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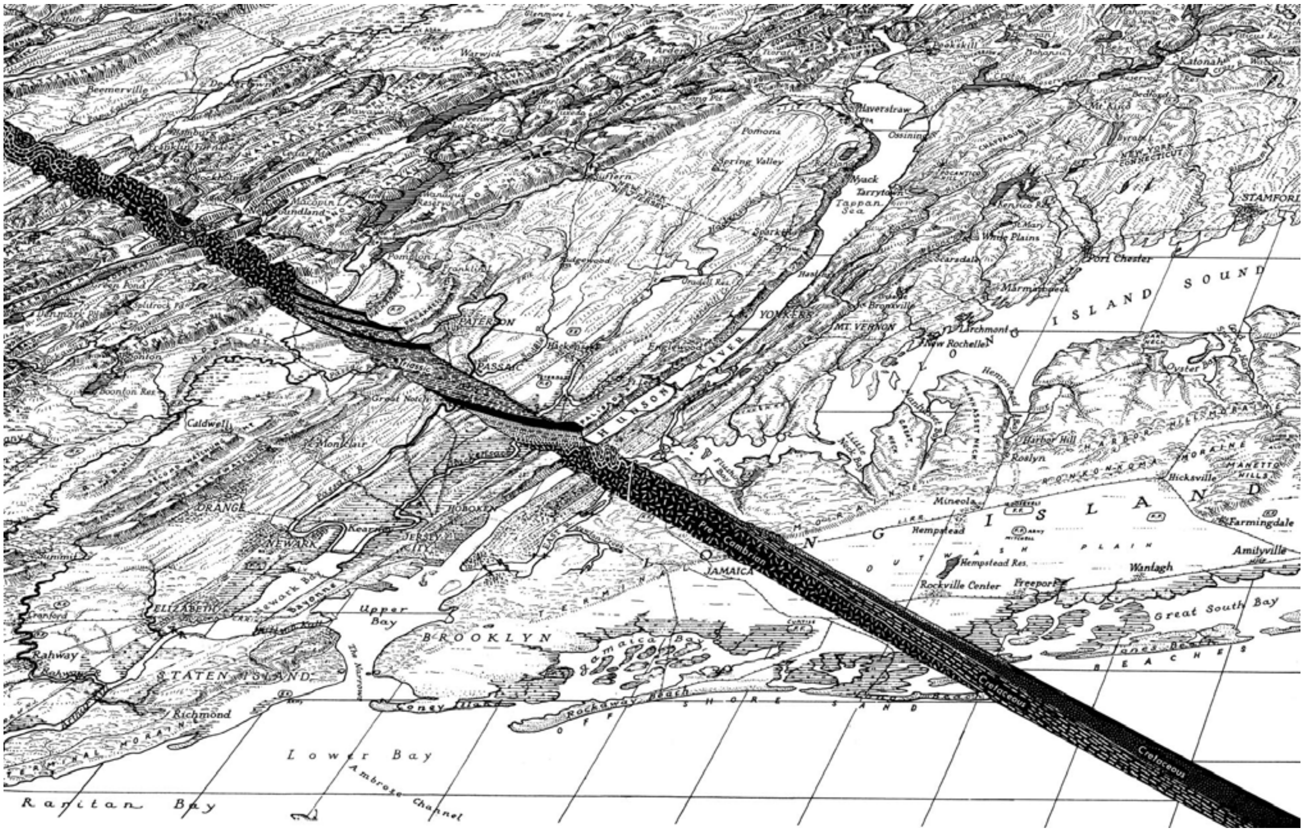
TRIPS ON THE ROCKS

Guide 08: Shawangunks and Bellvale Mountain, New York and New Jersey

Trip 09: 11 November 1989
Trip 36: 24 September 1995



Field Trip Notes by:

Charles Merguerian and John E. Sanders

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INTRODUCTION

Trip 36 is intended to enable the participants to sample several of the major parts of the Appalachian Mountains in northwestern New Jersey, and in particular, to understand the geologic relationships of two notable ridge-forming rock units of the post-Taconic strata in the Appalachians: (1) the older (Lower Silurian) Shawangunk Formation, and (2) the younger (Middle Devonian) Schunnemunk Formation. (See Table 1 for a geologic time chart for the names of the geologic eras and periods, the estimated times of their boundaries, and selected events in the greater New York City region; and Table 2, Generalized descriptions of major geologic "layers," southeastern New York State and vicinity.)

We will visit contrasting kinds of Proterozoic rocks, including the unusual "pegmatitic" Franklin Marble, study the slates and graywackes within the Martisburg Formation (Middle- and Upper Ordovician) of the Tippecanoe Sequence, but we will particularly concentrate our attention on two parts of the Appalachians where prominent strike ridges (within the Valley and Ridge Province and the isolated, wall-like ridge, Kittatinny Mountain--the continuation in New Jersey of the Shawangunk Mountain in New York--that forms the northwestern boundary of the Appalachian Great Valley) are underlain by thick, resistant sandstones/conglomerates. Within the Valley and Ridge Province are two prominent ridge-making formations: a) the Lower Silurian Green Pond Formation and b) the Middle Devonian Schunnemunk Formation. Kittattiny Mountain is underlain by the thick, resistant Shawangunk Formation (Lower Silurian), which in many localities dips NW as a monoclinal ridge toward the Pocono-Catskill Plateau, which adjoins the Appalachians on the NW. Near High Point, NJ, where we shall examine it, Kittatinny Mountain is crossed by many isoclinal folds within which are exposed not only the Lower Silurian Shawangunk Formation but also the unconformably underlying Martinsburg Formation (Tippecanoe Sequence). High Point is the type locality for the newly recognized High Point Member at the top of the Martinsburg Formation.

The Shawangunk, Green Pond, and Schunnemunk formations are parts of Layer No. III, the Shawangunk being in Layer IIIW, and the Green Pond and Schunnemunk, in Layer IIIE). Both are facies of a thick succession of strata that was deposited following the complete geologic- and topographic upheaval associated with the Taconic orogeny. Gone for 200 million years was the former passive continental margin with open ocean stretching away from the Equator off toward what was then the south direction. Newly emerged areas of former sea floor formed an extensive mountain tract that shed coarse sediment to the N and NNW (into an area where former sediment polarity was southward). Rivers draining the mountains built fans across vast alluvial plains, and deltas at the southern shore of the vast seaway that stretched across what is now the continental interior of North America.

Closely associated rocks include: (A) the Proterozoic "basement complex" (Layer No. I, of Table 2) of the Ramapo Mountains block, Wawayanda Plateau, and other blocks collectively designated as the Reading Prong of the New England Uplands-Appalachian Highlands physiographic province (as contrasted to the Manhattan Prong; Figure 1, on cover); (B) the unconformably overlying strata of the former passive continental margin, starting at the base with the Lower Cambrian Quartzite (Poughquag-Hardyston) and giving way upward to the Cambro-Ordovician Sauk-Sequence carbonates (Wappinger-Kittatinny Group or Supergroup, Layer No. IIA(W) of Table 2); and (C) the unconformably overlying Tippecanoe Seqeuence with its thin basal limestone (Balmville-Jacksonburg) and succeeding thick terrigenous flysch [Martinsburg Formation (Middle and Upper Ordovician, Layer No. IIB, Table 2)]. The Taconic allochthon [containing strata of the Taconic Sequence, Layer IIA(E), Table 2] is present in the New Jersey sector of the Appalachians, but for the most part, lies buried beneath the Upper Triassic-Lower Jurassic strata of the Newark Supergroup (Layer No. V, Table 2).

The Shawangunk "Mountains" refer to a complex of one or more strike ridges underlain by the lower Silurian white-colored sandstones and -conglomerates that extend from southwest of Kingston, NY, to the New York-New Jersey state line (Figure 2). Near its NE termination, between New Paltz and Ellenville, many small, parallel anticlines and synclines cause the resistant formation to form a series of 4 finger-like prongs. These ridges constitute what most people think of as "The Shawangunks" (or "Gunks" for short). From a point SE of Ellenville, a single wall-like strike ridge extends to the NY-NJ state line SE of Port Jervis. At that point, as between New Paltz and Ellenville, the single ridge is crossed by several folds and becomes a complex of several ridges and intervening valleys. Southwest of Wallpack, NJ, a single ridge continues to the southwest with name changed to Kittatinny. It is cut by the Delaware River to form the Delaware Water Gap. The strata underlying the single strike ridge dip to the NW, a direction that constrasts notably with the SE direction of dip in most of the strike ridges in the Appalachians.

Bellvale Mountain is the name of a small part of the narrow belt of valley-and-ridge aspect, underlain by complexly deformed strata of Silurian- and Devonian ages, that extends from W of Dover, NJ, to the NE end of Schunnemunk Mountain in SE New York State. This belt is noteworthy in that the strata within it have not only been tightly compressed into overturned folds (some of which have been broken by thrusts along which the overturned limb has been thrust against the right-side-up limb) but also have been faulted against older rocks (in many places, the Proterozoic basement complex of the Reading Prong, but also including the Cambro-Ordovician rocks). Newly recognized flower structures within this belt imply that strike-slip faults have been active.

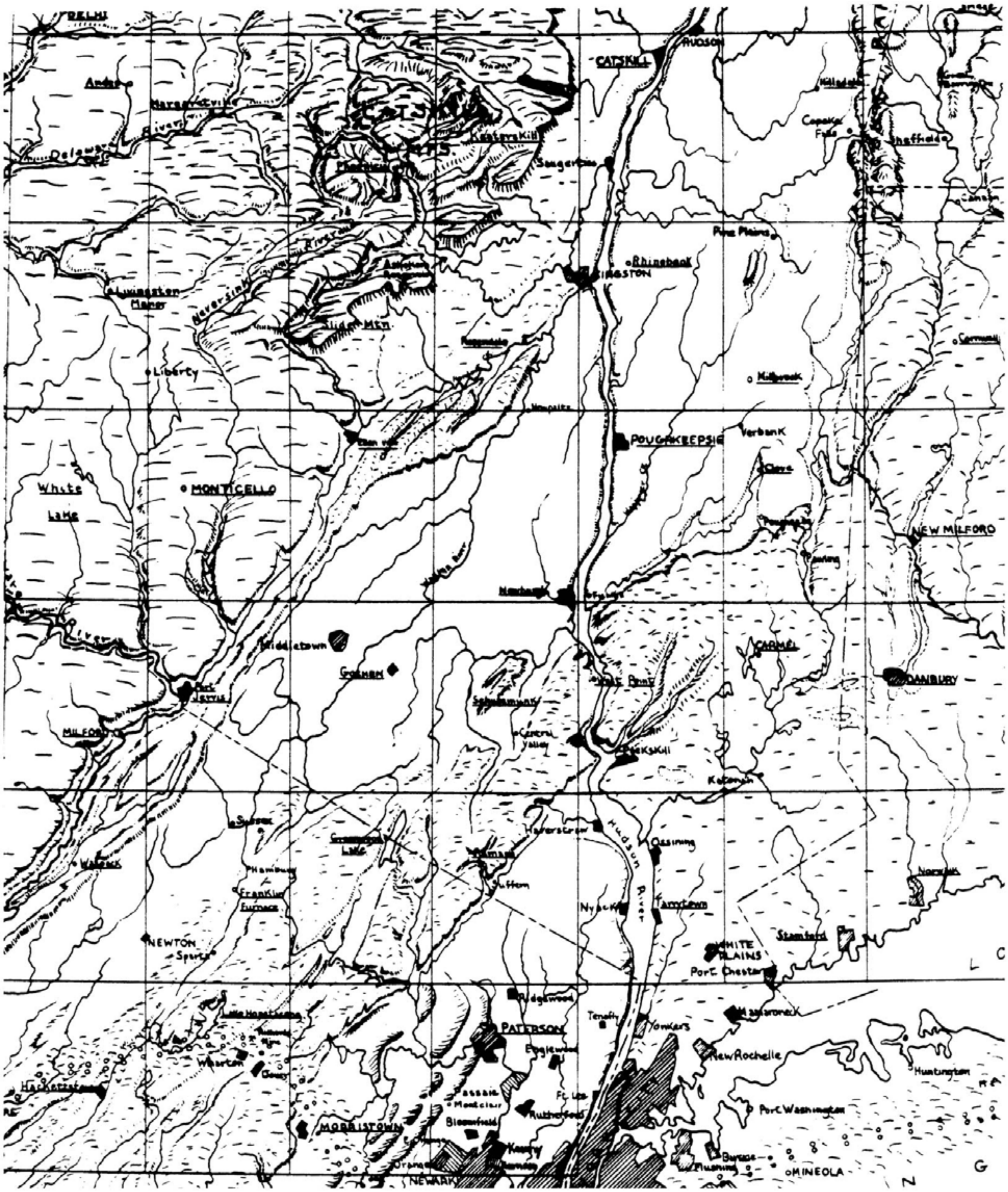


Figure 2. Physiographic sketch map of southeastern New York and adjacent parts of northern New Jersey and western Connecticut. Grid lines are boundaries of U. S. Geological Survey 15-minute topographic quadrangle maps. (Drawn by Frank P. Conant, Wesleyan University, in 1930s.)

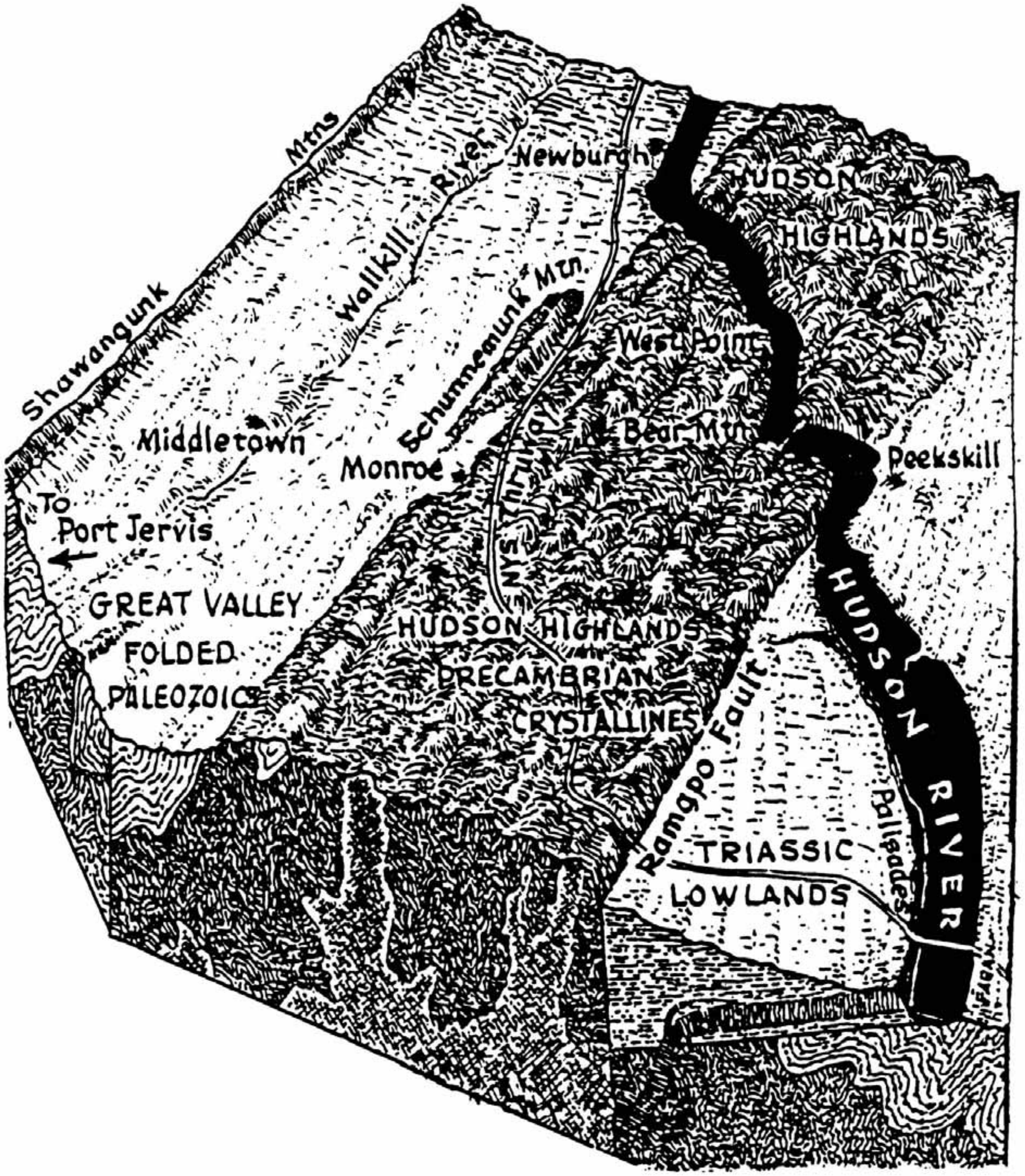


Figure 3. Physiographic block diagram with three sides sliced to show interpretation of subsurface geologic structure according to the view that all the Proterozoic rocks are autochthonous and were folded along with the Paleozoic strata. The only late-stage, high-angle fault shown is the Ramapo fault, which bounds the Newark basin-filling strata on the northwest. The Silurian- and Devonian strata of the Green Pond-Bellvale-Schunnemunk belt are shown as a simple syncline. (Jack Fagan, from cover of 1989 New York State Geological Association Guidebook to Field Trips, 61st annual meeting, 13-15 October 1989, Middletown, NY, Dennis Weiss, ed.)

