revealed mastodon bones.

Hogwash

Under this facetious heading JES would rank all interpretations of the pre-Woodfordian Pleistocene continental ice sheets that mention "lobes" and "fishes."

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

OBJECTIVES

1) Examining the regional stratigraphy and structure of the Appalachians in the vicinity of northwestern New Jersey.

2) Identify evidence for Late Paleozoic (terminal-stage Appalachian) deformation in the Great Valley and Valley and Ridge Province.

3) Taking a leisurely walk through a part of the Delaware Water Gap National Recreation Area for a detailed look at folds and superposed cleavage.

4) Pointing out evidence for large-scale overthrusts of Paleozoic and older strata during protracted Phanerozoic orogeny.

5) Looking for glacial features along the walls of the Delaware Water Gap, and,

6) To get to all of our intended stops for the day.

LIST OF LOCALITIES TO BE VISITED

Stop 1: Allamuchy Mountain
Stop 2 (Optional): Scenic view
Stop 3: NW side Co. Route 519, NE of Hope, NJ
Stop 4 (Optional): Scenic view
Stop 5: NE wall, Delaware Water Gap
Stop 6: Bioherm, PA Route 191, Analomink, PA
Stop 7: PA Route 191 nr. Henryville, PA
Stop 8: Along Cherry Valley Rd., SW of Stroudsburg, PA
Stop 9: Resort Point Overlook, Delaware Water Gap
Stop 10: PA Route 611, Point of Gap Overlook
Stop 11: Cloverleaf, I-80, US Route 46, NJ Route 94, Columbia, NJ
Stop 12: US Route 46, S. of Manunka Chunk, NJ

ROAD LOG AND DETAILED DESCRIPTIONS OF LOCALITIES "STOPS"

Begins at NE corner Fort Washington Avenue and 179 Street, Manhattan, by Holy Rood Episcopal Church. Figure 31 is a road map showing the location of our intended trip stops.

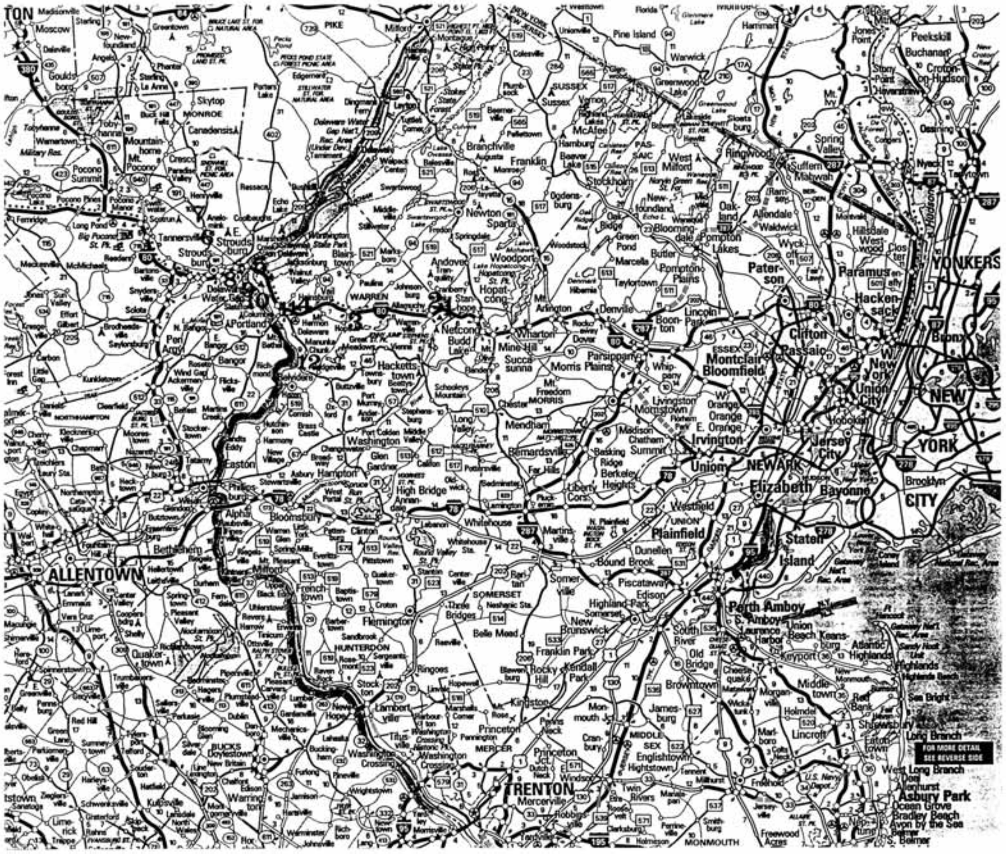


Figure 31 - Field stop locality map.

0.0 Bear L for ramp to George Washington Bridge, upper level.
1.5 Passing tollgate on L; keep L for I-80 and I-95.
2.1 Bear R for I-80 local.
2.3 Take ramp on L to I-80 local.
2.7 Jones Road overpass; upper contact of Palisades sill exposed on R.
2.9 Top of sill at road level. Note contact metamorphosed Lockatong Formation. Ahead is the strike ridge underlain by a sandstone in the Passaic Formation.
4.8 Bear R for Exit 69 to I-80 local (Paterson).
5.8 Red sandstones and shales of Passaic Formation exposed on R.
6.2 More Passaic sandstones exposed on R.
7.6 Pass Exit 65 on R.
8.0 Pass Exit 64B on R.
8.5-8.6 More Passaic strata dipping NW exposed on R.
9.4 Pass ramp on R for Exit 63.
9.7 More Passaic strata exposed on R.
11.0 Pass ramp on R for Exit 52, Garden State Parkway.
11.6 MP 62 on R.
13.4 Passing ramp on R for Exit 59 to US Route 46 and NJ Route 20.
13.7 MP 60 on R.
14.4 View ahead to contact between top of red Passaic Formation and base of overlying Orange Mountain Basalt (=First Watchung of pre-Paul Olsen terminology).
15.9 Large cut on L of Orange Mountain Basalt showing columnar joints cut by five sub-vertical faults.
16.5 Passing ramp on R for Exit 56 to Paterson.
17.4 Bridge over Passaic River.
18.4 Pass ramp on R for Exit 55B.
18.7 Pass ramp on R for Exit 55A.
20.1 Pass ramp on R for Exit 53, US Route 46 and NJ Route 23.
21.1 Bridge over Passaic River (again).
21.5 Pass ramp on R for Exit 52, Lincoln Park. View ahead to Second Watchung Basalt Ridge (Preakness Basalt).
23.0 MP 51.
25.7 Bridge, entering Montville Township.
26.2 MP 48; pass ramp on R for Exit 48.
26.4 Cuts of Preakness (2nd Watchung) Basalt.
27.7 Pass ramp for Exit 47 on R to US Route 46 (Westbound) toward Parsippany.
28.0 Road divides. Keep L for I-80, do not veer R to I-287 (Morristown).
31.3 MP 43.
31.4 Pass ramp on R for US Route 202.
33.1 Exposures on L of subvertical Proterozoic gneiss.
33.4 Interlayered mafic- and felsic gneisses (See guidebook by John Puffer; also Avery Drake).
34.4 MP 40.
35.0 Passing Exit 39 on R (Denville) to US Route 46 and NJ Route 59.
36.5 MP 38.
36.8 Entering Rockaway Township.
36.9 Pass ramp on R for Exit 37.

37.5 Proterozoic gneiss on R.
39.0 Pass Exit 35B ramp on R. (to Mt. Hope).
39.3 Pass Exit 35A ramp on R.
40.2 Passing ramp for Exit 34B, NJ Route 15 Northbound.
40.6 Passing ramp for 34A NJ Route 15 Southbound on R.
41.0 I-80 on bridge over Rockaway River.
42.3 Passing rest area on R.
42.5 Passing MP 32 on R.
43.4 Leave Dover quadrangle, enter Stanhope quadrangle.
43.6 Passing MP 31 on R.
43.8 Passing Exit 30 on R (Howard Blvd.)
44.6 Passing MP 30 on R.
45.1 Low exposure of Proterozoic rocks on R; foliation dips N.
45.3 More Proterozoic rocks in cuts.
45.6 Passing MP 29 and Exit 28 on R; to NJ Route 10 (Ledgwood and Lake Hopatcong).
46.7 More Proterozoic rocks exposed on R.
46.9 More of same; in cuts, both sides of I-80.
47.2 Passing Exit 27B on R; to Route 183 Northbound to Netcong.
47.4 Passing Exit 27A to US Route 206 Southbound to Somerville.
48.0 Passing Exit 26 to US Route 46 Westbound (Budd Lake and Hackettstown).
48.2 Powerline crossing overhead.
48.6 Passing MP 26 on R.
49.2 Passing Exit 25 on R (US Route 206 Northbound to Stanhope and Newton).
50.3 Leave Stanhope quadrangle, enter Tranquility quadrangle.
50.4 Proterozoic in cut on R; both sides
50.4 Smokey T. Bear hiding in bushes on slope at L with radar gun aimed at westbound traffic.
51.4 Passing sign on right marking entry into Byram Twp.
51.6 Passing MP 23 on R.
51.7 Proterozoic dioritic gneiss exposed in cuts on R; then in cuts on both sides ahead going uphill.
52.1 Passing sign on R announcing Rest Area 2 mi. ahead.
52.2 Entering Allamuchy Twp.; hills ahead are Allamuchy Mountain, underlain by Proterozoic rocks. Allamuchy Mountain is a part of the massive Reading Prong klippe composed of Proterozoic basement rocks that Isachsen (1964) suggested had been thrust over the Paleozoic rocks during the Taconian orogeny.
52.3 Leave Sussex Co., enter Warren Co.
52.6 Passing MP 22 on R.
52.7 Proterozoic exposed both sides.
53.4 Leave I-80 via ramp on R to Rest Area. Drive to far end and park vans. (Port-A-Potty right here.)

STOP 1 - Proterozoic rock cuts on exit ramp from rest area/truck-parking area on I-80 westbound, Town of Allamuchy, NJ. [UTM Coordinates: 518.0E / 4530.3N, Tranquility quadrangle.]

The rocks here are part of the Allamuchy nappe of Drake and Lyttle (1980, p. 98), of which they wrote: "The Allamuchy nappe is typical of the other crystalline-cored nappes de recouvrement of the Reading Prong nappe megasystem as described to the west (Drake, 1969, 1970; MacLachlan, 1979b; MacLachlan and others, 1975). It has not been studied in any detail as yet, but parts of both its upper (sic) and lower limbs appear to be exposed at the present level of erosion. This nappe was proved by diamond drilling by the New Jersey Zinc Company (Baum, 1967). Rocks of this nappe are brought above those of the Jenny Jump klippe of the Jenny Jump thrust sheet and Johnsonburg-Greendell-Huntsburg unit on the major Shades of Death thrust fault (see Figure 1). This fault is probably the northeast continuation of the Lower Harmony fault (Drake, 1967a, 1967b; Drake and others, 1969)."

