DUKE GEOLOGICAL LABORATORY

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TRIPS ON THE ROCKS

Guide 21: Northeastern Newark Basin, New York and New Jersey

Trip 29: 14 November 1993

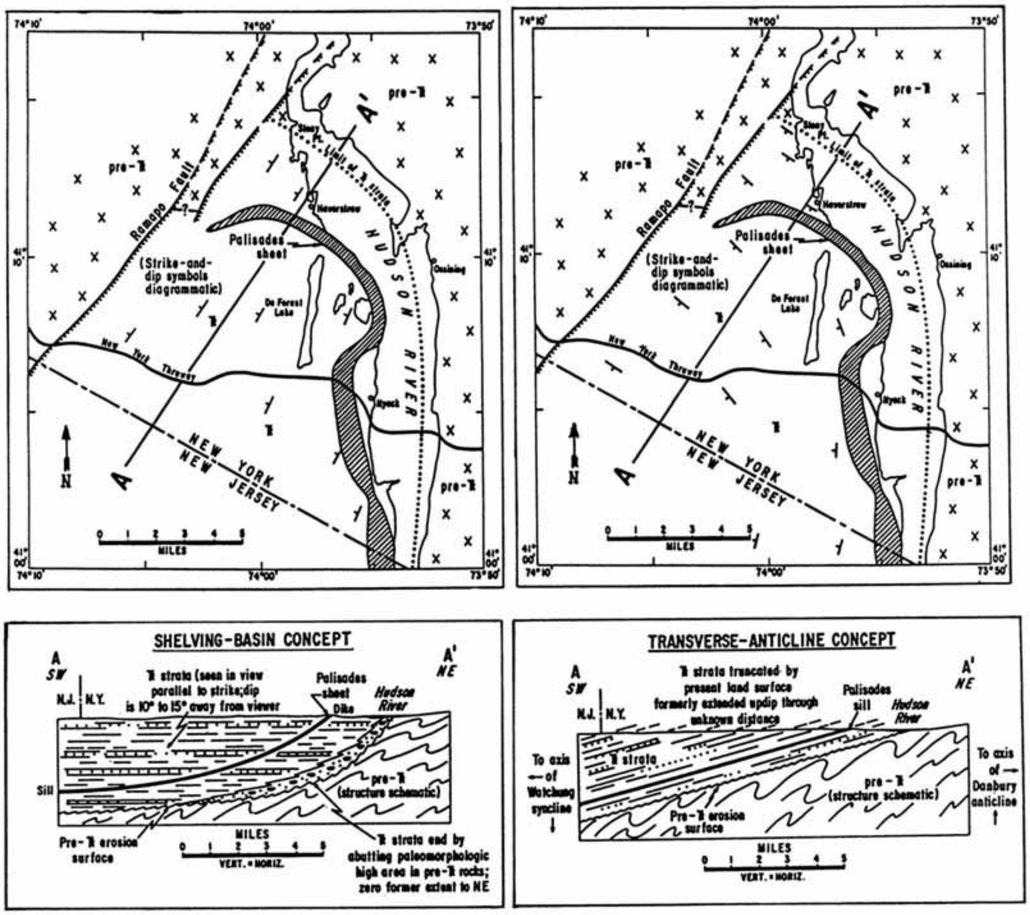

Figure 1. Schematic geological maps of NE end of Newark Basin in Rockland County, NY and profile sections from Hudson River at Haverstraw to NY-NJ state line showing contrasting interpretations of the geological relationships. (From Sanders 1974b, Figs. 7 and 8.)

Field Trip Notes by:

Charles Merguerian and John E. Sanders

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Guide 21: Northeastern Newark Basin, New York and New Jersey

Trip 29: 14 November 1993

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

INTRODUCTION

The Newark basin is considered to end on the northeast where the outcrop belt of the basin-filling strata stops. The modern-day limit of these basin-filling strata more or less coincides with the reach of the Hudson River that extends from the Tappan Zee bridge north to Stony Point. Just S of Stony Point, the boundary between Newark strata and the pre-Newark "basement complex" of metamorphic- and igneous rocks (of Paleozoic- and Proterozoic ages) comes out of the river and curves around to the NW (Figure 1, on cover). The question before us today is: "What are the geologic circumstances that control(led) the northeastward termination of the Newark strata?" An important related question is: "Did the Newark basin, during the time when it was receiving its fill of sediment, end at the present outcrop edge, or did this basin formerly extend farther toward the NE and SE?"

Two polar-opposite answers have been formulated to these questions. As with many polar-opposite positions, they could both be wrong, but only one of them can be right. These two positions are known as the "isolated-basin" school (a synonym with respect to the NE end is "shoaling-basin") and the "broad-terrane" school. According to the "isolated- (or "shoaling-") basin" viewpoint, the Newark strata end where they do because they never extended much beyond the limits of their present outcrop belts. In other words, not only does the modern-day outcrop belt come to an end, but its edge marks the depositional limit during the time of basin filling. What you see is not only what you get, but all you ever had. To use the vernacular, not only is it true that "there ain't no more," but "there weren't never no more." It's all there, folks. Why bother about looking further?

According to the "broad-terrane" concept, as initially proposed by I. C. Russell (1878, 1880), the Newark rocks were deposited as a widespread blanket of strata, covering a much-broader area that extended in all directions away from the present outcrop belts. According to this view, the preservation of the Newark strata as we see them today is merely an artifact of local postdepositional downdropping, tilting, and near-total erosion of the formerly widespread blanket (Figure 2). In other words, the outcrop edge marks nothing more than the limit of erosion; the active basin previously extended beyond the outcrop edge. A key point of the "broad-terrane" concept is that the outcrop edge of the Newark basin-filling strata and the depositional limit of the Newark basin do not coincide.

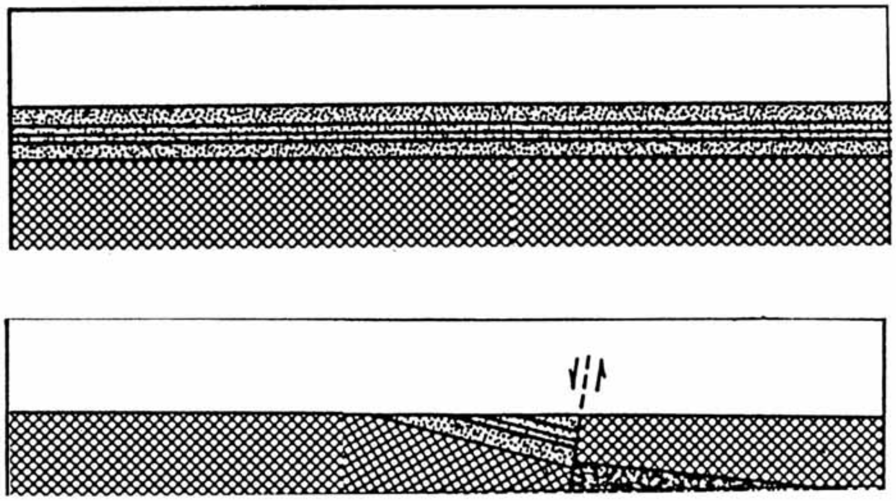


Figure 2. "Broad-terrane" hypothesis for Newark strata, based on I. C. Russell's (1878, 1880) original version that the Newark strata were deposited as a widespread sheet (above), but after uplift, tilting, faulting, and great erosion, have been preserved only on local downdropped blocks (below). (J. E. Sanders.)

A fundamental modification of I. C. Russell's hypothesis was made by Joseph Barrell (1915) in Connecticut [supported later by W. L. Russell (1922), C. R. Longwell (1922, 1928, 1933, 1937), Longwell and Dana (1932), and Krynine (1950)]. Barrell showed that the marginal fault between the Newark-age strata in the Connecticut River Valley lowland in Connecticut and Massachusetts (now known as the Hartford basin) and the pre-Newark rocks underlying the Eastern Highlands had been active during sedimentation. By analogy with features common in the Basin-and-Range province of western United States, Barrell inferred that such a syndepositionally active fault probably served as the eastern limit of the subsiding basin during the time when sediment was accumulating (Figure 3). As a result of Barrell's work, a significant change took place in the "broad-terrane" interpretation. Advocates of the concept that the former extent of the Newark strata was greater than it is now confined the direction of inferred former extensions to the updip edges of the tilted Newark strata (Figure 4).

Figure 1 (on cover) shows the two contrasting interpretations of the NE end of the Newark basin, as schematic geologic maps and as profile sections drawn along the same NE-SW line. In left-hand pair of sketches, the "isolated-basin" viewpoint is expressed as the "shoaling-basin" interpretation (McLaughlin, 1957, p. 1497-1498). [By "shoaling" is meant that the "bottom" (i. e., the surface on the pre-Newark rocks) becomes higher toward the NE; if one visualized the surface of a body of water as a horizontal reference plane, then toward the NE, the water would become shallower, i. e., form a shoal. Hence the use of "shoaling."] A key point about the "shoaling-basin" interpretation is that the modern-day outcrop edge coincides with the original depositional limit. This means that the Newark strata end where they do today because they never extended any farther to the NE: the outcrop edge marks the depositional limit of the basin.

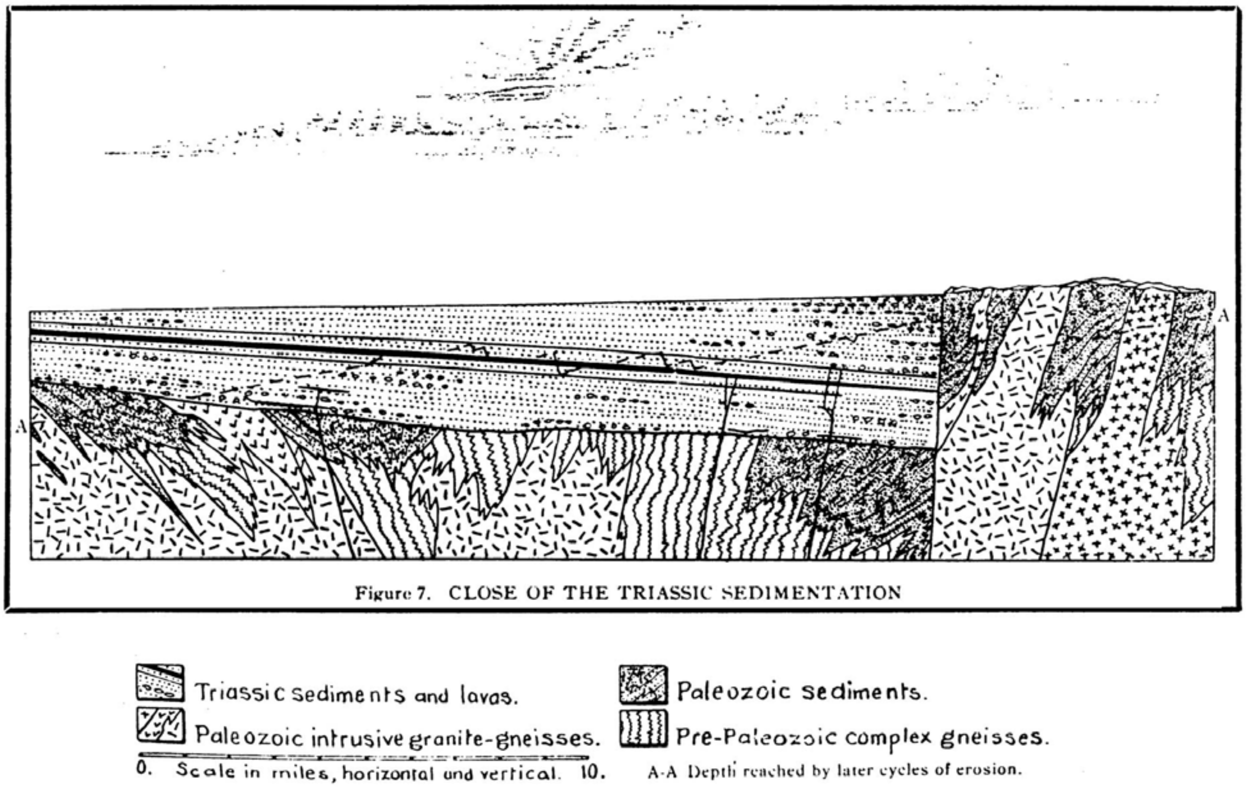


Figure 7. CLOSE OF THE TRIASSIC SEDIMENTATION

Figure 3. Restored profile-section along latitude 40°35'N in central Connecticut showing inferred conditions along E side of Hartford basin at end of episode of sediment accumulation. The basin-marginal fault, which was active intermittently during deposition, marks the general limit of the strata in the direction of the former highland area from which the sediments were derived (at extreme R). (J. Barrell, 1915, fig. 7, facing p. 28.)

According to the way JES applies the modern version of the "broad-terrane" hypothesis to the NE limit of the Newark strata, the modern outcrop edge is nothing more than the limit of erosion. Accordingly, the Newark strata previously extended up the dip both to the SE and to the NE and therefore, the depositional limit of the Newark basin in these two directions was some unknown distance beyond the modern outcrop edge of the basin-filling strata. Because the strata were deposited in horizontal positions, their modern attitudes (i. e., strikes and dips) have resulted from postdepositional uplift (lower right-hand sketch of Figure 1, on cover). According to JES, such uplift took place along two anticlines whose axes intersect at right angles. (1) The axis of one of these anticlines trends NE-SW; it is parallel to the Ramapo fault that formed the basin margin on the NW. JES argues that upward movement along this anticline is responsible for the regional NE-SW strike and NW dips of the Newark basin-filling strata in many parts of northern New Jersey. Because the axis of this regional anticline is parallel to the margin of the Newark basin, JES classifies it as a longitudinal fold. No generally accepted name has been applied to this longitudinal anticline; J. B. Woodworth (1932) referred to it as the "Taconic geanticline" (Figure 5). (2) The axis of the other anticline trends NW-SE, at right angles to the Ramapo fault at the NW margin of the Newark basin. Because its axis is perpendicular to the margin of the Newark basin, JES classifies anticline No. 2 as a transverse fold (Figure 6). Girard

Wheeler (1939) wrote a splendid, but generally ignored, paper about these transverse folds in the Newark basin-filling strata. JES (Sanders, 1960) proposed the name "Danbury anticline" for the transverse fold along whose SW limb the Newark strata in Rockland Co., NY and the base of the Newark curve around toward the NW. As far as we know, JES is the only geologist who has ever used the term "Danbury anticline."

Believe it or not, JES thinks that the correct interpretation about the NE end of the Newark basin can be established by as simple- and as basic a field exercise as obtaining correct readings of the strikes- and dips of the strata. (Some geophysicists refer to this as taking magnetic data!) We plan to visit localities where this can be done. We will make the measurements, and you will then be in a position to decide for yourself which interpretation is correct.

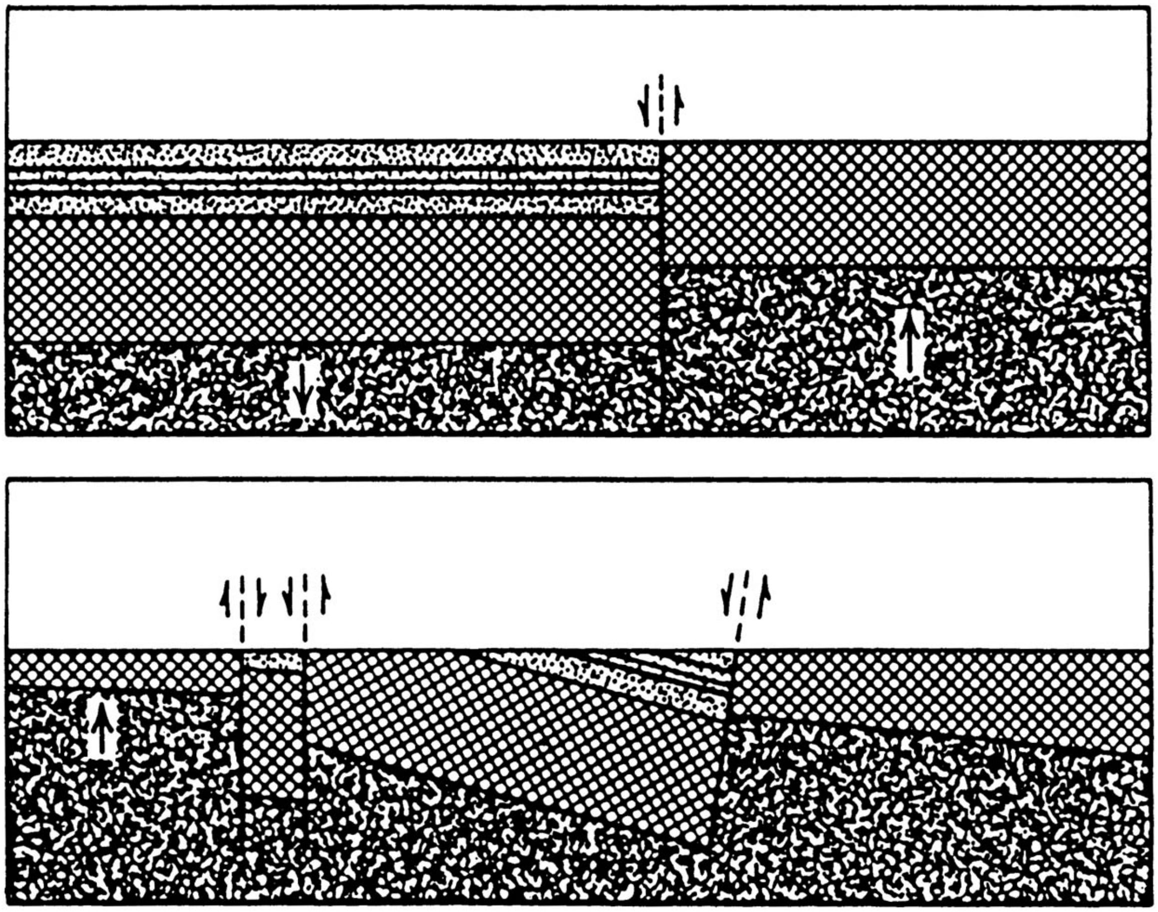


Figure 4. Post-Barrell version of broad-terrane hypothesis for Newark strata showing basin terminating at basin-marginal fault and extending for a considerable distance away from this fault (above). After regional elevation (and other kinds of deformation, not shown) to give the Newark basin-filling strata their existing dips, and much erosion (below), the strata are inferred to have extended more widely only in a direction that is up the regional dip (to left in this example). (After J. E. Sanders in G. M. Friedman and J. E. Sanders, 1978, fig. 14-16, C and D, p. 452.)

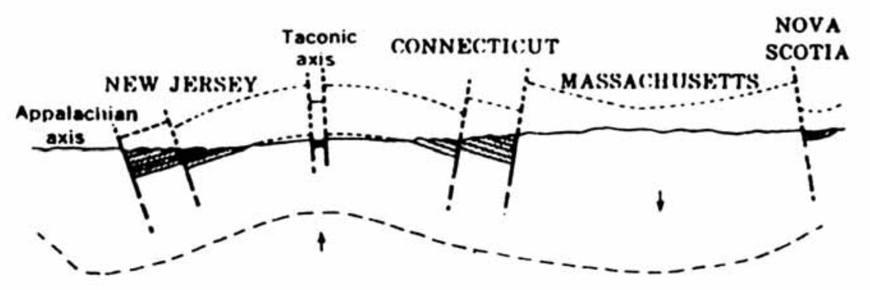


Figure 5. Schematic profile-section from New Jersey to Nova Scotia showing J. B. Woodworth's (1932) interpretation of a broad, regional anticline between the Newark basin-filling strata (under the label New Jersey) and the Hartford basin-filling strata in central Connecticut (under the label Connecticut). The way this profile-section has been drawn, it crosses both the regional longitudinal anticline and the transverse Danbury anticline (of Sanders, 1960). (G. T. Faust, 1975, fig. 8.)

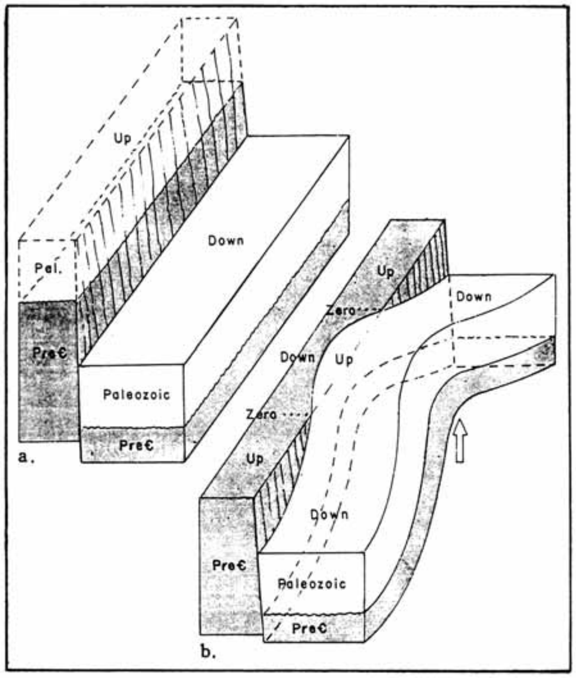
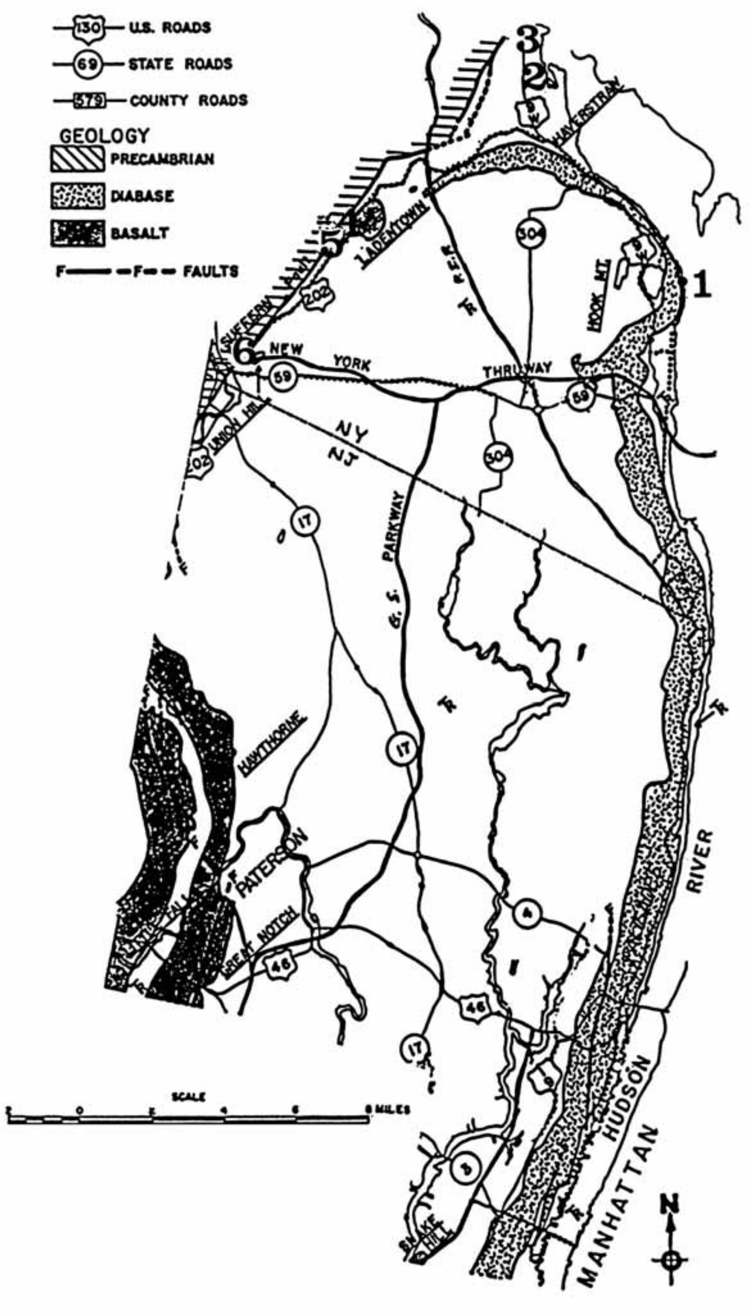


Figure 6. Schematic blocks showing the NW end of the Danbury anticline where it ends against the Ramapo fault. Paleozoic, not subdivided, shown in white; Precambrian rocks, not subdivided, shown by light stipple. In a, the right-hand block has been lowered along the Ramapo fault during the period of sedimentation in the Newark basin (Newark basin-filling strata not shown). During the mid-Jurassic deformation, the Danbury anticline formed (b), causing a sector of the formerly dropped block to be raised by an amount greater than it was previously dropped (the exact amount is whatever was required to give a SW dip of about 12° to the Newark strata in Rockland County, NY). Notice that after the Danbury anticline has formed, the displacement on the Ramapo fault diminishes to zero toward the NE, then reverses (at the axis of the Danbury anticline). Still-farther to the NE, the sense of movement returns again to zero and then increases further toward the NE. (J. E. Sanders.)

Another topic of disagreement that is closely coupled to interpretations about why the Newark basin ends where it does is over the interpretation of the extrusive basalts at the Union Hill quarry, in the town of Suffern, Rockland County, NY; and in the outcrops at Ladentown (Figure 7) and whether or not these extrusives are now or ever were physically connected to the Palisades intrusive sheet.



TRIASSIC SEDIMENTARY ROCKS (Ꞧ) HAVE NOT BEEN DIFFERENTIATED.

Figure 7. Geologic sketch map showing major roads, localities, Newark-age igneous rocks, and trip stops. (E. L. Savage, 1968, fig. 1, p. 50.)