The Proterozoic rocks of the Hudson Highlands and the Reading Prong, long considered to indicate greatly elevated parts of the "basement complex" underlying all the Paleozoic strata of the Valley and Ridge Province (and thus continuing indefinitely downward through the felsic-crust part of the continental lithosphere), are now thought to be parts of a vast allochthon. According to the allochthon interpretation, first proposed by Isachsen in 1964, the Proterozoic rocks do not extend indefinitely downward into the "ewige Tiefe", but rather end abruptly downward against a great low-angle thrust, beneath which are Paleozoic strata (and, of course, beneath them, the expected "basement complex"). The older interpretation of all the Proteorozic rocks as "basement complex" is expressed in the structure section drawn on the cutaway slice of Figure 1 (on the cover) and is shown in more detail by Jack Fagan's drawing on the cover of the field-trip guidebook for the 1989 meeting (61st) of the New York State Geological Association (Figure 3). The extent- and date(s) of the low-angle thrusting of Proterozoic rocks over Paleozoic rocks (Figure 4) are topics now engaging the efforts of some of the current generation of Appalachian structural geologists.

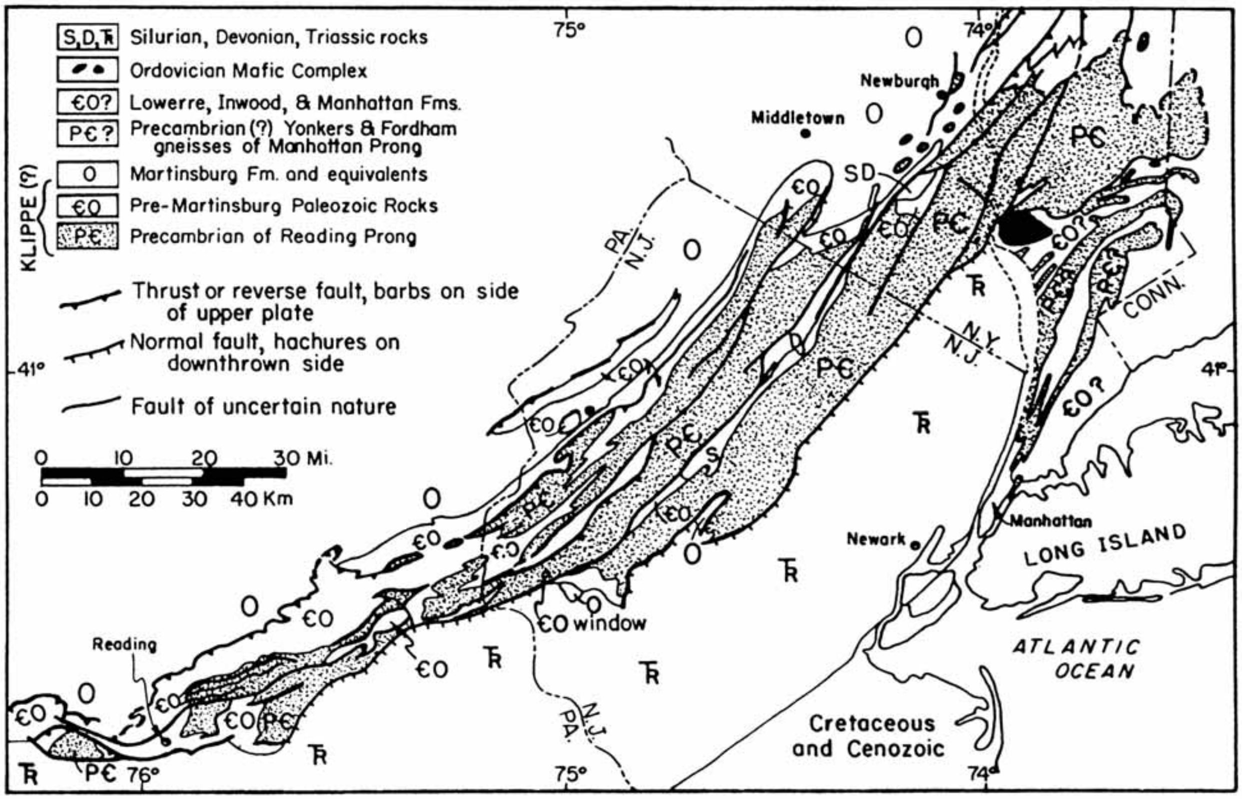


Figure 4. Sketch map showing extent of Reading Prong klippe [stippled areas]. (Yngvar W. Isachsen, 1964, fig. 5, p. 821.)

The first proof of such thrusting came to light about 100 years ago when the Lehigh Railroad excavated a tunnel through Musconetcong Mountain, NJ. Isachsen, (1964, p. 822) cited Kümmel (1940) as his source for what the tunnel revealed, but Kümmel (1940) does not mention the tunnel. Rather, the correct citation should be Lewis and Kümmel (1915), a source not included among Isachsen's list of references. JES has sought in vain to find out if the geologic relationships disclosed by this geologically important tunnel are described anywhere else in the geologic- or engineering literature. JES has attempted to construct a new interpretation of the Middletown gas well based on the concept of low-angle thrusts comparable to the "bedding-plane thrusts" of J. L. Rich (1934), but extending down deep enough to include the basement (Sanders, 1983). If JES is correct, then the fact that the Middletown well did not yield sufficient quantities of gas for it to become a commercial success in the 1950s and the geologic interpretation based on outcrop data should not be the basis for condemning the petroleum possibilities of the territory. Quite the contrary, JES thinks this region's gas potential is sufficiently great to warrant further exploration. CM applauds this attempt to gain investor confidence at the grassroots level of an On-The-Rocks trip!

Isachsen (1964) suggested that the age of overthrusting of the Proterozoic had been Taconian (late Ordovician), but the current preference of A. A. Drake and associates, of the U. S. Geological Survey, based on extensive detailed mapping in eastern Pennsylvania and NW New Jersey, is Late Paleozoic ("Alleghanian," a term we prefer to cease using in favor of the prior term "Appalachian"). Trip 36 does not do justice to the topic of the overthrusting of the Proterozoic rocks. We mention it but briefly; it has been the theme of other On-the-Rocks field trips and offers no particular investor potential.

Our route of travel begins on the Manhattan Prong and takes us across the Newark basin. Accordingly, we include brief summaries of the rocks underlying these two features. Moreover, we will see features related to the Pleistocene glaciation(s) of the region and cross rivers whose drainage history calls for a few comments.

The remainder of this guidebook is organized under the first-order headings of: GEOLOGIC BACKGROUND, OBJECTIVES, LIST OF LOCALITIES TO BE VISITED, DRIVING DIRECTIONS, DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS"), ACKNOWLEDGEMENTS, and REFERENCES CITED.

GEOLOGIC BACKGROUND

Under this heading, we discuss the physiographic setting, some fine points of geologic structure and stratigraphy (a primer), the bedrock units, the glacial deposits, and the drainage history of our field-trip route.

PHYSIOGRAPHIC SETTING

The area of northwestern New Jersey that we shall study today is part of the Appalachians, near the boundary between the Central Appalachians and the Northern Appalachians (two of the transverse subdivisions). From NW to SE, the longitudinal subdivisions of the Appalachians are: Appalachian Plateau; Valley and Ridge Province, of which a prominent feature is the Appalachian Great Valley; Appalachian Highlands; Newark Lowland; and the New England Upland-Manhattan Prong-Piedmont (Figure 5). Today, we focus on two prominent ridge-making formations within the Appalachian Valley and Ridge Province (Schunnemunk Formation of Bellvale Mountain and Green Pond Formation of Green Pond

Mountain) and on the ridge (Kittatinny Mountain), which forms the boundary beteen the Appalachian Great Valley and the Appalachian Plateau (here, the Pocono Plateau). Refer to Figure 1 (on cover) in connection with the remainder of this section on the physiographic setting. Our discussion of these subdivisions is in the order we shall cross them, thus beginning on the SE with the Manhattan Prong of the New England Upland.

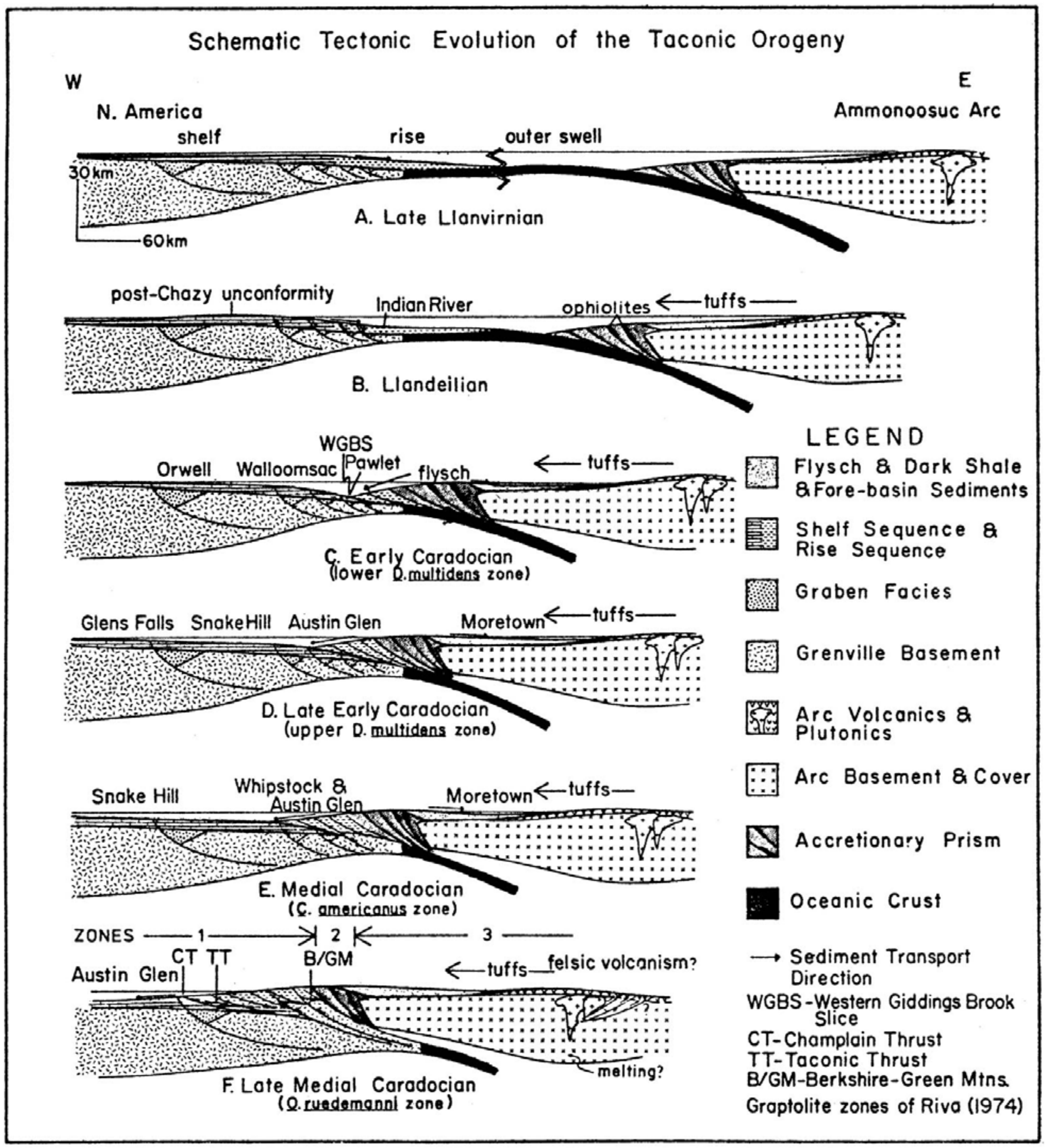


Figure 5. Sketch map of physiographic provinces in NW New Jersey. (Kemble Widmer, 1964, fig. on p. 9.)

Manhattan Prong of New England Upland

The crystalline bedrock of New York City is part of a physiographic province known as the Manhattan Prong (Figure 6) that widens northward into the New England Upland physiographic province of the Appalachian mountain belt. The Manhattan Prong is underlain by several sequences of metamorphosed rocks, one Proterozoic in age, and several of Early Paleozoic ages. Although these rocks have been subjected to several episodes of deformation, their effect on the landscape is controlled by a late episode of tight folds whose axes trend NNE-SSW and plunge dominantly southward. Erosion of these folds has produced a landscape of elongate ridges and -valleys. The ridges are underlain by gneisses or schists and the valleys, by a thick carbonate unit, the Inwood Marble.