Exposed here is a coarse felsic gneiss displaying effects of extensive brittle deformation. Almost all rock faces are limonite-lined fractures (probably a result of oxidation of original pyrite films). Near the E end of the cuts are steep normal faults, that strike parallel to I-80 (NE-SW) and dip about 70° SE on which dip-slip slickensides are well developed. By the guard rail, the gneissic foliation is clear; its strike is roughly perpendicular to I-80 and its dip is to the NE. Near the drain pipe at the end of the cut is a splendid example of a fault-mirror slickenside displaying right-lateral strike slip offset. The strike of this fault surface is about 45° to I-80 (E-W?). More strike-slip slickensides are visible beyond the pipe; these are not horizontal but rake about 15° to the SE (?). It should be possible to park the vans along the far end of the cuts.

After Rest Stop, I-80 goes downhill to Scenic Overlook.

53.8 On I-80 westbound.
54.1 Enter ramp to Scenic Overlook on R if we make Optional Stop 02.

STOP 2 (Optional) - Scenic Overlook on I-80 westbound. [UTM Coordinates: 516.0E / 4530.2N, Town of Allamuchy, NJ, Tranquility quadrangle.]

At the breathtaking elevation of 1100' above sea level, we may be able see through gaps in the trees a panoramic vista toward the NW across the Great Valley (here named the Kittatinny Valley; it is underlain by the Sauk Sequence carbonates and limestones/slates of the Tippecanoe Sequence) to the Delaware Water Gap, which cuts through the otherwise-unbroken ridge along the NW side of the Appalachian Great Valley. This ridge is underlain by massive Lower Silurian conglomerate and sandstone units that generally dip to the NW. Note that the elevations of the tops of the local mountain ridges are all approximately the same height. Such summit accordance is indicative of prolonged erosion and development of a planation surface. (Mileage into and out of scenic overlook omitted.)

Leave Scenic Overlook, return to I-80.

54.4 Merging onto I-80 westbound.
54.8 Passing MP 20 on R.
55.1 Passing Exit 19 on R. (Co. Route 517).

55.8 Passing MP 19 on R.
55.9 Proterozoic rocks exposed in cuts on both sides of I-80. From the road log by Drake and Lyttle (1980, p. 104) we quote the following: "This outcrop of granite gneiss contains mafic segregations of plagioclase, epidote, garnet and magnetite surrounded by a rind of almandine garnet in a more felsic (sic) matrix of potassium feldspar, quartz, plagioclase, epidote, and accessories. Foliation appears to parallel gneissic layering and is oriented N45°E, 39°SE. Pegmatites are roughly parallel to foliation, but upon close inspection are seen to cut it."

56.5 I-80 passing beneath bridge for local road.
56.6 I-80 passing beneath bridge for Lehigh and Hudson River Railroad.
56.8 Passing MP 18 on R; crossing valley underlain by Sauk Sequence carbonates.
57.1 Sauk Sequence carbonates exposed in cuts on both sides of I-80; strike is N82°W and dip 15° to NNE. (The strata belong to the Upper Cambrian Allentown Formation according to Drake and Lyttle, 1980.)
57.8 Passing MP 17 on R.
58.3 Leave Tranquility quadrangle, enter Blairstown quadrangle. No cuts exposing bedrock for a stretch.
58.8 Passing MP 16 on R. I-80 goes uphill on Jenny Jump Mountain, the locality where geologic mapping by Lewis Gardner Westgate (1896) demonstrated that the Proterozoic rocks form a klippe. From the Drake and Lyttle (1980) road log: "Begin the ascent of Jenny Jump Mountain, here we are crossing the trace of the Shades of Death thrust which brings rocks of the Allamuchy nappe onto rocks of the Jenny Jump klippe of the Jenny Jump thrust sheet. The Proterozoic rocks here are dominated by a sequence of marble, amphibolite, and lesser calcsilicate rock."

Drake and Lyttle (1980) describe the Jenny Jump thrust sheet as follows: "The Jenny Jump thrust fault is the most obvious (sic) of such structures in northern New Jersey. It was recognized in the early geologic mapping of that state (Lewis and Kümmel, 1910-12; Bayley and others, 1914). Geologic sections drawn at that time show the important fact that a very large thrust sheet has been fragmented into several different, essentially flatlying, klippen of both Proterozoic Y and Lower Paleozoic rocks, and that the thrust fault itself was folded. In 1929, George Stose, H. B. Kümmel, and M. E. Johnson made a more thorough (sic) study of the thrust which led to an excellent manuscript which, for some reason, was never published. A copy of this manuscript which contained the important conclusion that the Jenny Jump thrust was somehow related to the Reading overthrust of Stose and Jonas (1935), came into Drake's hands upon the death of Anna Jonas Stose. [For all their knowledge of early geologic investigations, Drake and Lyttle somehow overlooked the fundamental paper of L. G. Westgate (1896) on the mapping of Jenny Jump Mountain.]

"The litter of klippen which constitute erosional remnants of this thrust sheet in the Kittatinny Valley led Drake (1969, 1970) to the recognition that tectonism had operated at a higher level here than in eastern Pennsylvania and, because of the characteristic Musconetcong aeromagnetic signatures along the leading edge of the Jenny Jump klippe (fig. 5), to the erroneous belief that the thrust sheet was the result of the core of the Musconetcong nappe shearing through its cover. This thrusting was considered at that time to be of Taconic age. This seems unlikely, however, as the largest klippe of Proterozoic Y rocks, the Jenny Jump, transects several folds in the Kittatinny Supergroup and lies on a variety of carbonate rocks of Ordovician age as well as Martinsburg Formation (fig. 4). The carbonate rocks beneath the klippe do not have a penetrative thrust fabric; however, they contain abundant subsidiary thrust faults which are marked by zones of ductile deformation (sic) (fig. 6), selectively occurring along layers of chert and(or) metabentonite within the //(p.100) carbonate rock, a phenomenon recognized some years ago by Stevens (1962). At many places the mylonitic foliation was folded during the northeast-trending fold phase (fig. 7). The Proterozoic Y rocks of the klippe show the effects of two Paleozoic deformation phases, in which a mylonite fabric is overprinted by a more brittle (sic) fabric.

"The other klippen of the thrust sheet lie in troughs in the slaty cleavage within the Martinsburg Formation, and therefore, obviously were emplaced subsequent to the early folding and attendant cleavage formation. Some of these klippen transect contacts between the Bushkill and Ramseyburg Members of the Martinsburg Formation. The slaty cleavage in klippen areas is marked by an extreme extension lineation (see above) and the rock below klippen soles is severely smeared and tectonically disrupted into autoclastic mélange (fig. 8). The carbonate klippe are reminiscent of those of the southern Appalachians in their general lack of obvious body deformation. The Proterozoic Y rocks of the small Silver Lake-I klippe show the effect of both ductile mylonitic and brittle deformation (fig. 9). This klippe is likely polykinematic, as the Proterozoic Y rocks appear to be in thrust contact with rocks of the Leithsville Formation.

"If the various fragments of the Jenny Jump thrust sheet were reconstituted, they would likely form the crystalline core and upper limb of a nappe as the various klippen contain right-side-up, northwest-dipping rocks of the Kittatinny Supergroup from Hardyston Quartzite through Epler Formation. The thrust sheet probably stemmed from a nappe intermediate between the Allamuchy and Lyon Station-Paulins Kill nappes. This is far from certain, however, as the south end of the thrust sheet is cut off by the Shades of Death thrust (fig. 4) and too little work has been done in New Jersey as yet to allow palinspastic reconstructions.

"We believe that the Jenny Jump thrust sheet was emplaced during the Alleghanian orogeny, perhaps as a phase I (sic) feature (Drake, 1980) as it is deformed by two fold phases. It clearly post-dates Alpine-type nappe tectonism and the regional slaty cleavage. The problems of the cleavage age have been treated above, but we believe that the dichotomy in age noted by many workers may be real. That is, we may not be dealing with a Taconic versus an Alleghanian age for the regional slaty cleavage, but with Taconic and Alleghanian age for that cleavage."

59.1 Deep cuts on both sides of I-80; Proterozoic dark-colored fine rocks; some display excellent foliation; others are massive.
59.8 Passing MP 15 on R. The overthrust contact is just about at MP15; the Paleozoic rocks beneath the thrust are the Jacksonburg Limestone, the basal unit of the Tippecanoe Sequence, dipping at a low angle SE.
60.1-60.4 Sauk Sequence carbonates; I-80 passing underneath bridge for local road above.
60.8 Passing MP 14 on R; in Allentown Formation (Upper Cambrian part of Sauk Sequence characterized by well-developed algal stromatolites) on NW side of a normal fault that is upthrown on the NW side, bringing Upper Cambrian Allentown into contact with Lower

Ordovician Ontelaunee Formation at the top of the Sauk Seuqence. From the Allentown formation upward, the succession is complete.

61.0 End of cuts exposing Sauk Sequence carbonates.
61.3 More cuts on R; dip to NW. From Drake and Lyttle (1980 road log, p. 105): "Large outcrop of sandy, mottled, laminated dolomite of the Epler Formation. The contact with the Rickenbach Dolomite is about in middle of this cut. It is placed at the contact of laminated, burrowed, mottled, finely crystalline dolomite (Epler) with thick-bedded, dark-medium-gray, medium crystalline dolomite (Rickenbach). Rock contains abundant cascade-type folds which plunge 5°-10° N. 25° E."

61.6 End of cuts exposing Sauk Sequence carbonates.
61.8 Passing MP 13 on R.
62.0 Cuts on R expose dark-colored rocks of basal Tippecanoe Sequence (Jacksonburg Formation). From Drake and Lyttle (1980 roadlog): "Outcrops of Jacksonburg Limestone. Most of rock here is crystalline limestone but some beds are dark-gray, more argillaceous (sic) cement rock. Axes of small folds here plunge 20° N. 5° W. Slickensides on bedding surfaces plunge down the dip."
62.4 More Jacksonburg Limestone, with limestone-pebble conglomerate.
62.6 Leave I-80 via ramp on R to Exit 12 (Co. Route 521 to Hope and Blairstown).
62.7 Bear L on road to Hope.
62.6 Enter Co. Route 521 southbound. The road is on the Bushkill Member of the Martinsburg Formation. From Drake and Lyttle (1980 roadlog, p. 105, their mileage 48.6): "Outcrops to right are Allentown Dolomite in the large Hope klippe of the Jenny Jump thrust sheet. The dolomite beds face up, dip gently northwest, and contain abundant algal stromatolites and oolite."
63.0 Passing ramp on R for traffic exiting from I-80 eastbound.
63.3 Passing Foundry Road on R.
63.5 Entering the town of Hope, a pre-Revolutionary Moravian settlement.
63.6 Outcrop on right is Leithsville Formation of Early and Middle Cambrian age. According to Drake and Lyttle (1980), the gently northwest-dipping rocks are right at the sole of the Hope klippe (Figure 32). They display a vague mylonitic foliation that strikes N. 45° E. and dips 18° NW., and appear to have been generally mangled.
63.9 Turn L on Co. 519.
64.0 Crossroads, center of Hope; continue ahead on Co. 519.
64.4 Passing MP 49 on R.
64.7 Passing Jenny Jump Road on R; hill to SE is Jenny Jump Mountain, where L. G. Westgate (1896) mapped the Jenny Jump klippe (Proterozoic rocks thrust over Paleozoic).
65.2 Passing Ridgway Avenue on L.
65.4 Pull over to R and park on wide shoulder.