According to advocates of the "shoaling-basin" school, the Palisades sheet changes from being a sill near the base of the Newark strata and cuts discordantly upward through virtually the entire thickness of the Newark Supergroup (Figure 8) and thus served as a feeder to the extrusive basalts at Union Hill and Ladentown. We discuss several aspects of this point about the bodies of igneous rock, including the possibility of resolving the dispute by means of a little "geobarometry." (That's a twenty-five dollar word for using pressure-sensitive minerals to infer the depth within the Earth at which a mineral lattice grew.) If the Palisades sheet orginally cut upward from near the base of the Newark Supergroup to feed a lava flow at the former surface of the sediment fill in the Newark basin, then within the magma that cooled to form the Palisades intrusive igneous rock, a pressure gradient equal to the stratigraphic thickness from near the base of the Newark Supergroup to the base of the Ladentown Basalt must have existed. Minerals within the sill part would have crystallized under the pressure prevailing at considerable depth, possibly 2 or 3 km, whereas those that crystallized within the putative feeder channel to the Ladentown Basalt would have grown under progressively lower pressures along the outcrop toward the NW, finally reaching virtually atmospheric pressure.

Other work related to the origins of these extrusives and their relationships to the Palisades sheet has involved collecting cores from selected drill holes and making chemical analyses of the rocks (Ratcliffe, 1980, 1982, 1988; Puffer, Geiger, and Camanno, 1982) and carrying out gravity- and magnetic geophysical surveys (Kodama, 1983). We discuss the igneous rocks in the section on Geologic Background and again in the text describing Stop 4.

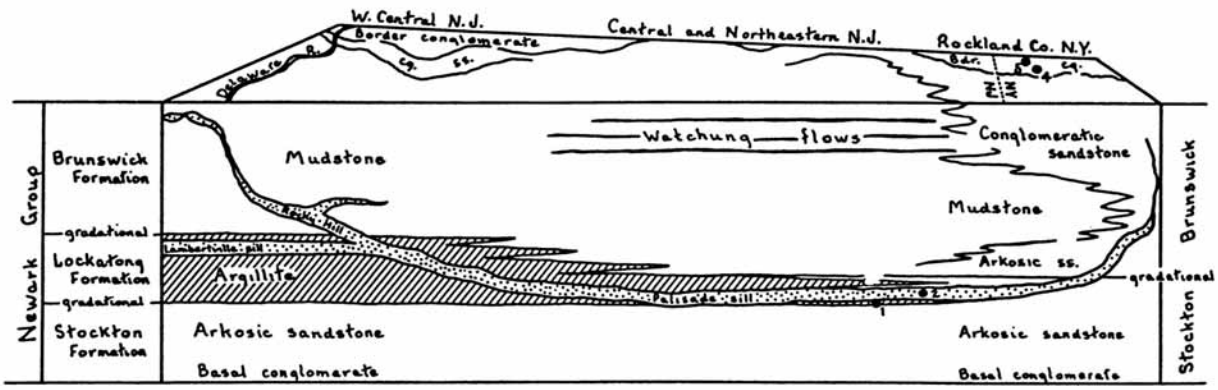


Figure 8. Schematic view of Newark basin looking toward the basin-marginal Ramapo fault from a point above Manhattan, NY. Shown on the front panel are the argillite of the Lockatong Formation (diagonal parallel lines), the intrusive sheets (stipple pattern), the three Watchung extrusive sheets (thin lines) and local conglomerates. The relationships sketched are based on the views of H. B. Kümmel (1900) and others that in Rockland County, NY the only deformation of the Newark basin-filling strata has been a simple tilting toward the NW along a major longitudinal anticline. The prominent curvature to the NW of the Palisades ridge is inferred to be the result of the effect of this regional tilting to the NW of a sheet of igneous rock that changes from being concordant where it intrudes the Lockatong Formation (and thus locally a sill) to discordant (a dike). Where the Palisades sheet is shown as a dike, it cuts across the strata from near the base of the Newark Supergroup to near the top (extreme R). (F. B. van Houten, in E. Lynn Savage, 1968, fig. 2, p. 52.

PHYSIOGRAPHIC SETTING

Today's trip will begin on the Manhattan Prong of the New England Upland province of the Appalachians, cross the Hudson River, and there pass through the northeastern end of the Newark basin "Lowland." We will also trespass on the Ramapo Mountain block, which bounds the Newark-basin lowland on the NW, and a small outlier of the Manhattan Prong that exists west of the Hudson River at Stony Point. The "bird's-eye" view of the territory shown in Figure 9 displays the prominent ridge (the Palisades) that frames the Newark-basin lowland on the NE and SW sides. We describe the Newark-basin lowland first and then move on to its surroundings.

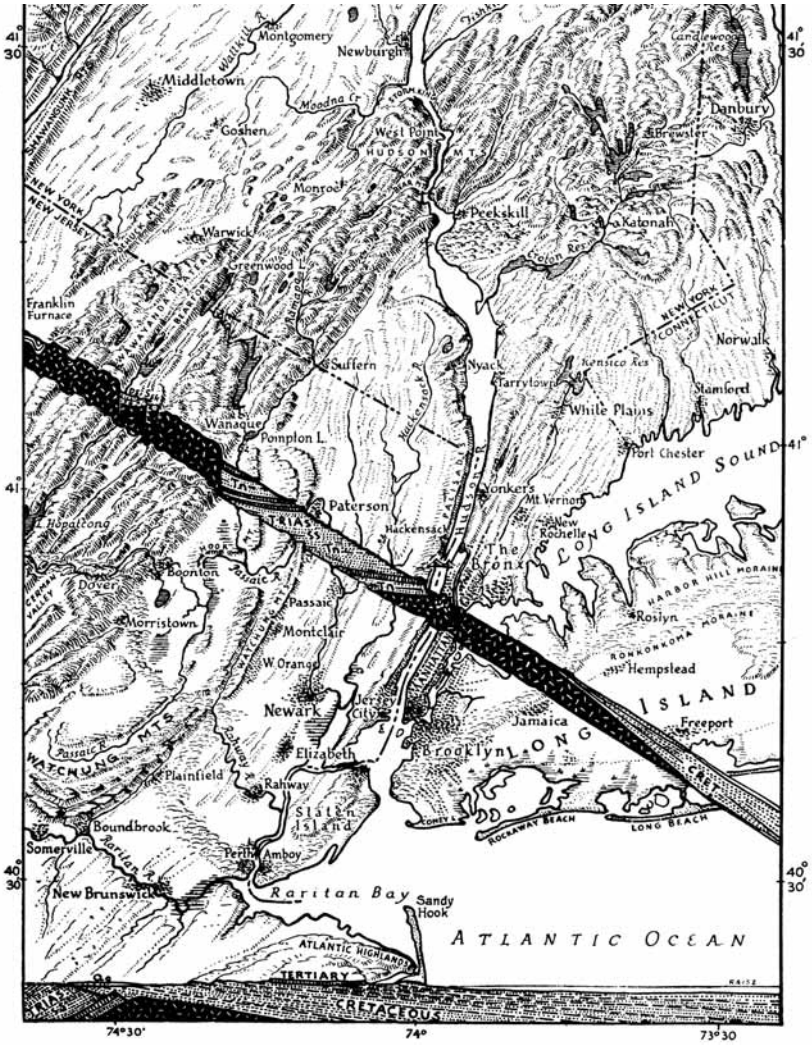


Figure 9. Physiographic diagram of northern New Jersey and adjacent SE New York showing part of the Manhattan Prong, Newark-basin lowland, and Hudson Highlands. The vertical cutaway slice shows the effect of regional tilting of the Newark basin-filling strata (labeled as Trias ss) toward the NW along the NW limb of the longitudinal anticline having its NE-SW-trending axis passing through western Connecticut. Notice the general similarity of the curvature of the Palisades sheet and that of the NE ends of the First and Second Watchung ridges. (E. Raisz, but with labels under Long Island modified by the authors.)

As mentioned, the Palisades ridge, which forms the most-prominent landscape feature along the W side of the Hudson River, is something of a misnomer with respect to the Newark-basin "lowland." The Newark-basin so-called "lowland" does not begin until after one has passed beyond this prominent ridge. The altitude on the crest of the Palisades ridge reaches a maximum at High Tor (UTM coordinates 586.8E - 4559.8N, Haverstraw 7.5-min. quadrangle; more than 810, less than 820 ft. according to the 10-ft contours on the Haverstraw quadrangle, but 827 on the lower profile of Figure 10) and becomes less both to the W and S. The crestline is broken by several prominent gaps, at Short Clove and Long Clove just SE of High Tor (Haverstraw quadrangle), near Nyack (used by the NY Thruway approach to the Tappan Zee Bridge), and Sparkill Gap at Piermont and the adjacent area of Tallman Mountain State Park (Nyack quadrangle). According to Thompson (1959, p. 1106) both of the two chief previous students of the geology of Rockland County (Darton, 1890 and Kümmel, 1900) believed that streams formerly crossed the Palisades ridge through these gaps. (Today, Sparkill Creek is the only stream that crosses the Palisades ridge; it does so by flowing northeast into the Hudson. Previously, according to Douglas Johnson, 1931, the Hudson itself flowed SW through Sparkill Gap.) Thompson argued convincingly that these gaps are related to faults that have offset the resistant igneous rock. We return to this topic in the section on the Geologic Structure of Rockland County.

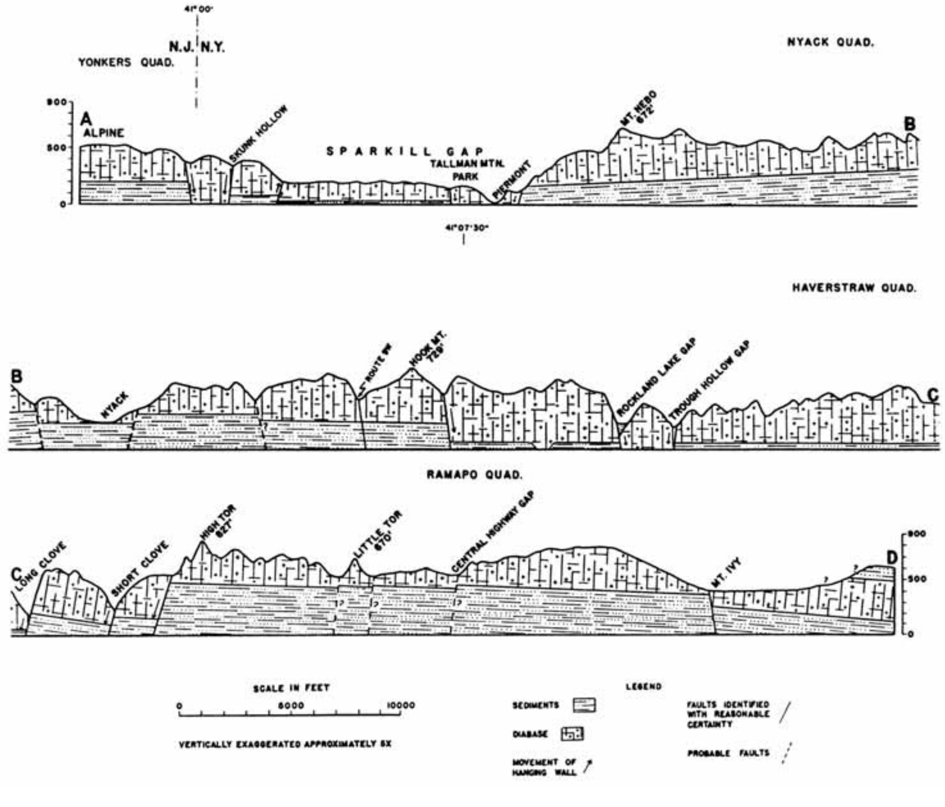


Figure 10. Profile-sections of the scarp face of the Palisades ridge from just S of the NY-NJ state line to the termination of the ridge just W of the Palisades Interstate Parkway. The basal contact of the Palisades sheet is interpreted as being concordant (a sill) with changes in altitude of the contact resulting from displacement along high-angle faults. (H. D. Thompson, 1959, fig. 3, p. 1110, with layout changes made by authors.)

The Palisades ridge ends on the W just beyond the Palisades Interstate Parkway. As described by Thompson (1959, p. 1118):

> "At Mt. Ivy the ridge terminates by sloping down from an altitude of 750 feet to the general level of the country at about 400 feet, and the traprock disappears beneath a covering of glacial overburden. Although the dip of the enclosing sediments (sic) becomes westerly in this vicinity, the slope of the end of the ridge is substantially greater than the westward inclination of the rocks. A contributing cause for the termination of the ridge at this place appears to be that of downfaulting on the west. In the road cut of the Interstate Parkway the diabase in shattered and slickensided, and the columnar joints are well obscured by other fractures. That the base of the diabase did not here rise to the surface is attested by a recent well at the home of T. J. Connor, just west of Route 45. The bottom of this well, 100 feet below the surface, is still in the diabase. Another suggestion of faulting at Mt. Ivy is a traprock quarry located where the diabase is already fragmented to a size for easy handling.
>
> "The present rather gradual slope at the termination of the range does not reflect the angle of the fault here. Perhaps the fault has (sic) a high angle, but subsequent weathering and mass movement have subdued the slope. In addition, the Pleistocene ice, moving southward through this lowland, also modified the structural slope by abrading it and by leaving a mantle of till and outwash in the lowland."

The morphologic aspect of the Newark-basin lowland in Rockland County has resulted from the effects of the most-recent Pleistocene glacier (the Woodfordian), which flowed almost due N-S across this region. The most-prominent hills, having relief of up to 200 feet and whose tops typically reach altitudes of 600 ft or more) are enormous ridge-like drumlins (or drumlinoidal hills). JES notes a close analogy with the topographic relationships in south-central Connecticut. Wherever the last ice sheet was forced to flow across a ridge underlain by igneous rock that trended across the direction of ice flow, the glacier tended to plaster the countryside just S of the ridge with drumlins.

In the old days in Rockland County, many apple orchards were planted on these hills. (For many years, this relationships between drumlins and apple orchards rejoiced under the banner of "Sanders' Law." Among the reprints that JES inherited from Prof. C. H. Behre's reprint collection, however, was an article by R. B. Millington, 1930, clearly stating the connection between apple orchards and drumlins in central Massachusetts and explaining why.

Hereafter, we shall refer to the drumlins-orchards association as Millington's Law.) Today, these hills "grow" housing subdivisions.

No prominent ridges other than the Palisades are present to reflect the structure of the bedrock. As we shall see, earlier geologists evidently presumed that these linear ridges resulted not from glacial action but are strike ridges thus reflecting the structural grain of the bedrock. For example, if one regards the prominent N-S-trending ridges in the SW part of the Haverstraw 7.5-min. quadrangle (say between Rockland Lake and De Forest Lake) as strike ridges underlain by the Newark sedimentary strata, then one could easily accept the notion that the curving part of the Palisades ridge at Verdrietege Hook is caused by a discordant sheet of igneous ("city") rock that is cutting upward through the strata of the country rock. Consult your friendly neighborhood strikes and dips on this topic.

The Newark-basin lowland ends on the NW against the steep wall-like SE side of the Ramapo Mountains whose rounded hilltops reach altitudes of about 1000 feet. In Rockland County at the base of this steep slope, the Mahwah River flows SW along a swampy lowland at altitude 400 feet. Buried beneath this swampy lowland is the Ramapo fault, which separates the Mesozoic rocks of the Newark-basin fill from the Proterozoic rocks underlying the Ramapo Mountains, which are part of the Hudson Highlands physiographic province. As Ratcliffe (1970, 1971) has demonstrated, the Ramapo fault is a veritable geologic Methusala; its period of activity stretches back more than 1 billion years! Nearly all modern-day geologists agree that the Ramapo fault was particularly active during the time when the Newark basin formed and was filling. Indeed, the coarse basin-marginal rudites that are scattered through such a large stratigraphic thickness within the Newark Supergroup indicate that the NW side of the Ramapo fault (marked by today's Ramapo Mountains) was repeatedly elevated and the SE side (marked by today's Newark-basin lowland) repeatedly depressed. A point on which less agreement exists among modern-day geologists is how much, if any, and what kind(s) of movement took place along or near the Ramapo fault after the Newark basin had been filled with strata. Either way, the modern topographic scarp and the scarp that probably existed during Late Triassic and Early Jurassic time are more or less the same. We suspect that the Ramapo Mountains might have penned in the dinosaurs that wandered about in the Newarkian "Jurassic Park."

The last bit of physiographic description that we include includes the extreme NW corner of the Haverstraw quadrangle, in the vicinity of Stony Point State Park. In this small area are rocks that belong to the Cortlandt Complex, the bulk of which is exposed on the E side of the Hudson River (OTR trip 14). The rounded rocky knoll known as Stony Point displays many varieties of igneous rocks. Nearby are the metamorphosed equivalents of the Ordovician terrigenous Tippecanoe Sequence (the "Good Old Manhattan Schist") and the Cambro-Ordovician Sauk Sequence carbonate rocks (that were quarried at the large Tomkins Cove quarry (but Inwood marble in the contact aureole of Cortlandt plutons).

GEOLOGIC BACKGROUND

Under this heading, we discuss the bedrock units (pre-Newark "basement" rocks and the Newark basin-filling strata and associated mafic igneous rocks); the geologic structure of Rockland County, NY; and the Pleistocene glacial sediments. Refer to Table 1 for a generalized tabular summary of the geologic history of southeastern New York and vicinity, to Table 2 for a generalized description of the major "layers" of rocks in southeastern New York and vicinity, and to Table 3 for our interpretation of the Pleistocene glacial sediments.

BEDROCK UNITS

The central focus of today's trip is the Newark Supergroup, which we list collectively in Table 2 as Layer V. The Newark Supergroup rests with profound angular unconformity atop folded- and faulted units of Layers I and II, the pre-Newark complex of Paleozoic- and older metamorphic rocks that underlies the Manhattan Prong of the New England Uplands (Figure 11). Rocks of Layer I crop out immediately west of the Ramapo fault zone. Here, they underlie the Ramapo Mountains, a tract of hilly, highly glaciated crystalline rocks whose lithologic units trend northeast-southwest parallel to that of the range.

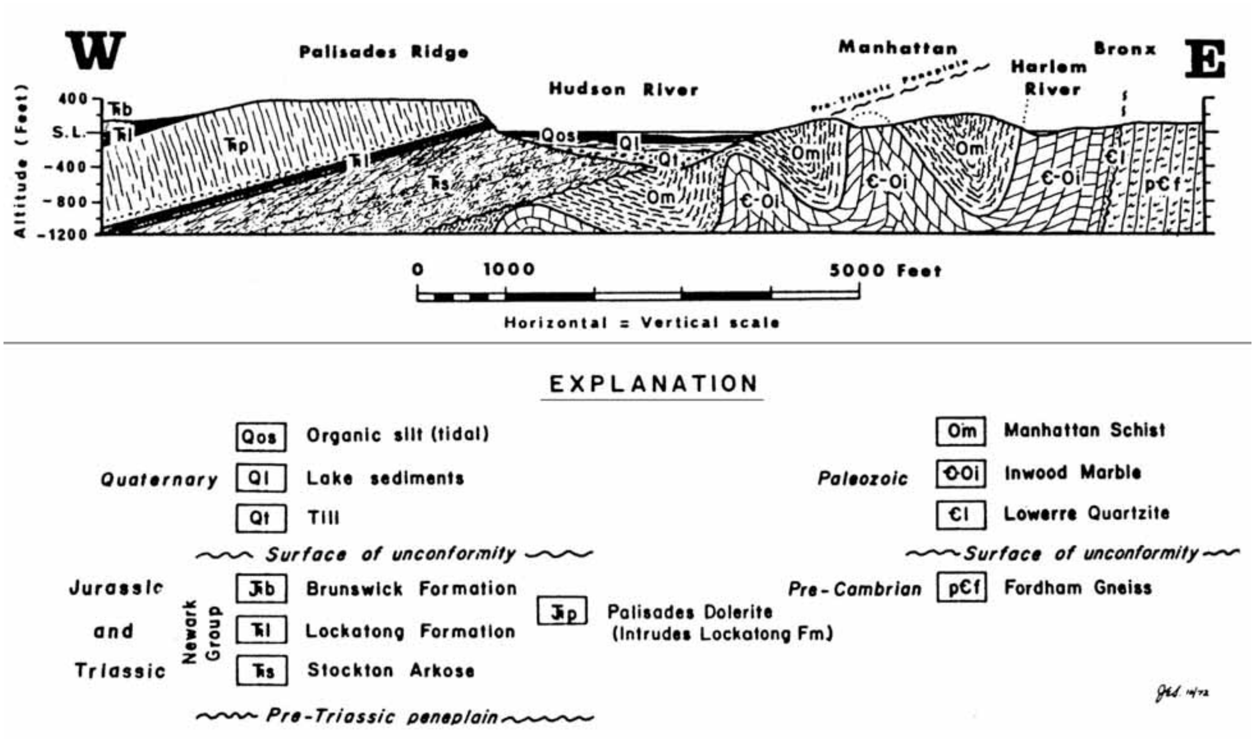


Figure 11. Profile-section across Hudson River at George Washington Bridge. Topography from United States Geological Survey Central Park 7.5-minute quadrangle. (J. E. Sanders, 1974a, Fig. 3, p. 11.)

These rocks lie along strike and are continuous with correlative rocks of the Hudson Highlands examined on our NYAS On-The-Rocks Trips Nos. 2 and 14. And, as we saw on the trip to Staten Island (On-The-Rocks Trips Nos. 4 and 19), the tilted- and eroded edges of the Newark strata were overlapped and covered by the strata of Layer VI, the coastal-plain strata. Although we will not study the coastal-plain strata on today's trip, we mention them because they are products of a totally contrasting geologic setting from the Newark basin-filling strata, and their position above the tilted- and eroded Newark strata places a definitive upper limit on the time of the deformation of the Newark strata (pre-Late Cretaceous) by an amount of time sufficient to enable the Newark strata to have been deformed and trucated by erosion). We review these layers in general terms, starting with the oldest and progressing to the youngest.

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

Before we begin our geological journey from the New York Academy of Sciences, a few thoughts about the rocks beneath our feet. The crystalline bedrock of New York City marks the southern terminus of an important sequence of metamorphosed Proterozoic- to Lower Paleozoic rocks of the Manhattan Prong (Figure 12) which widens northward into the New England Upland physiographic province.

The oldest rocks of the Manhattan Prong do not crop out in Manhattan. These oldest rocks consist of a sequence of layered feldspathic- and massive granitoid gneiss, amphibolite, and calc-silicate rocks of uncertain stratigraphic relationships known as the Fordham and Yonkers gneisses (Layer I). These formations were complexly deformed during the Grenville Orogeny roughly 1.1 Billion years ago. This complexly deformed basement sequence of Layer I represents the ancient continental crust of proto-North America.

The Paleozoic bedrock units in New York City (Layer II) now form a deeply eroded sequence of highly metamorphosed-, folded- and faulted sedimentary- and igneous rocks (Figure 13). After the older basement complex had been exposed, eroded, and subsided the Paleozoic units were deposited above them. This pre-Paleozoic erosion surface marks a gap in the geologic record known as an unconformity. It has been encountered in numerous borings and has been mapped by Hall (1968a,b) in White Plains, New York, and vicinity.

The formations of Layer II were deposited as thick accumulations of both shallow- and deep-water sediments adjacent to the Early Paleozoic shoreline of proto-North America roughly 500 million years ago. 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. Layer IIA can be split into two facies that differ in composition as a function of 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 (originally sandy and limey sediments, respectively; it is the eastern part of the Sauk Sequence of Sloss, 1963). Farther east, in the former offshore direction (which happens also to be the same as the offshore direction today), fine-textured terrigenous time-stratigraphic equivalents of the shallow-water strata of the shelf sequence were evidently deposited in deep water [Layer IIA(E)], possibly on oceanic crust. This inferred deep-water sequence is also of Cambrian to Ordovician age. In upstate New York, it is known as the Taconic Sequence (named from the Taconic Range, where it is prominently exposed) and in Manhattan, as units Ꞓ-Om and Ꞓ-Oh of the Manhattan Schist(s). (See Figure 13 and as described below.)