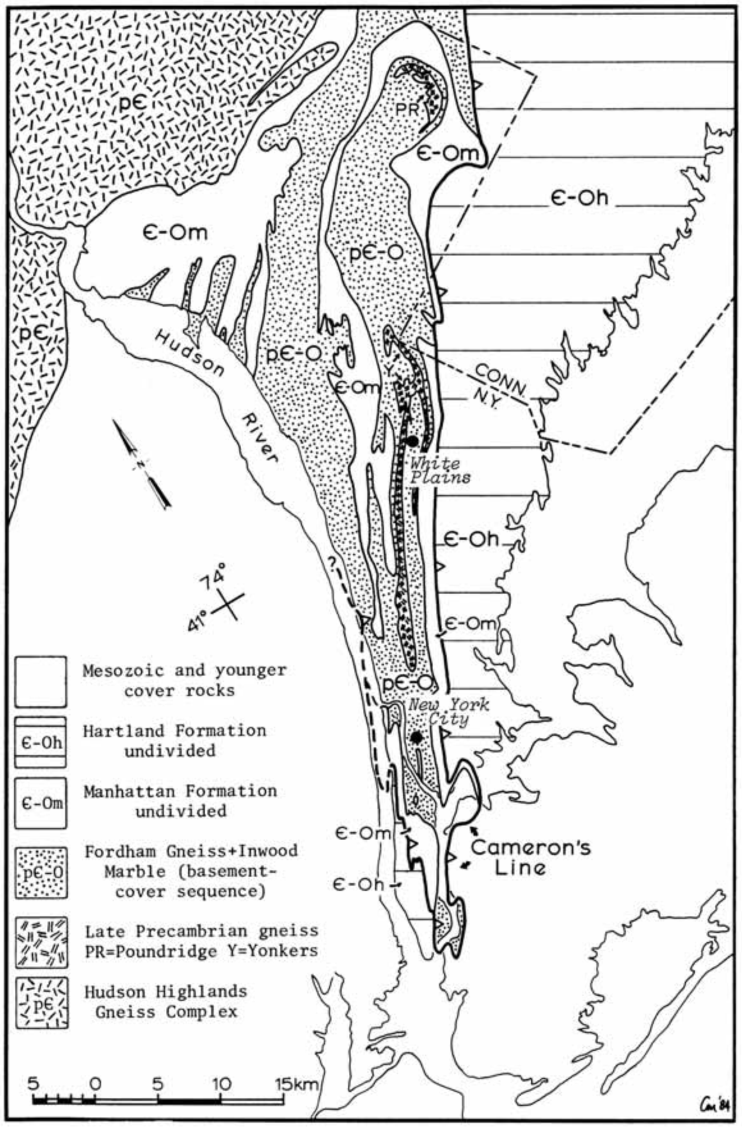


Figure 6. Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted. (Douglas G. Mose and Charles Merguerian, 1985, fig. 1, p. 21.)

Newark Lowland

The Newark Lowland refers to the territory underlain by the Neark basin-filling strata. These strata, originally horizontal, now dip more-or-less uniformly NW about 12ø. (See cutaway slice across middle of Figure 1 and Figure 7.) The Newark strata are thick, possibly 8 km or so in north-central New Jersey (Olsen 1980b). They consist mostly of nonmarine sedimentary rocks and 4 associated sheets of mafic igneous rock. The sedimentary strata are of Late Triassic and Early Jurassic ages. The Triassic-Jurassic boundary is placed at the base of the ancient lava flow underlying the First Watchung Mountain (=Orange Mountain Formation of Olsen, 1980a, b). The sedimentary rocks generally underlie lowlands that have been thickly blanketed by Pleistocene glacial sediments, whereas the igneous rocks form curvilinear ridges. From SE to NW these ridges are the Palisades, First Watchung (=Orange) Mountain, Second Watchung (=Preakness) Mountain, and Third Watchung (=Hook) Mountain. The ridges, too, have been glaciated; along their crests evidence of glacial erosion is abundant. The most-obvious characteristic of the Newark Lowland is reddish-brown color. Most of the sedimentary bedrock and virtually all of the Pleistocene glacial sediments found toward the S and SE display this distinctive color. Ground elevations in the true lowland part of this province range from sea level in the Hackensack Meadowlands to 150 feet up to 200 feet in the lowland enclosed between the Third Watchung Mountain and the wall-like SE margin of the Ramapo Highland block to the NW. The relief of the ridges underlain by igneous rocks locally amounts to 800 feet but generally falls in the range of 500 to 600 feet.

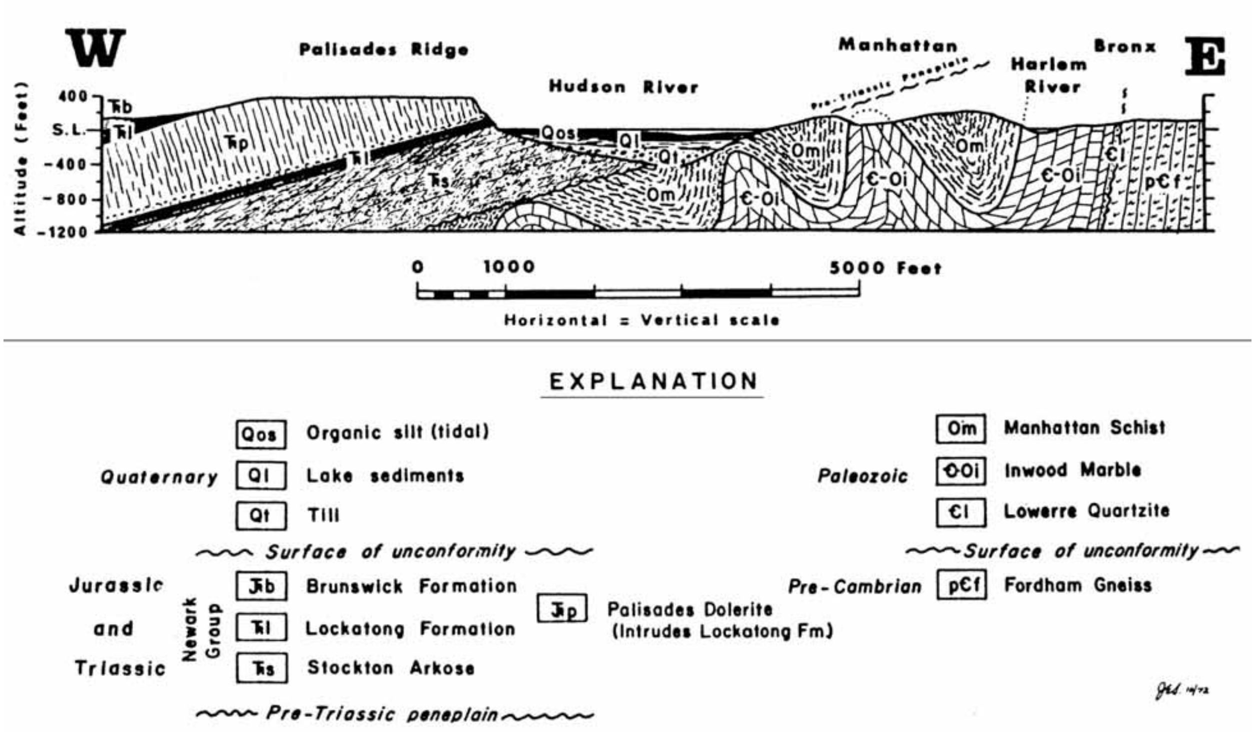


Figure 7. Profile-section across Hudson River at George Washington Bridge. Topography from U. S. Geological Survey Central Park 7.5-minute quadrangle. (J. E. Sanders, 1974a, fig. 3, p. 11.)

Appalachian Highlands

The Appalachian Highlands province in northwestern New Jersey consists of several elongate blocks that trend NE-SW and are separated by elongate lowland/ridge areas. (See Figure 1.) The highlands are underlain by resistant Proterozoic rocks, mostly various gneisses, but locally include other rocks such as granites, coarse marbles, and amphibolites. The intervening lowland/ridge areas are underlain by Paleozoic sedimentary strata. On the cutaway slice across Figure 1, the Proterozoic rocks are shown as consisting of elevated horst-type blocks composed of pre-Paleozoic basement, and the lowland/ridge areas as downdropped graben blocks underlain by folded Paleozoic strata. (For definitions of horst and graben, see following section entitled Geologic Structure--A Primer.) Collectively, these highland blocks are classified as part of the Reading Prong of the New England upland (as contrasted with the Manhattan Prong, previously mentioned).

Ever since Isachsen (1964) assembled the evidence in favor of the interpretation that the Proterozoic rocks of the Reading Prong have been massively displaced over the Paleozoic rocks along one or more low-angle thrusts (See Figure 4 and also the section in the text entitled Geologic Structure--A Primer.), the subject of the regional relationships of the rocks in northwestern New Jersey has been unsettled.

Appalachian Valley and Ridge Province

The Appalachian Valley and Ridge Province designates a subdivision within the Appalachian chain underlain by Paleozoic sedimentary rocks that are parts of large folds (anticlines and synclines). Deep erosion of these folded strata has created a pronounced linearity to the landscape consisting chiefly of elongate valleys and -ridges. Resistant formations, usually of sandstone, underlie the ridges. Weaker formations, usually shales or carbonate rocks, tend to underlie the valleys (Figure 8). Folds are not the only major geologic structural features found in this province; low-angle thrusts and high-angle faults are also present.

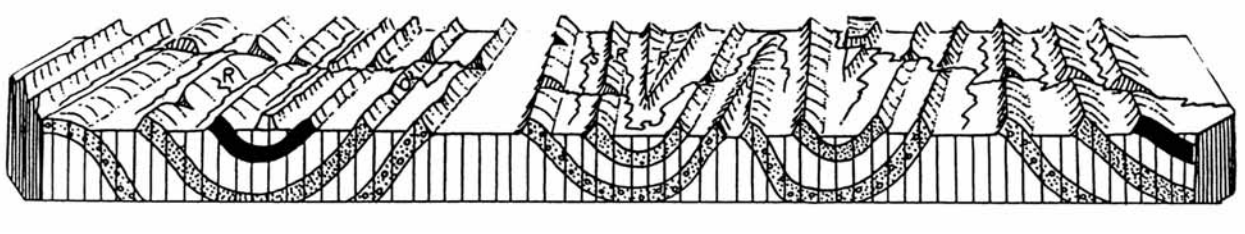


Figure 8. Schematic block diagram through eroded anticlines and -synclines showing how resistant layers form linear ridges and weak layers, linear valleys. The relationships shown here are common in the Appalachian Valley and Ridge Province of central Pennsylvania. (A. K. Lobeck, 1939, fig. on p. 588.)

Strangely enough, the best place in northwestern New Jersey to see typical Appalachian Valley-and-Ridge-type landscape is in the Schunnemunk-Bellvale-Green Pond belt within the Highlands. In this belt are two thick resistant, ridge-making formations: the Lower Silurian Green Pond Conglomerate and the Devonian Schunnemunk Conglomerate, which are separated by thick shale/siltstone units that form valleys. These strata have been folded on a large scale; deep erosion of these folds has created a typical ridge-and-valley landscape. (See Figure 8.)

Where the Cambro-Ordovician rocks of the Sauk and Tippecanoe Sequences are thick, the stratigraphic column lacks any prominent ridge-making units. Accordingly, the outcrop of these rocks has been eroded into a wide lowland known as the Great Valley of the Appalachians. The local representative of the Great Valley subprovince in northwestern New Jersey is Kittatinny Valley.

The Kittatinny Valley is bounded along its NW side by a nearly continuous ridge, Kittatinny Mountain, which is underlain by the thick, resistant Lower Silurian sandstone known by the New York name of Shawangunk Formation. Kittatinny Mountain is part of a prominent ridge that extends from the Shawangunks SW of Kingston, New York, to Harrisburg, Pennsylvania. The major break in this mighty ridge is the Delaware Water Gap, occupied by the Delaware River. High Point State Park is situated at a place where several folds cross the ridge.

Appalachian Plateau

The Appalachian Plateau province refers to a region of rough countryside that is underlain by essentially flat-lying strata that are of Devonian age in the Catskills of New York State and of Mississippian age in the Poconos in northeastern Pennsylvania. Two essential features must be fulfilled to qualify a region as meeting the geologic definition of a plateau: (1) it is an area displaying high relief; and (2) the strata underlying the high-relief area are still horizontal; they have not been closely folded. In this respect, the strata underlying the Appalachian Plateau contrast with the much-deformed strata in the adjoining Appalachian Mountain belt. Because of the contrast between folded- and faulted strata of the Appalachian Valley and Ridge Province and the flat-lying strata of the Appalachian Plateau, geologists have tended to presume that a major tectonic boundary exists between these two provinces. The term "Appalachian Structural Front" has been used to designate this boundary, long thought to separate the deformed strata from nondeformed strata. As we shall see, however, evidence has now been discovered that at least one major horizontal thrust fault underlies the Appalachian Plateau and that along this thrust, the flat-lying strata have been shifted westward. Accordingly, any appropriate "structural front" between deformed strata and nondeformed strata, should be located wherever the thrust fault beneath the Appalachian Plateau comes to the surface, and not at the boundary between the Appalachian Valley and Ridge Province and the Appalachian Plateau.

GEOLOGIC STRUCTURE - A PRIMER

Geologists use terminology to confuse the layman and to enable them to amass a huge library of terms that are undeniably useless in most social situations. Luckily, our On-The-Rocks trips are an exception. We will not try to bury you in a mountain (how about a deeply eroded mountain range?) of terms to help you understand the major types of structures and geologic features that you will read- and hear about today. But, if you are to understand what we are talking about, you need to know some important definitions. What we hope to do in this section is make the reader aware of the kind of information that enables a geologist to infer that deformation has taken place, to define some of the major geologic structural features formed as a result of tectonic activity, and to evaluate the evidence upon which geologists establish the time when deformation took place. We begin with sedimentary strata and work our way upward through geologic structures to lithosphere plates. The term geologic structure refers to any feature made as a result of deformation related to tectonic activity. Nowadays, we ascribe most tectonic activity to the motion of the Earth's lithosphere plates.

Along the way, we examine some mechanical aspects of rock deformation. Up next are descriptions of folds, faults, effects on sedimentary strata of deformation, structures in sedimentary- vs. metamorphic rocks, and tectonostratigraphic units. We conclude this section with a summary of methods for geologic dating of episodes of deformation.

Strata

The most-important single feature used by geologists to infer that a body of rocks has been deformed is the primary attribute known as stratification. During normal deposition, or settling from a fluid in a rainfall of particles, a thick body of more-or-less featureless sediment may be deposited. The presence of original sedimentary layers, technically known as strata, implies that conditions of deposition changed. As a result, most geologists appreciate the fundamental point that layers in sedimentary rocks imply CHANGE in big letters. The change may have been in the parent area of the sediment, in the sizes of particles supplied, or in the style of deposition.

Thick layers are known as beds and thin layers as laminae. (The word laminae is the plural of lamina. The attribute word applicable to sediments displaying laminae is lamination. Please avoid the temptation to perpetuate the widespread usage indulged in by geologists who don't seem to know their attributes from a hole in the ground, namely the use of lamination in the plural form when they are discussing laminae.)

The particle sizes within a stratum may be uniformly distributed across the bed or may display grading in which larger particles are present at the base of a particular layer and the sizes diminish or "grade" upward into finer particles (Figure 9). A graded bed is the result of a kind of a "lump-sum distribution" from a current carrying a wide range of particles and depositing them within a short time span, largest first and progressively smaller ones later. A common kind of current that deposits layers showing size grading is a gravity-induced turbidity current that flows down a subaqueous slope and crosses a flat part of the basin floor.

Fundamental principles about strata were recognized in the 1660s by Nicolaus Steno. He proposed four "rules" for understanding strata of which we include only the following two:

Steno Rule No. 1: Most strata are deposited with an original orientation that is horizontal. (We explain some important exceptions to this rule farther along.) Therefore, strata that are not horizontal usually lost their horizontality as a result of tectonic activity.

Steno Rule No 2: The oldest stratum is at the bottom and successively younger strata occupy higher positions. Two important corollaries of this rule are that each stratum was spread out, one at a time, at the Earth's surface. The materials forming the stratum, therefore, buried a former surface of the Earth. In turn, the top of the stratum was itself such a surface. The top, or face, of a stratum was initially in the up position. (Therefore, if strata are vertical, the tops of the strata indicate the former up direction.) As is discussed in a following section, certain features on the bottoms, within, or on the tops of strata, enable the former top direction to be determined unambiguously. Such features are known as geopetal criteria (Shrock, 1948).