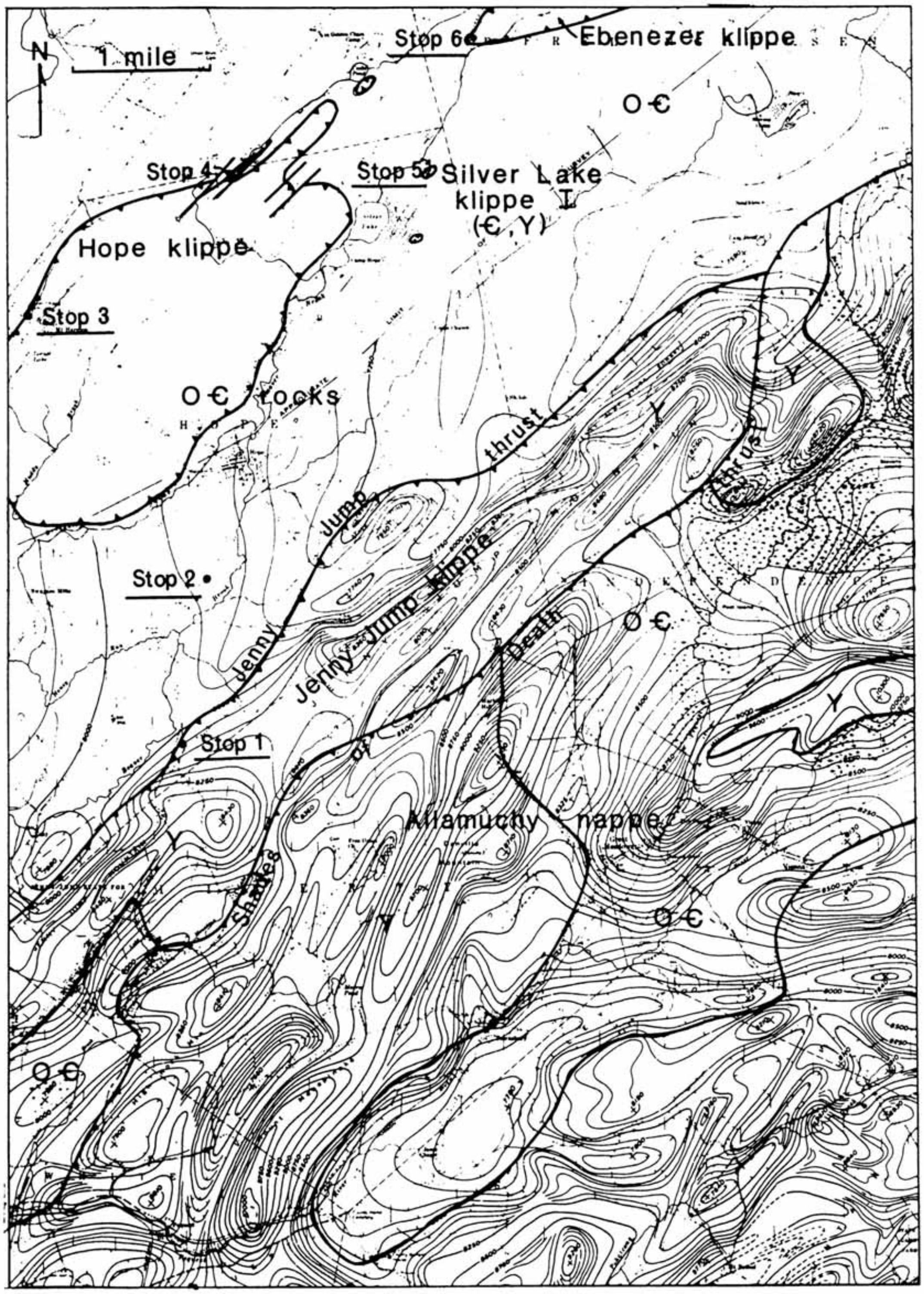


Figure 32 - Aeromagnetic map of the S half of the Blairstown and N half of the Washington 7-1/2-minute quadrangles, New Jersey, on which has been drawn a simplified tectonic map. (A. A. Drake, Jr., and P. T. Lyttle, 1980, fig. 5, p. 99.)

STOP 3 - Cuts on County Route 519, NE of Hope, Warren Co., NJ (carbonate-pebble conglomerate (the Jacksonburg Limestone) at base of Tippecanoe Sequence, beneath the Jenny Jump thrust. [UTM Coordinates: 504.0E / 4529.3N, Blairstown quadrangle.]

Exposed on L is a nearly flat-lying limestone-pebble conglomerate at base of Tippecanoe Sequence (Jacksonburg Limestone in these parts). The rocks here are equivalent to the Balmville of the central Hudson Valley, New York. Note that the clasts are well-rounded and consist predominately of Cambro-Ordovician "Sauk" carbonates. Also included are clasts of black chert and Cambrian quartzite. Steep quartz and calcite veins cut the pebbles and are related to a NW-trending regional cleavage or faults. The outcrop is not laterally continuous as black slates crop out in the next road cut. We regard these as localized channels at the Sauk-Tippecanoe disconformity. We have crossed the Jenny Jump thrust and these are the rocks below this fault.

Re-board vans; turn around and retrace route to I-80.

66.6 Passing sign on R for entering Hope.
66.8 Old stone house on R, now an Inn; turn R before crossing over Beaver Brook.
67.1 RJ at MP 5; turn R on Co. 521 and head for I-80 ramp.
68.0 Turn R into ramp for I-80 westbound.
68.2 Entering I-80 westbound.
68.3 Passing MP 12 on R.
68.5 More Sauk carbonates exposed; they are above the Jenny Jump thrust (and form the Hope klippe of Drake and Lyttle, 1980).
68.7 Sauk carbonates still dipping NW.
69.3 Passing MP 11 on R.
69.5 Sauk Sequence carbonates dipping at a low angle NW; asymmetric backfolds (axial surfaces dip NW and steep limbs are on the SE, cf. anticline on NJ Route 23 east of Newfoundland).
70.0 More cuts exposing Sauk Sequence carbonates; another good example of an asymmetric backfold on L.
70.1 Cuts expose dark-colored slates of Tippecanoe Sequence (again, the Bushkill Member of the Martinsburg Formation).
70.2 End of cuts exposing Sauk carbonates; leave Blairstown quadrangle, enter Portland quadrangle.
70.3 Passing MP 10 on R.
71.3 Passing MP 09 on R.
72.3 Passing MP 08 on R.
72.9 Cuts expose dark Tippecanoe slates dipping S.
73.3 Passing MP 07 on R.
73.9 Passing ramp for Scenic Overloook on R; view into Delaware Water Gap. (On pre-trip inspection, we entered here, but we may not do so on trip day; it adds to the mileage if we do.)

STOP 4 (Optional): Scenic Overlook, I-80, Columbia, NJ. [UTM Coordinates: N/A, Portland quadrangle.]

We quote the following from the caption of a photograph taken from this spot (Epstein, 1980, fig. 4, p. 77):

> "...Kittatinny Mountain underlain by resistant quartzite and lesser siltstone and shale of the Shawangunk Formation. The Shawangunk generally dips moderately to the northwest, such as at Delaware Water Gap (2), but is overturned to the southeast in places. The dark laminated slates exposed along Interstate 80 below (3) are in the lower (Bushkill) member of the Martinsburg Formation. Paulins Kill Valley (4) is underlain by carbonate rocks of the Allentown Dolomite, Beekmantown Group, and Jacksonburg Limestone that are in a window and are separated from the Martisnburg by the Portland Fault. The hills in the middleground (sic) beyond the Paulins Kill (5) are underlain by the Bushkill and Ramseyburg Members of the Martinsburg Formation. The upper (Pen Argyl) Member of the Martinsburg first appears across the Delaware River in Pennsylvania, coming out from under the Taconic unconformity with the overlying Shawangunk Formation (6)..."

74.3 Passing MP 6 on R; view ahead directly into Delaware Water Gap; road curves L and downhill.
74.8 Cuts exposing dark-colored Tippecanoe Sequence slates (Bushkill Member of Martinsburg Formation); dip of cleavage is at a low angle to the SE.
75.3 Passing MP 05 on R.
75.4 Passing ramp for Exit 4 for US Route 46 and NJ Route 94 on R.
75.7 Cuts expose Sauk Sequence carbonates in the Ackerman anticline that Drake (1978 and Drake and Lyttle, 1980) infer form a part of the Paulins Kill window beneath the Portland thrust (Figure 33). We have not made a careful study of the contacts, but from the general relationships merely raise the question of whether or not this belt of carbonate rocks could be a klippe of a thrust sheet of older carbonates thrust above younger slates that possibly has been faulted down into the slates, as at Hope, rather than a folded overthrust of younger slates over older carbonates. We plan to return to these exposures as Stop 11.

76.3 Passing MP 04 on R.
76.7 Passing beneath bridge for Conrail RR above.
77.0 Passing Hainesburg Road on R.
77.3 Passing MP 03 on R. View ahead on L shows cliff of Lower Silurian sandstone dipping NW.
78.2 Passing ramp on R for U turn.
78.3 Passing MP 02 on R.
78.9 Passing point where NW-dipping Lower Silurian sandstone (quartzite?) is at road level on NJ side of Delaware River.
79.0 Delaware River alongside I-80 on L; passing ramp to rest area on R.
79.4 Passing MP 01 on R; leave Portland quadrangle, enter Stroudsburg quadrangle.

80.1 Leave I-80 via ramp on R, last exit before toll; to Worthington State Forest and HQ of Delaware Water Gap National Recreational Area.
80.2 At bottom of ramp, STOP 05.
80.3 Pull up on R just past sign announcing traffic signal.