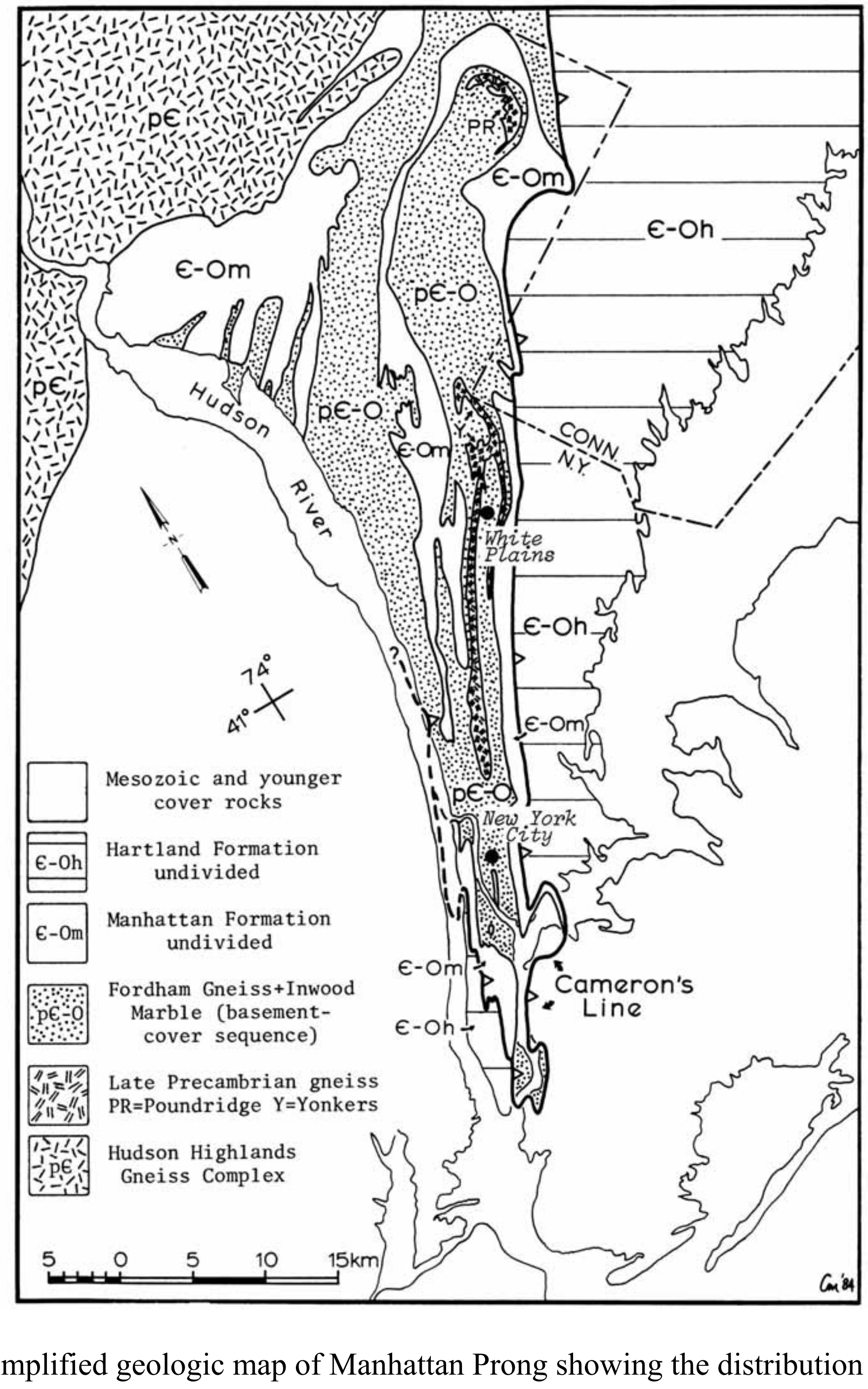


Figure 12. Simplified geologic map of Manhattan Prong showing the distribution of metamorphic rocks ranging in ages from Precambrian to Early Paleozoic. Most intrusive rocks have been omitted. (Mose and Merguerian, 1985).

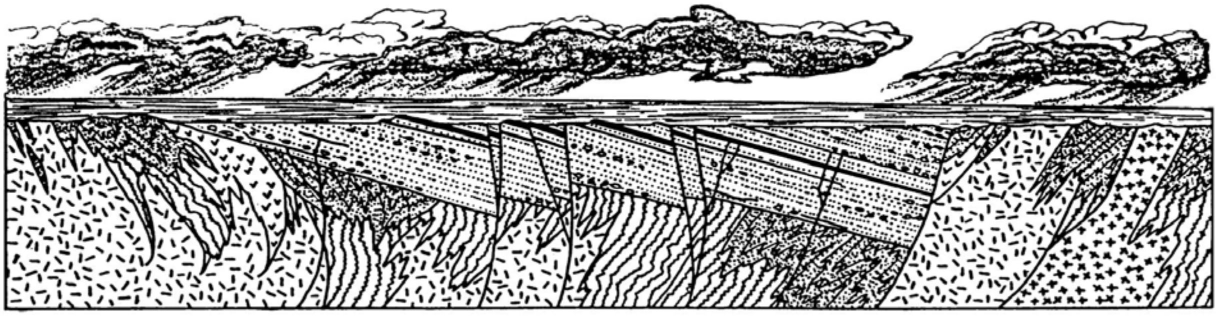


Figure 13. Geologic map and section of Manhattan. (C. Merguerian, unpublished data.)

Layer IIB consists of younger strata that depositionally overlie, and thus were originally above, the western shallow-water platform/shelf strata [Layer IIA(W)] of the Sauk Sequence. In New York City, it is the Manhattan Schist unit Om, which belongs to the lower part of the Tippecanoe Sequence of Sloss (1963). According to CM, at Inwood Hill Park in Manhattan (NYAS On-The-Rocks Trips Nos. 3, 16, and 21), this unit (Om) is demonstrably interlayered with the Inwood Marble and contains thin layers of calcite marble (Balmville equivalent) at its base. This field evidence is used to indicate that unit Om of the Manhattan Schist(s) is in place where found and is therefore not older nor the same age as Manhattan units Ꞓ-Om and Ꞓ-Oh. Accordingly, it should not be classified with these two units.

During a series of Paleozoic mountain-building episodes (the Taconic, Acadian, and Appalachian orogenies), the sedimentary protoliths [Layers IIA(W and E) and IIB] of the New York City rocks were folded and metamorphosed into the Lowerre Quartzite, Inwood Marble, and Manhattan Schist(s). Here, the term schist(s) is intentionally plural to indicate that the Manhattan Schist is actually composed of three, ductile-fault-bounded units (Units Om, Ꞓ-Om, and Ꞓ-Oh in Figure 13) that were imbricated during the Taconic orogeny (Merguerian, 1983a, Merguerian and Baskerville, 1987).

Much of the bedrock in New York City (OTR Trips 16, 26, and 28) is therefore interpreted as being allochthonous (a fancy term intended to confuse the layman which simply means transported from somewhere else or not deposited where found today!) and the root zone for much of this sequence is thought to be from the broad tract of land to the east of Cameron's Line in western Connecticut (Merguerian, 1983b).

As such, Cameron's Line, which is now traced through the heart of New York City, marks a fundamental plate-tectonic boundary separating autochthonous rocks (another fancy word to confuse and impress the general public which means "in place" or deposited where found) of North America (the Fordham, Lowerre, Inwood, Manhattan Unit Om) from allochthonous rocks of the Manhattan Formation (Ꞓ-Om and Ꞓ-Oh). Merguerian's mapping in New York City and New England indicates that the allochthonous Manhattan Schist(s) are directly correlative with rocks of western Connecticut and Massachusetts along the east flank of the Berkshire and Green Mountains massifs. A simplified geologic section is shown in Figure 11 which is drawn roughly east-west across the latitude of the George Washington Bridge (GWB).

Note that the New York City bedrock units are strongly folded into overturned anticlines and synclines and unconformably overlain by the Newark Supergroup. The unconformity surface projects out of the Hudson River over Manhattan and dips toward the west along with the overlying units of the Newark Supergroup.

Layer V: Newark Basin-Filling Strata and Associated Mafic Igneous Rocks

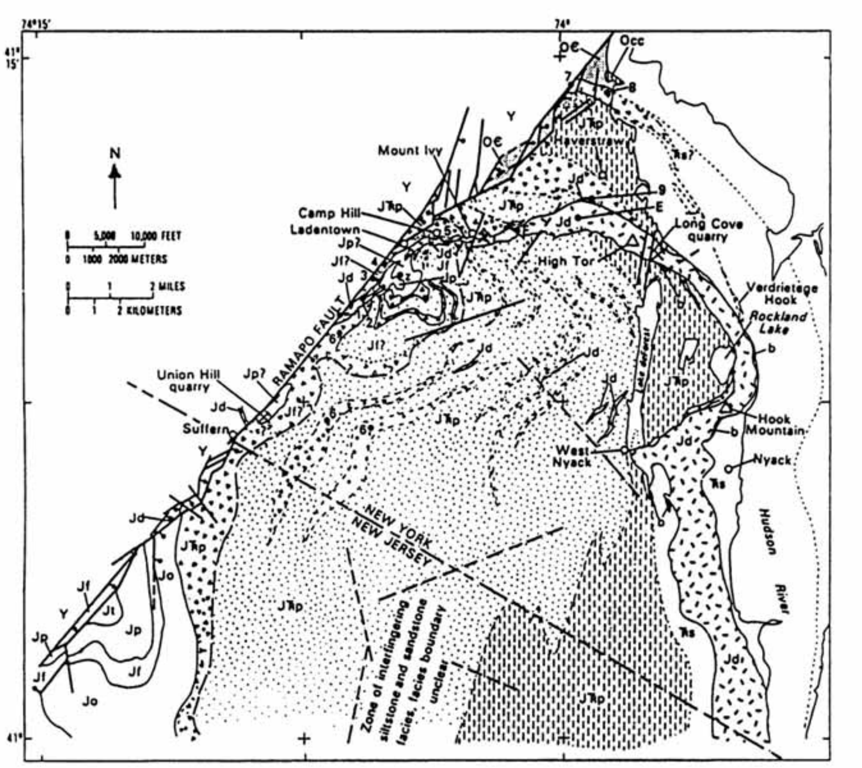
The Newark Supergroup is a thick sequence of Upper Triassic to Lower Jurassic (Mesozoic) sedimentary strata and interbedded sheets of mafic volcanic rocks whose basal part was intruded by a thick body of mafic magma that cooled to form intrusive igneous rock of the Palisades Sill. We discuss these further under the heading of sedimentary strata and mafic igneous rocks.

Sedimentary Strata

Figure 14 shows a schematic geologic map of the northeast end of the Newark basin based on Nick Ratcliffe's mapping in 1979-1981. The EXPLANATION lists the currently accepted names of the formations for most of the Newark Supergroup (based on Paul Olsen, 1980). Not present in this explanation are the Lockatong Formation, which separates the basal Stockton Formation fom the overlying Passiac Formation; and the uppermost extrusive sheet (Hook Mountain Basalt) and the sedimentary strata that overlie it (Boonton Formation).

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

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



Schematic geologic map of southern Rockland County, New York, and northern Bergen County, New Jersey, showing the location of drill sites, the relationship of igneous rocks to strata of Triassic and Early Jurassic age, and the disposition of basalt flows and intrusives (based on mapping by Ratcliffe in 1979–81). Localities 1–9 discussed in text.

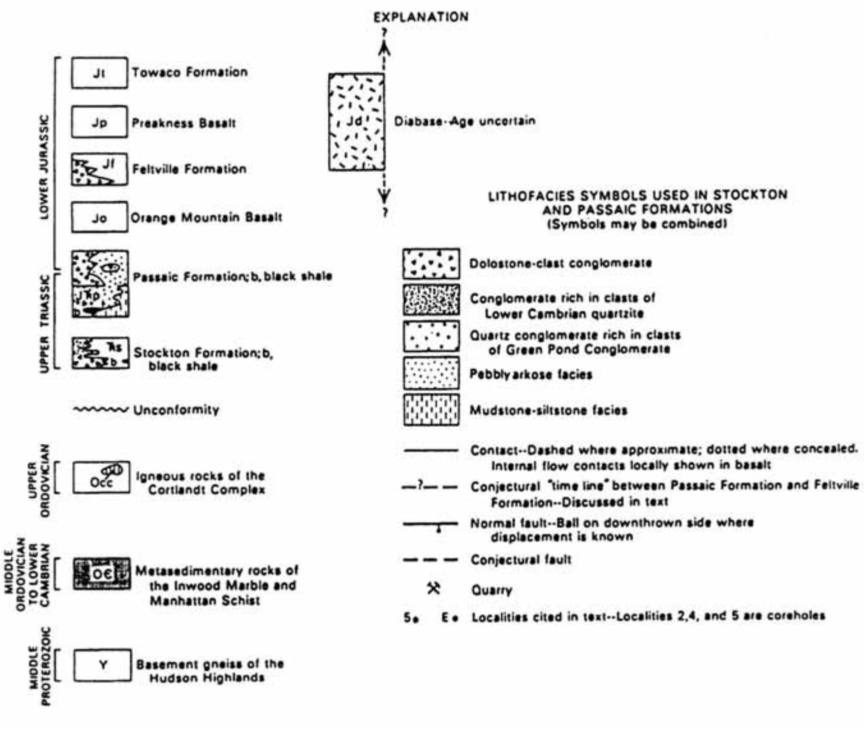


Figure 14. Schematic geologic map, NE Newark basin & vicinity based on geologic mapping in 1979-1981 by N. M. Ratcliffe. (N. M. Ratcliffe, 1988, fig. 1, p. 116-117.)

Where the three well-known sheets of extrusive basalt (First-, Second-, and Third Watchung basalts; named by Paul Olsen, the Orange Mountain Basalt, Preakness Basalt, and Hook Mountain Basalt, respectively) and/or the distinctive black argillites of the Lockatong Formation are present, the Newark sedimentary strata are easy to subdivide. But where one is faced with an isolated exposure of a Newark-type reddish-brown sandstone, -siltstone, or -shale, or even a coarse conglomerate with reddish-brown sandstone matrix, the problem of assigning the correct formation verges on hopeless. Ultimately, some mineral- or lithologic criteria may prove to be helpful for stratigraphic assignment. For example, progressively deeper erosion in the elevated Ramapo block that supplied sediment from the NW side of the Newark basin may have reached a distinctive rock type. Accordingly, the first appearance of that rock type in the Newark strata would mark a distinctive level in the sediments derived from that particular drainage network. Similarly, a radiogenic age on a feldspar may serve the same purpose (Abdel-Monem and Kulp, 1968). In this connection, Ratcliffe (1980, 1988) has pointed out several significant provenance relationships: boulders in the Newark derived from contact-metamorphosed Manhattan Schist near the Cortlandt pluton complex and fragments of dike rocks from Rosetown suite of igneous rocks. Unfortunately, the stratigraphic levels at which these distinctive rocks appear is not known with certainty. Therefore, at the present time, the problem of the correct stratigraphic position of isolated exposures of Newark sedimentary strata is bedeviled with uncertainty.

An important general characteristic of the Newark sedimentary strata is that near the basin-marginal Ramapo fault, nearly all of them pass laterally into coarse basin-marginal rudites. Such rudites have long been known under the name of "border conglomerates" (J. K. Roberts, 1928) or "fanglomerates." By whatever name they are known in this world, they imply that at the foot of the basin-marginal escarpment was a virtually continuous supply of coarse sediment. Ever since 1915, when Joseph Barrell published his analysis of central Connecticut in the geologic past, nearly all geologists familiar with the Newark strata have adopted the view that all this coarse sediment (some angular, some rounded) implies that the relief was continuously rejuvenated by recurrent uplift along the basin-marginal fault block.

Ratcliffe is something of a dissenter on this subject. He rejects the evidence for significant syndepositonal movement on the Ramapo fault (Ratcliffe, 1980, p. 288). In so doing, we think he too-casually ignores the evidence from the stratigraphic distribution of basin-marginal rudites near the Ramapo fault. The same kind of evidence has been compiled from the Newark strata filling the Hartford basin in south-central Connecticut (W. L. Russell, 1922; C. R. Longwell, 1922, 1929, 1937). The definitive proof comes from making a traverse parallel to the basin-marginal fault where one of the transverse folds extends to the basin-marginal fault. In such a setting, a traverse parallel to the basin-marginal fault crosses the strata at right angles to their strikes. Almost no other kinds of rocks except coarse basin-marginal rudites are present through a stratigraphic range spanning at least 1010 m of sedimentary strata (not counting the thickness of the extrusive sheets), from the Boonton Formation above the uppermost extrusive sheet to the Passiac strata underlying the lowest extrusive sheet (Sanders, 1972). (In New Jersey, this includes the Towaco Formation and the Feltville Formation, and the top part of the underlying Passaic Formation).

Mafic Igneous Rocks

Newark mafic igneous rocks include both intrusives (the Palisades sheet in Rockland County, NY) and extrusives (the three "Watchung" basalt sheets in the Watchung syncline and several scattered areas along the Ramapo fault in Rockland County, NY: Union Hill and Ladentown.

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

In discussing this topic (without being very careful to distinguish magma from igneous rock), Ratcliffe (1988, p. 114) reviewed the work of K. R. (not Frederick) Walker:

> "As far north as the Haverstraw quarry at Long Cove (sic), Walker (1969) could define the base of the second Palisades magma (sic) by the bronzite dolerite 34 m above the base of the sill. According to Walker (1969), the upper chill zone of the Palisades was quenched from the initial magma pulse as well. According to Walker, the upper (sic) and lower chill compositions of the sill should be identical and representative of the melt composition. Recent work by Shirley (1985) in the area of Walker's (1969) Edgewood Cliffs section has discovered evidence for a third pulse of magma 60 m above the base. The remaining 80 percent of the sill then crystallized as a closed system having variable percentages of trapped residuum locally affected by compaction and filter pressing. According to Shirley (1985), the upper chill contact and the internal contact 60 m above the base may represent this last magma pulse, which is different from the magma (sic) quenched at the lower contact."

Ratcliffe also reviewed the results of chemical analyses made by Puffer and others (1982) from specimens collected from the northern Palisades, from the Ladentown area, and from the basalts at Union Hill:

> "They conclude that the northern part of the Palisades sampled by them consists of slightly differentiated magma (sic) characteristic of the bulk of the second pulse of Palisades magma (sic),

> having a relatively low (sic) and restricted range of MgO (5-6 percent). The normal chill composition of the first pulse of the Palisades magma as recognized by Walker (1969) is MgO rich (7.5 percent) and similar to that of the Orange Mountain Basalt. Puffer and others (1982) propose that the initial Palisades magma extruded to form the Orange Mountain Basalt and that the second Palisades magma (the one that differentiated to form the diabase of northern Palisades) erupted to form the basalts at Ladentown. Ratcliffe (1980, 1982) proposed that the basalts at Ladentown formed from a fissure-flow eruption of Palisades sill (sic) magma but chose not to assign a time for that extrusive event."

Apart from the evidence based on chemical analyses of major elements, the timing of extrusions can be viewed with relationship to basin-marginal rudites containing clasts of basalt. For example, if an extrusive sheet is found overlying a rudite containing basalt clasts, then such an extrusive cannot be the oldest extrusive sheet. A still-older extrusive is required--one that extended across the Ramapo fault and then cooled so that during subsequent uplift, basalt would be available for recycling as clasts back into the Newark basin.

Use of a basalt-clast rudite in this way can be done accurately only if one knows the full record of episodes of extrusion. As noted previously, all the Newark basalt sheets include at least 2 or more flow units. At issue is whether these isolated basalts along the Ramapo fault belong to only one of the three basalt formations or to more than one. Ratcliffe (1988, p. 115-117) has assigned an upper flow unit at Ladentown to the Preakness Basalt on the grounds that it overlies a rudite containing basalt clasts. In so doing, Ratcliffe infers that these clasts were eroded from the older Orange Mountain Basalt. This may very well be correct, but because the Orange Mountain episode involved at least two periods of extrusion separated by deposition of sedimentary strata, the extrusive sheet above the basalt-bearing rudites does not have to be the Preakness; it could equally well be from one of the younger flow units of the Orange Mountain episode.

For example, the exposures of pillows along McBride Avenue, Paterson that we studied during OTR Trip 20 to the Palisades and Newark basin are about in the middle of the outcrop belt of the Orange Mountain Formation. Farther south, the pillows are reported from exposures that look to be near the base of the formation (J. V. Lewis, 1908a, 1915b). JES is not familiar with the local stratigraphic details within the Orange Mountian Formation in Paterson, but sees indications that the Orange Mountain Formation of New Jersey closely resembles the expanded Talcott Formation that JES mapped in southern Connecticut (Sanders, 1962b, 1970). If the Orange Mountain and Talcott are indeed closely similar, then the possibility exists that the Orange Mountain Formation is thicker than many believe and that its pillowed part will be about in the middle.

In his summary of the results from the first round of core drilling along the Ramapo fault, Ratcliffe (1980, p. 292) wrote:

"Mapping of the Ladentown exposures reveals abundant evidence for multiple flows, pahoehoe lava (sic), and composite lava flows. Three main flow units separated by vesicular zones, are recognized. The basaltic rocks extend southwestward to the Ramapo fault where the lavas (sic) have been cored in two holes that document a thickness greater than 450 feet."

"The Ladentown exposures are especially significant because of the apparent crosscutting relationship of the flows to structure in the underlying Triassic fanglomerate. Ladentown flows fill a structural basin produced by intersection of two fold systems, a longitudinal northeast-trending syncline parallel to the Ramapo fault and a transverse northwest-trending syncline (Fig. 8).

"The base of the lava flows appears to decrease in elevation from northeast to southwest and to cut across, flowing in an apparent channel, northeast-dipping strata on the western limb of the longitudinal syncline (sic). Pahoehoe tongues and lobate bulges suggest flow directions to the southwest down the apparent channel.

"One possible interpretation of the data is that the Ladentown lava flows are a surface representation of the Palisades magma that was erupted from a fissure feeder into already folded strata. Flowage of lava in a southwesterly incised drainage pattern resulted in ponding against the border fault in the vicinity of the Sky Meadow drill site. Pre-flow rotation of the Triassic strata could have been produced bu drag on the border fault, causing the longitudinal northeast-trending syncline.

"Subsequent northwest (sic) and additional northeast folding postdated the flows as the border fault was reactivated as a right-oblique normal fault as documented by core drilling at the Sky Meadow site.

"Drill coring at the western edge of the Ladentown flows showed composite flows resting on black organic siltstone. This organic siltstone may have been deposited in sag ponds locally developed near the border faults.

> "If the above interpretation proves correct, then faulting (sic) and folding of Triassic strata preceded eruption of the lava flows at about 193 m.y. or earliest Jurassic time. These are the first observations that suggest that longitudinal folding near the border fault may have developed during sedimentation.

Subsequently, Ratcliffe (1988, p. 114-115) abandoned this interpretation. His latest version is:

> "Detailed gravity (sic) and magnetic surveys in the covered area between the exposed diabasic rocks at Camp Hill (fig. 1, loc. 5) and the western termination of the Palisades sill were conducted by Ken Kodama. His results (Kodama, 1983) indicate that a south-dipping sheet of magnetic rock is near the surface in the critical area at Mount Ivy that is buried by surficial deposits, thus establishing the subsurface connection of the sill and the area of vesicular basalt at Camp Hill" (Ratcliffe, 1988, p. 114-115).

Quoting again from Ratcliffe (1980, p. 292):

> "Despite extensive hydration of the Ladentown basalt, table 1, the TiO2, Fe2O3, and SiO2 values are comparable with the values for the Palisades chill dolerite and to pigeonite dolerite corresponding to Palisades magma types 1 and 2 of Walker (1969).
>
> Total iron oxide for the Ladentown is distinctly lower than third Watchung basalts (Faust, 1975, table 2). The TiO2 content and major-element chemistry (sic) of the basal flows of the Ladentown resemble magma types of Pennsylvania at Rossville and York Haven and the "First" and "Second Watchung" flow units (Black and Piburn, 1972; Smith, Rose and Lanning, 1975). Chemical analyses of Ladentown basalt (Geiger, Puffer, and Lechler, 1980) reportedly resemble closely the second Palisade magma type. They suggest, as did Savage (1968, p. 80), that the Ladentown flows (sic) are Palisades magma (sic) that erupted on the Early Jurassic land surface.
>
> "The available geophysical (sic), geochemical (sic), and geologic data suggest that the Ladentown lavas (sic)

> represent a fissure-flow eruption fed by the Palisades sill or an offshot (sic) of the the same magma chamber that fed the Palisades. The indications are that the lava extruded across previously folded and dissected (sic) Triassic strata.
>
> "If we can assume that the lava (sic) is 193 m.y. old (coeval with the Palisades sill), then we are looking approximately at the same level of erosion with respect to Palisades sill (sic) as existed in earliest Jurassic time."

We return to some of these topics in a following section devoted to the geologic structure of the Newark strata in Rockland County, NY. First, we review some fundamentals of geologic structure.

GEOLOGIC STRUCTURE – A PRIMER

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

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

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

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

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

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

When subjected to differential forces, under high confining pressures and elevated temperatures, rocks (like humans) begin to behave foolishly, squirming in many directions and upsetting the original orientation of primary- or secondary planar- and linear features within them. Geologists try to sort out the effects of deformation by working out the order in which these surfaces or linear features formed using a relative nomenclature based on four letters of the alphabet: D, F, S, and M. Episodes of deformation are abbreviated by (Dn), of folding by (Fn), of the origin of surfaces (such as bedding or foliation) by (Sn), and of metamorphism by (Mn), where n is a whole number starting with 1 (or in some cases, with zero). Bedding is commonly designated as S_0 (or surface number zero) as it is commonly overprinted by S_1 (the first foliation). To use this relative nomenclature to describe the structural history of an area, for example, one might write: "During the second deformation (D_2), F_2 folds formed; under progressive M_1 metamorphic conditions, an axial-planar S_2 foliation developed."

In dealing with the geologic structures in sedimentary rocks, the first surface one tries to identify positively is bedding or stratification. The boundaries of strata mark original sub-horizontal surfaces imparted to sediments in the earliest stage of the formation of sedimentary rock. Imagine how such strata, buried by the weight of overlying strata and laterally compressed by the advance of lithospheric plates, are subjected to the differential force necessary for folds to form. Contrary to older ideas, we now realize that vertical burial cannot cause regional folds (although small-scale slumping and stratal disharmony are possible). Rather, tangential force must be applied to provide the driving force to create folds and faults.

It's time to turn to some geometric aspects of the features formed as a result of deformation of rocks in the Earth. We start with folds.

Folds

If layers are folded into convex-upward forms we call them anticlines. Convex-downward fold forms are called synclines. In Figure 15, note the geometric relationship of anticlines and synclines. Axial planes (or axial surfaces) physically divide folds in half. Note that in Figure 15, the fold is deformed about a vertical axial surface and is cylindrical about a linear fold axis which lies within the axial surface. The locus of points connected through the domain of maximum curvature of the bedding (or any other folded surface of the fold) is known as the hinge line (which is parallel to the fold axis). This is geometry folks; we have to keep it simple so geologists can understand it.