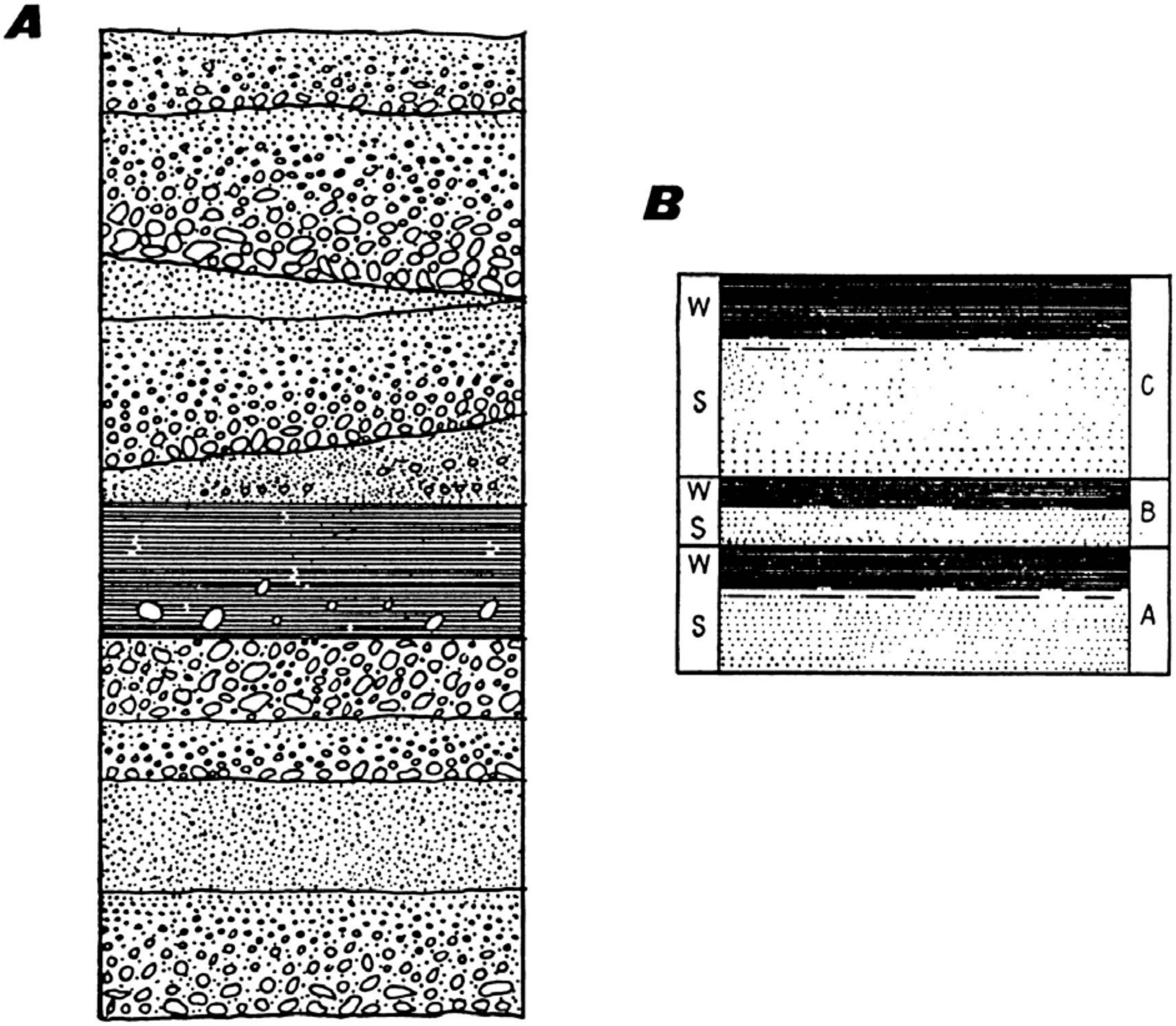


Figure 9. Contrasting kinds of sediments showing internal upward-fining grading.
A. Conglomeratic layers, some graded, some uniform, interbedded with shale containing scattered pebbles. Nonmarine Wamsutta Formation, (Pennsylvanian), E side of Great Pond, Braintree, MA. (R. R. Shrock, 1948, fig. 43, p. 84)
B. Schematic view of varved silt and -clay deposited in a proglacial lake showing light-colored, coarser graded silty layers deposited during the short summer season when lake is free of ice (marked with S) alternating with dark-colored clay layers deposited during the much-longer winter season when the lake surface is frozen over (marked with W). (R. R. Shrock, 1948, fig. 44, p. 85)

Strata are such fundamental reference surfaces that we emphasize the importance of being able to recognize strata. Where all the particles are about the same size, bedding may not be so easy to identify. This is especially true with uniformly fine sediments (silt size, for example) or with uniformly coarse sediments (boulder gravel). In some cases, such recognition is self evident: materials of contrasting composition or -particle size (Figure 10) form distinct layers that are set off from adjacent layers by prominent surfaces along which the rock separates easily. These are termed bedding-surface partings. In many exposures, the most-prominent partings visible are the bedding-surface (or "bedding-plane") partings. In other exposures, however, tectonic activity has imposed a secondary (structural) parting that may be more prominent than the bedding-surface partings. (Such secondary partings are discussed farther along.)

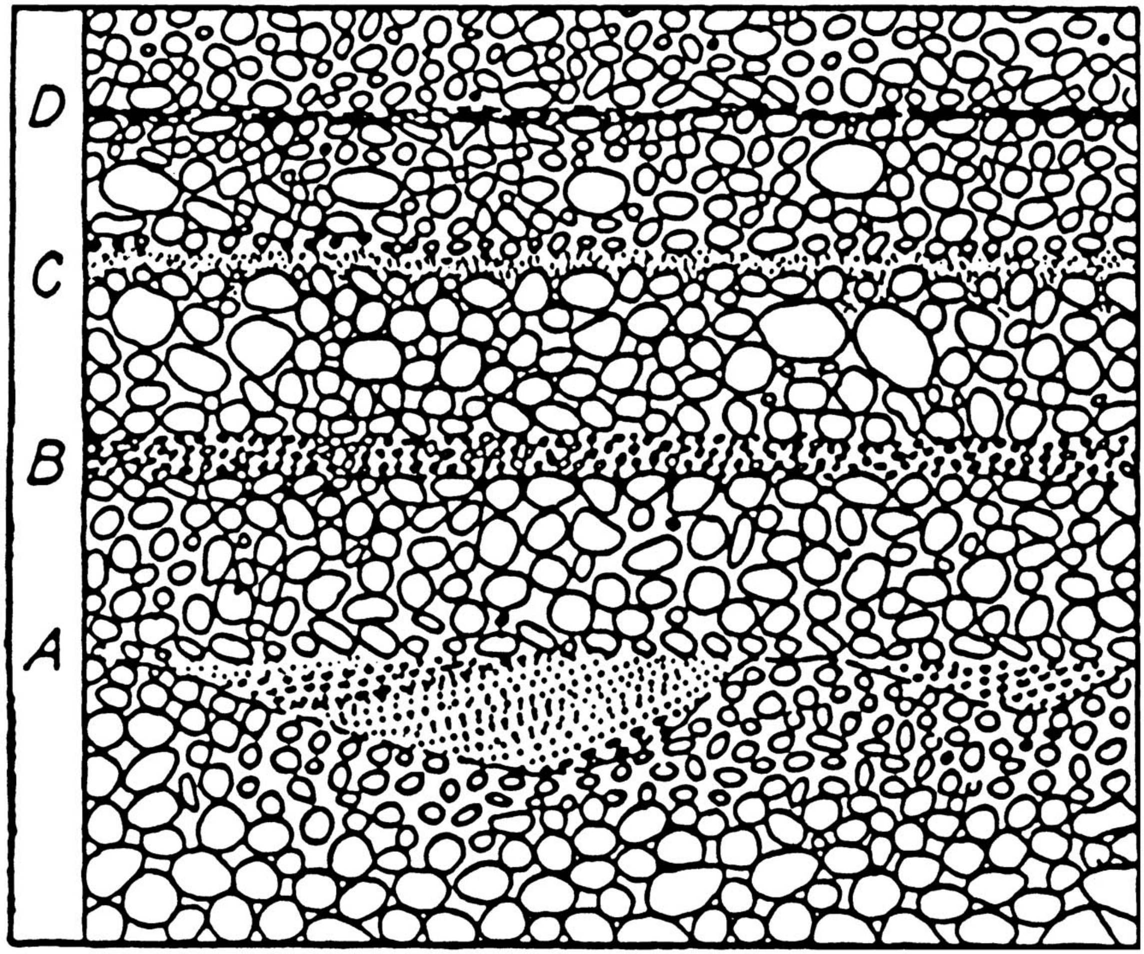


Figure 10. Sketch of gravel (or conglomerate) showing how bedding is revealed by finer sediment in planar layers (such as B, C, and D) or in lenses (as in A). (R. R. Shrock, 1948, fig. 3, p. 12.)

Always make careful note of the feature or features that you have used to support your identification of the bedding. Some such features include changes of color, changes of particle sizes (Figure 11), aligned shells of invertebrates, differences in degree of cementation, or whatever.

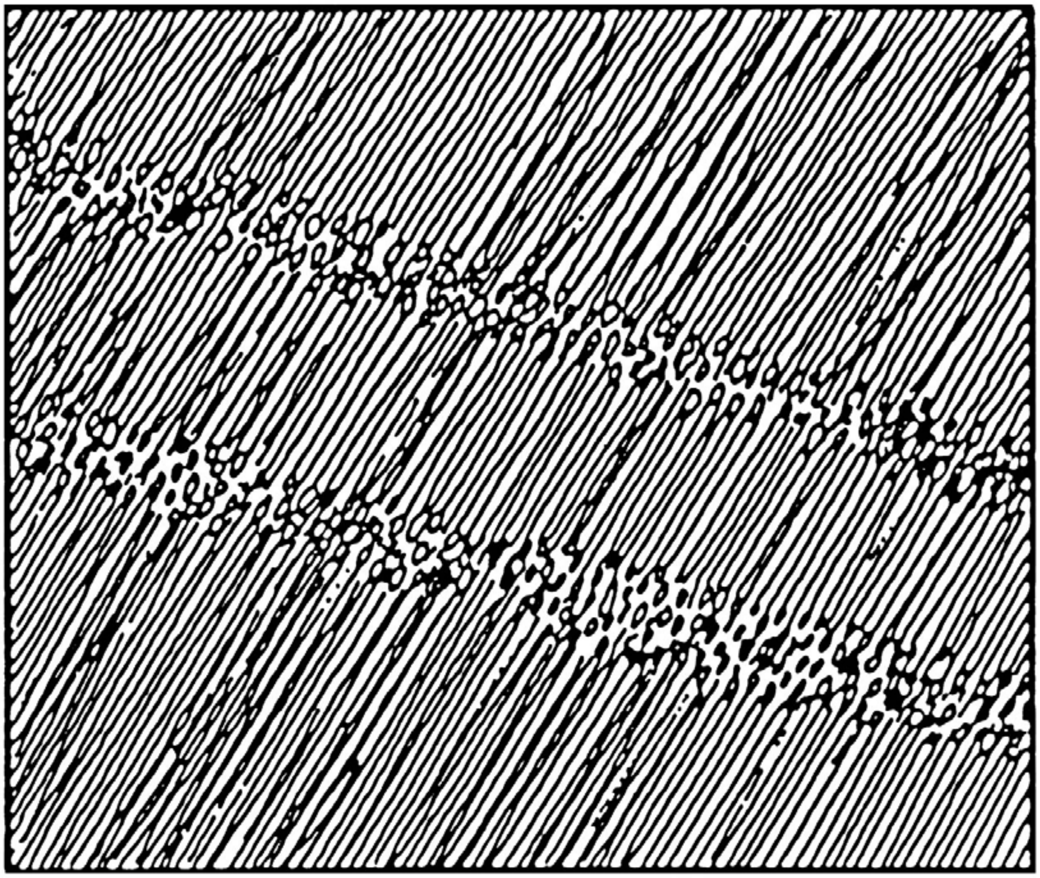


Figure 11. Sketch of slate (dark color) with prominent parting (slaty cleavage) dipping steeply to the left; two layers composed of silt-size sediment (stipple) show that bedding dips gently to the right. (R. R. Shrock, 1948, fig. 7, p. 15.)

Sedimentary Structures

During deposition in a variety of environments, primary- and secondary sedimentary structures can develop above-, below-, and within strata.

During high-energy transport of sand-size or coarser particles (defined as cohesionless sediment), a moving current reacts with the sediment it is transporting and over which it is flowing to create repeating patterns of linear- or curvilinear relief features having long axes that may be transverse to- or parallel with the direction of the current. These are collectively designated as bed forms (Figure 12). In many cases, the tops of sandstone beds display such bed forms, which are named ripples if their relief and crestal-separation distances are measured in centimeters or up to a few tens of centimeters or dunes, if their dimensions measure in meters, tens of meters, or even kilometers. Many bed forms are asymmetric; they slope gently into the current on their upcurrent sides and steeply downcurrent on their downcurrent sides. The shearing-drag effect of the current on the cohesionless-sediment substrate causes these bed forms to migrate downcurrent. They migrate bodily as sediment is eroded from their upcurrent sides and added to their downcurrent sides. The result is a distinctive kind of internal cross strata in which the layers are concave up, tangential at their bases, and truncated at their tops. If the crests of the bed forms are linear, then downcurrent migration creates planar cross strata. (See Figure 12, A.) If the crests of the bed forms are sinuous and concave downcurrent, then downcurrent migration creates trough-type cross strata. (See Figure 12, B.)