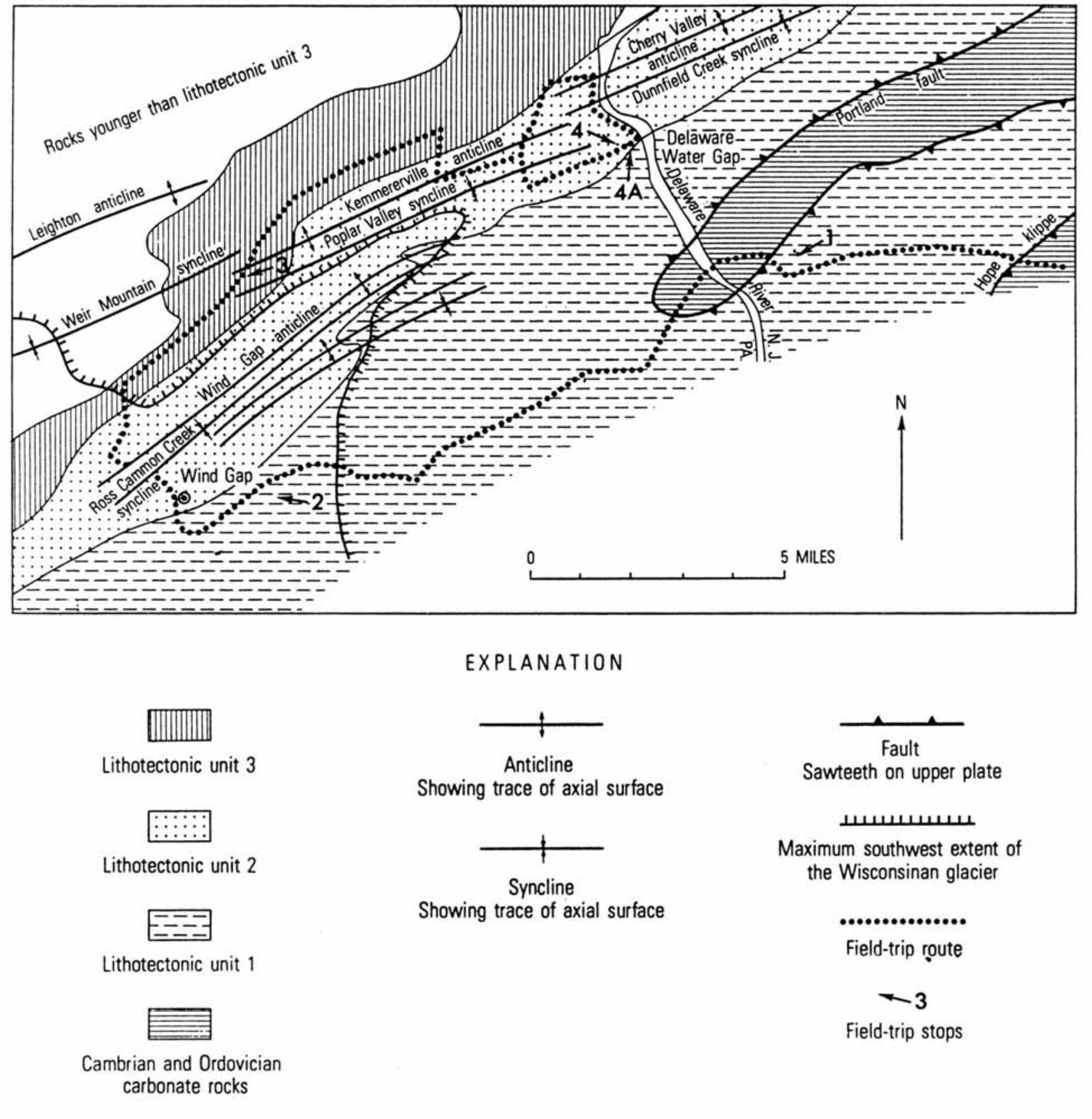


Figure 33 - Generalized geologic map of a part of the Valley and Ridge province, northwestern New Jersey and eastern Pennsylvania. (J. B. Epstein, 1980, fig. 2, p. 74.)

STOP 5 - Northwest slope of Delaware Water Gap (Lower Silurian red quartzites and siltstones) under I-80 bridge. [UTM Coordinates: 488.4E / 4535.9N, Stroudsburg quadrangle.]

The rocks exposed alongside I-80 consist of reddish sandstones, shales, and siltstones of the Silurian Bloomsburg Formation (equivalent to the High Falls Formation of previous On-The-Rocks trips - See Table 2). The sediments composing these rocks were deposited roughly 400 Ma (million years ago) in a broad deltaic fan complex; they are essentially non-fossiliferous excepting a few preserved remains of fish and plant fossils. The strata have been folded and display many aspects of cleavage. [What is the age of this cleavage? This cleavage is regional and probably Appalachian. If so, then this cleavage deals a fatal blow to the Woodward et al. flock that wants to downplay the Late Paleozoic Appalachian orogeny to some miniscule "Alleghanian" something or other.] For general relationships refer to Figure 34.

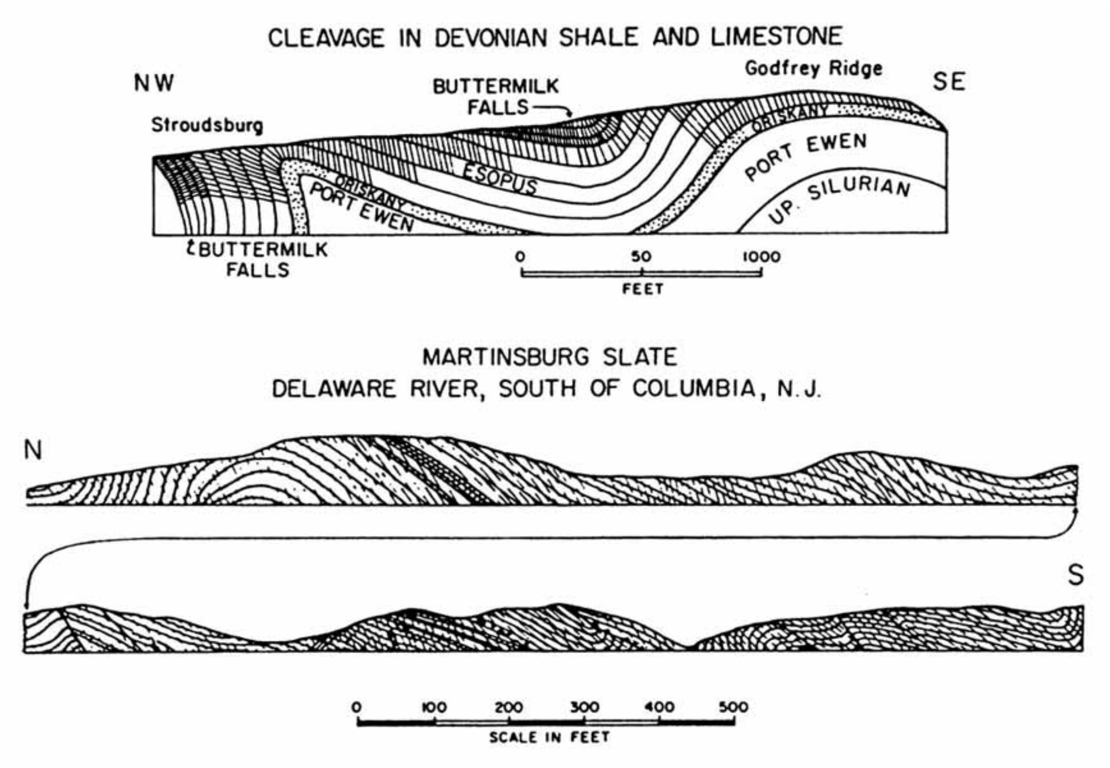


Figure 34 - Slaty cleavage in the Martinsburg Formation (lower section) and fracture cleavage in the Devonian sedimentary rocks (upper section). (J. C. Maxwell, 1962, fig. 3, p. 286.)

The features to see in the bedrock include gentle upright folds, inclined regional cleavage, and refracted cleavage. Before we leave this place, would you believe your eyes and that you can see glacial striae(!) parallel to the road (i.e., N20°W to S20°E)? These striae indicate that the Delaware Water Gap is as least as old as the last glacier from the NW. (Compare this situation with the lack of glacial striae in the Bronx River gorge.) Figure 30 shows a reconstruction of the relationships when the last ice, which flowed from the NE to the SW, covered this region.

Return to vans. Make U turn and keep to R where road divides.

80.5 Passing ramp on L for entering I-80 eastbound. Continue ahead to Recreation Area HQ.
80.65 Passing ramp on L for traffic leaving I-80 eastbound. Continue ahead.
81.1 Turn right into parking lot for Recreation Area HQ. REST STOP. Leave parking lot, turn R, follow signs for I-80.

81.2 Turn L to go under I-80 for westbound ramp.
81.3 After passing under I-80, turn L again for I-80 westbound.
81.5 On I-80 westbound.
82.2 I-80 on bridge crossing Delaware River.
82.7 Toll plaza; entering Pennsylvania. (At a cost of $1.00, do you think they're selling themselves cheap? Ask Red Adair.)
82.9 Passing ramp for Exit 310 [Old Exit 53] on R (to PA Route 611).
83.7 Passing ramp on R for entering traffic to I-80 westbound; low-dipping Devonian strata exposed on R.
84.0 I-80 on bridge over Broadhead Creek before Exit 309 [Old Exit 52].
84.2 Passing ramp on R for Exit 309 (to US Route 209 northbound, Marshall Creek, Milford, Shawnee).
85.1 Passing ramp on R for Exit 308E [Old Exit 51E], Stroudsburg.
85.7 I-80 on bridge over Broadhead Creek again.
86.0 Leave I-80 via ramp on R at Exit 307 [Old Exit 50] (Broad Street, to PA 191 N).
86.1 Curve R to follow PA Route 191 northbound.
86.2 On bridge crossing McMichael Creek, a tributary of Brodhead Creek.
86.3 At traffic light (Fifth St.--the one we want but can't enter from here) just over bridge, turn R onto Main Street to E. but be prepared for an immediate L turn.
86.4 Turn L into Fourth Street for PA 191 N (by Starvation Army). Fear not, we shall eventually get to Fifth St.
86.5 After one block, another traffic light (at McConnell St., which is a one-way street to the W). Turn L, but keep to R for upcoming R turn. If you're not confused by now, you should be running these trips!
86.6 Turn R onto Fifth Street, PA 191 N.
87.5 Leave Stroudsburg quadrangle, enter East Stroudsburg quadrangle (which is actually N of Stroudsburg!).
87.8 Turn L turn to enter parking lot for Beseckers Diner on L.

REST STOP

87.8 Leave diner; turn L to continue N on PA 191.
88.2 Passing Clearview School on R. (Boise Sch on old map).
88.6 After sharp R bend, pass crossroad at Loyson Rd.
89.5 Curve to L. PA 191 follows valley of Broadhead Creek, which trends NW-SE and will be our entry point to the Poconos.
89.8 Pull over to R and park for STOP 06.

STOP 6 - Cuts on PA Route 191, valley of Broadhead Creek, N of Stroudsburg, PA. [UTM Coordinates: 482.4E / 4541.8N, East Stroudsburg quadrangle.]

Be prepared to make withdrawals from a Devonian bank (bioherm). Fossils are plentiful in the siltstone here. Where original skeletal calcite remains in the fresh rock, its color is white. The best collecting is in rust-colored pieces that are full of holes where the calcite has been dissolved away, leaving external- and/or internal molds. Bedding is oriented N65°E, 18°NW and is cut by a penetrative cleavage with ~8 cm spacing. This regional cleavage is oriented N55°E, 57°SE. We found many varities of bryozoa, corals, gastropods, and brachiopods. Champion critter collector CM found a coiled trilobite, pygidium and all. Novice collector Christopher (Vern) Merguerian made a fabulous brachiopod discovery on our pre-trip runthrough in 1992.

Re-board vans and continue NW on PA 191.

94.1 Pull over to R and park for STOP 07.

STOP 7 - Cross-bedded and folded Devonian sandstone cuts on PA 191, valley of Broadhead Creek, between Analomink and Henryville, N of Stroudsburg, PA. [UTM Coordinates: 480.6E / 4547.2N, East Stroudsburg quadrangle.]

These sandstones, which prominently display large-scale cross strata, are probably equivalent to the Ashokan Flags of New York State. The cross strata imply that these are fluvial deposits. As such, they are the lowest of the thick Devonian strata that are mostly of nonmarine origin. The siltstones below are the youngest marine Devonian hereabouts. Locally the sandstones are called “bluestone” because of their obvious bluish-gray color. In addition to the large-scale cross bedding, the sandstones are internally laminated indicating deposition by swift currents. Along the eastern limb of a broad anticline, imbrication of sandstone layers along the limb and overthickening of the sandstones and the reddish shale beneath the slip zone indicate strong deformation.