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

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

Realize that in the upright folds shown in Figure 15, axial surfaces are vertical and fold axes, horizontal. Keep in mind that folding under metamorphic conditions commonly produces a penetrative mineral fabric with neocrystallized minerals (typically micas and amphiboles) aligned parallel to the axial surfaces of folds. Such metamorphic fabrics are called foliation, if primary, and schistosity, if secondary. Minerals can also align in a linear fashion producing a metamorphic lineation. Such features can be useful in interpreting a unique direction of tectonic transport or flow direction. Because folds in metamorphic rocks are commonly isoclinal (high amplitude-to- wavelength aspect ratio) with limbs generally parallel to axial surfaces, a penetrative foliation produced during regional dynamothermal metamorphism will generally parallel the re-oriented remnants of stratification (except of course in the hinge areas of folds). Thus, in highly deformed terranes, a composite foliation + remnant compositional layering is commonly observed in the field. Departures from this common norm are important to identify as they tend to mark regional fold-hinge areas.

Folds could care less about the orientation of their axes or axial surfaces and you can certainly imagine that axial surfaces can be tilted, to form inclined or overturned folds. Or the axial surfaces may be sub-horizontal, in which case the term recumbent folds is used. In both overturned folds and recumbent folds, the fold axes may remain subhorizontal. (See Figure 15.) It is also possible for an axial surface to be vertical but for the orientation of the fold axis to range from horizontal to some angle other than 0° (thus to acquire a plunge and to produce a plunging fold). Possible configurations include plunging anticlines (or -antiforms) or plunging synclines (or -synforms). Vertical folds (plunging 90°) are also known; in them, the terms anticline and syncline are not meaningful. In reclined folds, quite common in ductile fault zones (See below.), the fold axes plunge directly down the dip of the axial surface.

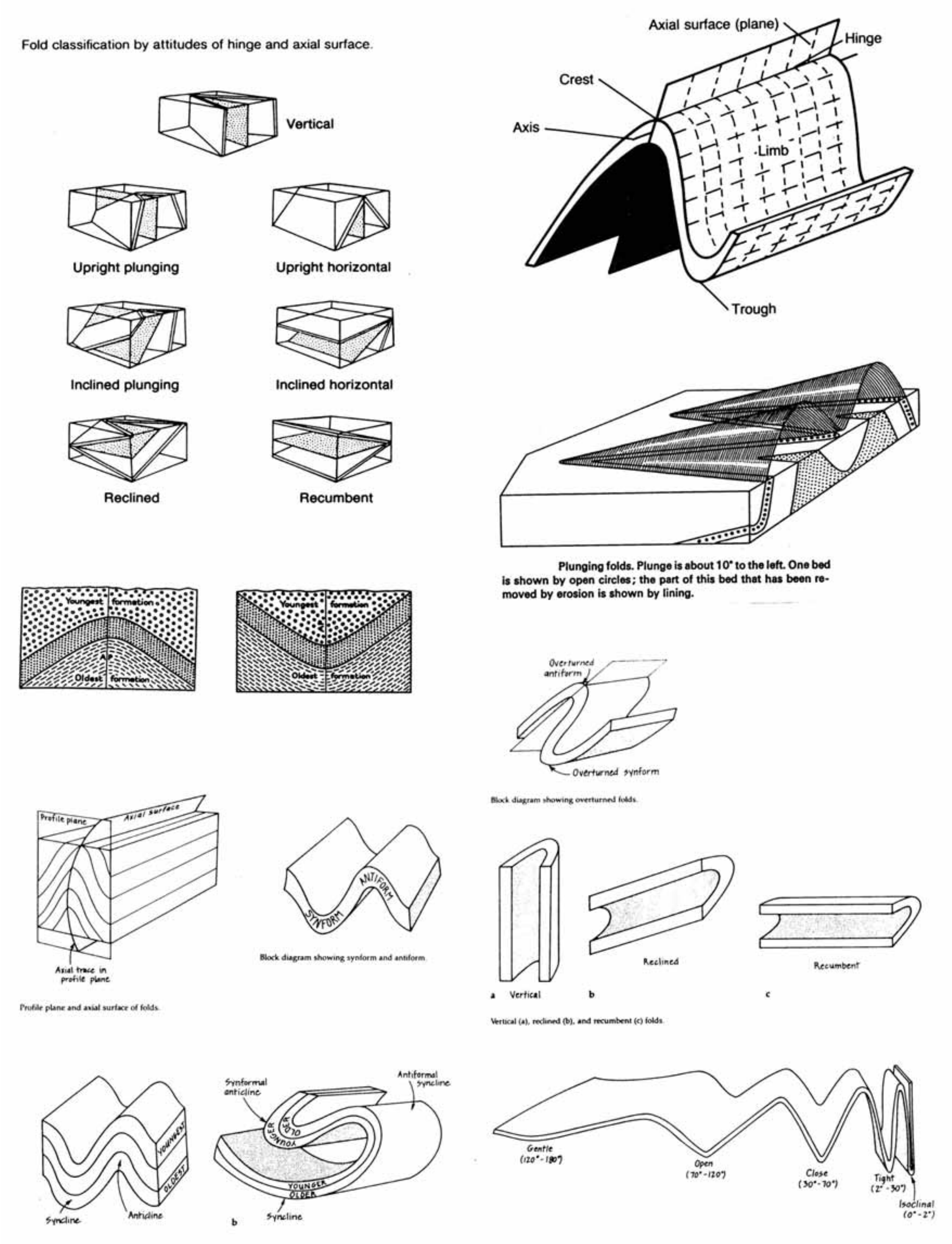


Figure 15. Composite diagram from introductory texts showing various fold styles and nomenclature as discussed in the text.

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

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

One final note on folding -- it is generally agreed, in geologically simple areas, that axial surfaces form perpendicular to the main forces that produced the fold. Therefore, the orientation of the folds give some hint as to the direction of application of the active forces (often a regional indicator of relative plate convergence). In complex regions, the final regional orientation of the structures is a composite result of many protracted pulses of deformation, each with its unique geometric attributes. In these instances, simple analysis is often not possible. Rather, a range of possible explanations for a given structural event is commonly presented.

Faults

A fault is defined as a fracture along which the opposite sides have been displaced. The surface of displacement is known as the fault plane (or fault surface). The enormous forces released during earthquakes produce elongate gouges within the fault surface (called slickensides) that may possess asymmetric linear ridges that enable one to determine the relative motion between the moving sides (Figure 16). The block situated below the fault plane is called the footwall block and the block situated above the fault plane, the hanging-wall block. Extensional force causes the hanging-wall block to slide down the fault plane producing a normal fault. [See Figure 16 (a).] Compressive forces drive the hanging-wall block up the fault plane to make a reverse fault. A reverse fault with a low angle (<30°) is called a thrust fault. [See Figure 16 (b).] In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane and the relationship between the tiny "risers" that are perpendicular to the striae make it possible to determine the relative sense of motion along the fault. Fault motion up- or down the dip (as in normal faults, reverse faults, or thrusts faults) is named dip-slip motion.

Rather than simply extending or compressing a rock, imagine that the block of rock is sheared along its sides (i. e., that is, one attempts to rotate the block about a vertical axis but does not allow the block to rotate). This situation is referred to as a shearing couple and could generate a strike-slip fault. [See Figure 16 (c).] On a strike-slip-fault plane, slickensides are oriented subhorizontally and again may provide information as to which direction the blocks athwart the fault surface moved.

Two basic kinds of shearing couples and/or strike-slip motion are possible: left lateral and right lateral. These are defined as follows. Imagine yourself standing on one of the fault blocks and looking across the fault plane to the other block. If the block across the fault from you appears to have moved to the left, the fault is left lateral [illustrated in Figure 16 (c)]. If the block across the fault appears to have moved to the right, the motion is right lateral. Convince yourself that no matter which block you can choose to observe the fault from, you will get the same result! Naturally, complex faults show movements that can show components of dip-slip- and strike-slip motion, rotation about axes perpendicular to the fault plane, or reactivation in a number of contrasting directions or variety. This, however, is no fault of ours.

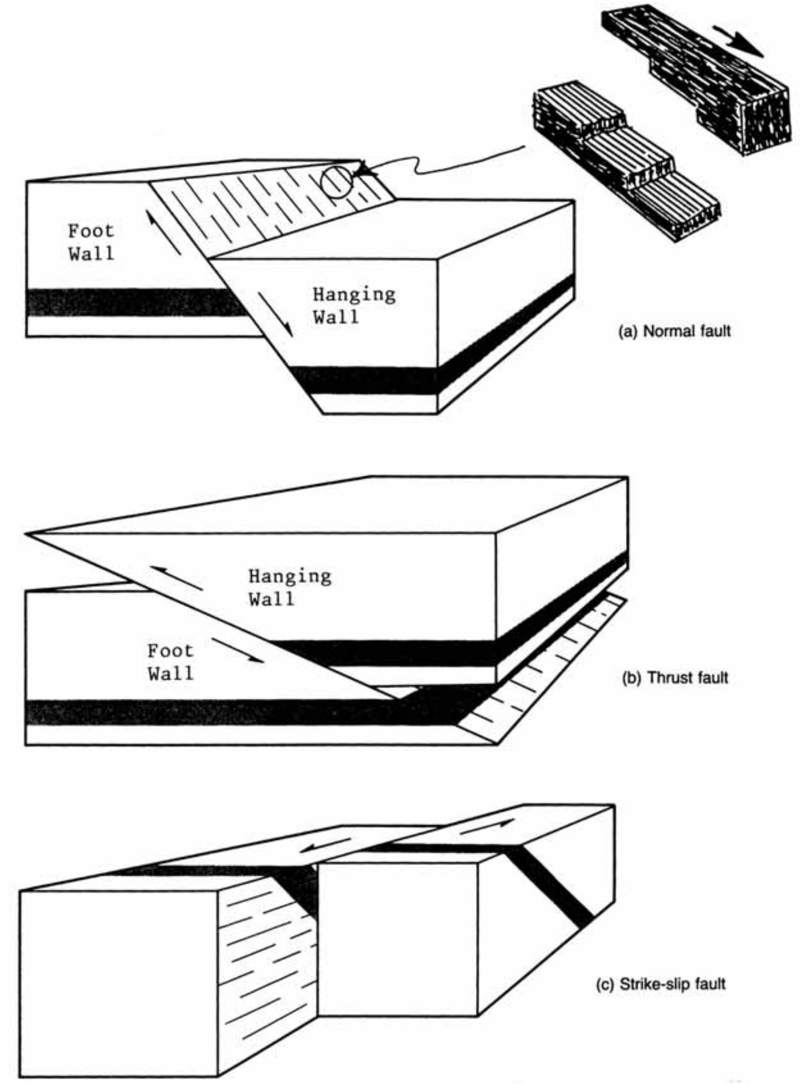


Figure 16. The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (black) has been offset by horizontal movement (left-lateral offset shown here). Inset (d) shows segments of two blocks along a slickensided surface show how the jagged "risers" of the stairsteps (formed as pull-apart tension fractures) can be used to infer sense of relative motion. [(a), (b), (c), Composite diagram from introductory texts; (d), J. E. Sanders, 1981, fig. 16.11 (b), p. 397.]

Tensional- or compressional faulting resulting from brittle deformation, at crustal levels above 10 to 15 km, is accompanied by seismicicity and the development of highly crushed and granulated rocks called fault breccias and cataclasites (including fault gouge, fault breccia, and others). Starting at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallizing during flow. These unique metamorphic conditions prompt the development of highly strained (ribboned) quartz, feldspar porphyroclasts (augen), and frayed micas, among other changes, and results in highly laminated rocks called mylonites. The identification of such ductile fault rocks in complexly deformed terranes can be accomplished only by detailed mapping of metamorphic lithologies and establishing their geometric relationship to suspected mylonite zones. Unfortunately, continued deformation under load often causes early formed mylonites to recrystallize and thus to produce annealed mylonitic textures (Merguerian, 1988), which can easily be "missed" in the field without careful microscopic analysis. Cameron's Line, a recrystallized ductile shear zone showing post-tectonic brittle reactivation, is an original ductile fault zone (mylonite) having a complex geologic history.

Surfaces of Unconformity

Surfaces of unconformity mark temporal gaps in the geologic record and commonly result from periods of uplift and erosion. Such uplift and erosion is commonly caused during the terminal phase of regional mountain-building episodes. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure 17), such surfaces represent mysterious intervals of geologic time where we really do not have a clue as to what went on! By looking elsewhere, the effects of a surface of unconformity of regional extent can be recognized and piecemeal explanations of evidence for filling in the missing interval may be found.

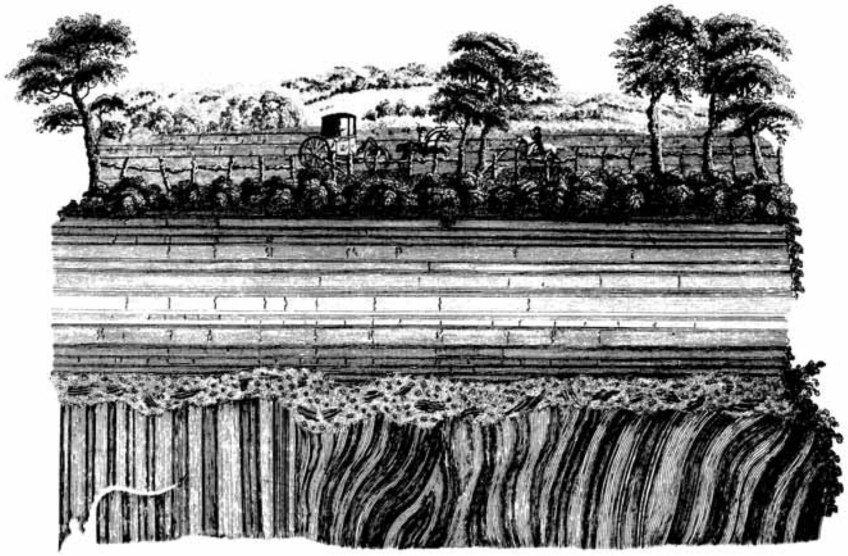


Figure 17. Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. From James Hutton's "Theory of the Earth", (1795).

Following the proposal made in 1963 by L. L. Sloss, surfaces of unconformity of regional extent within a craton are used as boundaries to define stratigraphic Sequences.

Sedimentary Structures

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

Secondary sedimentary features are developed on already deposited strata and include mud (or desiccation) cracks, rain- drop impressions, sole marks, load-flow structures, flame structures, and rip-up clasts. The last three categorize effects produced by a moving body of sediment on strata already in place below. A composite diagram illustrating these common structures is reproduced in Figure 18.

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

Structures in Sedimentary- vs. Metamorphic Rocks

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

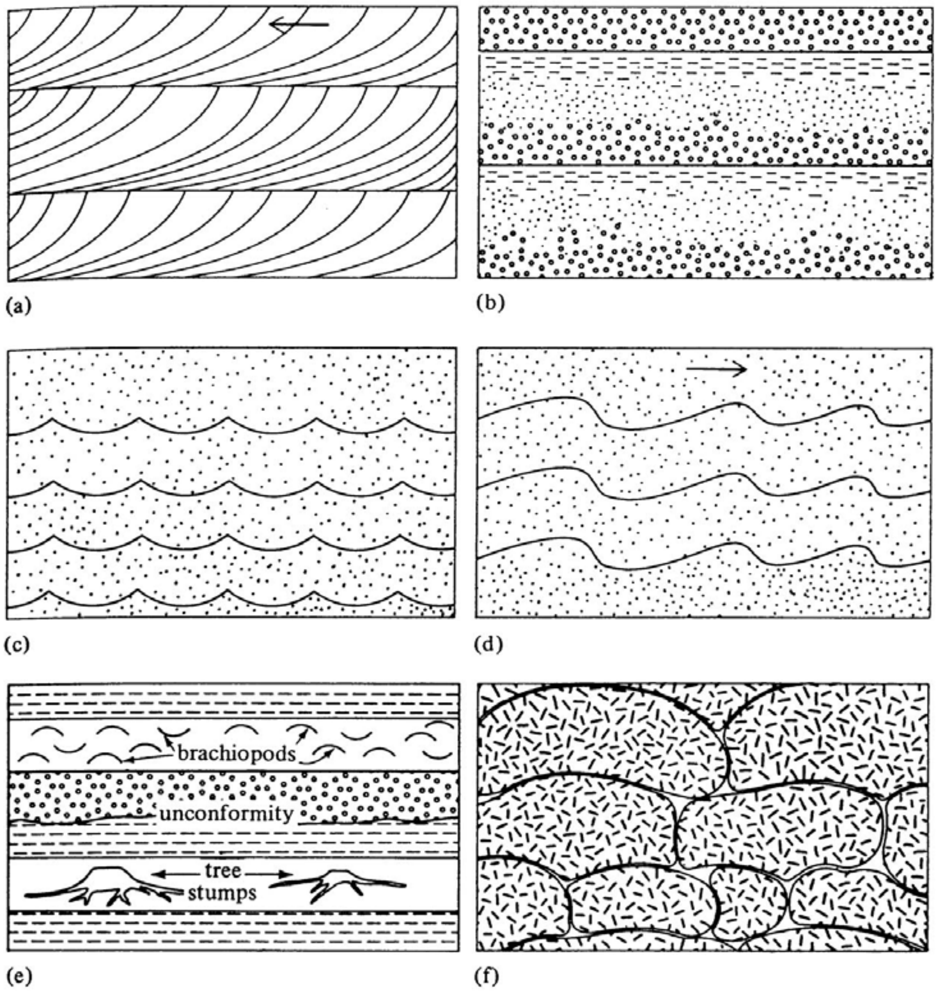


Figure 18. Diagrammatic sketches of primary sedimentary structures used in determining topping (younging) directions in stratified rocks.

GEOLOGIC STRUCTURE OF NEWARK ROCKS IN ROCKLAND COUNTY, NY

If you haven't figured it out by now, we'll tell you that JES thinks that the regional geologic structure of the Newark strata in Rockland county is the product of two large intersecting post-depositional anticlines involving the basement rocks as well as the Newark strata (right-hand pair of sketches in Figure 1 on cover).

Ratcliffe (1980; and 1988 map) shows folds in the rudites having axes trending E-W, more or less in accordance with the curvature of the Palisades sheet in hte Vertrietege Hook. (See Figure 14.) His map and the JES interpretation are fundamentally opposed. We do not have time to try to visit localities west of De Forest Lake that might resolve this conflict.

Instead, we shall concentrate of what JES thinks is a major structural anomaly that all previous workers have ignored. That anomaly is the existence of nearly horizontal Newark strata and associated extrusives sheets at Ladentown in a narrow zone lying just SE of the Ramapo fault and bounded on the SE by strata that JES thinks display a regional strike of NW-SE and SW dip of about 12° (as shown at the Mt. Ivy coring site, Figures 19 and 20).

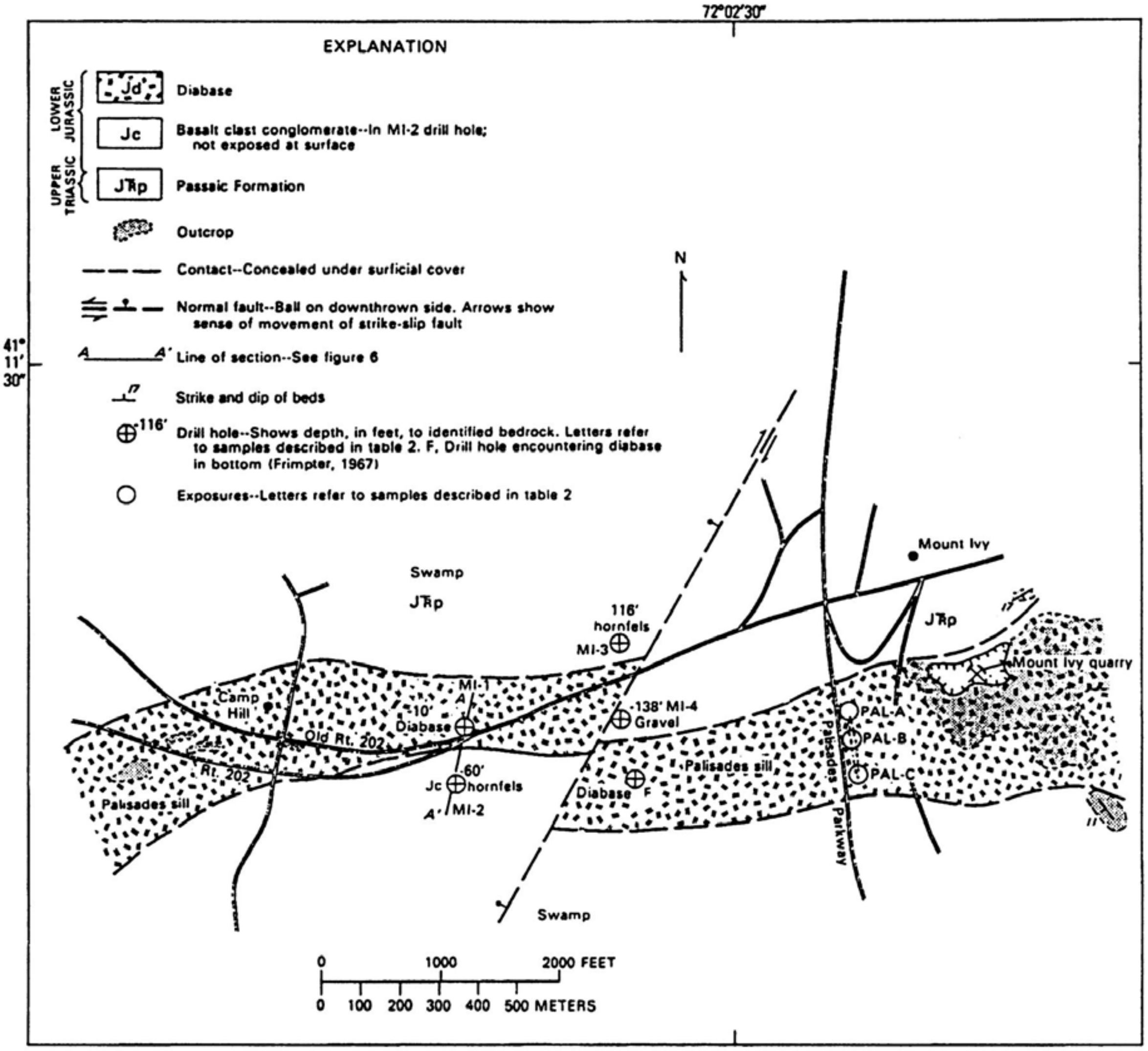


Figure 19. Geologic sketch map showing locations of U. S. Geological Survey Mount Ivy coreholes MI1 through MI4 and inferred offsetting of Palisades ridge by NE-SW-trending fault. (N. M. Ratcliffe, 1988, fig. 5, p. 123.

If the JES interpretation of the regional structural relationships of the northeast end of the Newark basin is correct, then at any place within Rockland County where the attitudes of the strata deviate significantly from a strike of NW-SE and a dip to the SW constitute first-order structural anomalies that require an explanation. The rocks to be seen at Stops 4 and 5 are cases in point. According to JES, near-horizontal Newark strata are present only in the axial parts of folds, either the crests of anticlines or the troughs of synclines. Given that relationship and the regional structure in Rockland County consisting of the SW limb of the Danbury transverse anticline, then the most-probable interpretation of the horizontal strata along the NW margin of the basin is that they belong to one or more faulted-off pieces from the axis of the Watchung syncline or from the axes of one of its subsidiary folds. The main axis of this syncline lies 44 km (29 mi) to the SW. The nearest possible subsidiary synclinal axis of the Watchung syncline lies 30 km (19 mi) SW of Union Hill. Moreover, if such strata do come from nearest possible synclinal axis of the Watchung synclinal feature, then they must have undergone a minimum of 30 km of right-lateral displacement in addition to possibly 3 km of upward dip-slip displacement along a fault paralleling the Ramapo fault but lying a km or so SE of it. At first glance, Ratcliffe's Thiells fault might be extended to the SW to account for these differences in attitudes of the strata. But, along the Thiells fault, the base of the Newark strata has been shifted to the SW. If any such large right-lateral strike-slip motion took place sufficient to shift Newark strata northeastward from the axis of a Watchung fold, then the base of the Paleozoic NW of the Thiells fault should be shifted far to the NE. The amount of vertical motion associated with the presumed fault is far too small to account for this offset complication.

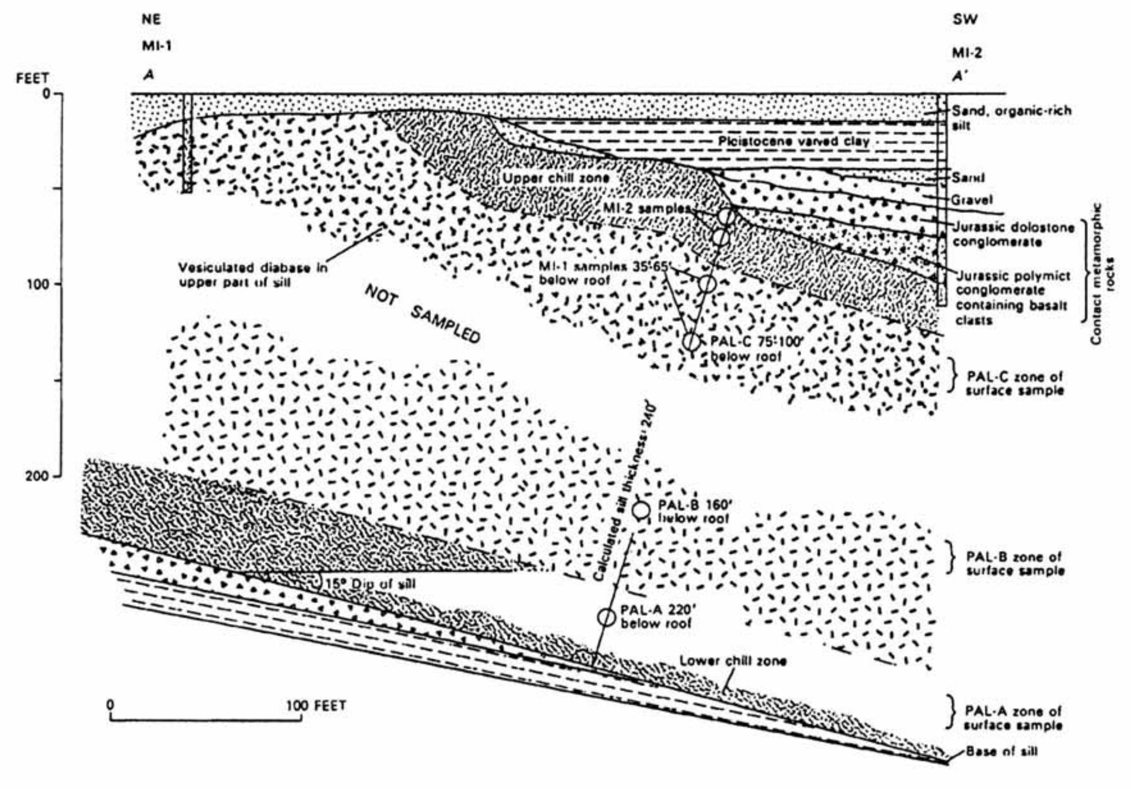


Figure 20. Profile-sections along line AA' of Figure 19 through coreholes MI1 and MI2. Notice that the sheet of igneous rock is generally concordant with the country-rock strata and that the strata dip about 15° SW. JES thinks that such a relationship in a locality so far to the W (W of the Palisades Interstate Parkway!) deals a fatal blow to the concept that the curvature of the Palisades sheet results from its becoming a dike that cuts the strata at a high angle. Notice also the Pleistocene varved clay present in corehole MI-2. (N. M. Ratcliffe, 1988, fig. 6, p. 125.)