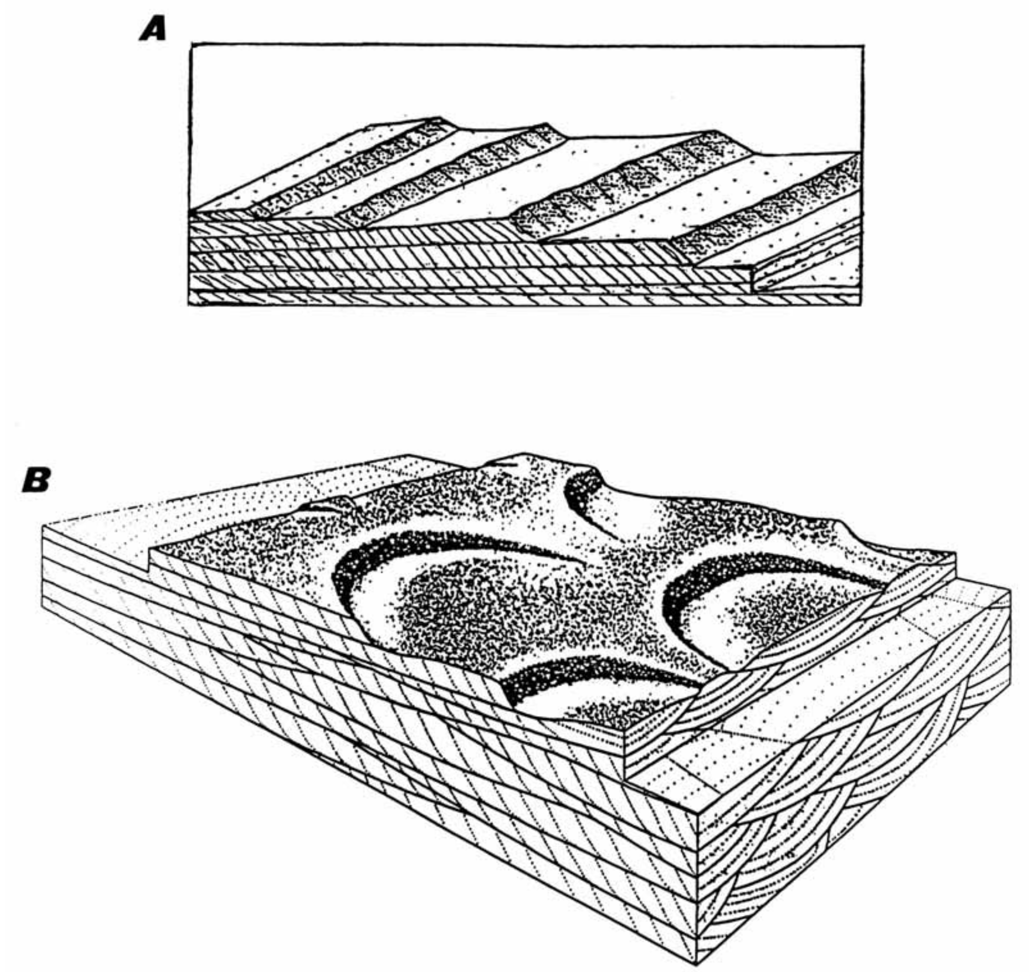


Figure 12. Sketches of contrasting shapes of bed forms created by a current flowing from left to right and cross strata resulting from their downcurrent migration.
A. Linear bed forms create planar cross strata. (G. M. Friedman, J. E. Sanders, and D. C. Kopaska-Merkel, 1992, fig. 5-19, A, p. 166.)
B. When cuspate (lunate) megaripples migrate downcurrent trough-type cross strata form. In sections that are parallel to the current, trough cross strata and planar cross strata look about alike. The difference between them is immediately apparent in sections normal to the current. (H. E. Reineck and I. B. Singh, 1980, fig. 52, p. 43.)

Not all cross strata result from downcurrent migration of rhythmic bed forms composed of cohesionless sediment (as in Figure 13, A and D). In some places, local depressions in the bottom are filled in by sand transported from one side and deposited in inclined cross strata (Figure 13, B). In other places, cross strata are deposited at the fronts of sediment embankments where a water current encounters a deeper place. The embankment lengthens in the downcurrent direction as sediment is deposited in inclined layers (cross strata) along the growing front of the embankment (Figure 13, C and E).

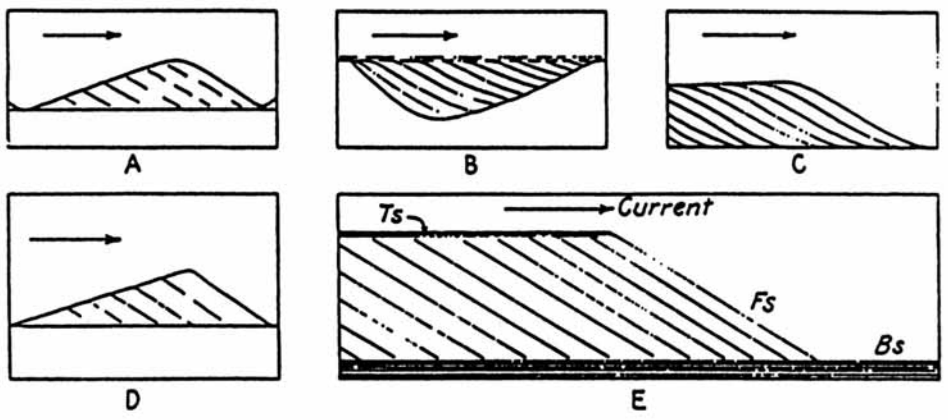


Figure 13. Sketches showing various settings in which cross strata dipping to the right can be deposited by a current flowing from left to right.
A and D, Longitudinal profiles through individual bed forms that have migrated to the right (downcurrent) by at least one wavelength, thus preserving as internal cross strata many former downcurrent faces.
B, Longitudinal profiles through cross strata that have filled in an asymmetric depression.
C and E, Longitudinal profiles through cross strata deposited by downcurrent growth of an embankment (such as a delta lobe), built where the flow enters slightly deeper water. (R. R. Shrock, 1948, fig. 207, p. 245.)

Once a current has established a pattern of asymmetric ripples, various kinds of ripple cross laminae are deposited depending on the abundance of sediment. At one extreme, the ripples may migrate and no new sediment is added (Figure 14, A). At the other extreme are ripples that persist as more sand-size- and other sediment is added from the suspended load of the current. Addition of sediment to a field of active ripples creates a kind of rolling-type stratification known as climbing-ripple strata (Figure 14, B).

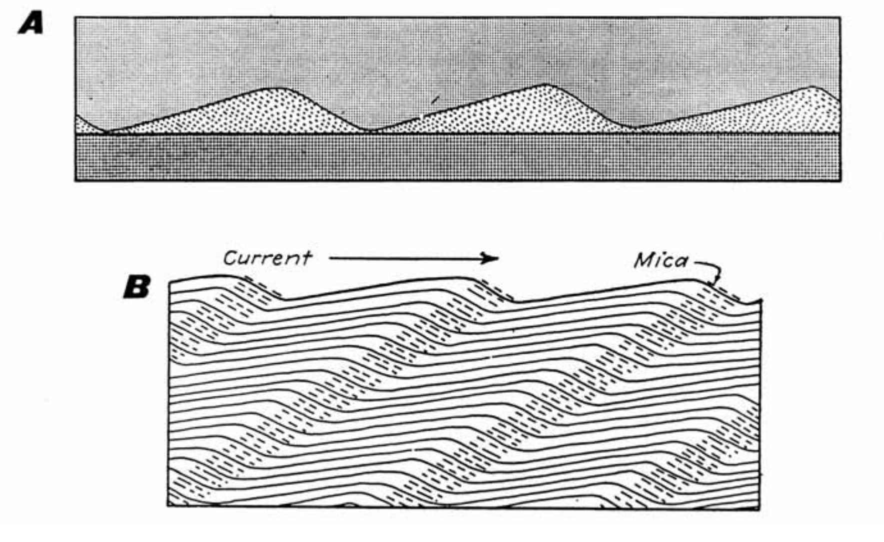


Figure 14. Sketches of ripple cross laminae formed under varying conditions of sediment supply.
A. Cross laminae formed by migration of ripples from left to right when no new sediment is added from the current. (R. R. Shrock, 1948, fig. 57, p. 103.)
B. Climbing-ripple laminae formed when sediment falls out from suspension while the current is still moving fast enough to form ripples. Concentration of mica on the downcurrent faces of ripples creates a large-scale "false bedding" dipping upcurrent (to the left). (R. R. Shrock, 1948, fig. 60, p. 105, based on J. B. Woodworth, 1901b.)

In some settings, the bed-form pattern is not one of regularly spaced linear ridges, but of irregular convex-up hummocks. Deposition in a field of hummocks yields hummocky strata (Figure 15).

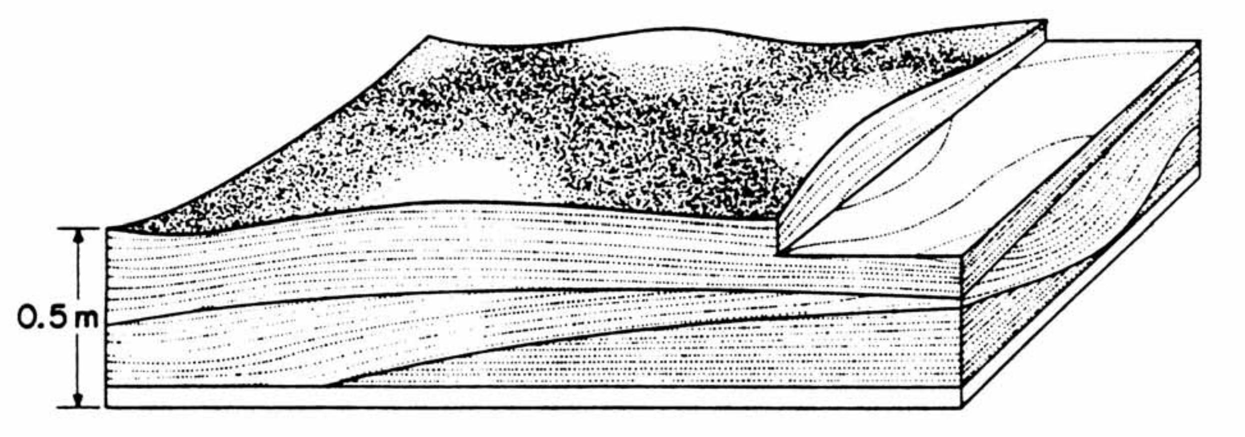


Figure 15. Sketch of hummocky strata. (R. H. Dott, Jr. and Joanne Bourgeois, 1982, fig. 1, p. 663.)

Where current direction oscillates, as it does every few seconds beneath shoaling waves or every few hours in some parts of the intertidal zone, the result may be symmetrical ripples that display pointed crests and broadly rounded, concave-up troughs (Figure 16).

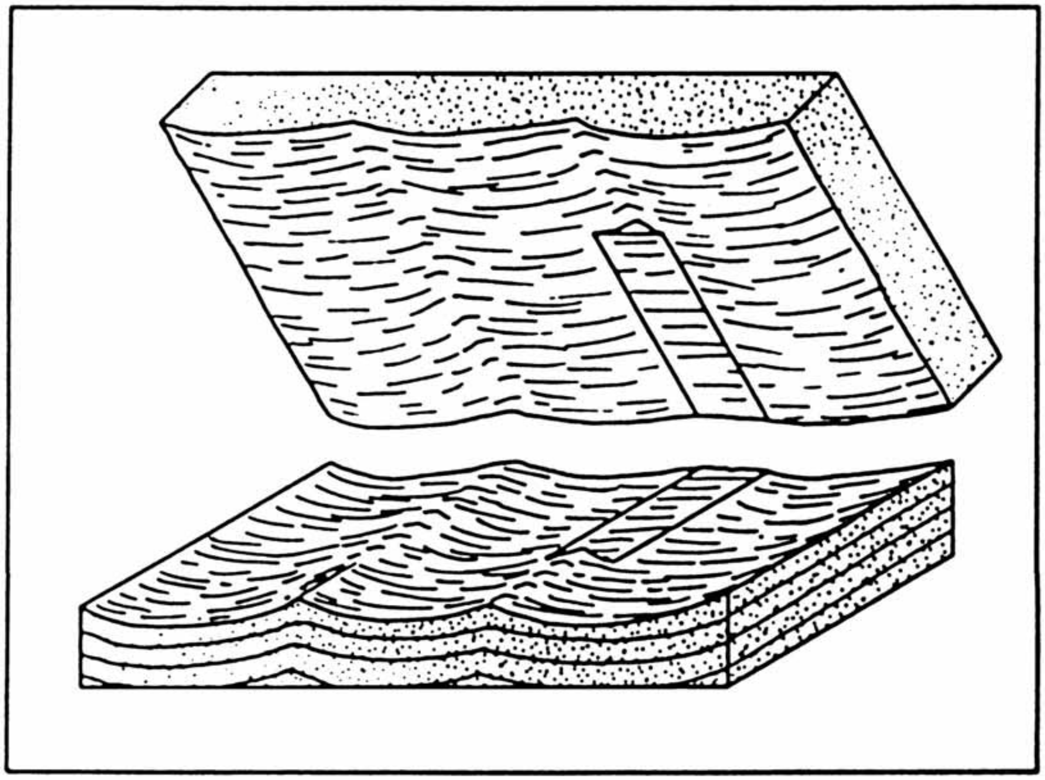


Figure 16. Sketch of symmetrical ripples.

A current carrying sand in suspension that crosses a substrate composed of cohesive fine sediment (as contrasted with the coarser, cohesionless sediment discussed previously) may interact with the bottom to form scour marks or tool marks. These features, sculpted in the cohesive "mud," are usually preserved in the geologic record as counterparts on the base of the overlying sandstone bed. All features found on the bases (i. e., the "soles") of such sandstone beds are collectively designated as sole marks. Patterns of sole marks vary, but many are elongated parallel to the direction of the current (Figure 17).

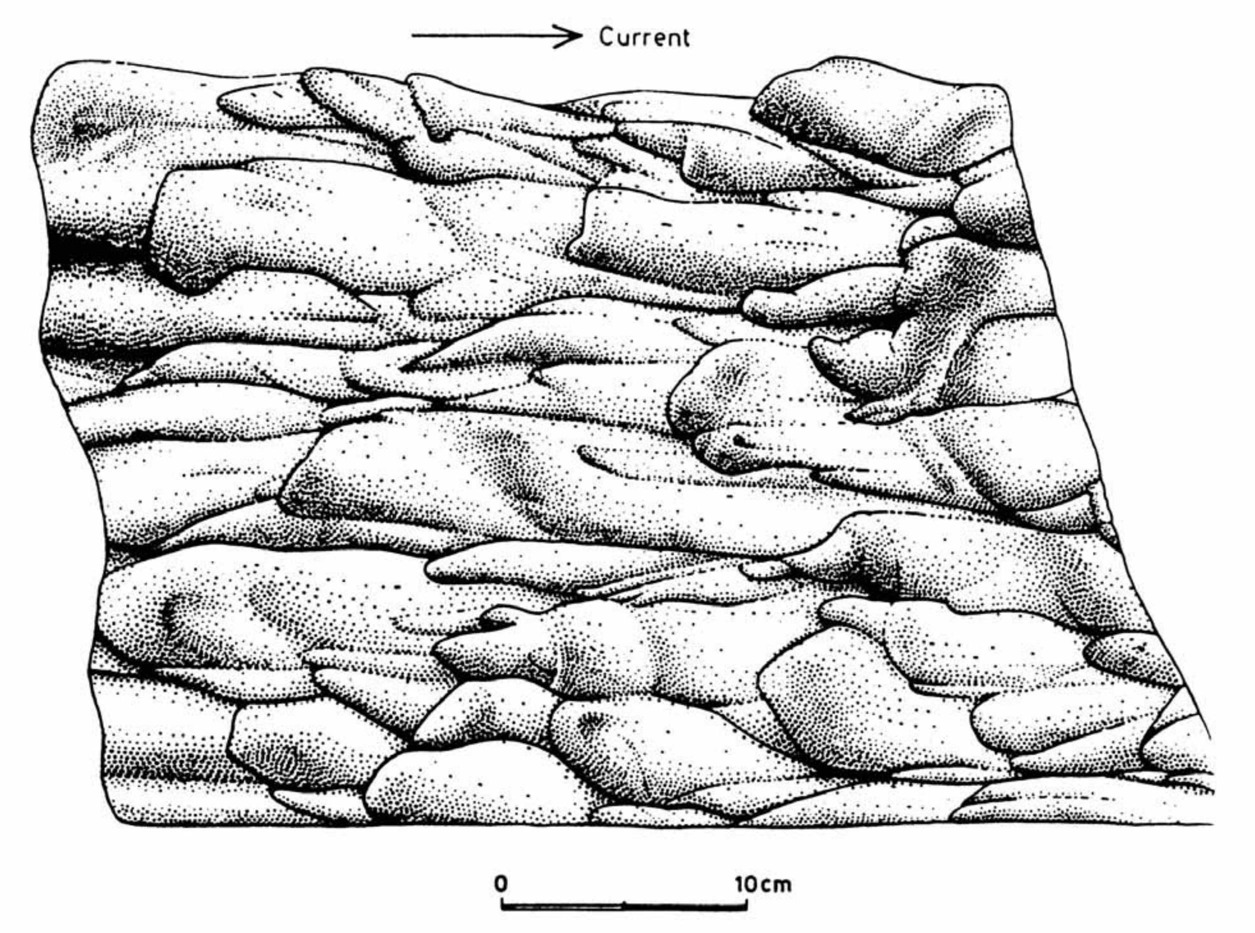


Figure 17. Sketch of counterparts of flutes, sole marks on base of Miocene sandstone bed, Apennines, Italy. (P. E. Potter and F. J. Pettijohn, 1977, fig. 5-2, p. 160, from E. ten Haaf, 1959, fig. 12.)