95.3 Henryville; turn L on PA Route 715, following sign to I-80.
95.8 Leave East Stroudsburg quadrangle, enter Mount Pocono quadrangle.
97.0 Passing Hunter Farm Rd. on R.
97.3 PA 715 bends R.
97.6 Stop sign; Meisertown; junction with PA Route 314; Pocono Union Church on L. After stop, cross PA 314 and continue on PA 715.
97.8 Passing farm pond on R.
98.2 Passing glacial boulder in till on R.
98.3 Passing Alpine Lake Road on R.
99.1 Passing road to Cherry Lane Church on L.
99.4 Passing Post Hill Road.
99.6 Passing Shine Hill Road.
100.5 Passing Munich Road on R, on downhill reach.

100.8 Tannersville Village sign on R.
101.2 Traffic light, Tannersville; turn R on PA 611 N, but be alert for almost-immediate left turn at next traffic light to follow PA 715.
101.3 Traffic light; turn L on PA 715 Southbound (sign to I-80).
101.4 PA 715 on bridge over Pocono Creek; curve to L.
101.6 PA 715 passing under overpass for I-80. Big hill on R ahead is Camelback Mountain in Big Pocono State Park, known to some perhaps for its ski facilities.
101.8 Turn L for ramp to I-80 eastbound (Interchange 45).
102.1 On I-80 eastbound.
102.2 Passing MP 299 on R.
103.1 Devonian strata dipping gently to NW; interbedded reddish siltstones (overbank deposits) and dark greenish-gray sandstones (stream-channel deposits).
103.7 More Devonian strata in cuts.
104.4 More of same by bridge before PorterBuilt on L.
105.3 Leave Mount Pocono quadrangle, enter Saylorsburg quadrangle.
105.3 Passing exit ramp on R for Interchange 46 (the interchange number marked on the topographic map. As we shall see, this should be 46W.)
106.8 Leave Saylorsburg quadrangle, re-enter Stroudsburg quadrangle; more cuts expose cleaved, dark gray Devonian siltstone and sandstone.
107.5 Going downhill off Pocono Plateau.
108.2 Passing MP 304 on R.
108.5 Passing ramp on R for US Route 209 (Interchange 47).
108.9 Passing ramp on R for Interchange 46; that's right; according to the information shown on the Stroudsburg quadrangle, an Interchange 46 lies between Interchange 47 and upcoming Interchange 48. Two Interchange 46's exist! What is going on with the numbering? Who couldn't count? You get what you pay for, ask Red Adair! We'll refer to this one as Interchange 46E).

109.5 Passing ramp for entering traffic on R (Interchange 48).
109.9 Passing ramp on R for Interchange 48.
110.3 Passing ramp on R for entering traffic on R (Interchange 49). I-80 makes big curve to L.
110.9 Leave I-80 by taking exit ramp on R at Interchange 50 to PA Route 611.
111.1 T intersection; turn R on PA Route 611 Southbound.
111.3 At blinker light, PA 611 and PA 191 Southbound angle sharply to L; be prepared for upcoming right turn.
111.4 Leave PA 611; turn R on PA 191 Southbound.
111.6 Passing sign on R for Stroud Twp. boundary. We are crossing Godfrey Ridge (Figure UU).
111.9 Passing Stroudsmoor Road on R going downhill. Devonian strata exposed in cut on R.
112.3 PA 191 S curves to R; passing on L, Cherry Valley Road; to Delaware Water Gap.
112.5 Y-shaped intersection; PA 191 South goes left; we leave PA 191 South and bear R (more or less straight ahead) on Cherry Valley Road. This road follows along the base of a strike ridge; Cherry Valley is the strike valley on L; notice small wind gap in ridge to L (an "outlier" of the main ridge, which is Kittatinny Mountain). Figure 35 indicates two gaps, Fox Gap on the W and Totts Gap on the E.

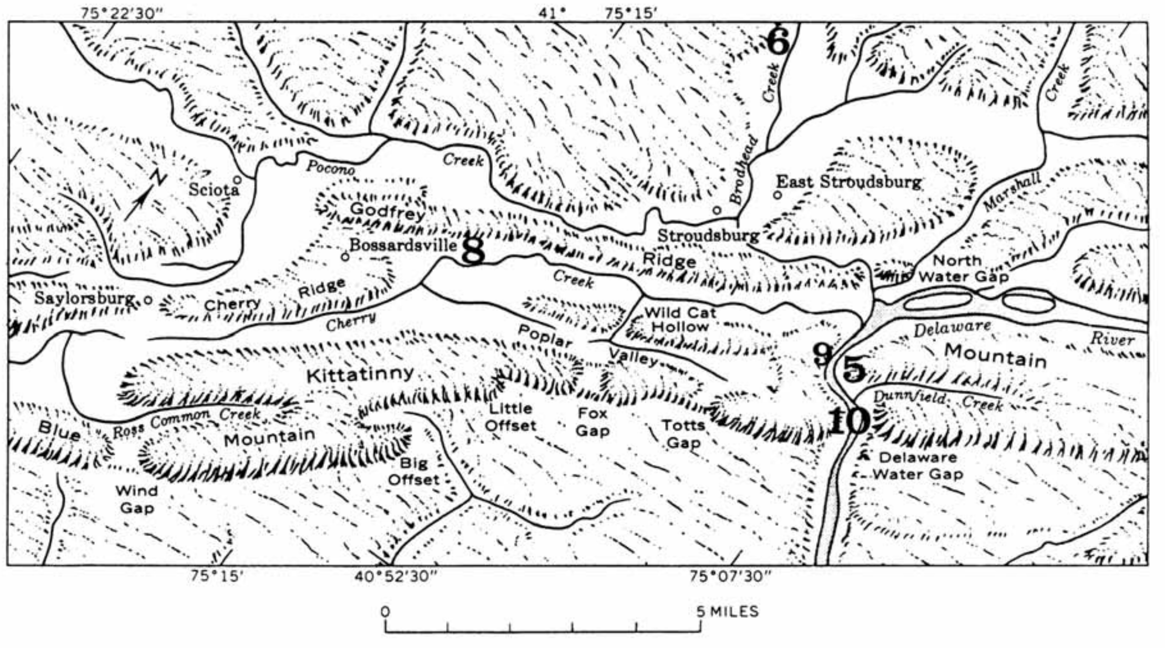


Figure 35 - Physiographic diagram of Stroudsburg area, Pennsylvania and New Jersey, showing some of the trip stops. (J. B. Epstein, 1969, fig. 1, p. 207.)

113.0 Passing Lessig Lane on L.
113.4 Passing Coursen Court on R; large new house on L (CM, an all-encompassing font of vital information, sez this one is owned by an Italian).
113.7 Passing Larsen Lane on L.
114.8 Rocks exposed on R just before sign for Hamilton Township line are objectives of STOP 08; continue ahead.
115.1 Stop sign at Blakesfield Rd; make U turn and backtrack.
115.3 Pull over to R at entrance to field; park vans off Cherry Valley Rd.; leave vans, cross road (be careful); walk ahead for STOP 08.

STOP 8 - Cuts on Cherry Valley Road, near boundary between Hamilton Township (Monroe Co.) and Stroud Township (Northampton Co.), S of Stroudsburg, PA. [UTM Coordinates: 480.3E / 4533.5N, Stroudsburg quadrangle.]

These rocks are approximately equivalent to the New York "Manlius" Limestone. The polygons here have long been pointed out to geology students as examples of polygons formed by superimposed mudcracks. Yet, the dissolution residues along the sides of the polygons show that polygons have resulted from dissolution cleavage and are comparable to stylolites, the other geologic feature formed as a result of high pore pressure dissolution. Our measurements indicate that the strata strike N75°E and dip 25°SE. The dissolution cleavage strikes N50° to 60°E and is vertical.

Re-board vans; retrace route on Cherry Valley Road back to intersection with PA 191.

116.4 Passing Larsen Lane on R.
116.7 Passing Coursen Ct. on L.
117.0 Passing Lessig Lane on R.
117.5 Stop sign at jct. with PA 191.
117.6 To join PA 191 going N, bear R then turn L into PA 191 northbound.
117.8 PA 191 curves to L; continue straight ahead on Cherry Valley Road toward Delaware Water Gap.
118.8 Passing Croasdale Rd. on R.
119.0 Passing Fenner Lane on R.
119.2 Passing sign at Smithfield Twp. line.
119.4 Cherry Creek alongside Cherry Valley Rd. on R.
119.8 On bridge over Cherry Creek.
119.9 Totts Gap Rd. on R.; Cherry Valley Rd. curves L.
120.3 Entering town (borough) of Delaware Water Gap.
120.4 Passing Kimberly Rd. on R.
120.8 Stop sign at Jct. PA 611 (Main St.); turn L.
120.9 Traffic light; turn R, following sign to Stroudsburg.
121.0 Passing(!) Water Gap Diner on R. Ask JES about the bread pudding at this diner!
121.2 Continue straight ahead, following sign for I-80 westbound.
121.3 Turn R for PA Tourist center. LUNCH STOP. Pay attention to where you walk your pets! The signs are full of hidden arrows that look like dashes. Thus, do not walk your dog near the Dog Walk sign, it's a felony - watch out for the grumpy, heavy set ranger. He's the one with the damp pants legs.

121.5 On leaving Tourist Center, turn L following sign to New Jersey.
121.7 Passing ramp on R that leads to I-80 E (New Jersey).
121.8 Passing once again Water Gap Diner on L.
121.9 Traffic light; turn L. onto Main St., PA 611 Southbound.
122.0 Passing Cherry Valley Road on R.
122.5 Turn L into Resort Point Overlook.

STOP 9 - Resort Point Overlook, Stroudsburg, PA. [UTM Coordinates: 488.2E / 4536.2N, Stroudsburg quadrangle.]

Get out of vans, fast! Scenic view. General discussion. The rocks in the large cuts directly opposite are the same rocks as at STOP 05. They show steep cleavage, refraction of cleavage, and thrust faults (Figure 36). We will not try to examine them here with a large group.

Re-board vans.

122.6 Turn L on leaving Resort Point Overlook; continue S on PA 611.
123.8 Leave Stroudsburg quadrangle, re-enter Portland quadrangle.
124.0 Turn R into Point of Gap Overlook parking lot. Park at far end and walk along PA 611 for STOP 10. EXTREME CAUTION HERE unless van is too crowded for return trip.