Other faults have offset the Palisades ridge. (See Figure 10.) As CM keeps saying, these post-Newark faults probably exist in Manhattan and elsewhere. We need to sort them out and apply what we learn in areas where no Newark rocks are present.

LAYER VII: QUATERNARY SEDIMENTS AND ASSOCIATED FEATURES ERODED BY GLACIERS ON BEDROCK SURFACES

Under this heading we include: (1) features of Pleistocene age (related to former continental glaciers) and (2) features (mostly sediments) of Holocene age that resulted from the Flandrian submergence, which took place as the continental glaciers disappeared.

FEATURES OF PLEISTOCENE AGE

Features of Pleistocene age are distinguished by their associations with the several continental glaciers that formerly flowed across the region. These glaciers eroded the bedrock, transported various erratics to new locations, and deposited blankets of sediment. These sediments consist of sheets of till and various bodies of outwash that were deposited when the glaciers melted. As veteran On-The-Rockers are well aware, JES and CM (the two chief "Off-Their-Rockers") have entered the debates about the glacial history of the New York region, initially by finding hitherto ignored- or not-noticed features of glacial erosion and/or indicator erratics. Such features have provided them with new insights into the stratigraphic relationships displayed by the Pleistocene sediments. Moreover, their studies of the Pleistocene sediments are now providing feedback into their continuing investigations into glacial sculpting of the bedrock. All their new information totally destroys the prevailing "one-glacier-did-it-all" concept that seems to have hypnotized most modern stratigraphers of the Pleistocene deposits. The "one-glacier" interpretation further specifies that the glacial features made in the New York metropolitan region are not only the work of a single glacier but that this glacier should be correlated with the Woodfordian episode (interval from about 20 ka to 13 ka, namely the most-recent general ice advance) and furthermore that this Woodfordian glacier flowed down to New York City from the Labrador highlands following an azimuth that is about N15°E to S15°W (a direction that is down the Hudson-Hackensack lowlands). JES and CM find that only a few local glacial features can be ascribed to the effects of the Woodfordian ice. Instead, they find numerous features that can be ascribed only to several older glaciers. Some of these older glaciers must have flowed from NNE to SSW (as did the Woodfordian ice), but many flowed from various azimuths in the NW quadrant toward the SE, across the Hudson Valley. We review briefly the features made by glacial erosion, summarize some data from indicator stones, and then discuss the Pleistocene sediments.

Features Made by Glacial Erosion of Bedrock

Features eroded by glaciers in bedrock include striae and grooves, crescentic marks, roche moutonnées, and rock drumlins. All are useful in determining one of the most-fundamental points about a former glacial, namely which way did the glacier flow?

In flowing over certain kinds of solid bedrock, a glacier may create a generally smooth, possibly rounded surface on which may be linear scratches (striae, erroneously referred to as "striations" by many geologists whose use of the English language is in such a state of disarray that they do not bother to distinguish between words for attributes and words for substantive things) and even large grooves. The linear scratches and -grooves provide a straightforward basis for inferring ice-flow direction: it is parallel the trend of the linear grooves, -striae, and other elongate features.

Such delicate marks as striae do not survive exposure to the atmosphere for more than a few decades or so. Examples that can be used for showing the rate of destruction of the marks come from Finland, where postglacial crustal elevation has caused many islands to emerge from beneath the water of the Baltic Sea. The water has removed the fines from the till, leaving behind a glaciated rock pavement on which rest various large erratics. Not many striae have survived for longer than a century.

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 consists 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.) Rockland County displays numerous large drumline having their long axes oriented nearly N-S. We interpret these as products of the Woodfordian glaciation (the most-recent one).

Pleistocene Sediments

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 (deposited directly from a glacier) and outwash (deposits made as the glacier melted). The thickness of Pleistocene sediments in Rockland County is impressively large; it ranges up to several hundred meters.

Till

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

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.

For many years, varved clays were dug at Haverstraw to make bricks. Varved clays were found in some of the core holes drilled by the U. S. Geological Survey (Ratcliffe, 1988).

Holocene Sediments Deposited by the Flandrian Submergence

The rapid melting of the Late Wisconsinan ice sheet returned vast quantities of water from the ice back to the oceans. As a result, the sea rose rapidly. This rapid rise of sea level has been named the Flandrian submergence (name from Flanders, in NW Europe). In the New York City region, the oldest deposit of the rising sea is the so-called gray "organic silt" found in the major river valleys, such as the Hudson. The thickness of the Holocene organic silt ranges up to 150 feet or so, as indicated in borings made for the Tappan Zee Bridge (Figure 21).

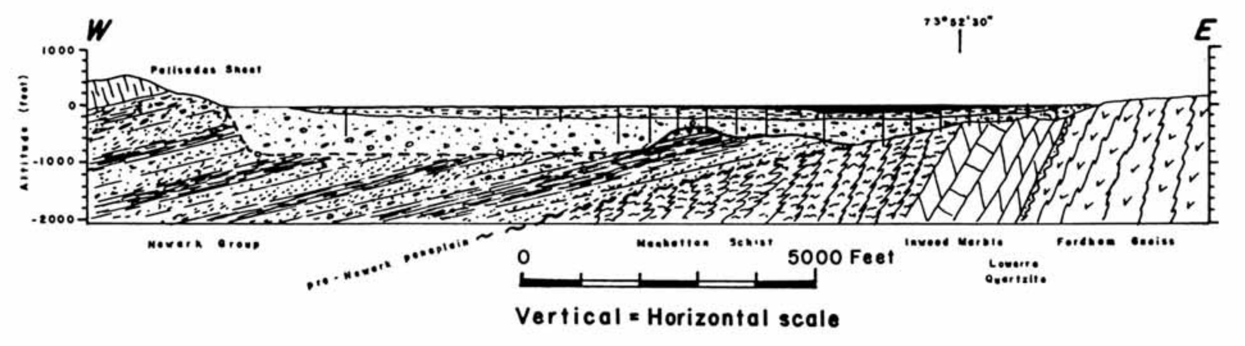


Figure 21. Profile-section across the Hudson Valley at Tappan Zee Bridge, based on soil-test borings and seismic surveys. Symbols for valley-fill materials: dots and circles, till; horizontal dashes, postglacial lake sediment; black, water and organic tidal silt. (Topographic profile drawn by J. E. Sanders from U. S. Geological Survey 7.5-min. quadrangle maps (Nyack and White Plains) that join along Longitude 73°52'30" W. Data for valley fill from J. L. Worzel and C. L. Drake, 1959, fig. 3, p. 1096-1097.)

Once this silt began to be deposited in an area, the pattern has not changed. We note a few points about this Holocene silt. First of all, it is full of gas bubbles. As a result, it is very reflective to sound waves. This means that the silt serves as a blanket which effective precludes the use of ordinary small-boat continuous seismic-reflection profiling, as with sparkers, boomers, and air guns. Many a hopeful investigator has supposed that it would be possible to obtain seismic profiles of the sediments in the Hudson Estuary. An equal number has been defeated; all they ever got was multiples (remember the chorus in the song about Mary Ann McCarthy who went out to dig some clams? "All she ever got was mussels, etc.")

Attempts have been made to date the basal silt from samples obtained at Iona Island and at the Newburgh-Beacon bridge on I-84. Based on samples dated by the radiocarbon method, Newman, Thurber, Zeiss, Rokach, and Musich (1969) concluded that the age of the oldest estuarine silt is 12,000 radiocarbon years. D. Weiss (1974) placed the date at 11,000 years B. P. (before present). Owens, Stefansson, and Sirkin (1974) compared the clay minerals from the lake sediments with those of the estuarine silt and also performed chemical analyses on the silt. Other papers devoted to the Holocene sediments are by Agron (1980) in the Hackensack meadowlands, New Jersey; and by Averill, Pardi, Newman, and Dineen (1980) for both the Hackensack and Hudson valleys.

New insights into the behavior of the fine sediments in the Hudson Estuary have come from the use of geochemical tracers, from the atmosphere, from discharges of radionuclides from the Indian Point reactors, and from the General Electric capacitor-manufacturing plants at Hudson Falls and Fort Edward (results from the geochemical laboratory at Lamont-Doherty Geological Observatory of Columbia University, by the team headed by H. J. Simpson, and including Richard Bopp, Curt Olsen, and others). Using the vertical distribution in sediment cores of the radioactive isotope of cesium (137; derived from nuclear-weapons tests carried out in the late 1950's and distributed worldwide via the atmosphere), these investigators have found two contrasting depositional settings: (1) marginal flats, where the post-fallout sediment is only a few millimeters thick (equals the modern rate of submergence); and (2) dredged channels, where the thickness of post-fallout sediment ranges up to several tens of centimeters. In the marginal flats, sediment has evidently built up to the profile of equilibrium and new sediment can be added only as this profile is lowered (as it is during submergence). In newly dredged channels, sediment fills in very rapidly, at rates in the tens of centimeters per year (C. R. Olsen, Simpson, Bopp, S. C. Williams, Peng, and Deck, 1978; Simpson, C. R. Olsen, S. C. Williams, and R. M. Trier, 1976).

In the spring of 1974, and again in 1976, two mighty surges of sediments highly contaminated with PCBs from the General Electric plants at Hudson Falls and Fort Edward spread throughout the Hudson Estuary and beyond. Prior to 1973, these sediments were kept upriver behind the ancient Fort Edward Dam. For reasons of safety, and to prevent a disastrous downriver surge of sediments that would accompany a damburst flood, the Niagara-Mohawk Power Company, owner of the dam, obtained permission from the Federal Power Commission and New York State Department of Environmental Conservation to remove the Fort Edward Dam. Granted this permission, Niagara-Mohawk dismantled the dam, starting in July 1973 and ending in October 1973. Two subsequent floods and a general time of high flows brought about the very result that removal of the dam was supposed to forestall!

The effects of industrial pollution have obliterated the once-fluorishing oysters of the Hudson estuary. In 1966, JES participated in a small experiment of lowering a TV camera and light to the bottom of the Tappan Zee off Irvington. The bottom is paved with dead oyster shells.

In many places, intertidal salt marshes are encroaching on the land as the sea rises. In order to become established, such marshes require a base of tidal sediments, usually silt/mud. But, an established marsh can keep up with a rising sea; and, the marsh spreads out landward as it grows vertically as the water-level rises.

OBJECTIVES

1) Evaluate the "shelving-basin" interpretation and the "transverse anticline" viewpoint.

2) Study an example of the Lockatong Formation that all previous workers evidently have overlooked.

3) Evaluate the significance of the curvature of the Palisades sheet in Rockland County, NY: is it a folded intrusive sheet or a steeply cross-cutting dike?

4) Briefly examine the pre-Newark rocks and the basal conglomeratic Newark strata near Stony Point State Park.

5) Look at the nearly horizontal strata in the Ladentown-Wesley Chapel area and try to figure out if they are anomalous with respect to the rest of the Newark strata in Rockland County, NY.

6) Compare weathered- with fresh rock in the Ramapo fault zone and record the orientations of the numerous fracture surfaces.

LIST OF LOCALITIES TO BE VISITED

Stop 1: W. shore of Hudson River, Hook Mtn. State Park: Stockton & Lockatong formations; Palisades mafic igneous rock.

Stop 2: Lowland Park, Town of Stony Point: lacustrine facies & caliche (Stockton? or Passaic? Formation).

Stop 3: Stony Point State Park and vicinity; basal Newark carbonate-clast breccias; pre-Newark metamorphic- and igneous rocks.

Stop 4: Limekiln Road (Town of Ramapo): "Ladentown" extrusive basalt.

Stop 5: Wesley Chapel; Jct. US 202 and Spook Rock Rd.: basin-marginal rudites (what formation? Passaic? Feltville?).

Stop 6: Pavilion Road, Suffern: Ramapo fault zone.

ROAD LOG AND DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

Distance (miles)
Ind. Cum. Directions and remarks

(From Manhattan to Tappan Zee Bridge via Madison Avenue, Major Deegan Expressway, and NY Thruway; from Friedman, Sanders, and Martini, 1982 IAS guidebook facies study).

0.0 0.0 Cor. 62nd and Madison.
1.65 1.65 Passing 96th St.
0.45 2.1 Passing 105th St and New York Medical College on the L; approximate position of a fault that trends NW-SE and cuts across the NE corner of Central Park. Along this fault, "Manhattan Schist" on the SW is in contact with the underlying Inwood Marble. Where "Manhattan Schist" is at or close to the land surface, high-rise buildings have been built. Where the bedrock has been thickly covered with Pleistocene sediments, however, no tall buildings have been constructed. The marble ahead underlies a parallelogram-shaped area known as Harlem.

0.7 2.8 Passing 120th St; on L is Mount Morris Park. CM's mapping shows that this high, rounded knob consists of an erosional remnant of the middle unit of the schists (composed of rusty- and locally, maroon-weathering, gray, biotite-muscovite-plagioclase-quartz-kyanite-sillimanite gniess and -schist with kyanite layers, zones of porphyroblastic kyanite + garnet, and layers of biotite-quartz-plagioclase + garnet granofels). The Inwood Marble (gray- to tan-weathering and containing schistose zones with layers- and nodules of diopside + tremolite + quartz) crops out on the Madison Avenue side of the park.

The overall structure of the park is a south-plunging klippe of the middle schist unit produced by the superposition of an F3
synform and a late, NW-trending synform (Merguerian, 1983). Along its southern margin, a fault, trending N69°W, and dipping 84°SW and exposed at street level, terminates the klippe. Slickensides in the fault surface are oriented N70°W @ 22° clearly indicating a strike-slip movement sense although the presence of Inwood Marble to the south suggests a component of reverse motion. The contact between the schist and Inwood Marble is marked by 10° truncation of lithologic layering in the marble, extreme flattening, 2- to 3-cm-scale annealed mylonitic layers, sheared- and imbricated lithologic units, and quartz veins.

Developed during thrusting and deformed by F3 folds, the S2 enveloping surface is variable but on average, trends N30°W, 20° SW and marks the axial surface of reclined- and isoclinal folds found both above- and beneath the thrust contact. Disharmonic F3 folds of mylonite, developed at the thrust contact, are exposed at the northern edge of the klippe. They trend N 32°E, 80°NW to 70°SE and plunge 23° into S25°W.

0.25 3.05 Crossing 125th Street. Two blocks W of this intersection, on the NE corner, is a state office building. When the foundation was dug in 1970, the flat lowland was found to be underlain by thick Pleistocene outwash, the top 10 m or so consisting of coarse reddish-brown sand having large-scale (co-sets several meters thick) cross strata indicating flow from W to E. To the W, borings on a N-S line beneath Manhattan Avenue (near Morningside Park on the

Upper West Side) for the Catskill Aqueduct tunnel across this fault indicated that the depth to bedrock is nearly 200 feet (61 m) (Berkey, 1933, p. 113-116; fig. 25, p. 115). Berkey named this fault the Manhattanville fault. JES suggests that the glacier(s) that flowed from NW to SE excavated and greatly deepened valleys formed along faults trending NW-SE. Many of these valleys were later obliterated as landscape features by the deposition in them of thick bodies of sediment, in some cases by a younger glacier that arrived from the NNE and flowed SSW, across these valleys (thus being analogous to the relationship between the glaciers from the NNW that flowed SSE across the Hudson Valley).

0.65 3.7 Bear R to cross Harlem River on 138th St. bridge.
0.1 3.8 Entering The Bronx; street bends R. The Harlem River valley is underlain by vertical Inwood Marble (NW limb of an anticline having a vertical axial plane; Berkey, 1933, p. 114, fig. 24; also Colony, 1933, p. 39, fig. 4).
0.1 3.9 Crossing above Major Deegan Expressway; move L to prepare for upcoming L turn. Turn L for entrance ramp to Major Deegan Expressway (I87) northbound.
0.2 4.1 Entering Major Deegan Expressway northbound.
0.2 4.3 Crossing above 149th St.
0.3 4.6 Yankee Stadium ahead on R. Name locality of the Earth's Mantle.
0.3 4.9 Crossing beneath 155th St at Macombs Dam Park; Expressway curves to L.
0.1 5.0 Expressway bends R; hill on R, leading up to the High Bridge section of The Bronx, is underlain by Fordham Gneiss (Proterozoic). Move into L lane.
0.75 5.75 Passing beneath High Bridge, built in the 1840's as part of the old Croton Aqueduct to bring water from reservoirs in Westchester County into New York City. Passing ramp on R leading to I-95 (Cross-Bronx Expressway and George Washington Bridge).

0.2 5.95 Passing beneath Alexander Hamilton Bridge on the Cross-Bronx Expressway. Figure 11 shows a profile-section from Fort Lee, NJ, to the Bronx, parallel to the Cross-Bronx Expressway. From here northward into Westchester County, the landscape displays a pronounced valley-and-ridge aspect. The ridges are underlain by Fordham Gneiss (in anticlines) or the "Manhattan Schist" (in synclines). The strike valleys, either limbs of folds, crests of anticlines, or in some cases, faults, are underlain by the topographically weak (in our present moist climate) Inwood Marble.

0.2 6.15 Passing entrance ramp on R from Cross-Bronx Expressway. At R is a reinforced concrete wall that extends for about 2 miles and covers Pleistocene sediments.
0.2 6.35 Passing beneath sign for 179th St.
0.05 7.4 Passing exit ramp on R for Fordham Road.
0.05 7.45 Passing sign on R indicating 1 mile to W. 230th St.
0.15 7.60 Passing beneath bridge for Fordham Road.
0.2 7.80 Passing entrance ramp on R from Fordham Road; Expressway bends L.
0.65 8.2 At N end of Manhattan Island, Harlem River on L curves sharply to W; there it passes through Spuyten Duyvil (="Spitting Devil") Creek to join the Hudson River farther to the W.
0.1 8.3 Passing beneath Kings Bridge Road.
0.2 8.5 Passing ramp for Exit 10 on R to W 230th St.

0.05 8.55 Leaving Central Park quadrangle; entering Yonkers quadrangle; passing beneath W 230th St.
0.2 8.65 Expressway bends R; sign on R indicating Van Cortlandt Park South.
0.25 8.9 Passing beneath W 234th St. (sign on bridge above).
0.15 9.15 Passing Exit 11 ramp on R for Van Cortlandt Park South.
0.1 9.25 Passing beneath bridge for Van Cortlandt Park South above expressway; begin curve to R; sign indicating Mosholu Parkway and Saw Mill River Parkway on R.
0.15 9.4 End curve; passing entrance ramp on R from Van Cortlandt Park South.
0.25 9.65 Passing ramp on R for Exit 12, Mosholu Parkway and Saw Mill River Parkway; Expressway curves to L.
0.15 9.8 Crossing above Mosholu Parkway.
0.1 9.9 Passing sign on R for 233rd St.
0.2 10.1 Passing Exit 13 ramp on R for 233rd St.
0.2 10.3 Passing service station on R.
0.3 10.5 Passing entrance ramp on R from Jerome Avenue.
0.2 10.7 Passing sign on R for McLean Avenue.
0.3 11.0 Passing Exit 14 ramp on R for McLean Avenue.
0.1 11.1 Leaving The Bronx, entering Yonkers; Major Deegan Expressway becomes Governor Thomas E. Deway Thruway.
0.15 11.25 Passing beneath bridge for McLean Avenue over Thruway.
0.05 11.3 Leaving Yonkers quadrangle; entering Mount Vernon quadrangle.
0.1 11.4 Passing Exit 1 ramp on R for Hall Place. Sign for Exit 2, Yonkers Raceway.
0.3 11.7 Passing entrance ramp on R from McLean Avenue.
0.2 11.9 On R is Hill View equalizing Reservoir of New York City water system. This reservoir has been built atop a drumlinoidal hill; its water level is 295 ft (90 m) above sea level and its capacity is about 2 days' supply. Earlier in 1993, a water-contamination problem in southern Manhattan was traced to sea-gull droppings along the shores of this reservoir. Passing sign on R for Exit 2, Yonkers Raceway.

0.1 12.0 Passing ramp for Exit 2 on R to Yonkers Raceway; reinforced concrete retaining wall on R.
0.1 12.1 Passing MP 1 and Yonkers Raceway on R.
0.2 12.3 Passing sign on R for Exit 3, Cross County Shopping Center.
0.2 12.5 Passing beneath bridge for Yonkers Avenue above Thruway.
0.1 12.6 Passing Exit 3 ramp on R for Mile Square Rd. and cross County Shopping Center; end of concrete retaining wall on R.
0.15 12.75 Passing sign on R for Exit 4, Cross County Parkway.
0.2 12.95 Passing exit ramp on R for Exit 4, Cross County Parkway; Thruway curves L.
0.3 13.25 Bridge over Thruway for Cross County Parkway.
0.15 13.4 Passing Exit 5 ramp on R for NY Route 100, Central Avenue. The Yonkers Granite-Gneiss exposed behind buildings at R is in the type area of the Yonkers Granite-Gneiss. A narrow outcrop belt of Yonkers Granite-Gneiss extends from Yonkers NNE to Rye Lake.

0.35 13.75 Yonkers Granite-Gneiss exposed in cuts on R; Thruway bends L.
0.05 13.8 Passing entrance ramp on R from NY Route 100.
0.05 13.85 Thruway passes over NY Route 100.

0.05 13.9 Quarry at L in Yonkers Granite-Gneiss.
0.2 14.1 Cuts of Yonkers Granite-Gneiss on both sides of Thruway; among its prominent features are the blocky joints. The Yonkers Grnaite-Gneiss is a pink rock, with the foliation expressed more by parallel, isolated biotite clusters and smeared-out feldspars (featuring plagioclase having a quartz-like vitreous luster) than by distinct alternating layers having contrasting mineral compositions, as in the Fordham Gneiss.

0.2 14.3 Passing sign on R announcing Tuckahoe Road (Exit 6) in 1 mile.
0.15 14.45 Thruway curves L.
0.05 14.5 Cuts in Fordham Gneiss; more on L than on R.
0.15 14.65 End curve.
0.25 14.9 Passing sign on R indicating Service Area in 3 miles; start curve to R.
0.25 15.15 Crossing over Tuckahoe Road and Sprain Brook.
0.05 15.2 Passing MP 4 and Exit 6 ramp on R for Tuckahoe Rd.
0.1 15.3 Passing entrance ramp on R from Tuckahoe Rd.; cuts in Fordham Gneiss on R; Sprain Brook valley, underlain by Inwood Marble (not exposed), on L. The Ridge to W is underlain by "Manhattan Schist" in a syncline; ridge to E is underain by Fordham Gneiss in the crest of an anticline. End curve.

0.1 15.4 Start new fence separating highway from roadcut (and from interested geologists!).
0.2 15.6 End rock-protective fence.
0.05 15.65 Passing sign indicating toll booth in 3/4 mile (the actual distance is 1.1 miles); passing exit ramp on R to Sprain Ridge "House of Rest." Yonkers Granite-Gneiss on R.

0.25 15.9 Passing Exit 6A ramp on R, to Corporate Drive, Yonkers; last exit before tolls.
0.15 16.05 Passing sign on R announcing Ardsley Service area ahead.
0.35 16.4 Passing Westchester County's new Materials Recovery Facility on R.
0.3 16.7 Toll booth (at Thruway Milepost 5.7). [For those who are not familiar with the mileage markers on the Thruway, the following may be useful to know. Markers such as this appear every 0.1 mile; larger blue markers record the even miles (from the New York City line). In addition, painted on all bridge abutments is the mileage to the nearest hundredth.]
0.3 17.0 Cuts expose Fordham Gneiss.
0.2 17.2 Leaving Yonkers, entering Hastings-on-Hudson.
0.1 17.3 Passing exit ramp on R to Service Area; Thruway bends to L.
0.15 17.45 Passing beneath bridge for Jackson Avenue over Thruway; Mount Hope Cemetery on R.
0.35 17.8 "Manhattan Schist" in cuts both sides; a synformal ridge underlain by Member C (uppermost unit) of Leo Hall's (1968) classification. Start roadcut-protective fence.
0.15 17.95 Passing sign on R indicating Exit 7 (to US Route 9A, Ardsley) in 1 mile.
0.15 18.1 MP 7 on R.
0.15 18.25 End roadcut-protective fence. Cuts behind fence on L expose "Manhattan Schist," Unit C.
0.45 18.6 Leaving Mount Vernon quadrangle; entering White Plains quadrangle. Saw Mill River Valley ahead on L is underlain by Inwood Marble (exposed in cuts beneath Thruway at Exit 7, NY Route 9A).
0.3 18.9 Passing ramp on R for Exit 7 (to US Route 9A, Ardsley).