Cross strata, hummocky strata, and asymmetric current ripple marks deposited by moving currents yield valuable clues for unraveling the paleocurrent directions in which the ancient currents flowed. Many such features are also useful for indicating the original facing direction.

Secondary sedimentary features are developed on already deposited strata and include mud (or desiccation) cracks, rain-drop impressions, and animal footprints. Figure 18 is a composite diagram illustrating common sedimentary structures.

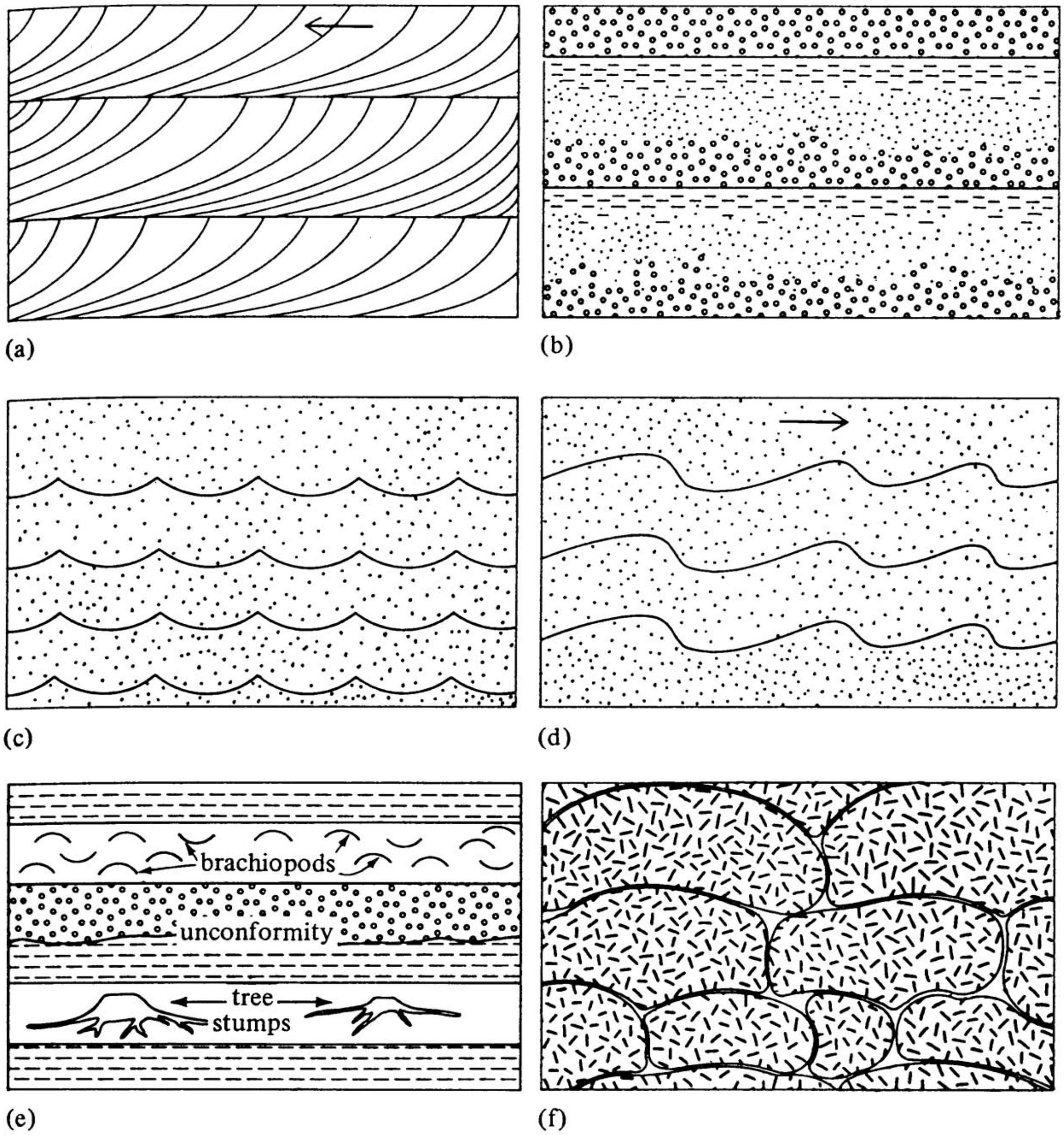


Figure 18. Diagrammatic sketches of of primary sedimentary structures (a through e) and cross sections of pillows (f) used in determining topping (younging) directions in layered rocks.

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.

It's now time to turn to some geometric aspects of the features formed as a result of post-depositional deformation of rocks in the Earth. We start with a brief lead-in discussion concerning the mechanical aspects of deformation and the strength of materials.

Mechanical Aspects of Deformation

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 feels that they need to perform these experiments over a longer time frame than a few generations of siblings will allow and thus relies more on observation of field relationships than 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 distortion 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 and/or joints. Once a brittle failure (fracture) has begun, it will propagate and may produce offset thus forming a fault surface. Joint surfaces commonly exhibit distinctive "feathers" which show the direction of joint propagation.

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 five letters of the alphabet: D, F, S, L, 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), of the formation of linear features (such as mineral streaking or intersection lineations produced by intersections of S1 and S0) by Ln, and of metamorphism by (Mn), where n is a whole number starting with 1 (or in some cases, with zero). Bedding, for example, is typically designated as S0 (or surface number zero) as it is commonly overprinted by S1 (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 (D2), F2 folds formed with the development of an L2 mineral lineation. An axial-planar S2 schistosity developed and crosscut both an early foliation (S1) and bedding (S0). These features were produced under progressive M1 metamorphic conditions."

Folds

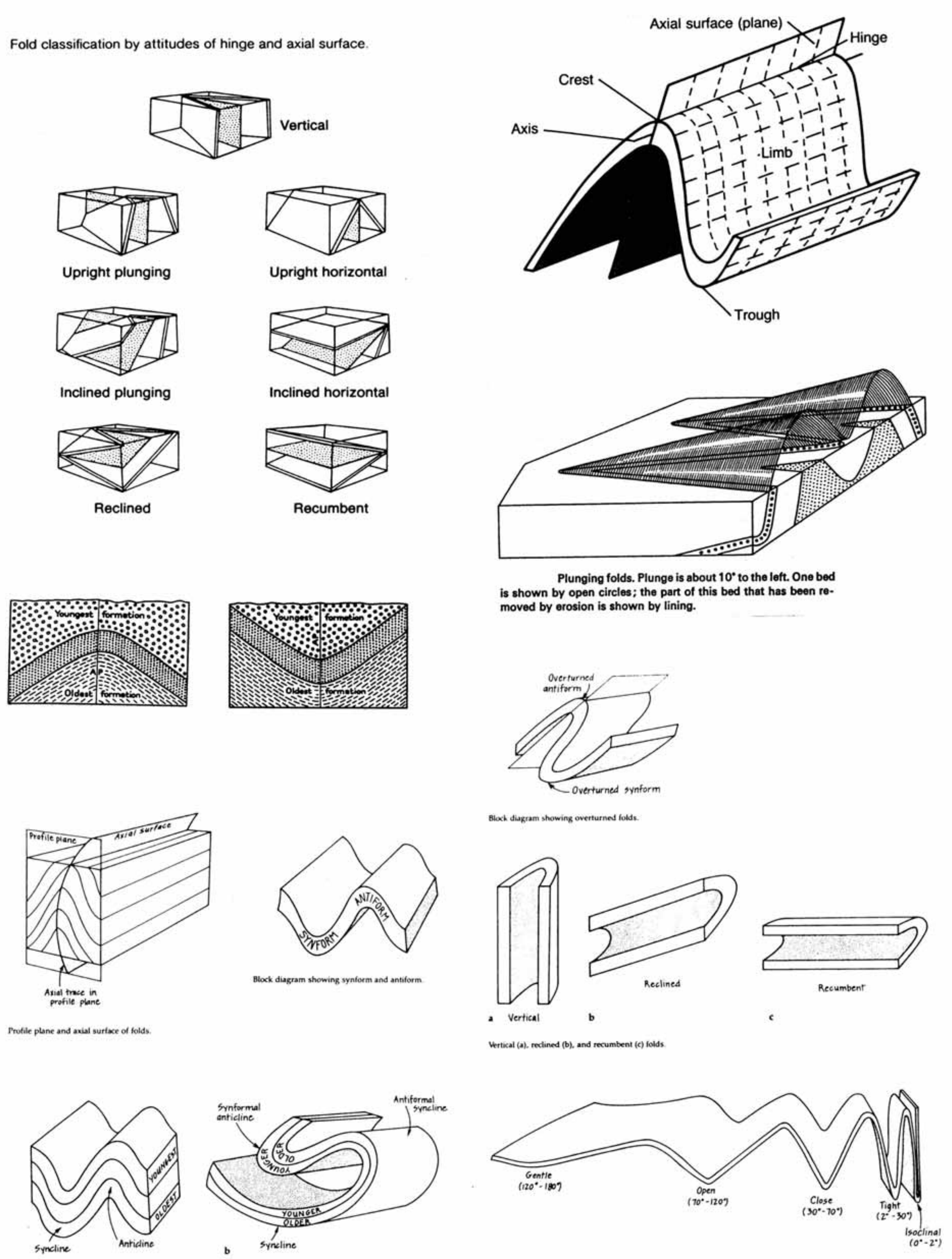
If layers are folded into convex-upward forms we call them anticlines. Convex-downward fold forms are called synclines. In Figure 19, note the geometric relationship of anticlines and synclines. Axial planes (or axial surfaces) physically divide folds in half. Note that in Figure 19, the fold has been 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 19, axial surfaces are vertical and fold axes, horizontal. This is a very rare case. Generally the axial surfaces are not vertical and the fold axes are not horizontal.

The scale of folds varies through an enormous range from tiny features that can be present in a hand specimen to great structures measuring many kilometers across and hundreds of kilometers long. A large anticline having a broad wave length and displaying smaller folds along its limbs is known as an anticlinorium. A companion large-scale synclinal feature is a synclinorium.



Fold classification by attitudes of hinge and axial surface.

Plunging folds. Plunge is about 10° to the left. One bed is shown by open circles; the part of this bed that has been removed by erosion is shown by lining.

Block diagram showing overturned folds.

Profile plane and axial surface of folds.

Block diagram showing synform and antiform.

Vertical (a), reclined (b), and recumbent (c) folds.

Figure 19. Composite diagram from introductory texts showing various fold styles and nopersonsclature (non-sexist terminology) as discussed in the text.

After the pioneering work of William Smith in 1812, who first mapped a large-scale plunging structure (we would call this a synclinorium today) in the southern England lowland areas, the Appalachians were the first mountains in which major geologic structures known as folds (anticlines and synclines) were demonstrated (by the Rogers brothers, H. D., and W. B., in the middle of the nineteenth century from their studies in Pennsylvania). To be sure, small folds had been recognized where seen in coastal exposures in numerous localities in western Europe. But, it was a giant step (and anything but an intuitively obvious leap) from seeing small folds in cross section to the reconstruction of very large-scale folds based on working out the stratigraphic relationships of Paleozoic strata, thousands of meters thick, underlying strike ridges that extend for tens, even hundreds of kilometers.

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 19.) 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 0ø (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 90ø) are also known; in them, the terms anticline and syncline are not meaningful. In reclined folds, quite common in ductile shear zones, the fold axes plunge directly down the dip of the axial surface.

In complexly deformed mountain ranges, most terranes show the superposed effects of more than one set of folds and faults. 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 additional point about the alphabet soup of structural geology. Seen in cross section, folds fall into one of three groups, the S's, the M's, and the Z's. Looking down plunge in the hinge area of a northward-plunging anticlinal fold, for example, dextral shearing generates asymmetric Z folds on the western limb and sinistral shearing forms S folds on the eastern limb. Usually only one variety of small, asymmetric 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 last forces that ultimately 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 20, inset). The block situated below the fault plane is called the footwall block and the block situated above the fault plane, the hanging-wall block.

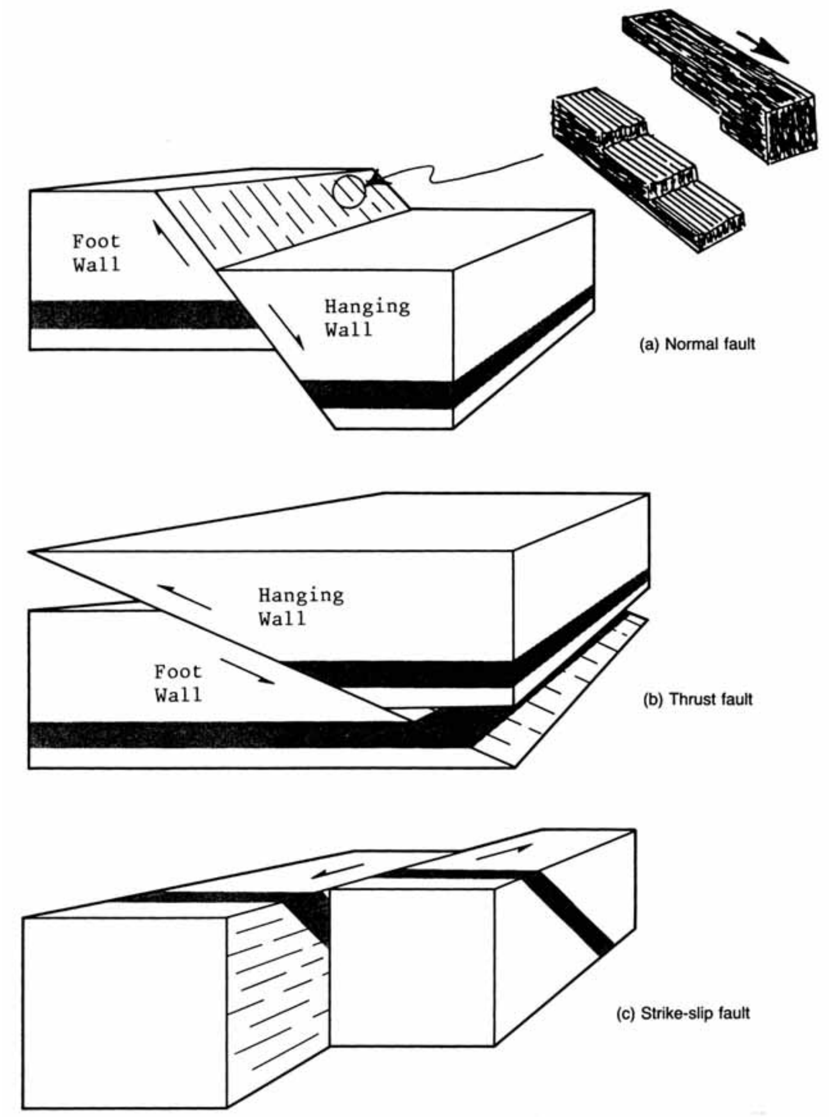


Figure 20. The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (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.]