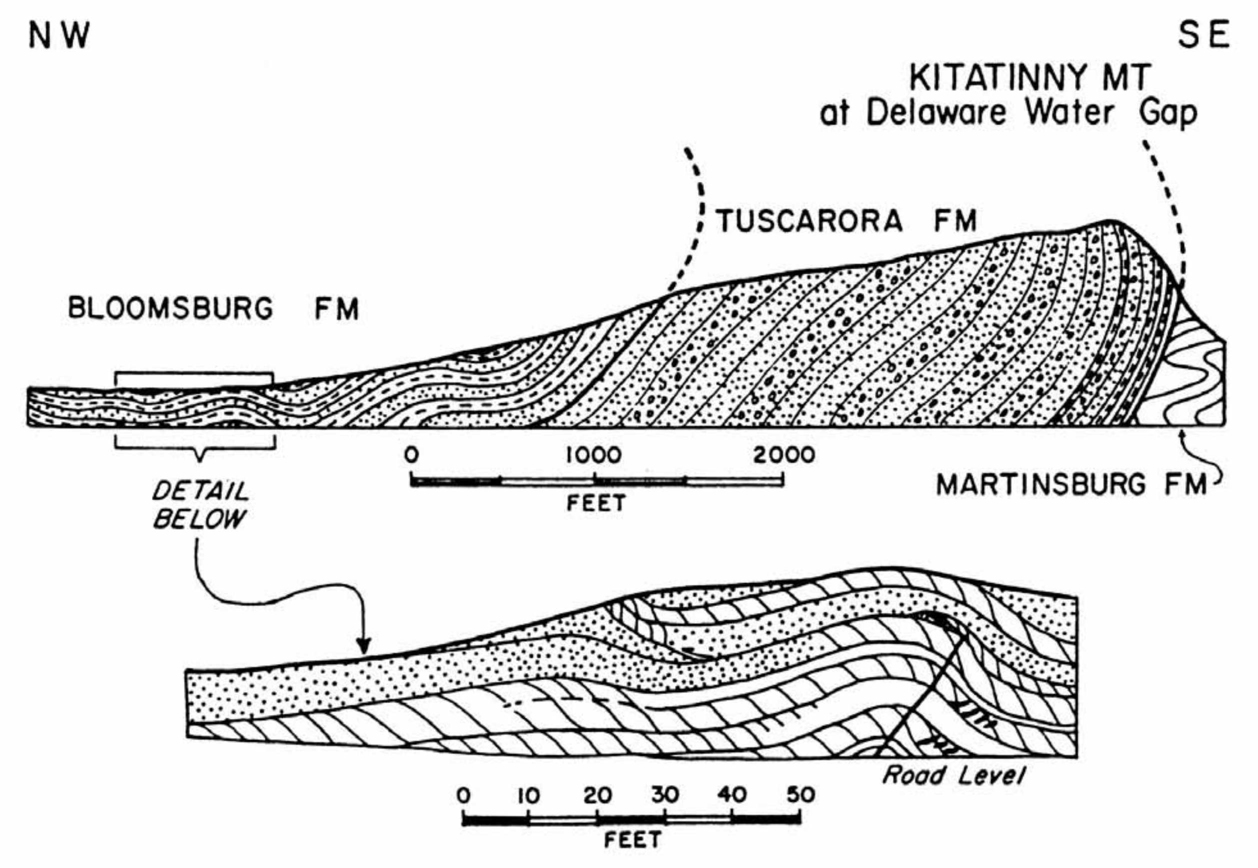


Figure 36 - Minor folding and fracture cleavage associated with major syncline north of the Delaware Water Gap. (J. C. Maxwell, 1962, fig. 9, p. 293.)

STOP 10 - Cuts on PA 611, Point of Gap Overlook S of Stroudsburg, PA. [UTM Coordinates: 489.8E / 4535.9N, Portland quadrangle.]

Refer to Figures 37 and 38 for the general setting here. The rocks in the cut belong to the Lower Silurian Tuscarora Formation (equivalent of Shawangunk in New York). The strike is N70°E and the dip 48°NW. Massive- to cross-stratified sandstone in layers 1 to 2 m thick are interbedded with slaty cleaved siltstones 5 cm to 0.5 m thick. The bases of some sandstones are channel fills; some beds pinch out; quartz pebbles are present in some beds.

The talus slope on hillside on NE side of Delaware River covers the Martinsburg Formation.

Re-board vans; reverse course back to I-80 eastbound.

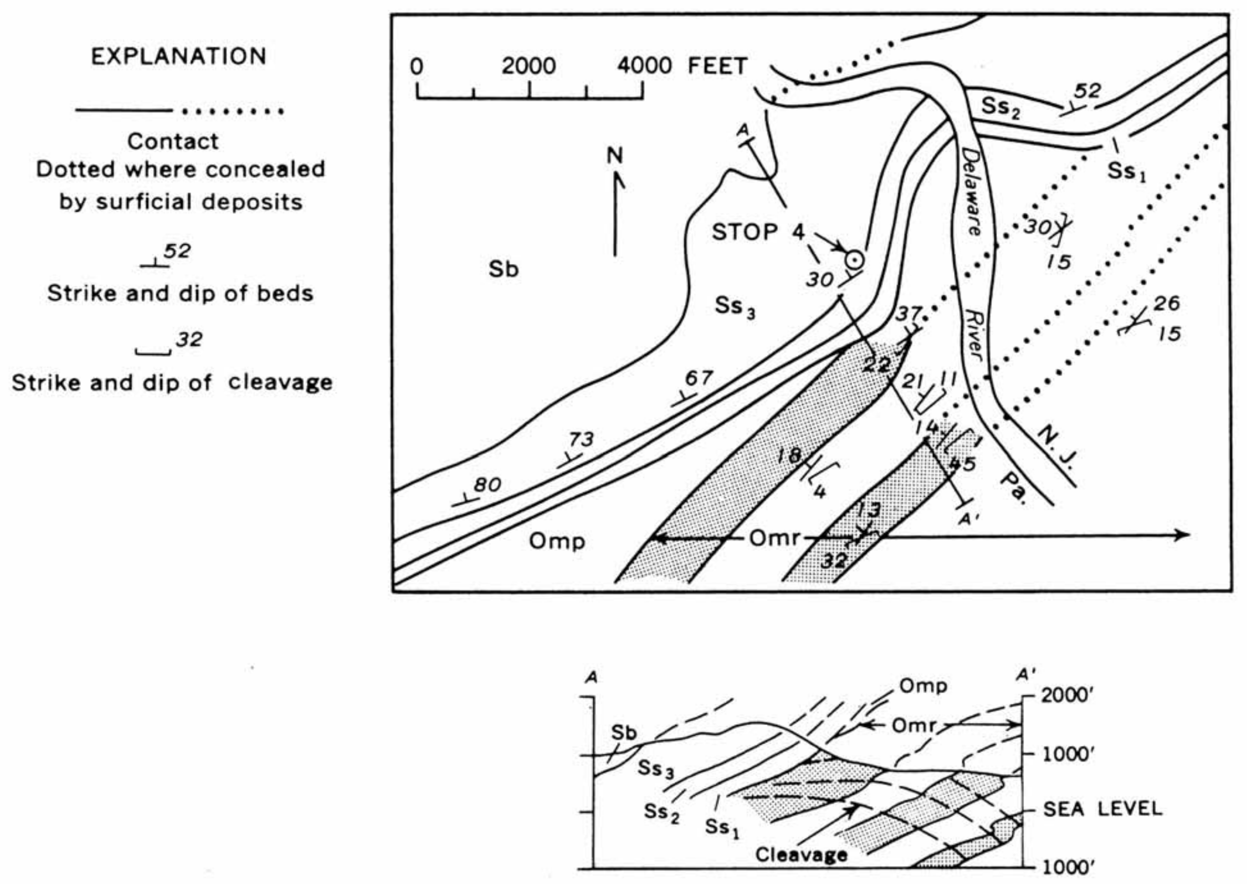


Figure 37 - Geologic map and section of the Delaware Water Gap area showing the angular unfonformity between the Martinsburg Formation and the Shawangunk Conglomerate. (Epstein and Epstein, 1969, fig. 70, p. 201.)

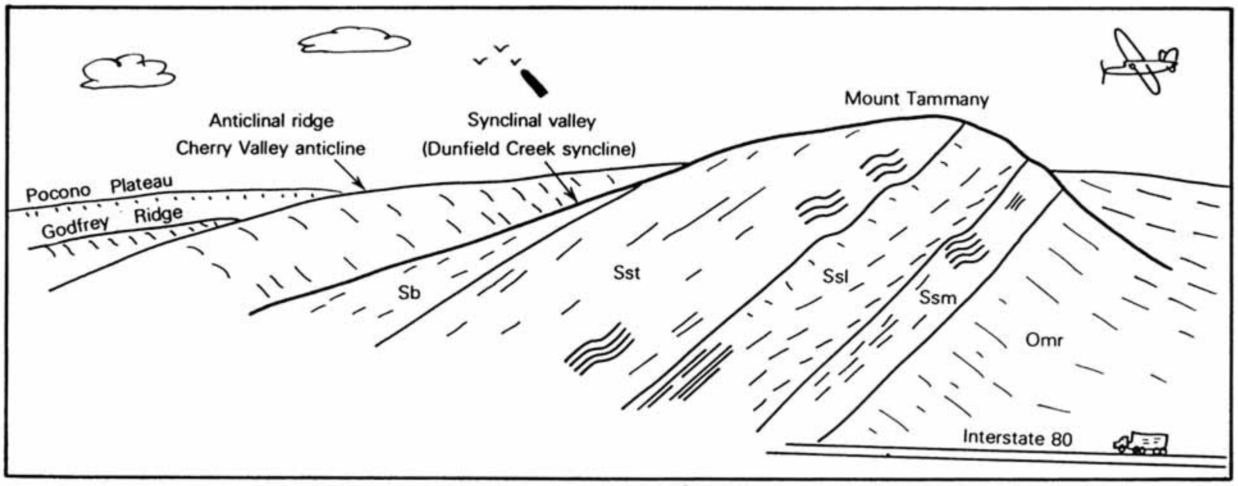


Figure 38 - View northeastward across the Delaware Water Gap. (Epstein, 1980, fig. 11, p. 86.)

124.2 Turn L into PA 611 Northbound alongside RR tracks.
126.3 After passing through village of Delaware Water Gap, at traffic light; turn R.
126.4 Passing Water Gap Diner again on R (will we ever stop here? Can JES resist the bread pudding???).
126.5 Turn L into ramp for I-80 eastbound (New Jersey).
127.1 Entering I-80 eastbound.
127.3 Passing toll barrier; a freebie in this direction.
128.0 Passing ramp on R for traffic entering I-80 from local road from Worthington Forest.
128.1 Passing ramp on R for traffic leaving I-80 eastbound.
128.6 Passing ramp on R for U Turn and Rec. Area HQ.
128.7 Leaving Stroudsburg quadrangle, re-enter Portland quadrangle.
128.9 Passing MP 01 in New Jersey.
130.9 Passing MP 03 in New Jersey.
131.9 Leave I-80 via ramp on R for Exit 4A to NJ Route 94.
132.4 Turn L for road over I-80; following signs for I-80 E detour.
132.9 Exit from curving ramp at drive-out place on R; park vans and walk through cuts on complex cloverleaf for STOP 11.

STOP 11 - Cuts on complex cloverleaf at junction of NJ 94, I-80, and US Route 46, Town of Columbia, NJ. [UTM Coordinates: 492.5E / 4530.5N, Portland quadrangle.]