0.2 19.1 MP 8 on R.
0.15 19.25 Thruway passing over US Route 9A (cuts in Inwood Marble on lower road) and Saw Mill River, Ardsley. Thruway curves R; is parallel to and just E of the Saw Mill River Parkway.
0.25 19.5 Thruway passing beneath bridge for Ashford Avenue over Thruway.
0.1 19.6 Thruway bends L.
0.15 19.75 End curve. Behind buildings on R. (E side of Route 9A in Ardsley) is an exposure of Inwood Marble capped by a gray till that is at least 20 m thick. Construction of a shopping center at the base of the till slope has created a situation that for many years was known as "Ardsley's slipping slope." Large boulders, erratics in the till, are exposed by the effect of trickling water in removing the fine matrix particles out of the till. When enough fines have been washed away, the boulders are released and fall down. After rainstorms of several inches or more, whole masses of the slope cascade down on the stores. In the last such episode, in April 1979, the back end of the A & P supermarket was broken through by a debris flow. This store was not rendered usable again for several years, and only after appropriate measures (including installation of gabions) had been implemented for controlling slope failure. The ridge on the L (west) is underlain by Fordham Gneiss in the western anticlinal belt that extends NNE nearly to the NY-CT state line.

0.3 20.05 Thruway bends R.
0.05 20.1 MP 9 on R; sign announcing Exit 7A to Saw Mill River Parkway.
0.25 20.35 S end of Woodland Lake on L.
0.7 21.05 Thruway curves R.
0.05 21.1 Massing MP 10 on R.
0.1 21.2 Passing Exit 7A ramp on R (to Saw Mill River Pkwy.).
0.2 21.4 Thruway curves L.
0.3 21.7 Thruway crossing over Saw Mill River Parkway; cuts on L are Fordham Gneiss.
0.15 21.85 Passing entrance ramp on R from Saw Mill River Parkway.
0.25 22.1 Thruway curves L; deep cuts on both sides, mostly of the Fordham Gneiss. These cuts were widened and terraced in the 1980s as a result of a fatality caused when a large block of gneiss crashed down on a passing automobile in the S-bound lane. As a result of this fatality, the Thruway turned teams of geologists loose to inspect all Thruway rock cuts and to indicate which ones posed comparable threats. A comprehensive program of building protective devices at deep cuts resulted. According to Leo Hall (1968), the light-colored masses of rock in these cuts consist of infolded Lowerre Quartzite (Lower Cambrian, which nonconformably overlies the Proterozoic Fordham Gneiss). The additional rock removed in the Thruway's roadcut-safety program suggest that the light-colored rock is associated with a granitic pluton.

0.8 22.9 End curve; passing Exit 8 ramp to I-287 (White Plains); from here to the Tappan Zee Bridge, the cuts expose bluish-gray plagioclase gneisses belonging to the Fordham Gneiss (Proterozoic), which form part of a major anticline in the pre-Newark rocks. The Fordham gneiss crops out in a belt about 2 miles wide that extends from the Hudson River to the Saw Mill River (whose valley is underlain by the Inwood Marble). The bedrock underlying the Pleistocene sediments composing the terrace (alt. 125 feet), on which the Hilton Inn has been built, consists of the Inwood Marble.

0.15 23.05 End deep cuts.
0.2 23.25 Passing entrance lanes on R from I287.
0.35 23.6 Straight stretch; Exit 9 ramp on R.
0.1 23.7 Begin curve to R.
0.5 24.2 Passing Exit 9 Ramp (to US Route 9, Tarrytown) on R.
0.2 24.4 Curve to R; cross beneath US Route 9, Tarrytown.
0.1 24.5 Passing entrance ramp on R. from US Route 9. View ahead to the scarp slope of the Palisades Ridge on the W side of the Hudson River. View to R (upriver) shows gently inclined E slope of the Hudson Valley, which descends to the river at an angle of 10° to 15° and curves around with the river toward the NW. The highest point on the Palisades Ridge is High Tor (alt. 815 ft). To the L and ahead is Sparkill Gap and the town of Piermont, Rockland Co., NY. At one or more times during the Cenozoic Era, the Hudson River flowed SW through the Sparkill Gap and crossed the Hackensack lowlands. Today, Sparkill Creek flows NE into the Hudson via this gap. Because its junction with the Hudson River makes an acute angle on the downstream side, instead of on the upstream side, Sparkill Creek is a barbed tributary of the Hudson River.

0.6 25.1. End of curve to L. Leave White Plains quadrangle, enter Nyack quadrangle.
0.3 25.4 Abreast of main bridge support on E side of ship channel. The borings here showed "Manhattan Schist" beneath the sediments.
0.2 25.6 Abreast of main bridge support on W side of ship channel. The borings here encountered conglomerate beneath the sediments. Therefore, the unconformable contact at the base of the Newark lies somewhere between the two main bridge supports that elevate the roadway high enough for ships to pass underneath. The ship channel is dredged to a depth of 40 feet; everywhere else the water of the Tappan Zee is very shallow, 10 to 15 feet or less. The bottom of the Tappan Zee is covered with a pavement of dead oyster shells, which are plainly obvious on underwater TV scans of the bottom. Beneath the bridge, the thickness of the gray organic silt, brought upriver by the tides and the upstream-flowing current in the saltwater wedge which lies beneath the surface current of freshwater, is 140 feet. This silt has been accumulating continuously for about 10,000 years at a mean rate of 0.014 ft/yr. It has shoaled the water of the Tappan Zee to its present mean depth of about 12 feet. Worzel and Drake (1959) carried out the geophysical surveys made in conjunction with the borings for the Tappan Zee bridge. Newman, Thurber, Zeiss, Rokach, and Musich (1969); Weiss (1971, 1974); Owens, Stefannson, and Sirkin (1974); Simpson, C. R. Olsen, Trier, and S. C. Williams (1976); and C. R. Olsen, Simpson, Bopp, S. C. Williams, Peng, and Deck (1978) have made stratigraphic studies of the Quaternary sediments. McCrone (1967) and Fabricand and others (1968) have published papers on the results of geochemical studies of the waters of the Hudson River. In 1974, Sanders (1974a) made his first attempt to summarize the geologic history of the Hudson Estuary. Leo Hall (1968) published a geologic map of the bedrock of the White Plains quadrangle. At the time of his death, Hall was working on other detailed maps in areas on the east side of the Hudson River. H. D. Thompson (1959) made a study of the relationship between the Sparkill gap and faults. Douglas Johnson (1931, 1932) proposed ideas about the former flow of the Hudson through Sparkill Gap. Lovegreen (1974 ms.) compiled a map of the buried bedrock surface in an area extending from the Tappan Zee Bridge to Newark Bay.

0.9 26.5 End of downhill stretch; crossing axis of deep sediment-filled valley in bedrock. The flat floor of this valley lies at a depth of 740 feet below sea level (Worzel and Drake, 1959; Figure 21). We are now crossing the strike of the Stockton Formation.
0.6 27.1 Curve to R. Low ground on the W side of the Hudson River here is underlain by till, Stockton sandstone and conglomerate (Upper Triassic part of the Newark Supergroup), and faulted slices of the Palisades Dolerite.
0.6 27.8 Mile marker 16.2 on New York Thruway on R.
0.4 28.2 Passing Exit 10 ramp on R; continue on Thruway upstate. The grassed-over slope on the left is a cut in till.
0.4 28.4 Red sandstones and conglomerates of the Stockton Formation (basal formation of the Newark Supergroup) were formerly exposed on the L. starting at Thruway mile 16.9 and
0.3 28.7 ending with retaining wall at 17.2. These are no longer visible, for two reasons. (1) From the northbound lane, riders in passenger cars are not able to see over the new taller center concrete divider. (Is your line of sight any higher from the vans?) (2) During the recent widening work, gabions were placed so that they cover up the rocks. Thus, one can't see these rocks even from the southbound lane. (The toll keepers are equipped with special punches to enter another notch in your TS cards!)

0.6 29.3 Passing Exit 11 ramp on R; continue on Thruway upstate. (Thruway mile 17.8)
0.5 29.8 Start deep cut in dolerite of Palisade sill (Thruway mile 17.85)
0.95 30.75 Keep R; prepare to leave Thruway at next exit. Exit 12 ramp on R; Route 303 West Nyack (Thruway MP 18.8) At traffic signal at end of exit ramp, turn L on NY Route 303. Road goes uphill; cuts on L side are in Palisades Dolerite.

0.3 31.05 Cuts in dolerite, both sides of road.
0.2 31.35 End of cuts in dolerlte.
0.1 31.45 Highway sign Valley Cottage
0.65 32.1 Small dolerite cut on R.
0.05 32.15 Traffic signal; turn R on Lake Road.
0.7 32.85 Wooded hill in distance on R is dip slope on W side of Palisades sill (Strike NS, dip 15° W).
0.1 32.95 Jct. Bellsville Rd.
0.5 33.45 Traffic signal, US 9-W. Cross US 9-W and enter Rockland Lake State Park; Rockland Lake at L. REST STOP. PIT STOP IF THE PITS ARE OPEN.
0.4 33.75 Wooded ridge ahead is dip slope of Palisades sill
0.2 33.95 Exposure of dolerite of slll on R; overlain by till.
0.5 34.45 Exposure of dolerite of sill in slope at R.
0.4 34.95 Intersection; turn R on street marked "Dead End."

0.05 35.00 Fire Station where we are supposed to park. Leave vehicles. Walk along street past barricade marked passage "For Official Cars Only." (We have permission to pass; requests for such permission should be addressed to Superintendent, Palisades Interstate Park, Bear Mountain, NY; Tel. 914-786-2701.)

Walk downhill past turnaround loop and bear R along the flat terrace at altitude ca. 65 feet along path downhill to west shore of Hudson River.

STOP 1 - Palisades igneous rock, Stockton and Lockatong formations of Newark Supergroup. Center of old quarry - [UTM Coordinates: 591.6E / 4554.8N.] Sandstone exposures along Hudson River at Upper Nyack - [UTM Coordinates: 591.80E / 4554.15N, Haverstraw quadrangle.]

The first thing visible is the massive igneous rock and its sets of regular intersecting joints. The joint surfaces are perpendicular to the surface of cooling. The color of the fresh igneous rock is bluish gray, but on most visible surfaces (weathered) is yellowish brown. This brownish color results from the presence of the iron-oxide mineral limonite, which coats most joint faces. The usual interpretation of limonite is that it is a breakdown product of the ferromagnesian-silicate minerals, chiefly pyroxene, composing the igneous rock. In the rocks before you, this is probably not the case. JES can demonstrate from study of quarry cores elsewhere (and also from the new roadcuts we shall study at Stop 6 later today) that below the depth of modern weathering, where the rock is fresh, a thin film of pyrite (iron sulfide, "fool's gold") coats most joint faces. Oxidation of this pyrite creates limonite; the essential ferromagnesian-silicate minerals, mostly pyroxenes, are still fresh and intact.

Follow the paved bicycle path down to river level to study the sedimentary strata exposed in the steep bluff.

On the E side of the Hudson River, opposite us, one can see several noteworthy features. At left is Croton Point Park; the S end of the wooded ridge at water's edge is Teller's Point, Stop 2 on our On-The-Rocks Trip 25 (21 November 1992) to Croton Point and Peekskill Hollow. To the right of Croton Point is a complex of large buildings, Sing Sing, the notorious destination of prisoners sent "up the river" (from New York City), which is in the Town of Ossining. The wide expanse of wooded countryside between Ossining and Tarrytown, near the Tappan Zee Bridge, is the Rockefeller family preserve, much of which has become Rockefeller State Park. In the pre-park days, the Rockefeller "patch" was shown on property maps as being owned by the "Hills Realty Company," the "Hills" standing for Pocantico Hills. Moreover, because Pocantico Hills was incorporated as a separate town, things were arranged so that nobody could levy local real-estate taxes on the Rockefellers except other Rockefellers.

The strata exposed along the path are situated about 300 m stratigraphically above the base of the Newark Supergroup, which is covered by the Hudson River. This number for the stratigraphic thickness above the base of the Newark is based on a JES projection from the profile-section of Figure 21, which relies on data from the borings made prior to construction of the Tappan Zee Bridge. The sedimentary strata underlying the Watchung basalt sheets have been subdivided into three formations, from base upward, initially named the Stockton, Lockatong, and Brunswick (Kümmel, 1899a). Subsequently, Paul Olsen (1980a) proposed the name Passaic Formation for the sedimentary strata overlying the Lockatong Formation and underlying the oldest of the extrusive basalts, his Orange Mountain Formation. (Refer to list of formation names on p. 12.)

We plan to study sedimentology of Stockton sandstones and evidence for possible fault contact with Palisades sheet and to view a long-overlooked exposure of the Lockatong Formation. Attitude of Newark strata: strike N20°W, dip 10° to 12°SW.

The most-persistent unit along the trail is a reddish-brown siltstone, 2 to 2.5 m thick, which is overlain- and underlain by various sandstones. At the N end of the exposure, which we shall see first, only the sandstones are present. From base upward, these include:

(Top)

Sandstone, coarse, pebbly; contains cross strata dipping toward 225° (on scale of 0° to 360°), which implies a current flowing from NE to SW. Thickness, 2 to 2.5 m.
Sandstone, medium, reddish; thickness 0.6 to 1.0 m.
Sandstone, coarse, pebbly, laminated, thickness 0.3 m.

(Base)

JES infers that the strata here exemplify an upward-fining succession of the kind formed by the migration of an ancient point bar deposited on the inside of meander bends of a river meandering across a flat floodplain. In such a river system, two contrasting kinds of sediments are present: sands and coarser materials from the bed load (which are for the most part confined to the channel and its margins), and silts and clays, materials from the suspended load (which form widespread blankets deposited from the flood waters that periodically inundate the floodplain and turn it into a shallow lake). The conversion of an extensive floodplain into a vast shallow lake is exactly what happened in the midwestern USA during the summer of 1993 when the upper Mississippi and lower Missouri rivers and tributaries breached their confining levees. Many folks will never forget this disastrous Flood of 1993. JES can still hear the words of Paul Shaffer, his first geology professor, lecturing about rivers. "The floodplain belongs to the river," said the good professor. "And every now and then the river will take it back."

The strata deposited by the former river channel consist of various upward-fining sandstones composing what is known as a point-bar succession. Such a succession begins with a channel-floor lag that cuts into the underlying overbank siltstone (usually, but in some cases, not a overbank siltstone but into the sandstones forming an older point-bar succession). Overlying the channel-floor lag are sandstones that generally become finer upward and are characterized by cross strata whose set thickness diminishes upward. In other words, the coarser sands lower down form larger-scale cross strata than do the finer sands toward the top. This is a function of changing flow conditions associated with various water depths within the channel. Observations on modern meandering rivers suggests that a minimum channel depth for deposition of large-scale migrating bed forms that result in large-scale cross strata is about 5 m.

As a meandering channel migrates across the floodplain (Figure 22), it deposits a succession of strata whose thickness equals the water depth in the channel during flood stages

(Figure 23). Notice that in the example shown from the modern Brazos River, the depth of the water in the channel at low stage is about 5 m, but that the thickness of the point-bar succession is about 17 m. The point-bar succession extends downward about 3 m below the bottom of the low-water channel and upward about 11 m above low-water level. This distribution reflects what happens during a flood, when the water level not only rises upward so that it spreads out of the channel but also scours downward, thus lowering the level of the channel floor.

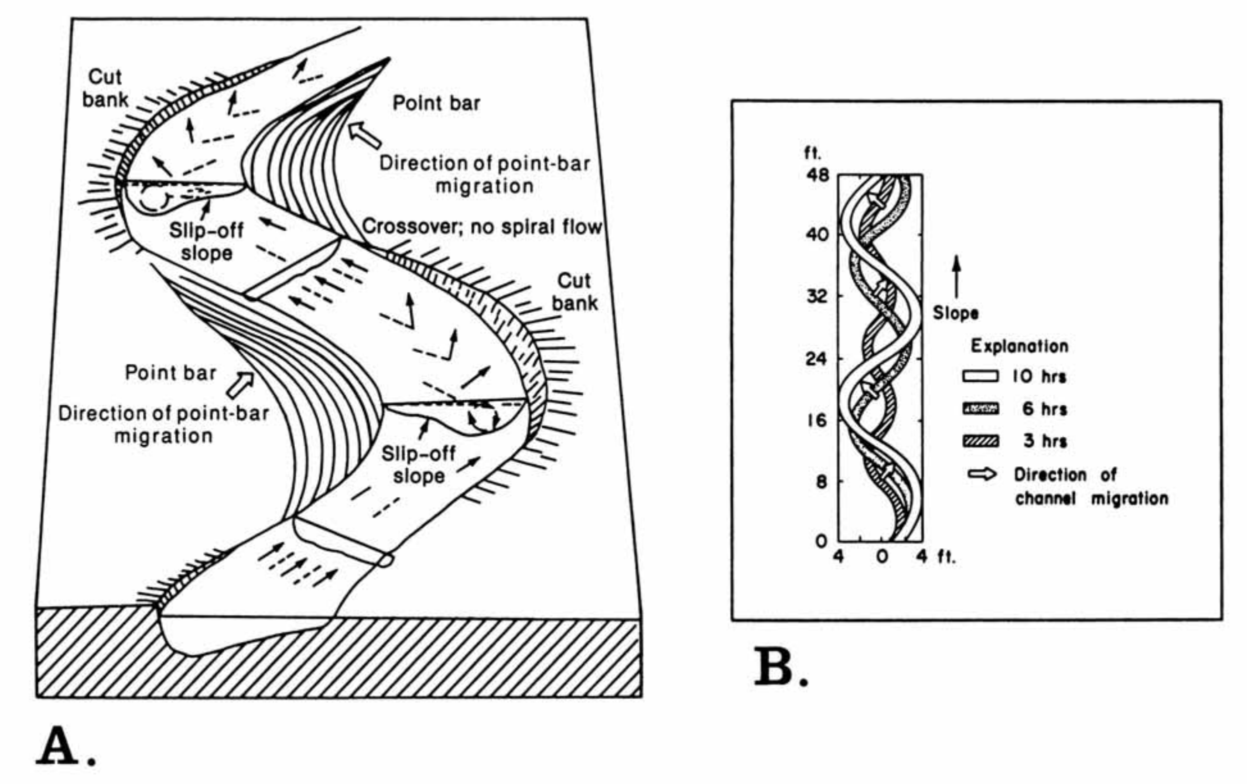


Figure 22. General principles of a meandering stream flowing through more-or-less uniform sand (and thus not subject to being "hung up" on bodies of tough clay deposited in abandoned parts of the channel).

A. Schematic block of two meander bends showing how superelevation of the water on the outside of the bend sets up a secondary clockwise circulation consisting of downward flow on the steep side (cut bank), across the bottom, and upward on the gently inclined shore (the point bar). Downstream from the curve, the channel floor levels off in a stretch known as a crossover. On the next meander downriver, the superelevation to the left creates a counterclockwise secondary flow cell. (G. M. Friedman and J. E. Sanders, 1978, fig. 8-39, p. 221; based on J. F. Friedkin, 1945, A laboratory study of the meandering of alluvial rivers: Vicksburg, MI, U. S. Army Corps of Engineers Mississippi River Commission Waterways Experiment Station, 40 p. (Reprinted in 1972, p. 237-281 in S. A. Schumm, ed., River morphology. Benchmark papers in geology: STroudburg, PA, Dowden, Hutchinson, and Ross, 429 p.)

B. Map view of laboratory meanders in uniform bank materials; the whole set of meanders has shifted uniformly after the amount of time during which the water flowed in the stream table. (J. F. Friedkin, 1945, pl. 25, facing p. 16.)

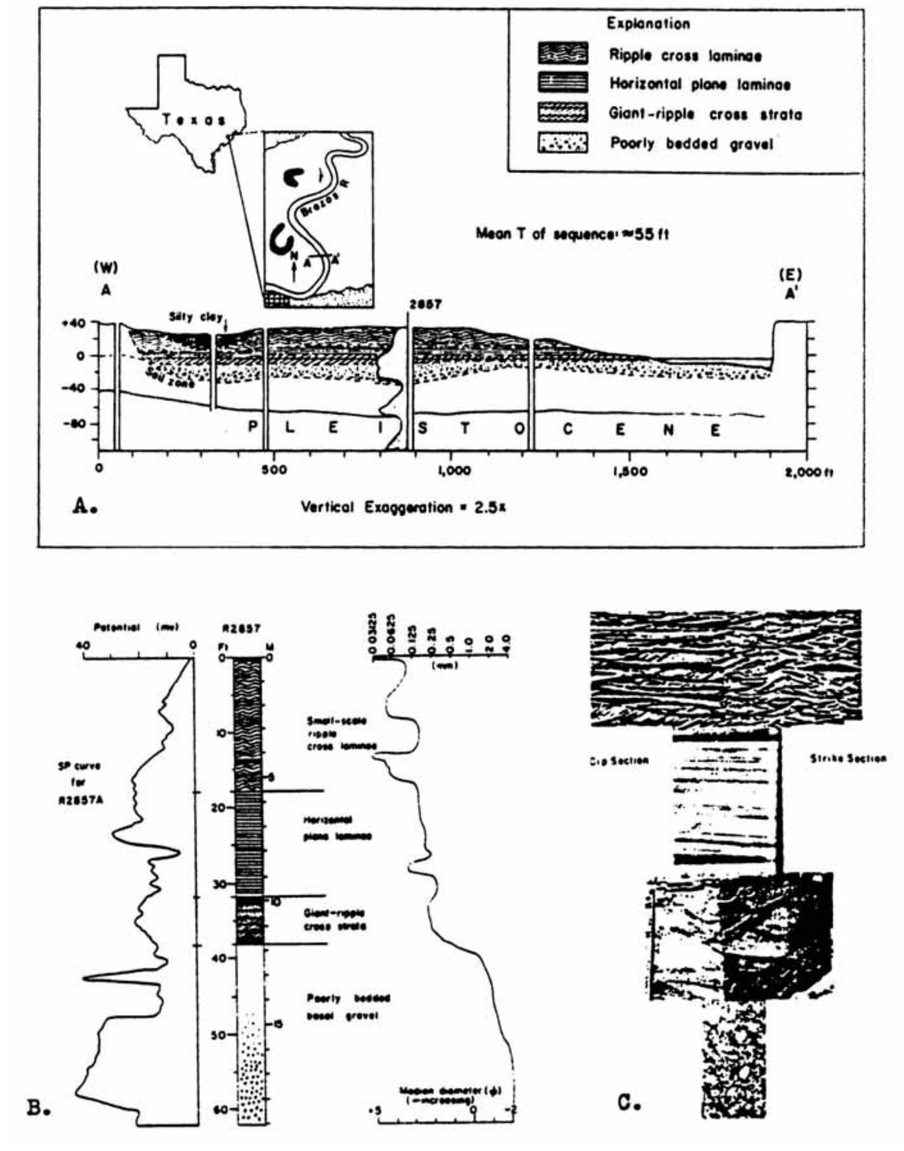


Figure 23. Point-bar succession deposited by meandering channel of Brazos River, SE Texas, based on borings made by Shell Development Company, Houston.

A. Location of profile across flodd plain; notice that the depth of water during fair weather is less than 20 feet (about 5 m), as shown at the right-hand end of the profile. By contrast, the mean thickness of the point-bar succession is 55 feet (about 17 m). This relationship proves conclusively the importance of floods in determining the thickness of the point-bar succession that will be recorded in the geologic record.

B. Detailed stratigraphic log and spontaneous-potential (SP; a kind of electrical log invented by the Schlumberger brothers) log for two closely spaced borings (R2857 for stratigraphic log; R2857A for SP curve). Curve at right shows mean diameter of sediment particles.

C. Photographs of the internal structures in sands at different levels in the succession. (G. M. Friedman and J. E. Sanders, 1978; A, fig. 8-41, p. 222; B and C, fig. 8-43, p. 225; both based on H. A. Bernard and others, courtesy R. J. LeBlanc, Sr.)

Assuming that all the sandstones visible here were deposited by the lateral migration of a single channel, then the thickness of the beds and the large-scale cross strata imply an inferred channel depth of about 5 m.

The overbank deposits here show clear evidence of current action, in the form of rippled fine sands and coarser lenses containing many mud chips. Another kind of feature resulting from current flow consists of flat-bottomed lenses of sand that are convex up and elongated in the direction of current flow (Figure 24, a). Savage interpreted one of these as a product of channeling from both sides, but we prefer the interpretation that such longitudinal sand ridges are products of deposition at the edges of helicoidal "flow tubes," also referred to by hydraulic engineers as "secondary flows." Between two such "flow tubes" where the water impinging on the bottom is moving in opposite directions, a longitudinal sand ridge is deposited (Figure 24, b).

Walk S to point where a small trail leads up to the 65-ft terrace (indicated by a small stone retaining wall). Right at this wall coarse dolerite of the sill is nearly in contact with reddish-brown sandstone. The absence of a chill zone in the igneous rock and of contact-metamorphic effects in the sandstones suggests that this contact is a fault. If so, its trend must be about N-S and its displacement down on the W. After we have inspected these rocks, walk up the steep trail to the terrace level to see the "hidden" exposure of the Lockatong Formation

The Lockatong Formation is known to disappear northeastward by interfingering with the underlying Stockton and overlying Passaic (van Houten, 1969). The general supposition is that this disappearance takes place at Fort Lee, NJ, near the George Washington Bridge. As we shall see, however, 5 meters or more of Lockatong strata are exposed above the 60-ft terrace. Given the presence of the Lockatong above this terrace, the strata of sandstone, conglomerate, and mudstone that we have seen exposed along the riverside trail belong to the Stockton Formation. When Lockatong strata are present to serve as a reference, no problem arises in defining the formations: whatever lies below the Lockatong is assigned to the Stockton. As we have just seen, the local strata lying below the Lockatong (thus in the Stockton) include red mudstones and -sandstones. Taken by themselves, these reddish rocks would be assigned to the Passiac Formation, which overlies the Lockatong. In the absence of the Lockatong, it is difficult to find a consistent stratigraphic level for separating Stockton and Passaic.