Normal- and Reverse Faults

Imagine extending (stretching) or compressing a block-like portion of the Earth's crust. Extensional force may causes the crust to rupture along a fracture that is not vertical. In this case, the block above the dipping fracture, known as the hanging-wall block, will slide down the fracture surface producing a normal fault. [See Figure 20 (a).] Compressive forces drive the hanging-wall block up the fracture surface to make a reverse fault. A reverse fault with a low angle (<30ø) is called a thrust fault. [See Figure 20 (b).] In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane and the relationship between the tiny "risers" that are perpendicular to the striae make it possible to determine the relative sense of motion along the fault. Experimental- and field evidence indicate that the asymmetry of slickensides is not always an ironclad indicator of relative fault motion. As such, displaced geological marker beds or veins are necessary to verify relative offset. Fault motion up- or down the dip (as in normal faults, reverse faults, or thrusts faults) is named dip-slip motion.

Low-angle Thrusts

A low-angle thrust is a special kind of reverse fault that initially contained one or more segments that are parallel to the originally horizontal strata. Such low-angle faults have also been referred to as overthrusts, but this term implies a sense of motion that may not be correct. In order to beg the question of whether motion was one of overthrusting or underthrusting, P. B. King (1960) advocated use of the term low-angle thrust.

The large-scale repetition of strata on low-angle thrusts was first shown in the Scottish Highlands. Soon thereafter, spectacular examples were found in the Alps and, indeed, in nearly all mountain chains. Studies in the Appalachians made possible new understanding between thrusts and folds. Examples were found illustrating all gradations from small breaks across the axes of overturned folds (Figure 21) to what are known as imbricate thrusts in which the deformed strata and the overthrusts dip southeastward at about the same angles; during deformation, the right-way-up strata of the northwest (normal) limbs of two synclines have been brought together and the southeastern (overturned) limbs and the central parts of the intervening anticlines have vanished (Figure 22).

Studies in the Appalachians led John L. Rich (1934) to propose the concept of "bedding thrusts." By this term, he referred to overthrusts along which two contrasting segments can be recognized: (1) segments that are parallel to the bedding; and (2) segments that cut across bedding at steep angles (Figure 23). (These segments that cut bedding at steep angles have subsequently been named ramps.) What was totally different about Rich's analysis is the relationship between thrusts and folds. Because of the geometric arrangement of the ramps and the beds, any forward displacement causes the strata of the upper block to be folded. As the strata are pushed against the ramp, they become parallel to it, forming one limb of a ramp-related anticline. Where the strata that have been displaced past the ramp return to the next bedding-parallel segment of the thrust surface, they dip downward toward this surface, thus forming the second limb of the ramp-related anticline. Where later deformation has not obscured the relationships, Rich's mechanism creates flat-topped anticlines whose widths are direct functions of the amount of displacement on the thrust and intervening flat-bottom synclines whose widths are determined by the spacing between adjacent ramps.

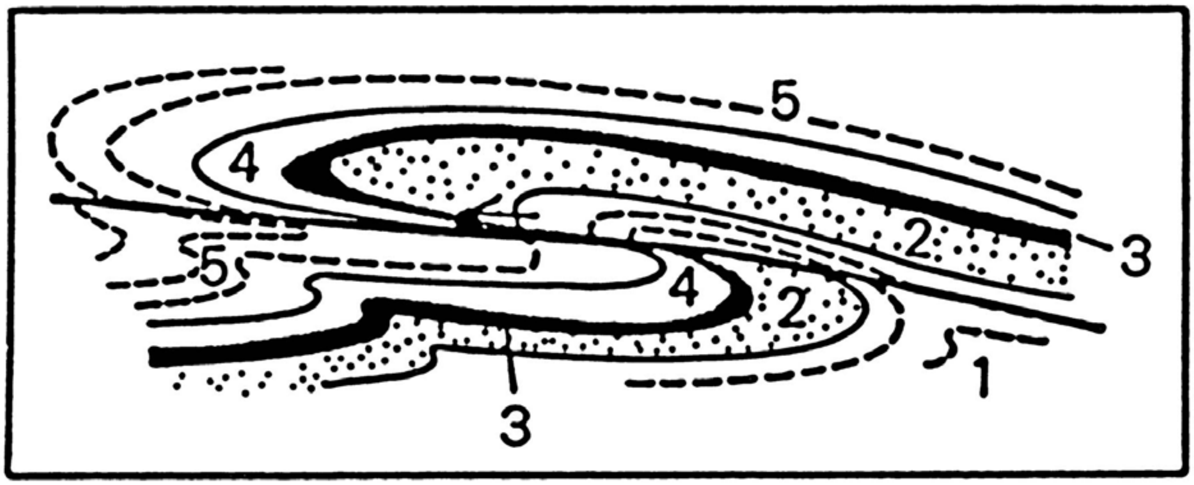
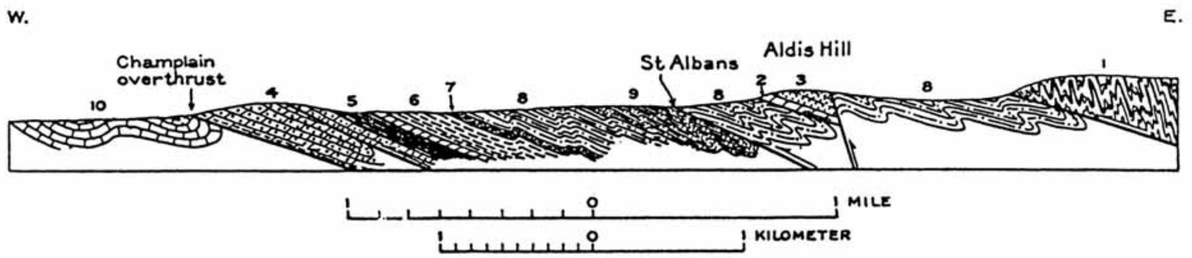


Figure 21. Overturned fold broken by a low-angle thrust fault, schematic profile section. Units are numbered in order of decreasing age, from 1 (oldest) to 5 (youngest). (J. E. Sanders, 1981, fig. 16.14, p. 398.)



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

Figure 22. Imbricate thrusts that are essentially parallel to the strata that have been duplicated; example from Paleozoic strata in northwestern Vermont. (C. R. Longwell, 1933, fig. 14, p. 63.)

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

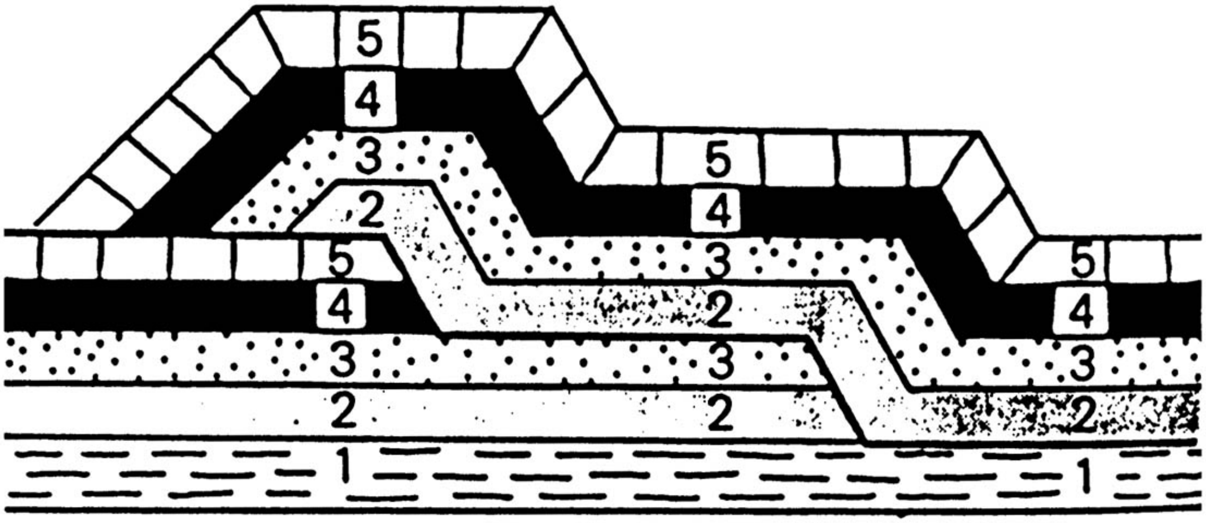


Figure 23. Folds formed by movement on a bedding-plane thrust according to the mechanism proposed by J. L. Rich; schematic profile section with units numbered in order of decreasing age from 1 (oldest) to 5 (youngest). (J. E. Sanders, 1981, fig. 16.1e, p. 390.)

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

All of which brings us back to the Appalachians. The next major point about Appalachian overthrusts is the displacement of basement rocks over the strata. In other words, the basement becomes "involved." (What's that story about ham and eggs? The hen is "involved" but the pig is "committed.") In this respect, northwestern New Jersey and adjacent southeastern New York provides some critical evidence that most Appalachian geologists have overlooked. In the discussions about "thin-skinned" vs. "thick-skinned" deformation, this part of the Appalachians seems to have been studiously avoided The evidence pointing to basement involvement in the northern Appalachian overthrusts was presented by Isachsen (1964). Isachsen argued that on a regional scale, the Proterozoic basement rocks had been thrust over the Paleozoic sedimentary strata. (See Figure 4.) He inferred that this displacement had taken place during the Late Ordovician Taconian orogeny. (We discuss the subject of age of deformation in a following section.)

A critical locality demonstrating the displacement of Proterozoic rocks over Paleozoic strata is the Musconetcong tunnel built by the Lehigh Railroad more than 100 years ago (Figure 24). Isachsen (1964, p. 822) cited Kümmel (1940) as his source of the information about this tunnel. As we pointed out in our On-The-Rocks Guidebook for Trip 12 to Franklin Furnace (17 June 1990), however, the correct citation is not Kümmel (1940) but rather Lewis and Kümmel (1915; fig. 3, p. 58).

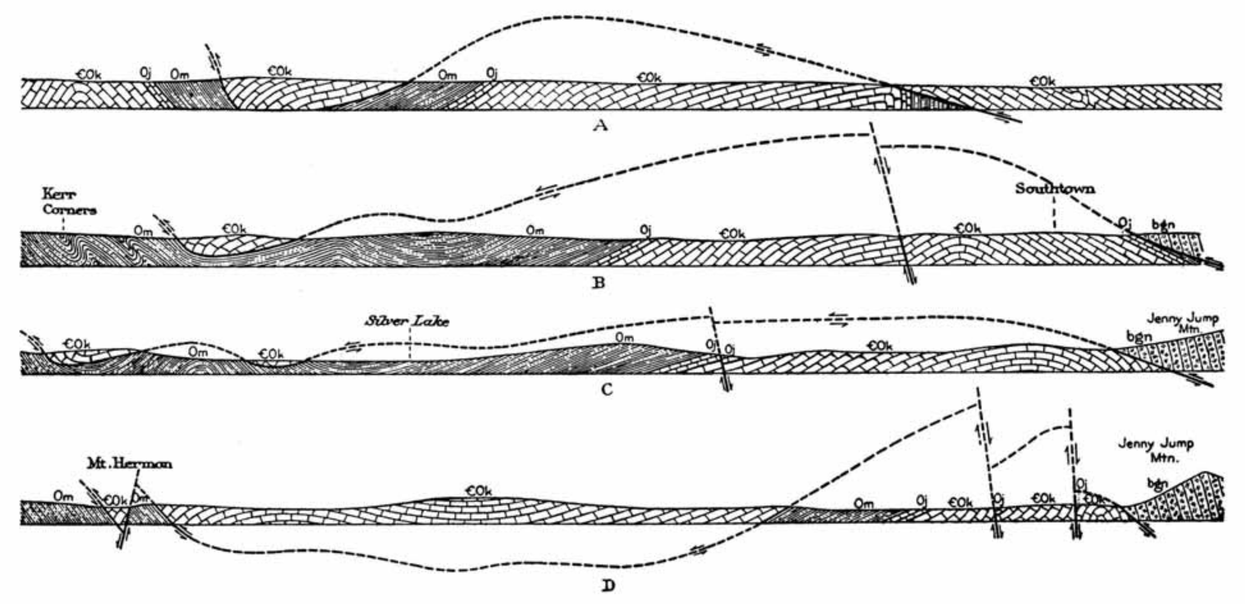


Figure 24. Geologic sections illustrating the vast thrust sheets of Cambro-Ordovician strata in the Kittatinny Valley and klippe composed of Proterozoic rocks at Jenny Jump Mountain. (J. V. Lewis and H. B. Kümmel, 1915, fig. 3, p. 58.)

In 1980, JES began to wonder about the geologic circumstances under which the gas had been trapped at the Middletown gas well in Orange County, New York. Not far SE of this well are several klippe in which Proterozoic rocks had been thrust over the Paleozoic strata (usually, but not exclusively, the Ordovician shales (Figure 25). Despite these clear examples of basement involvement with the Paleozoic strata, the authors who were writing about the "basement" vs. the "no-basement" style of Appalachian deformation seemed to be avoiding any discussion of the relationships in northwestern New Jersey and southeastern New York. JES (Sanders, Friedman, and Sternbach, 1981) concluded that the emphasis on the John L. Rich mechanism as a basis for the distinctness of "thin-skinned" deformation was omitting an important point, namely, that the Rich-style mechanism need not be confined to the strata. Deep seismic profiles were showing what appeared to be strata beneath outcropping basement (Ando and others, 1983; Ando and other others, 1984; Brown and others, 1983; Cook and others, 1979; Cook, Brown, and Oliver, 1980; Cook and Oliver, 1981). Therefore, JES suggested that the Rich-style low-angle thrusts were a general phenomenon, and that the depths of their horizontal segments could be the basis for classifying mountain belts into three longitudinal zones: (A) a distal zone in which strata were thrust over strata (the happy home of the "thin-skinned" style); (B) a median zone in which basement was thrust over strata (the habitat of the so-called "thick-skinned" style where basement was clearly "involved"); and (C) a proximal zone in which basement was thrust over basement (Figure 26).