As indicated by the remarks at Mileage 75.7, the complex of cuts in this cloverleaf complex expose Sauk Sequence carbonates (the Upper Cambrian Allentown Formation)in the Ackerman anticline that Drake (1978) and Drake and Lyttle (1980) infer form a part of the Paulins Kill window beneath the Portland thrust. (See Figure 33.) We have not made a careful study of the contacts, but from the general relationships merely raise the question of whether or not this belt of carbonate rocks could be a klippe of a thrust sheet of older carbonates thrust above younger slates that possibly has been faulted down into the slates, as at Hope, rather than a folded overthrust of younger slates over older carbonates. The Allentown Formation (approximately equivalent to the Pine Plains Formation of the Wappinger Group of southeastern New York State) is characterized by numerous meter-scale depositional cycles known in modern terminology as parasequences. Each begins with coarse dolostone that has resulted from dolomite replacement of original carbonate sediments of sand size (typically oolitic) and displaying evidence of currents (cross laminae, ripples, channels) and ends upward with dolostone that resulted from replacement of laminated carbonate mud, commonly displaying algal stromatolites and mudcracks. The lower member of each cycle is inferred to represent subtidal conditions; the upper, intertidal- to supratidal situations. The modern interpretation of these cycles is that they have resulted from rapid submergence (to form the subtidal conditions) and subsequent outward progradation of a carbonate peritidal complex. (The Pine Plains Formation of SE New York State features various sedimentary breccias; we shall look for these here.)

After returning to vans, continue ahead, following signs for US Route 46 E.

133.4 Passing more Sauk carbonates exposed in cuts along the ramps within the cloverleaf complex and eventually onto US Route 46 Eastbound. The Paulins Kill enters from NE here; it marks the boundary between Sauk carbonates on the NW and Tippecanoe (Martinsburg) slates on the SE. (See previous remarks on the interpretation of this contact.)
134.5 US Route 46 makes big curve to R; Tippecanoe dark slates (Martinsburg) exposed on L.
135.1 Passing MP 02 on R.
135.6 Going beneath RR bridge.
136.1 Passing MP 03 on R.
136.15 Traffic light at Roy Ace Road; continue ahead on US 46 E.
136.4 Crossroads; Ferry Lane on R.
136.9 Passing Co. Routes 606 and 605 on L; Sycamore Road on R.
137.1 Passing MP 04 and cemetery on R.
137.4 Passing Co. 609 on L.
137.5 Leaving Portland quadrangle, entering Belvidere quadrangle.
138.3 Passing MP 05 on R.
138.5 Passing Orchard Avenue on R.
138.7 Passing sign for White Township on R. (Manunka Chunk).
139.3 Passing MP 06 on R.
139.7 Passing King Cole Grove on R; slow down and be prepared for upcoming left turn.
139.8 Turn L into remnant of old road on L; park for STOP 12.

STOP 12 - Cuts on US Route 46, Manunka Chunk, New Jersey (slates of Bushkill Member of Martinsburg Formation). [UTM Coordinates: 495.2E / 4522.0N, Belvidere quadrangle.]

Before you is a marvelous example of slaty cleavage that is not parallel to the bedding in the dark-colored slates of the Bushkill Member of the Martinsburg Formation. This is the locality that John C. Maxwell (1962) made famous in his classic paper on the origin of slaty cleavage in the Delaware Water Gap area. Maxwell notes that the slaty cleavage in the water gap area is restricted to the Ordovician Martinsburg slates and antedates the overlying Lower Silurian to Devonian clastic and carbonate strata that rest unconformably above the Martinsburg. Thus, a Taconian (Ordovician) age for the slaty cleavage has been well documented in northwestern New Jersey.

As noted by Maxwell, the slaty cleavage in the Martinsburg is axial planar to northwest-vergent folds of bedding and is characterized by a flow foliation consisting of oriented illite (mica) and quartz. At this locality, the prominent slaty cleavage strikes N45°E and dips 31° SE. The bedding trends N70°E and is clearly defined by a deformed, subvertical calcareous siltstone layer (15 to 20 cm thick) and adjacent color bands in the slate produced by subtle compositional variations (Figure 39). Mechanical differences between the slate and calcareous siltstone have resulted in the relative brittle offset of the siltstone, local transposition of bedding into parallelism with cleavage, and development of quartz-calcite veining. (See Figure 39.) The axes of crenulate folds of the bedding plunge 2° into N60°E.

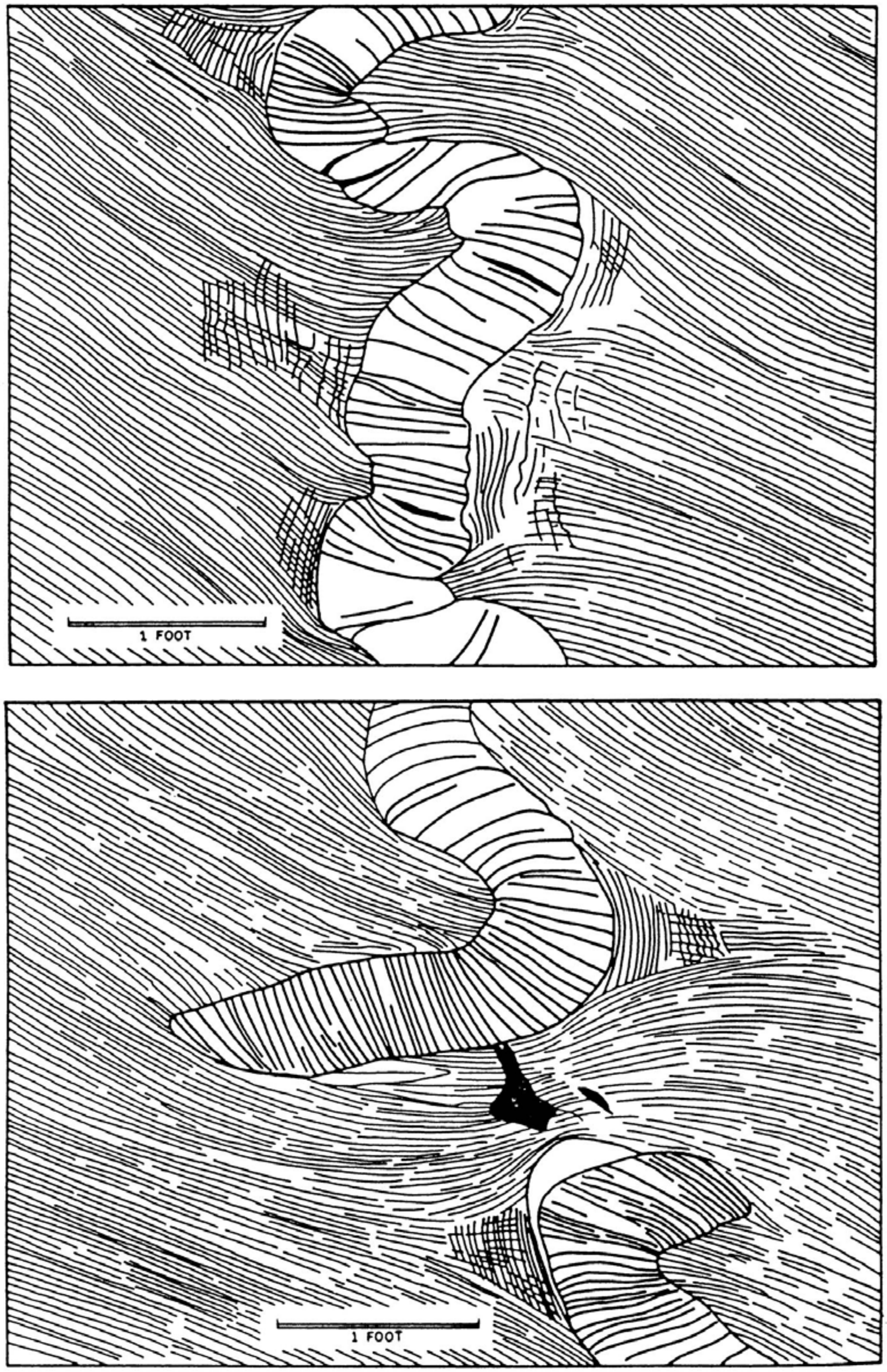


Figure 39 - Field sketches showing, a) folding of calcareous siltstone layer in Bushkill Member of Martinsburg Formation at Stop 12, and b) shearing and transport parallel to slaty cleavage at same location. (J. C. Maxwell, 1962, figs. 6 and 7, p. 290.)

Rumor has it that a few geologists have interpreted this classic exposure the result of "intrusion" of a clastic dike into the dark muds of the Martinsburg followed by flattening and deformation of the dike into the sinuous form shown in Figure 6a. Implied in this interpretation is the notion that the true bedding and the cleavage are parallel and that the clastic dike cut across the original bedding.

In trying to trace down the source of this clastic-dike rumor we have found the following passage in the second edition of L. U. DeSitter's widely used textbook on structural geology (1964, p. 276): "It [meaning the roadcut] shows a slate with almost horizontal cleavage crossed vertically by a folded sandstone." We suspect that Maxwell showed DeSitter the roadcut and that DeSitter understood the relationships. His use of the verb crossed in the statement quoted above may have confused a few geologists into thinking that that the calcareous siltstone layer is indeed a clastic dike but we, of course, disagree strongly with the clastic-dike interpretation. Rather, we agree with Maxwell that the supposed "dike" is normal compositional layering (stratification) and that the subhorizontal deformational fabric is related to the development of a pre-Silurian Taconian slaty cleavage. Measurements by Maxwell (1962) suggest that roughly 40% vertical shortening has occurred in the exposure, the combined result of transposition and flow parallel to the slaty cleavage (roughly 1 meter of which shows up across the calcareous siltstone layer in Figure 39) and by dewatering of the shales during development of the slaty cleavage. Let's look for evidence for another slaty cleavage or two and try to find some nice slate specimens showing a high angle bedding/cleavage relationship.

Re-board vans; turn around; make R turn into US Route 46 westbound.

140.0 Passing King Cole Grove on L.
140.3 Passing MP 6 on R.
140.9 Entering Knowlton Township, Manunka Chunk.
141.9 Leaving Belvidere quadrangle, re-entering Portland quadrangle.
142.1 Passing Ramseyburg Road on R (Co. 609).
143.1 Crossroads; Clarence Street and Ferry Lane; Knowlton School just beyond on R.
143.3 Blinker light at Roy Ace Avenue.
143.6 Passing under old arch railroad bridge.
143.8 On R, start of long cut with continuous exposure of Tippecanoe Sequence (Martinsburg Slate).
144.1 Passing MP 02 on R.
144.7 End of long cut in Martinsburg.
145.5 Leave US 46 Westbound via ramp on R for I-80 and NJ Route 94.
145.8 Entering ramp on R for I-80 eastbound; numerous exposures of low-dipping Sauk carbonates in cuts.
146.1 On I-80 eastbound.
146.2 Passing MP 05 on R.
146.6 Cuts expose Tippecanoe Sequence (Martinsburg) slates; cuts end at 146.8.
146.8 I-80 curves R.
147.4 Passing small pond (Delaware Lake?) on R.
148.1 Passing MP 07 on R.