Walk back to top of hill to vehicles parked by the Fire House. Just beyond Fire House (on L), take road to R, passing N end Rockland Lake. Thick glacial sediments cover bedrock here.
1.1 36.1 Intersection US Route 9W; turn R, proceed N toward Haverstraw.
0.3 36.4 Passing Swartwout Lake (on L).
0.7 37.1 Large borrow pit in till on R; note large erratics.
0.4 37.5 End of borrow pit.
0.2 37.7 Another small borrow pit on R.
0.2 37.9 Junction with Route NY 303; continue on US 9-W; exposure of Palisades dolerite on R.
0.1 38.0 Top of Palisades sheet.
0.3 38.3 Cut in dolerite on R; large trap-rock quarry (Long Clove quarry of TILCON Co.) on L.

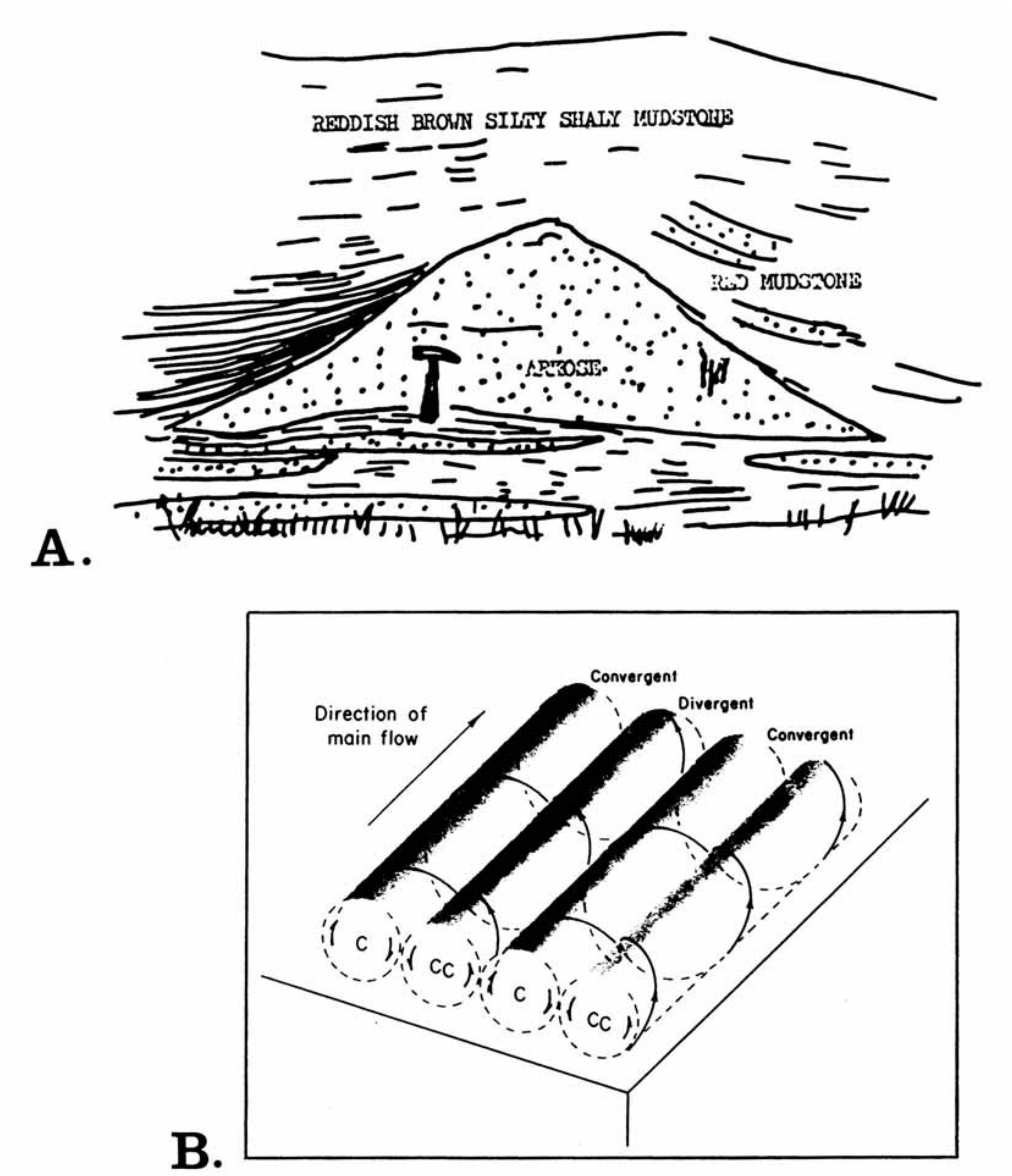


Figure 24. Origin of flat-bottomed lens of sandstone enclosed in mudstone, Stockton Formation, Hook Mountain State Park.

A. Sketch of lens of sandstone; described as "detail of arkose channeled on both sides." (E. L. Savage, 1968, fig. 18b, p. 86).

B. Alternative explanation based on behavior of "tubes" of secondary flows aligned parallel to main current. Schematic block diagram through base of a body of fluid in which helicoidal secondary flow has been established. Small curved arrows at "ends" of "cylinders" show sense of rotation in each. In such a flow, linear sand bodies accumulate between adjacent "cylinders" in which the local flow lines diverge from the bottom. Such sand bodies are entirely depositional; they are not doubly channeled remnants of a formerly wider layer, as suggested by Savage. (G. M. Friedman and J. E. Sanders, 1978, fig. 4-15, p. ; based on S. Dzulynski, 1965, fig. 3, p. 197.)

0.1 38.4 Blinker at junction NY Route 304.

0.1 38.5 Green sign on R for Haverstraw.

0.1 38.6 Cuts in dolerite on both sides of US 9-W.

0.2 38.8 Cuts in sandstone underlying Palisades sheet. Attitude: Strike N40°W dip 10° to 12° SW. The altitude of the highway here is about 225 ft. The contact between the dolerite and the underlying sandstone lies about 15 ft above the highway, thus at altitude 240 ft. (Figure 25, lower profile). This is an important locality but is not suitable for a study by a large group.

0.2 39.0 Parking driveout on R; we may make a brief stop here if space is available for driving off US Route 9W. <SCENIC VIEW.>

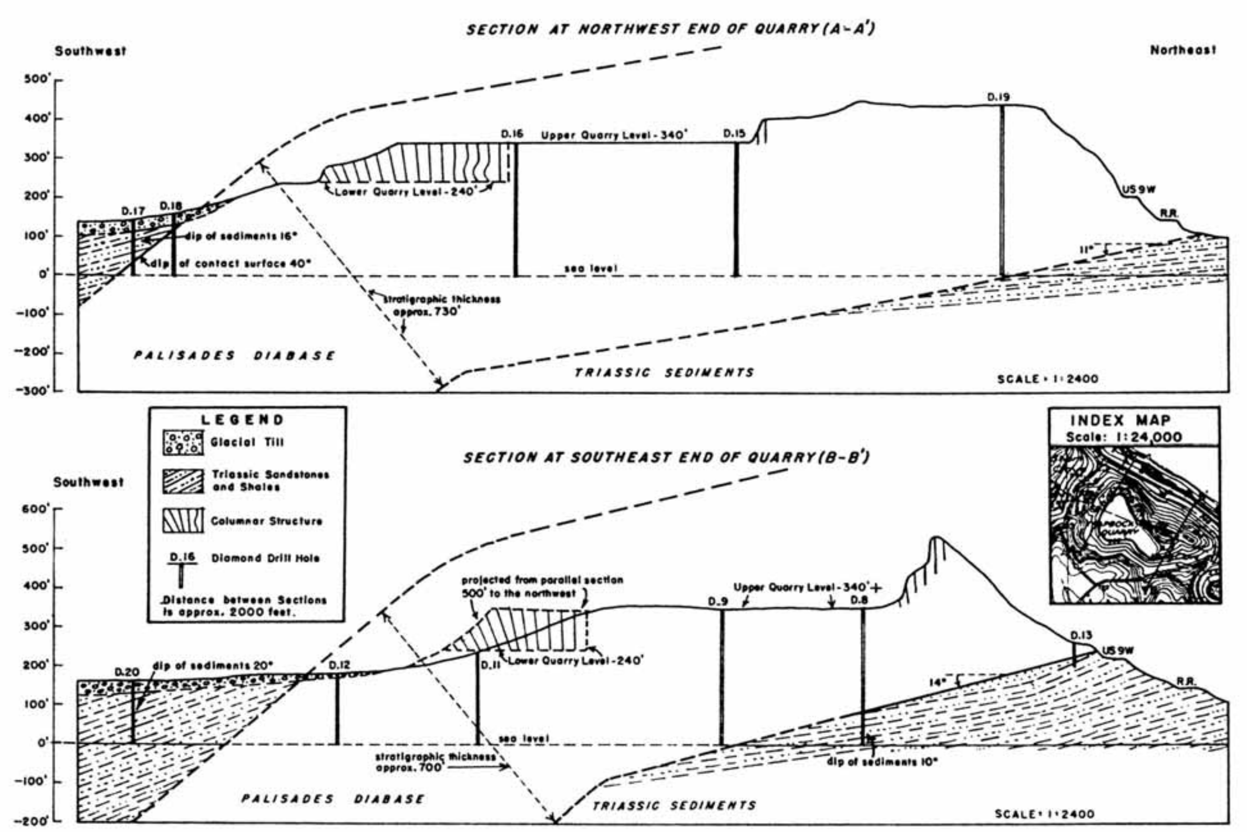


Figure 25. Profile sections showing elevation and dip of base of Palisades sheet in vicinity of Long Clove quarry, Haverstraw, NY.
(K. E. Lowe, 1959, fig. 8, p. 1133.)

0.1 39.1 Roadside sign for Rotary Club; dolerite exposed at road level on L. Altitude here is 180 ft., or 60 ft lower than that of the contact seen 0.3 mi. back. We agree with Thompson (1959; See Figure 10.) that this abrupt shift in the level of the dolerite has resulted from movement on a normal fault that trends NE-SW and throws relatively down on the NW by at least 100 ft.

0.3 39.4 Traffic signal; truck road to Short Clove quarry dolerite exposed at road level ahead on L and downhill at altitude 150 ft. (90 ft. lower than contact at mile 16.5).

0.1 39.5 Local street on R; end of dolerite cuts; large talus on L The flat terrace ahead at altitude about 70 ft is underlain by Pleistocene lake sediments.
0.5 40.0 New nursing home on L; cuts behind building are in till.
0.6 40.6 Traffic signal; New Main Street. Haverstraw business district to R. Continue on US Route 9-W. Highway parallels contours at altitude 110 ft on glacial sediments. Steep scarp slope of Palisades sheet on L.

The topographic contours here show a distinct change in slope at altitude 250 ft. Such a slope change is usually caused by the change from igneous rocks (underlying the steep part of the slope) to sedimentary rocks (underlying the less-steep slope). If this is correct, it implies that the basal contact of the Palisades sheet lies at about 250 ft, nearly the same level as at mile 38.8. Possibly we have crossed another fault, which would bound a small graben, within which the base of the Palisades sheet has dropped by about 100 feet.

0.3 40.9 Junction US 202; continue on US 9-W. Mount Repose Cemetery on L.
0.8 41.7 Green official sign for West Haverstraw on R. Till exposed in cuts behind Hi Tor Lanes bowling alley and in borrow pits beyond.
0.4 42.1 Traffic signal; Railroad Ave., continue on US 9-W.
0.3 42.4 State Research and Rehabilitation Hospital on L.
0.2 42.6 Traffic light at road to Stony Point industrial park (Kay-Fries Chemical Inc. plant).
0.1 42.7 Traffic signal; Filors Lane on L; continue on 9W.
0.3 43.0 Official green sign for Stony Point.
0.1 43.1 Jct. local street; continue on US Route 9-W (which curves to L here).
0.3 43.4 Intersection Co. Hwy 66 (NY Route 210); follow US 9-W (curves to R).
0.1 43.5 Bridge over Cedar Pond Brook.
0.1 43.6 Turn R at end of bridge before traffic signal; take Lowland Hill Rd.
0.2 43.8 Drive downhill to entrance of Lowland Park, Town of Stony Point; enter park;
0.1 43.9 Leave vans for STOP 2. This park is closed for the season, but we have permission to be here courtesy Mr. Steven M. Hurley, Supervisor of the Town of Stony Point.

STOP 2 - Non-marine lacustrine facies in lower part of Newark Supergroup (Stockton? or Passaic? Formation), Lowland Park, Stony Point. [UTM Coordinates: 585.05E / 4564.2N, Haverstraw quadrangle.]

The objective of this stop is to examine at close range the strata exposed on the S bank of the creek and beneath the bridge for Route 9 (overhead). This can best be done by driving the vans to the area of the picnic tables and then crossing the creek. Whether we do that or not will depend on the amount of rain that has fallen lately.

Reddish-brown siltstones and associated gray carbonate rocks about 1250 ft. above base of Newark succession and 3 miles SE of Ramapo fault. Lithologically, these strata are ancient mudstones and nonmarine limestones that were deposited in the offshore parts of a lake. We assign them to the Brunswick (on the presumption that we are above the level of the Lockatong Formation; if they are below the Lockatong, then they belong in the Stockton). The greenish nodules are composed of calcite; they are caliche--the products of upward movement- and evaporation at the surface of water in the ancient soil in a semi-arid climate zone. James Gates Percival (1842, p. 316-317) first noticed carbonate nodules in the "Secondary" strata underlying the lowland of central Connecticut (now designated as the Hartford basin). J. F. Hubert (1978) made a detailed study of comparable ancient caliche in the New Haven Arkose exposed in new cuts at Mt. Carmel, Hamden.

Attitude of strata here: strike N45°W; dip 15°SW. This attitude can be measured on several of the limestone beds; it clearly supports the JES interpretation of the existence of the Danbury transverse anticline in contrast to the "shoaling-basin" interpretation. The fact that the strata here lack conglomerates indicates they were deposited well away from areas having high relief. We are close enough to the NE end of the Newark outcrop belt that if the "shoaling-basin" hypothesis were correct, then these strata should show the effects of the higher area of basement against which the strata would be overlapping. Our verdict about the "shoaling-basin" hypothesis on the basis of the evidence before you here is the same one-word evaluation Wayne Gretzky gave to Bo Jackson's hockey ability based on Bo's cameo appearance wearing ice skates and hockey pads in a TV commercial made a few years ago: "No."

Return to vans.

0.2 44.1 Follow uphill on Lowland Hill Rd. to US Route 9W; turn R onto US 9W. Traffic signal for NY Route 210 ("The first road across the Hudson Highlands" in 1760); stay on US 9W northbound.
0.2 44.3 Blinker light at Fire Station (on L).
0.1 44.4 County drainage project; local street on R.
0.3 44.7 Road on R to Stony Point Battlefield; continue on US 9-W.
0.2 44.9 Restaurant building (formerly "Bluebird") on R; drive into parking lot for pullover stop. Remain in vehicles.

Newark conglomerate is exposed in cut on W side of US 9-W; clasts consist chiefly of carbonate rocks. We will visit another exposure of these rocks after lunch. Continue N on US 9-W.

0.2 45.1 At crest of knoll, turn R into Park Road. This RJ is about on the contact of the Newark with the Paleozoic Sauk Sequence (Cambro-Ordovician) carbonate rocks. At left is Tomkins Cove quarry in these carbonate rocks, which are overlain by till.
0.1 45.2 Cuts on both sides of road in Cambro©Ordovician carbonate rocks.
0.1 45.3 Turn L; follow road to Stony Point Battlefield.
0.05 45.35 Turn R on gravel road.
0.05 45.4 Take first fork to R. The lowland along the road carved along the contact at the base of the Newark. Paleozoic rocks underlie the hills to the L; Newark conglomerates form the hill on the S side of the creek (on R).
0.2 45.6 Exposure on L; finely foliated gneiss.
0.1 45.7 Entrance to Stony Point State Park. Cuts along RR are in gneiss; igneous rocks underlie Stony Point itself. STOP 3.

STOP 3 - Newark Conglomerate, pre-Newark metamorphic- and igneous rocks, and west edge of Cortlandt intrusives at Stony Point State Park, Stony Point, NY. [UTM Coordinates: 585.62E / 4565.8N, Haverstraw quadrangle.]

We plan to make two small traverses at Stony Point State Park; one to the south along the railroad cut to see conglomerate of the Newark Basin and one along the railroad cut that exposes intrusive rocks of the Stony Point-Cortlandt Complex. PLEASE BE AWARE! These rail lines are used and if a train comes, there will be little warning and we don't carry bandaids! Stay off the tracks and prepare to leap for cover in the event of a train.

Walk south on the railroad tracks to a low exposure of red-colored basal rudite of the sedimentary fill of the Newark Basin. Here, in a deeply iron-stained exposure, angular clasts of gray-colored Wappinger Limestone, 3 to 6 cm in size, are set in a reddish feldspathic sandstone matrix. Bedding is crudely developed in this low exposure and is oriented roughly N60°W, 35°SW. Compared to the basin-marginal rudites (which we will examine later) exposed near Suffern, New York, consisting of rounded- to angular boulders of Proterozoic gneiss together with quartzite, Green Pond Conglomerate, limestone, reddish shale, and -arkose, this exposure is surprisingly monomict (fancy word for a rudite whose fragments consist of only one kind of rock). One explanation for this difference embraces the concept that during the early Mesozoic episode of uplift, erosion, and deposition in what is now preserved as the northern part of the Newark Basin, the adjacent elevated area had not yet been denuded below the stratigraphic level of the Cambro-Ordovician carbonate rocks that formerly covered the Proterozoic basement.

Walk back on the tracks beneath the bridge at the entrance to Stony Point Park. Here, dike rocks and two stock-like masses of mafic- to ultramafic plutonic rock, representing westerly appendages of the Cortlandt Complex on the E side of the Hudson River, cut across isoclinally folded, probable lower Paleozoic rocks of the Annsville Phyllite and Inwood Marble (Figures 26, 27). At the southern end of the railroad cut, the Annsville exhibits a large-scale recumbent fold plunging 17° into S78°E with an axial surface oriented N42°E, 20°SE.

Regionally, these country rocks are less-metamorphosed equivalents of Layers IIA and IIB the Inwood Marble and Manhattan Schist, respectively, as suggested by stratigraphic- and paleontologic data from the Tompkins Cove and Verplanck quarries on either side of the Hudson River. Here, the Annsville contains sillimanite (a very high-grade metamorphic index mineral) near the contact with the hornblende pyroxenite (Cortlandtite) intrusives. Porphyroblastic muscovite (related to post-intrusive regional cooling) overgrows the sillimanite contact assemblages (Ratcliffe and others, 1983). This is the type locality for poikilitic Cortlandtite as described by Williams (1885).

Deformational features related to regional folding episodes mapped in the Lower Paleozoic country rocks are truncated by the earliest pluton of biotite diorite (Pluton II of the Cortlandt Complex). The diorite and the country rocks are further cut by the cortlandtitic rocks which are correlative and probably continuous with Pluton IV of the eastern "funnel" of the Cortlandt Complex. Dating of these intrusive rocks at 435 Ma has established a Taconian age for deformation of the bedrock sequences.

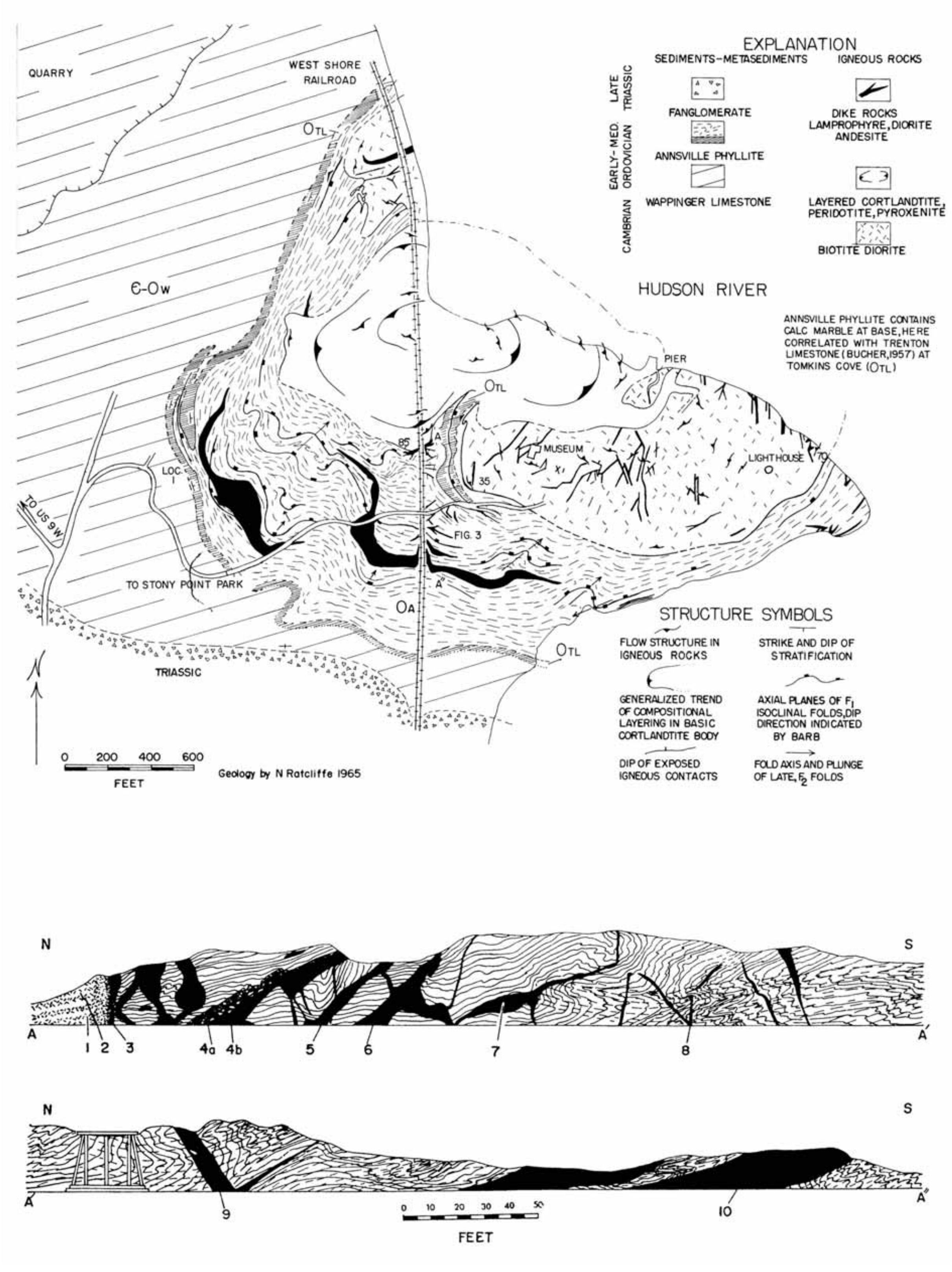


Figure 26. Geologic map and sections from Stony Point showing plutonic rocks and their contact with metamorphosed bedrock. From Ratcliffe (1968).

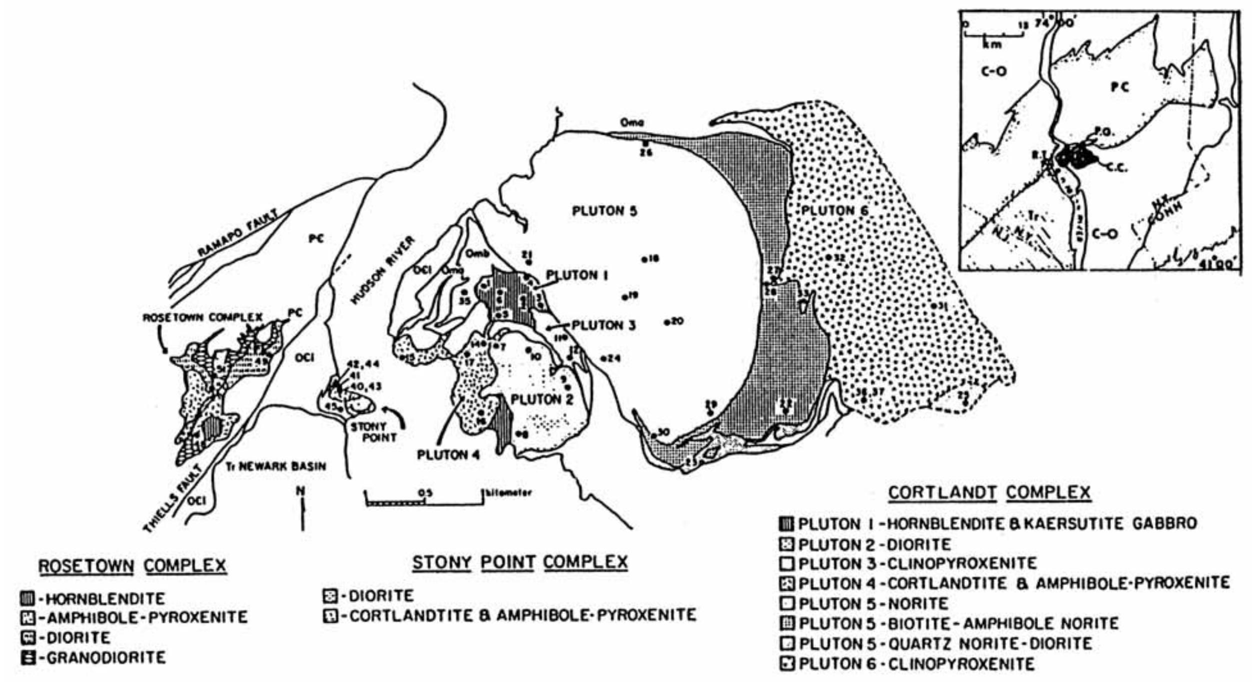


Figure 27. Generalized geologic map of the Cortlandt, Stony Point, and Rosetown Complexes. From Ratcliffe (1980).