148.2 Entering ramp on R for Rest Area.

148.6 **PIT STOP**. If it is a clear day, after we have re-boarded the vans, we shall drive up the road to the overlook. If we do so, add 0.5 mi to road log, pass Go and collect $200.
148.8 End of ramp from Rest Area; Tippecanoe (Martinsburg) slate exposed in cuts.
149.1 Passing MP 09 on R; on I-80, three lanes become two.
150.1 Passing sign announcing Exit 12 in 2 mi. on R. Leave Portland quadrangle, re-enter Blairstown quadrangle.
150.2 Passing MP 10 on R.
150.3 Martinsburg slates in cuts.
150.4 Contact between Tippecanoe (Martinsburg) and Tippecanoe basal limestone (Jacksonburg); Sauk Sequence beyond.
150.7 Cuts expose Sauk carbonates to 110.7.
151.2 Passing MP 11 on R.
151.7 Cuts expose Sauk Sequence carbonates on both sides; end at exit ramp.
152.0 Passing ramp on R for Exit 12 (to Blairstown and Hope).
152.4 Passing ramp on R for traffic entering I-80 eastbound from Exit 12.
152.6 Cuts expose Sauk carbonates.
153.1 Passing MP 13 on R.
153.3 Cuts on both sides of I-80 expose Sauk carbonates.
153.6 End of Sauk exposures.
153.8 More cuts exposing Sauk carbonates.
154.0 I-80 passing under bridge for local road above.
154.1 Passing MP 14; end of Sauk cuts.
155.1 Passing MP 15 on R.
155.6 Cuts expose Proterozoic rocks of Jenny Jump klippe on both sides; I-80 narrower by large cut on R.
155.7 Passing sign on R. for Allamuchy Township.
155.8 Traverse loop for trip closed; repeat log in reverse order.
157.1 Passing MP 17 on R. End of log for today - you're on your own.

We hope you've enjoyed today's trip into the wilds of western New Jersey and eastern Pennsylvania and will look forward to seeing you in the field again, On-The-Rocks................;)

ACKNOWLEDGEMENTS

In addition to thanking our usual list of suspects (Matt Katz, and his Executive Assistant (Marcie Brenner) and staff at the New York Academy of Sciences, Mickey and Chris (“Vern”) Merguerian assisted (or is that distracted) us in our pre-trip checkout.

TABLES

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	(Passive-margin sequence II).
(Jurassic)		Baltimore Canyon Trough forms and fills with 8,000 feet of pre-Cretaceous sediments.
		Atlantic Ocean starts to open. Newark basins deformed, arched, eroded.
	190	Continued filling of subsiding Newark basins and mafic igneous activity both extrusive and intrusive.
(Triassic)		Newark basins form and fill with non-marine sediments.

PALEOZOIC 245

(Permian)		Pre-Newark erosion surface formed.
	260	**Appalachian orogeny.** (Terminal stage.) Folding, overthrusting, and metamorphism of Rhode Island coal basins; granites intruded.
(Carboniferous)		Faulting, folding, and metamorphism in New York City area. Southeastern New York undergoes continued uplift and erosion.
(Devonian)	365	**Acadian orogeny.** Deep burial of sedimentary strata. Faulting, folding, and metamorphism in New York City area. Peekskill Granite and Acadian granites intruded.
(Silurian)		
	440 450	**Taconic orogeny.** Intense deformation and metamorphism. Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line). Arc-continent collision.
(Ordovician)		Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata. Ultramafic rocks (oceanic lithosphere) sliced off and transported 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, part of Manhattan Schist Fm.). Deep-water terrigenous silts form to east. (= Taconic Sequence; protoliths of Hartland Formation, parts of Manhattan Schist Fm.). (Passive-margin sequence I).

PROTEROZOIC

	570	Period of uplift and erosion followed by subsidence of margin.
(Z)	600	Rifting with rift sediments, volcanism, and intrusive activity. (Ned Mountain, Pound Ridge, and Yonkers gneiss protoliths).
(Y)	1100	**Grenville orogeny.** Sediments and volcanics deposited, compressive deformation, intrusive activity, and granulite facies metamorphism. (Fordham Gneiss, Hudson Highlands and related rocks).

ARCHEOZOIC

	2600	No record in New York.
	4600	Solar system (including Earth) forms.

Table 02 - Generalized Descriptions of Major Geologic "Layers", SE New York State and Vicinity

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

LAYER VII - QUATERNARY SEDIMENTS

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

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

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

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

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

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

marine)	(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].

~~~~~~~~~~~~~~~~~~~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. / Manhattan Schist (Om - lower unit).
Normanskill Fm. / Annsville Phyllite

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

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

LAYER IIA[W] - SAUK SEQUENCE

Western shallow-water
platform (L. Cambrian-
M. Ordovician)

Copake Limestone
Rochdale Limestone
Halcyon Lake Fm.
Briarcliff Dolostone
Pine Plains Fm.
Stissing Dolostone
Poughquag Quartzite
Lowerre Quartzite [Base not known]

LAYER IIA[E] - TACONIC SEQUENCE

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

Stockbridge
or Inwood Marbles

(Ꞓ-Oh) Hartland Fm.
(Ꞓ-Om) Manhattan Fm.
(in part).

[**Pre-Iapetus Rifting Event**; extensional tectonics, volcanism, rift-facies sedimentation, and plutonic igneous activity precedes development of Iapetus [Layer II = passive continental margin I] ocean basin. Extensional interval yields protoliths of Pound Ridge Gneiss, Yonkers granitoid gneisses, and the Ned Mountain Formation (Brock, 1989, 1993). Followed by a period of uplift and erosion. 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.

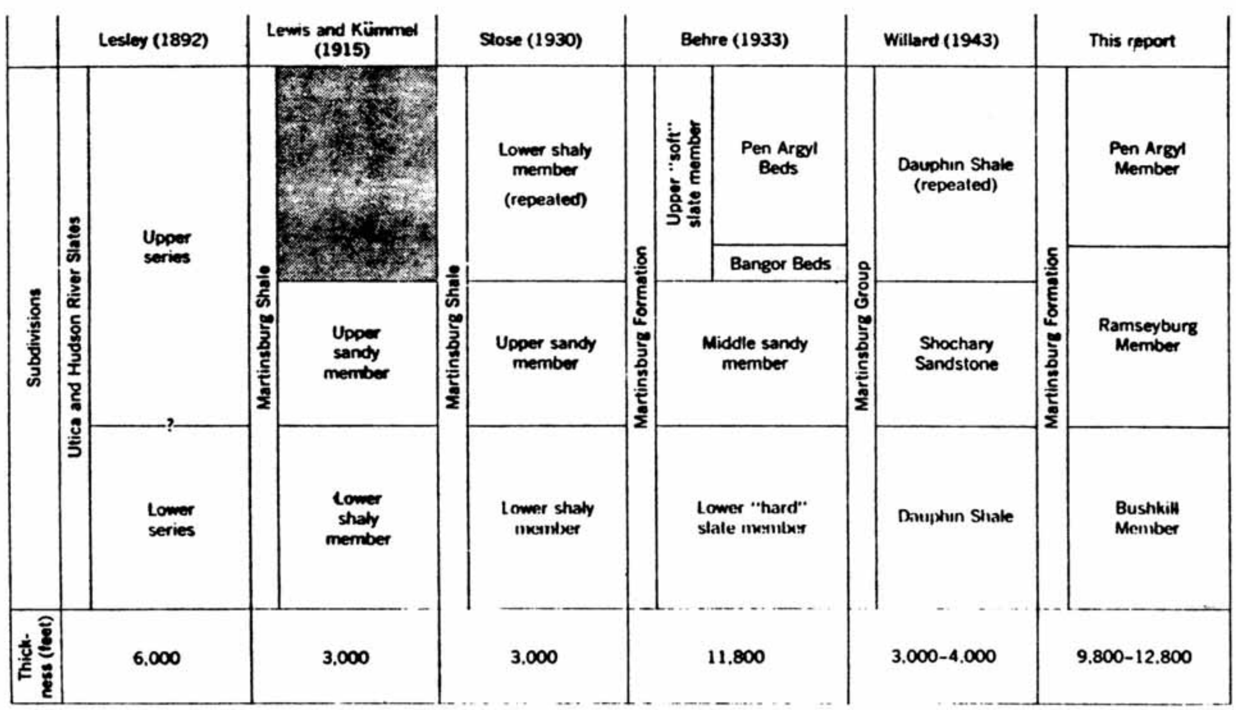
~~~~~~~~~~~~~~~~~~~~Surface of unconformity~~~~~~~~~~~~~~~~~~~~

[**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 - Comparative columns illustrating subdivisions of the Martinsburg Formation according to various authors. "This report" refers to Drake, A. A., and Epstein, J. B., 1967, The Martinsburg Formation (Middle and Upper Ordovician) in the Delaware Valley, Pennsylvania-New Jersey: United States Geological Survey Bulletin 1244-B, 16 p., their Figure 1, p. H4, from which this table was copied.



	Lesley (1892)	Lewis and Kümmel (1915)	Stose (1930)	Behre (1933)	Willard (1943)	This report
Subdivisions	Utica and Hudson River Slates	Martinsburg Shale	Martinsburg Shale	Martinsburg Formation	Martinsburg Group	Martinsburg Formation
	Upper series		Lower shaly member (repeated)	Upper "soft" slate member Pen Argyl Beds	Dauphin Shale (repeated)	Pen Argyl Member
				Bangor Beds		Ramseyburg Member
		Upper sandy member	Upper sandy member	Middle sandy member	Shochary Sandstone	
	? Lower series	Lower shaly member	Lower shaly member	Lower "hard" slate member	Dauphin Shale	Bushkill Member
Thickness (feet)	6,000	3,000	3,000	11,800	3,000-4,000	9,800-12,800

Table 04 – Proposed new classification of the Pleistocene deposits of New York City and vicinity
(Sanders and Merguerian, 1998, Table 2)

Age	Till No.	Ice-flow Direction	Description; remarks
Late Wisconsinan ("Woodfordian"?)	I	NNE to SSW	Gray-brown till in Westchester Co., Staten Is., Brooklyn, & Queens (but not present on rest of Long Island); Hamden Till in CT with terminal moraine lying along the S coast of CT; gray lake sediments at Croton Point Park, Westchester Co.
Mid-Wisconsinan (?)			Paleosol on Till II, SW Staten Island.
Early Wisconsinan(?)	II	NW to SE	Harbor Hill Terminal Moraine and associated outwash (Bellmore Fm. in Jones Beach subsurface); Lake Chamberlain Till in southern CT.
Sangamonian(?)			Wantagh Fm. (in Jones Beach subsurface).
	IIIA	NW to SE	Ronkonkoma Terminal Moraine and associated outwash (Merrick Fm. in Jones Beach subsurface).
Illinoian(?)	IIIB		Manhasset Fm. of Fuller (with middle Montauk Till Member; in lower member, coarse delta foresets (including debris flows) deposited in Proglacial Lake Long Island dammed in on S by pre-Ronkonkoma terminal moraine.
	IIIC		
Yarmouthian			Jacob Sand, Gardiners Clay.
Kansan(?)	IV	NNE to SSW	Gray till with decayed stones at Teller's Point (Croton Point Park, Westchester Co.); gray till with green metavolcanic stones, Target Rock, LI.
Aftonian(?)			No deposits; deep chemical decay of Till V.
Nebraskan (?)	V	NW to SE	Reddish-brown decayed-stone till and -outwash at AKR Co., Staten Island, and at Garvies Point, Long Island; Jameco Gravel fills subsurface valley in SW Queens.
			Pre-glacial (?) Mannetto Gravel fills subsurface valleys.

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