We urge you to revisit this area to examine the Stony Point Battlefield and walk through the outdoor exhibit in order to relive the important battle that took place here in July, 1779. Our Hudson Valley field-trip guidebook (Trip 14, 28 October 1990) discloses more details on the importance of the park during the Revolutionary War.

Re-board vehicles and retrace route along park road.

0.4 46.1 Jct. Park Road. Continue ahead.
0.1 46.2 Exposure on R of basal Newark carbonate-clast rudite. Continue S on local street.
0.2 46.4 Park Road rejoins US 9-W. Follow US 9-W south (bear L).
0.1 46.5 Conglomerate exposed in bank on R of road.
0.5 47.0 Route 110 enters on L.
0.2 47.2 Traffic light.
0.3 47.5 Traffic light; Co. Route 108; NY Route 210; turn R.
0.1 47.6 Passing Presbyterian church on R.
0.4 48.0 Cricketown Rd. on R.
0.3 48.3 Passing Rd on L coming up from valley; keep R.
Leave Haverstraw quadrangle, enter Thiells quadrangle.
0.5 48.8 Stop sign; turn L onto Co. Route 108 W.
0.1 48.9 Stop sign; turn R on widened NY Route 210. & Co. Route 106.
0.7 49.6 Passing Cedar Flats Rd. on R; continue W on NY Route 210.
0.8 50.4 Crossing over PIP on NY Route 210.
0.1 50.5 Turn L into S-bound ramp for PIP.

0.1 50.6 On PIP Southbound.
1.2 51.0 Passing Exit 14 (Willow Grove) on R.
2.4 53.4 Leave PIP at Exit 13 on R; US Route 202 (Haverstraw-Suffern).
0.7 54.1 Old US Route 202
0.1 54.2 Village of Pomona Sign on R.
0.1 54.3 Camp Hill Rd.
0.5 54.8 Passing beneath powerline (before drumlin).
0.1 54.9 Deep roadcut in till, Ladentown, near N end of large drumlin that is 1.3 mi. long. This drumlin is one of many drumlins found in the SE corner of the Thiells quadrangle. The N-S ice-flow direction implied by these drumlins is inferred to have been a product of the latest Wisconinan (=Woodfordian) glacier to cover the area.

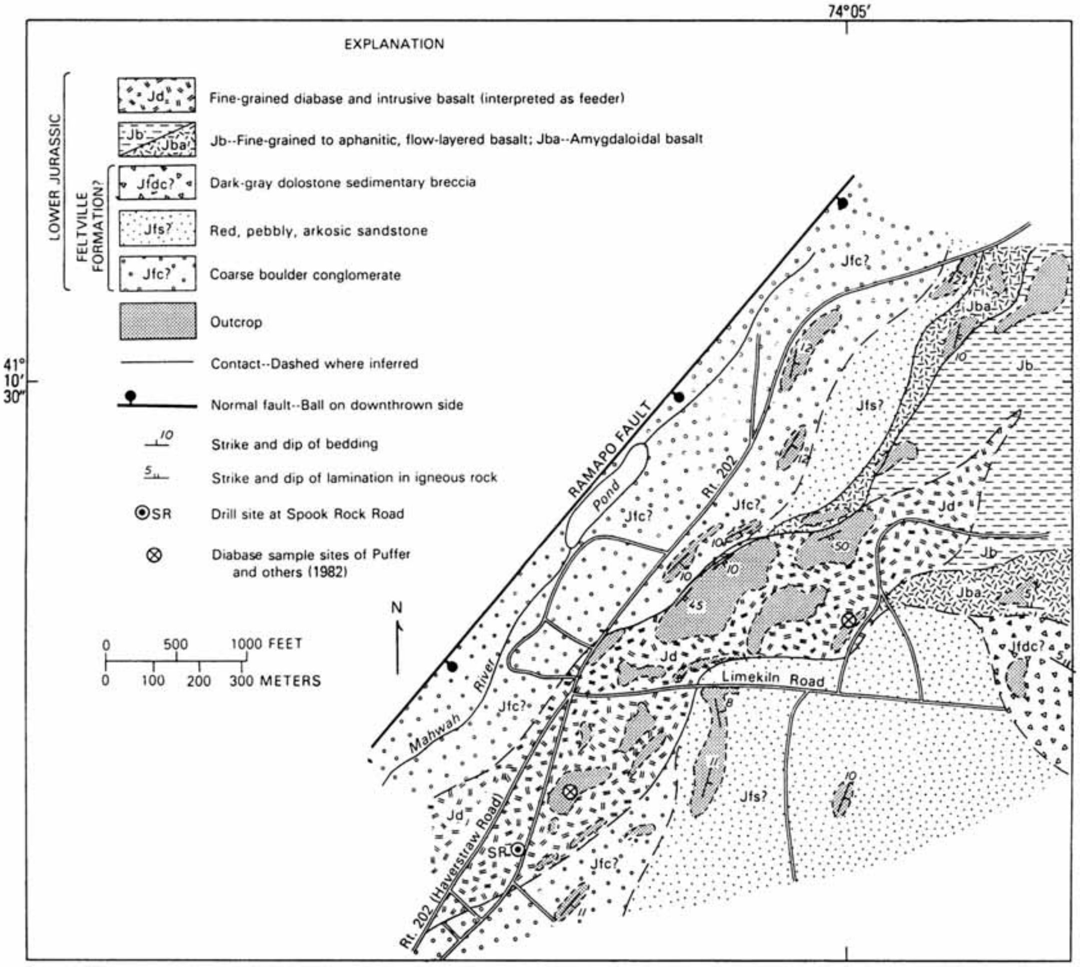
0.2 55.1 Jct. NY Route 306; continue SW on US Route 202. Ahead are the Ramapo Mountains, underlain by resistant Poterozoic rock on the NW side of the Ramapo fault. Judging by the composition of the Newark conglomerates (almost exclusively Paleozoic carbonate rocks), these Proterozoic basement rocks were not exposed at the Earth's surface in many places until early in the Jurassic Period. Some local exceptions to this do occur; feldspars in the Brunswick Formation in Rockland County have been dated by K-Ar methods at 870 Ma and 930 Ma (Abdel-Monem and Kulp, 1968). These feldspars indicate that in at least one drainage basin feeding into the area of Newark sedimentation, Proterozoic rocks were exposed before the end of the Triassic Period.

The Ramapo fault lies concealed within the valley along which the Mahwah River now flows (from NE to SW).

0.3 55.4 Mafic igneous exposed on L side of road. This may belong to the Ladentown extrusive sheets; Ratcliffe (1988, fig. 1) shows this as being a westward continuation of the Palisades sheet.
0.9 56.3 Jct. Wilder Rd on L; continue on US Route 202.
0.05 56.35 Mafic igneous rock exposed on R side of road; part of the Ladentown extrusive basalt.
0.15 56.5 Conglomerate on both sides of road, chiefly on L (exposures described in detail by Carlston, 1946).
0.1 56.6 More conglomerate on R.
0.2 56.8 Conglomerate on R.
0.4 57.2 Mafic igneous rock exposed on L. Jct. Limekiln Rd.
Turn L onto Limekiln Rd. A lime kiln formerly existed about 0.4 mi. from here; the lime came from carbonate rocks in a Newark coarse rudite. (Stop 4 of NYSGA 40th mtg. trip, Savage 1968.)
0.2 57.4 Turn L into street leading uphill to new houses. Drive to top of knoll; turn around and park for Stop 4.

STOP 4 - Vesicular- and amygdaloidal basalt of the Ladentown Basalt of Kümmel (1900) on Limekiln Road. [UTM Coordinates: 576.3E / 4557.1N, Theills quadrangle.]

When construction was underway for these houses, pillowed basalt was exposed at the top of the knoll. Figure 28 shows the geologic relationships inferred by Ratcliffe (1988) in connection with the Spook Rock core site.



Geologic sketch map of corehole locality at Spook Rock Road (locality 2, fig. 1) showing interpreted intrusive rocks and feeder(?) and basaltic flows. The diabase forms a prominent line of ridges that rise approximately 100 ft above Jurassic(?) strata to the west. Flow structures within chill diabase on the hills and northwest of Limekiln Road are interpreted as minor-scale protrusion structures similar to the textures described in the text that refer to figure 6. Sedimentary rocks of uncertain age and correlation beneath basalts are tentatively assigned to the Feltville Formation.

Figure 28. Geologic sketch map of Spook Rock Road core hole localities from Ratcliffe (1988, Figure 7).

Re-board vehicles, retrace route to Limekiln Rd., turn R.

0.2 57.6 Jct. with Spook Rock Rd.; turn L, following sign to Antrim Playhouse.
0.2 57.8 Passing US Geological Survey's Spook Rock Rd. core site on R.

0.2 58.0 Passing Cemetery on L.
0.2 58.2 Road forks; Spook Rock Road veers L; take fork to R.
0.2 58.4 Wesley Chapel; near Jct. US Route 202. Park vehicles on R and get out for STOP 5. Newark conglomerate.

STOP 5 - Near-horizontal sedimentary strata near Ramapo fault: rudites and well-laminated to cross-stratified sandstone. [UTM Coordinates: 575.25E / 4555.9N, Theills quadrangle.]

JES has expended another of his big plant-eradicating efforts here in order that participants on this trip can view an unobscured roadcut exposure. Key points: conglomerate at far SW end along US Route 202; well-bedded and horizontally laminated sandstones near the intersection of US Route 202 and Spook Rock Road; and along Spook Rock Road, cross strata showing water movement from NE to SW, nearly at right angles to the direction from that traveled by the boulders from the elevated Ramapo Mountains block into the subsiding Newark basin.

The conventional wisdom about these coarse basin-marginal rudites is that they were deposited on fans at the toe of the steep fault scarp. Indeed, these rudites are commonly designated as "fanglomerates." We have deliberately avoided using the term "fanglomerate," because the sedimentary characteristics of these strata do not match those of subaerial fans.

JES interprets these strata as having been deposited on a beach at the shores of a very large lake that occupied most of the Newark basin during one of the climatic episodes when water was abundant. Cross strata are oriented N25°W, 41°SW. JES infers that the trend of the former shoreline was NE-SW, parallel to the Ramapo fault, and that waves approached this shore from the E and SE. In so doing, they would form breaker bars that migrated northwestward toward shore. Such migration would create the cross strata dipping westward (Figure 29).

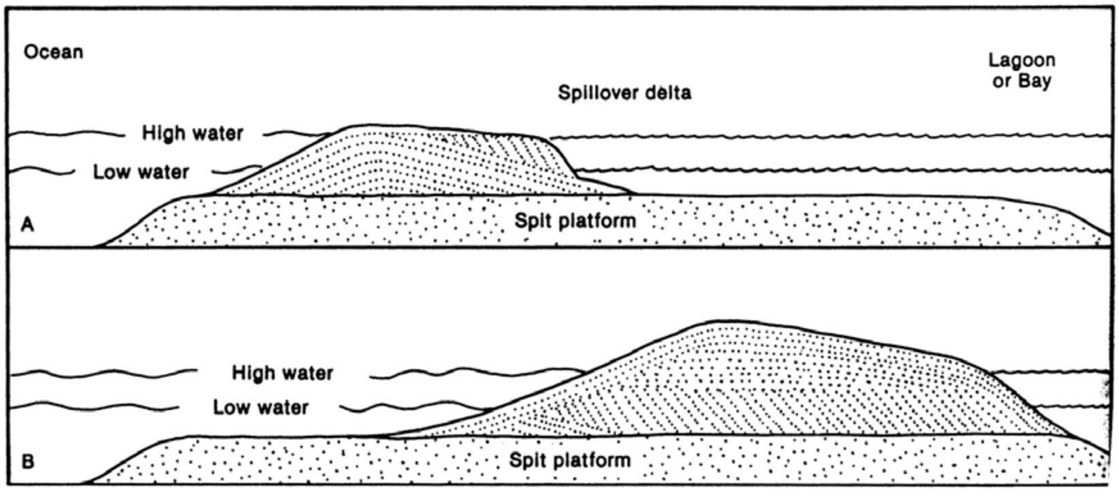


Figure 29. Sketch profiles at Democrat Point spit, Robert Moses State Park, Fire Island, Long Island, NY, showing landward-dipping cross strata. (J. E. Sanders in G. M. Friedman and J. E. Sanders, 1978, fig. 11-10, p. 315.)

The stratigraphic position of these strata is not known. Because we are adjacent to the Ramapo fault, a common opinion is that these strata should be from high in the Newark Supergroup, say from the Boonton Formation. Some insight into the subject may come from a final decision about the relationship between the Ladentown Basalt and the Watchung extrusives. If the Ladentown equals Orange Mountain (First Watchung), and these strata underlie the Ladentown Basalt, then they could be from the top of the Passaic Formation. Stay tuned.

Reboard vehicles; turn L and proceed SW on US Route 202

0.4	58.8	On L, Grandview Ave., Ramapo College; continue on US Route 202.
0.7	59.5	On R, Kings Gate R., bridge across creek.
0.3	59.8	US Route 202 curves R, on L Viola Rd.
0.1	59.9	Enter Sloatsburg Quadrangle
1.5	61.4	Suffern sign on R.
0.2	61.6	Leave Thiells Quadrangle; enter Ramsey Quadrangle
0.3	61.9	Pass Lake Antrim on L, turn R into Pavilion Road. Leave vehicles for STOP 6.

STOP 6 - Proterozoic rocks in Ramapo fault at Pavilion Road and newly excavated exposure on I-87. [UTM Coordinates: 571.6E / 4552.3N, Ramsey quadrangle.]

This area allows an interesting view of the rocks in the Ramapo fault zone in both weathered- and fresh exposure. We prefer weathered rock for the analysis of fault motion and fresh rock for samples of cataclasite. As such let's begin at the weathered zone and examine the steeply dipping fault surface. The slickensides vary from large-scale corrugations to minor streaks and, given proper lighting conditions, as you step away from the exposure, are very obvious. Based on 13 measurements, the average orientation of the fault surface is N68°E, 75°SE (Figure 30). The rake of the slickensides ranges from 44° to 62° toward the SW indicating that the slicks plunge 43° into S58°W on average. The asymmetry of steps on the slickensides indicate that during the latest motion, hanging wall (the missing block) moved up the fault surface away from the SW. Hidden beneath the obvious slickensided fault surface are traces of subhorizontal slickensides that suggest an episode of horizontally directed motion antedated the more-obvious SW-raking slickensides. Thus, the movement history along the Ramapo fault has been complex. We would define the last (most-obvious) motion sense on the Ramapo fault as being oblique slip with composite left-lateral strike-slip and reverse dip-slip movement.

After we have walked over to the fresh cuts on the shoulder of I-87, note the variation in lithology of the Proterozoic orthogneisses (meaning metamorphosed plutonic rocks) that include granitoid-, dioritic-, and gabbroic rocks. The thin seams of blackish material cutting through the rocks are cataclasite (finely granulated pre-existing fault rocks and new minerals produced by fault motions in the brittle zone (upper 10 km) of the crust). Slickensides are common and where faults cut through the more-mafic lithologies some serpentine-group minerals have developed. Numerous fault orientations are measureable here and as an On-The-Rocks exercise we will measure as many as we can and see if the results make sense with what we just observed at the weathered area near the vans. To most of you, the contrast between fresh- and weathered rock may be astounding as they look like totally different rocks.

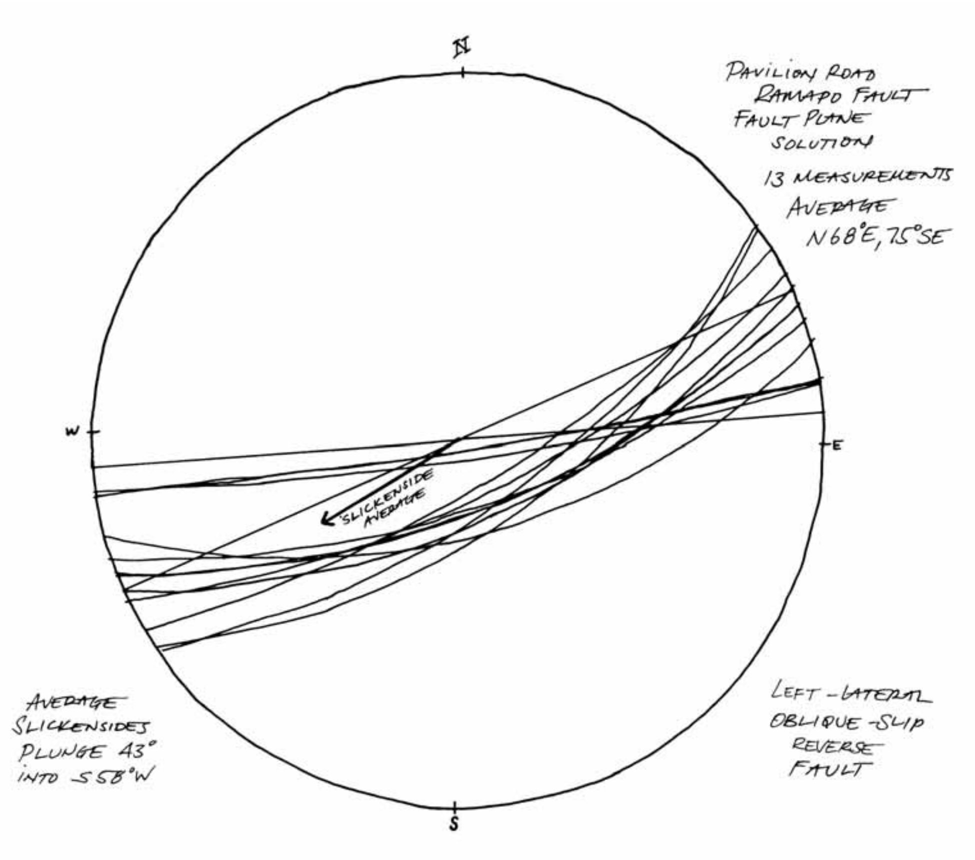


Figure 30. Equal-area stereonet showing thirteen measurements of the strike and dip of the Ramapo fault exposed on Pavilion Road in Suffern, New York. Field observations indicate that the last displacement on the Ramapo fault was left-lateral oblique-slip reverse motion. (Merguerian and Hofstra students, unpublished field data.)

At this point we will head back to the Academy, a little tired, a bit enlightened, and a tad wiser. Thanks for your continued support for our On-The-Rocks trips. See you next Spring!

ACKNOWLEDGEMENTS

We express our usual thanks to Matt Katz and Marcie Brenner of the New York Academy of Sciences, and to "the boys" of Duke Geological Laboratory for their able assistance. We are indebted to Mr. Jack Driver, Hook Mountain State Park, for permission to enter from the north end and to park vehicles by the Fire House. We thank the desk sergeant of the Stony Point Police for helping us find the office of Stony Point Supervisor Steven M. Hurley, who arranged for our access to Lowland Park. Thanks also to Site Manager Don Loprieno for allowing off-season access to the Stony Point State Historic Site.

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	**Taconic orogeny.** Intense deformation and metamorphism.
	450	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	LAYER IIA[E] - TACONIC SEQUENCE
Western shallow-water platform (L. Cambrian-M. Ordovician)	Eastern deep-water zone (L. Cambrian-M. Ordovician)
Copake Limestone Rochdale Limestone Halcyon Lake Fm.	Stockbridge or Inwood Marbles
Briarcliff Dolostone Pine Plains Fm. Stissing Dolostone Poughquag Quartzite Lowerre Quartzite [Base not known]	(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 – 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.

Table 04 - Chemical analyses of Newark igneous rocks, New Jersey
(J. V. Lewis, 1908a, p. 121-122)
(Palisades Sill, from bottom, lower part, middle, and top)

Element	**IV**	**V**	**VII**	**VIII**	**IX**	**X**
SiO_2	51.88	50.40	49.62	51.14	51.03	49.02
TiO_2	1.35	1.35	1.01	1.13	0.93	0.99
Al_2O_3	14.53	15.60	10.51	12.99	11.92	10.14
Fe_2O_3	1.35	3.65	0.64	1.50	1.52	1.54
FeO	9.14	6.30	12.02	9.14	10.85	10.46
MgO	7.78	6.08	15.98	11.58	12.08	17.25
CaO	9.98	10.41	7.86	10.08	9.22	8.29
Na_2O	2.06	3.57	1.40	1.72	1.50	1.59
K_2O	0.93	0.62	0.67	0.42	0.39	0.40
H_2O	----	----	----	----	----	----
H_2O^+	0.97	1.67	0.49	0.59	0.54	0.59
H_2O^-	0.12	1.02	0.39	0.14	0.17	0.16
MnO	0.10	0.06	0.09	0.16	0.15	0.16
P_2O_5	0.14	0.16	0.16	0.06	0.08	0.11
CO_2	----	----	----	----	----	----
Totals	100.33	99.89	100.71	100.75	100.38	100.70
Sp.Gr.	2.98	2.89	3.118	3.051	3.122	3.152

IV: Basaltic diabase, Weehawken; lower contact in Pennsylvania RR tunnel, R. B. Gage, analyst.
V: Basaltic diabase, New York, Susquehanna and Western railroad tunnel, upper contact at west portal, R. B. Gage, analyst.
VII: Olivine diabase, Weehawken, road to West Shore Ferry; typical coarse diabase, R. B. Gage, analyst.
VIII: Diabase, Englewood Cliffs, below the olivine diabase, R. B. Gage, analyst.
IX: Diabase, Englewood Cliffs, coarse rock above the olivine diabase, R. B. Gage, analyst.
X: Olivine diabase, Englewood Cliffs; typical, coarse. R. B. Gage, analyst.

Table 05 - Chemical analyses of Newark igneous rocks, New Jersey
(J. V. Lewis, 1908a, p. 159, 161)

	(Orange Mountain Formation)						**(Hook Mountain Fm.)**		
Element	**I**	**IV**	**VI**	**II**	**V**	**III**	**VII**	**VIII**	**IX**
SiO_2	50.19	51.82	51.36	51.09	51.84	51.77	49.68	49.17	49.71
TiO_2	1.13	1.17	----	1.30	1.22	1.13	1.39	1.50	1.53
Al_2O_3	14.65	14.18	16.25	14.23	15.11	14.59	14.02	13.80	13.66
Fe_2O_3	3.41	0.57	2.14	2.56	1.78	3.62	4.97	4.90	5.49
FeO	6.96	9.07	8.24	7.74	8.31	6.90	9.52	10.61	9.51
MgO	7.95	8.39	7.97	7.56	7.27	7.18	5.80	5.04	6.13
CaO	9.33	8.60	10.27	10.35	10.47	7.79	6.50	9.87	5.85
Na_2O	2.64	2.79	1.54	1.92	1.87	3.92	3.49	2.21	4.51
K_2O	0.75	1.26	1.06	0.42	0.34	0.64	1.41	0.54	0.37
H_2O	----	----	----	----	----	----	----	----	----
H_2O^+	2.38	1.40	1.33	1.01	1.33	1.85	1.89	0.73	2.66
H_2O^-	0.66	0.30	----	1.66	0.56	0.46	0.54	1.04	0.48
MnO	0.07	0.13	0.09	0.25	0.09	0.05	0.18	0.07	0.13
P_2O_5	0.18	----	0.21	0.16	0.13	0.18	0.17	0.24	0.10
$Ni0_2$	----	----	0.03	----	----	----	----	----	----
SrO	----	----	----	----	----	----	tr	0.03	----
Totals	100.30	99.85	100.28	100.25	100.32	100.08	99.60	99.75	100.13
Sp.Gr.	2.92	2.95	----	2.936	2.93	2.91	2.949	2.997	2.91

Orange Mountain Formation:
I. Hartshorn's Quarry, nr. Springfield and Short Hills ("lower gray").
(An. No. 121; spec. and thin section 309-L; R.B. Gage, analyst).
IV. Hatfield and Weldon's Quarry, Scotch Plains ("lower gray").
(An. No. 130; spec. and thin section 35-L; R.B. Gage, analyst).
VI. O'Rourke's Quarry, West Orange (large columns near bottom).
(U. S. Geol. Survey Bull. 150, p. 255; L. G. Eakins, analyst).
II. Hartshorn's Quarry, nr. Springfield and Short Hills ("middle black layer").
(An. No. 120; spec. and thin section 308-L; R.B. Gage, analyst).
V. Hatfield and Weldon's Quarry, Scotch Plains ("middle black layer").
(An. No. 131; spec. and thin section 36-L; R. B. Gage, analyst).
III. Hartshorn's Quarry, nr. Springfield and Short Hills ("upper gray layer").
(An. No. 122; spec. and thin section 310-L; R.B. Gage, analyst).

Hook Mountain Formation:
VII. Morris County Crushed Stone Co.'s Quarry, Millington ("lower gray").
(An. No. 123; spec. and thin section 245-L: R.B. Gage, analyst).
VIII. Same locality ("middle black layer")
(An. No. 124; spec. and thin section 246-L; R.B. Gage, analyst).
IX. Same locality ("upper gray layer")
(An. No. 125; spec. and thin section 247-L; R.B. Gage, analyst).

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