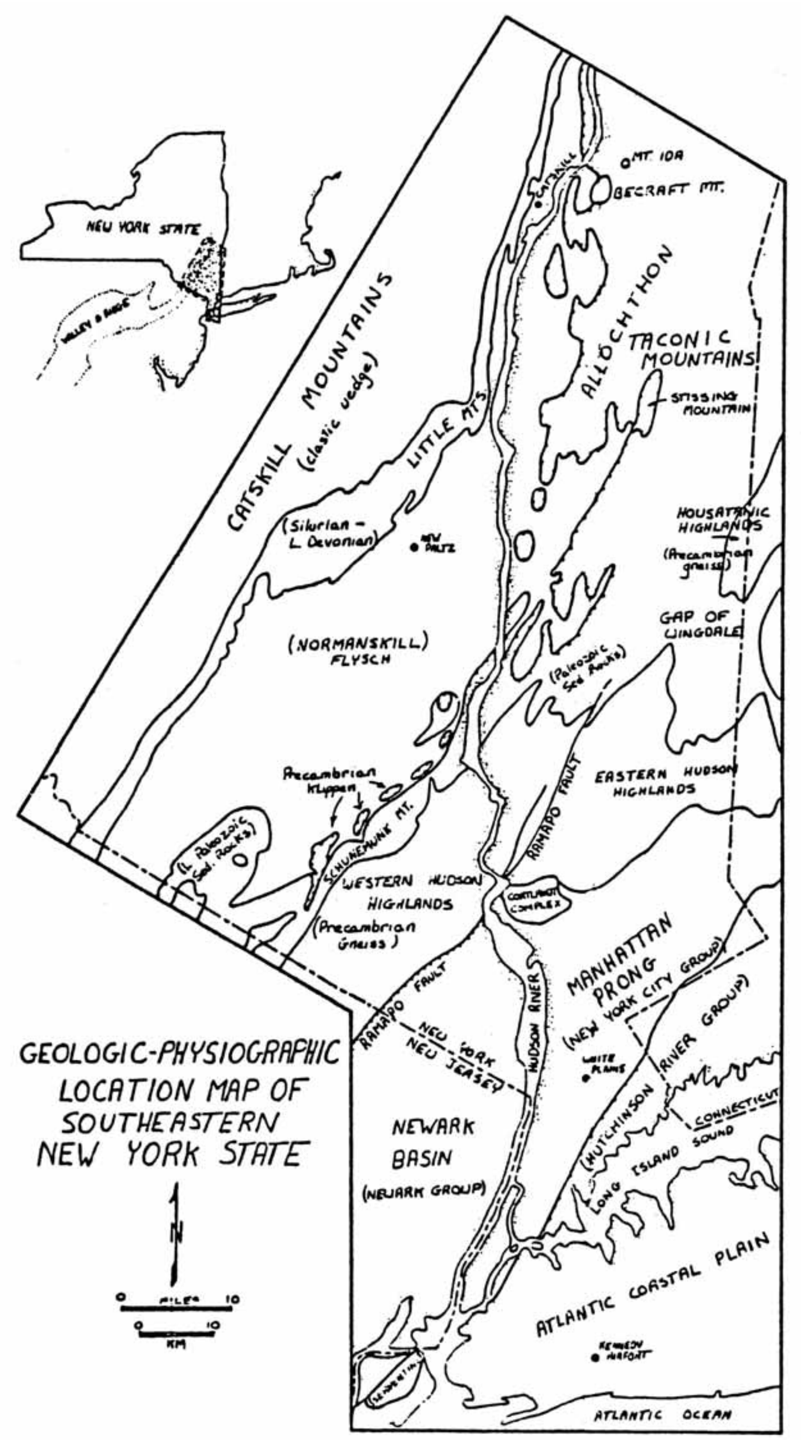


Figure 25. Tectonic sketch map of southeastern New York State showing klippen of Proterozoic rocks lying NW of Schunnemunk Mountain. This linear belt of klippen lies between the main belt of Proterozoic rocks of the Hudson Highlands and the NE-plunging anticline south of Middletown, NY. (Terry Engelder, from guidebook to solution-cleavage field trip.)

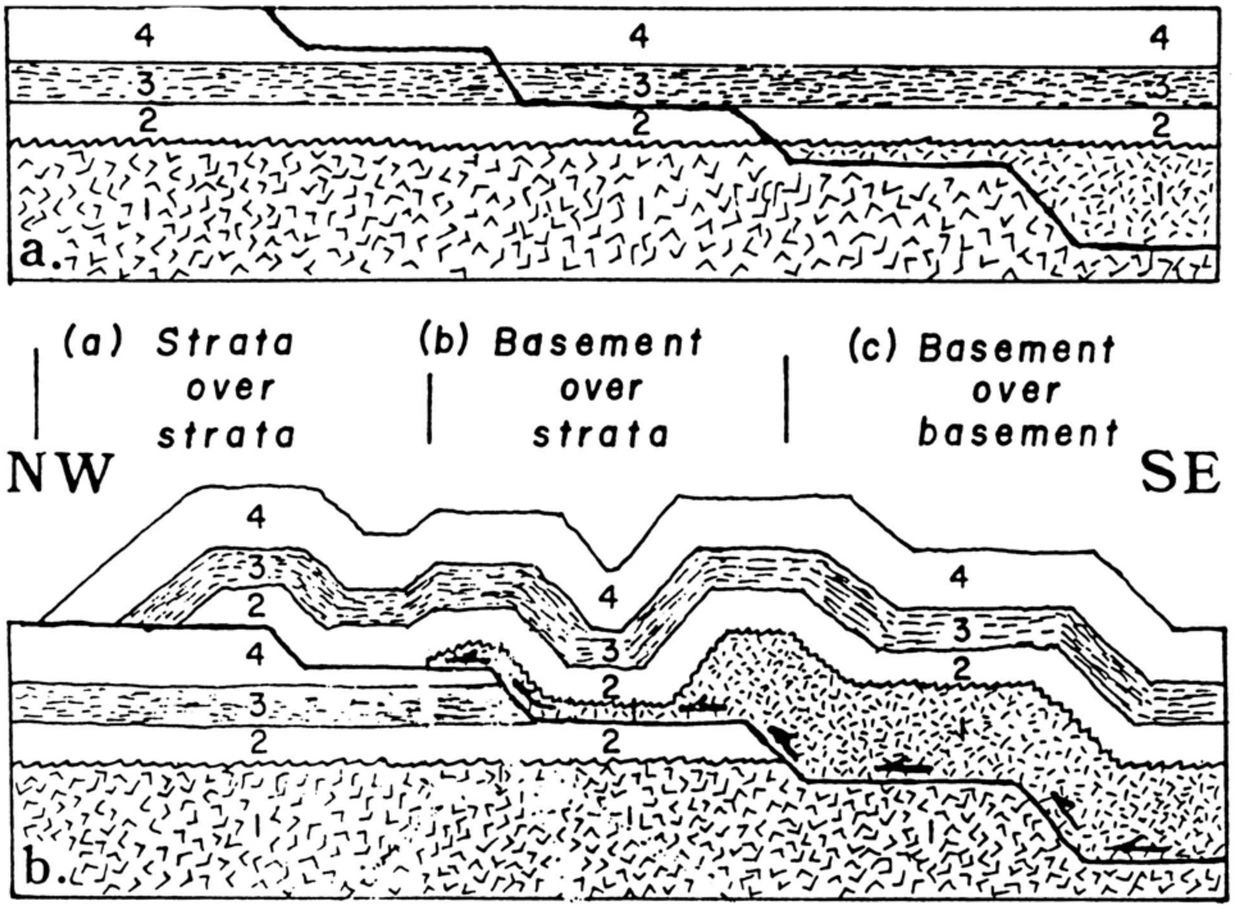


Figure 26. "Bedding thrusts" as described by J. L. Rich (1934), but extended downward so as to includes sheets of basement rock, schematic profile-section with no erosion. Where basement rocks move over other basement rocks, the cause of the separation is probably thermal, as argued by Armstrong and Dick (1974).
a. Reference sketch before movement on multi-level thrust (thick line).
b. Result of motion forward and up the footwall ramps has created anticlines above each ramp. Three thrust zones: (a), (b), and (c), are based on the relationships of the overthrust strata to other strata, of overthrust basement to strata, and of overthrust basement to other basement. (J. E. Sanders, G. M. Friedman, and C. A. Sternbach, 1981, Fig. 15, p. 218.)

Using this approach, JES (Sanders, 1983) reinterpreted the geologic structure at the Middletown well. He inferred that the large anticline south of Middletown in which the basement is exposed is a ramp-related anticline above a tectonic ramp that extended upward from some level within the Proterozoic rocks to a higher level in the Ordovician shales (Figure 27). A corollary of this interpretation is that the NW dips of the Silurian strata of Shawangunk Mountain/Kittatinny Mountain and the Devonian strata underlying the adjacent strike valley to the NW should not flatten with depth under the Catskill-Pocono Plateau, as generally presumed, but rather should be as shown in Figure 28. That is, the NW dips should continue downward to a horizontal segment of a bedding-type thrust beneath which the strata should be horizontal. Since 1983, JES has seen the seismic profile that was shot along N.Y. Route 17. Much to his delight, this profile shows that the dip of the Silurian strata continues downward more or less unchanged from its surface value to a level where these strata are truncated. At greater depth the reflector traces are horizontal. JES takes this to be dramatic confirmation that bedding thrusts on a regional scale are present beneath the Catskill-Pocono Plateau. It establishes on a regional scale the local relationships of NW-dipping bedding thrusts that JES found in the Devonian strata exposed NW of Catskill, New York (Sanders, 1969).

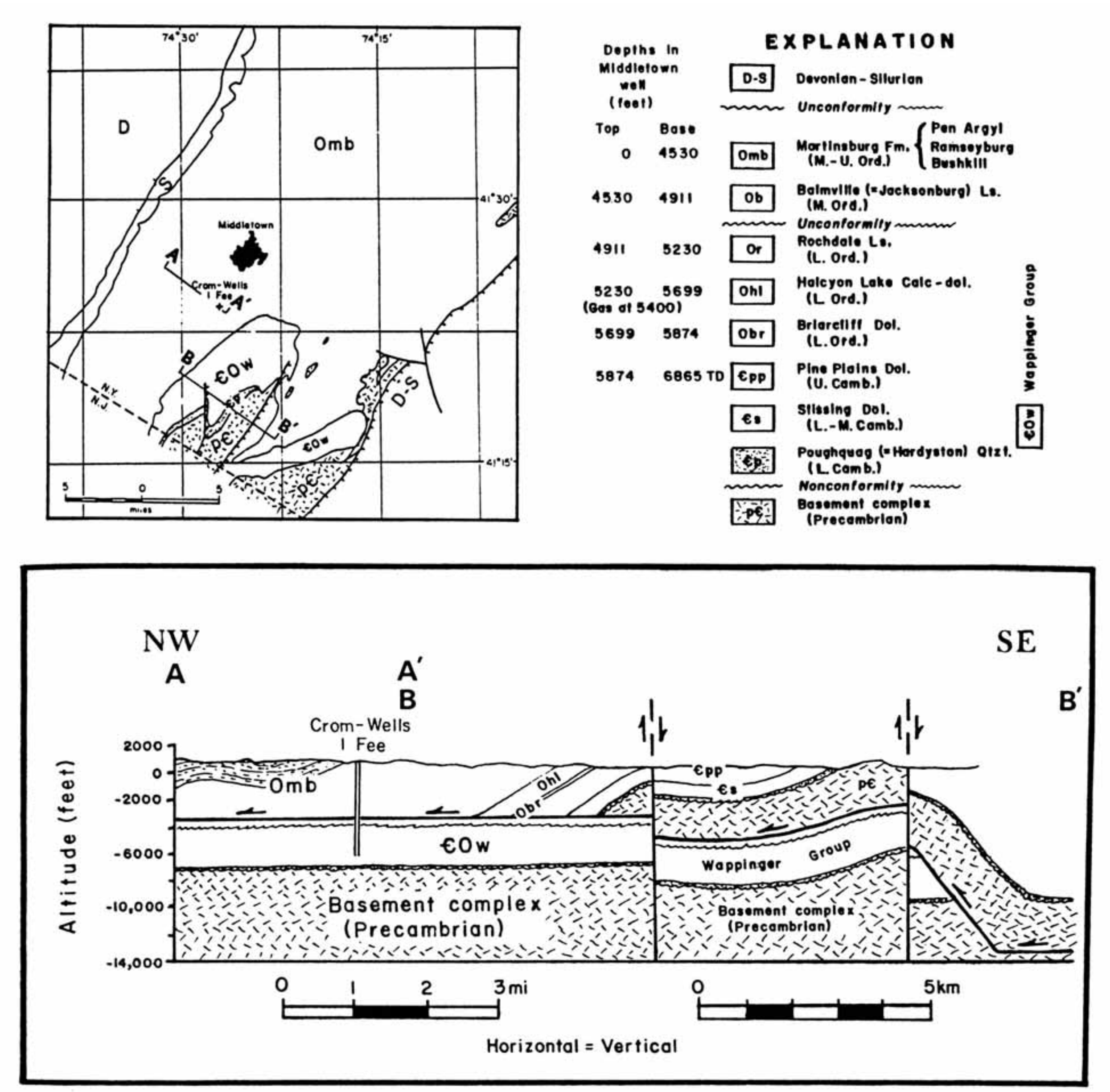


Figure 27. Geologic setting of Middletown gas well (Crom-Wells 1 Fee), Orange County, NY.

a. Simplified geologic map showing locations of lines of sections AA' and BB'. (J. E. Sanders, 1983, fig. 3, p. 173, after New York State Geologic Map, 1970, Lower Hudson Sheet.)

b. EXPLANATION of geologic map and sections including depths of formation boundaries in Midletown well (depths from Warthin and Pack, 1956 ms., in Offield, 1967). (J. E. Sanders, 1983, fig. 4, p. 174.)

c. JES interpretation of structure along lines AA' and BB.' Contacts of formations at surface from Offield (1967), but with subsurface relationships changed to show one possible arrangement according to overthrust interpretation. (J. E. Sanders, 1983, fig. 8, p. 176.).

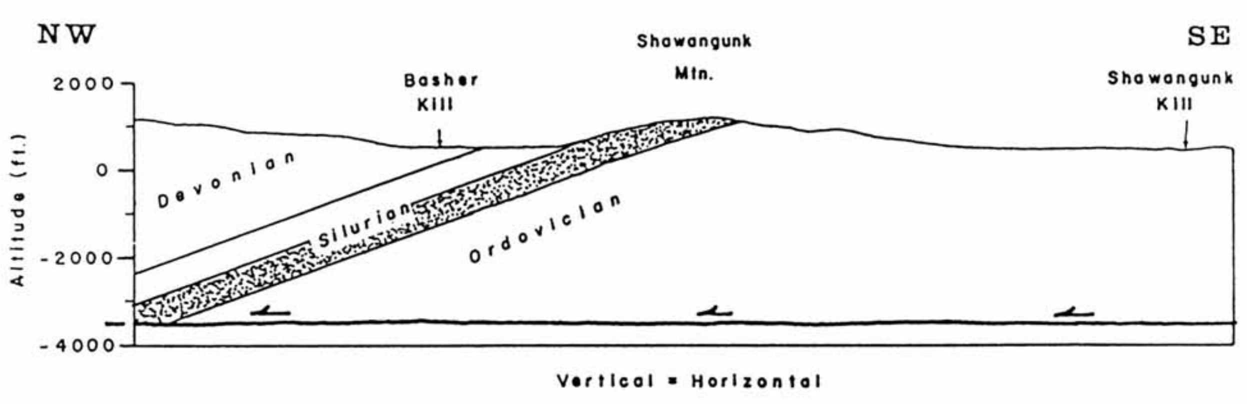


Figure 28. Profile section across the Shawangunk Ridge based on seismic data showing northwest-dipping strata abruptly truncated against a horizontal surface.

Over the years, field geologists have noted special geologic features associated with thrust faults. Because they propagate at low angles with respect to bedding, thrusts commonly duplicate strata. In addition, thrust faults can displace strata for great distances and wind up transporting rock deposited in one environment above rocks deposited in markedly disparate environments. In such cases, we call the displaced strata of the upper plate above a thrust fault an allochthon or describe an entire displaced sequence of strata as an allochthonous terrane (see Tectonostratigraphic Units below). In other words, allochthonous rocks were not originally deposited where they are now found. By contrast, regions consisting of rock sequences that were originally deposited where they are now found constitute an autochthon or autochthonous terrane.

Interesting geometric patterns result from the erosion of overthrust sheets of strata that have been folded after they were overthrust. Where a "hole" has been eroded through the upper plate (allochthon), it is possible to peer downward through the allochthon and see the autochthon exposed in a window (synonyms: inlier, or, in the German tongue, fenster) surrounded by the trace of the thrust fault that was responsible for the dislocation (Figure 29). By contrast, if most of the upper plate has been eroded, only a remnant outlier or klippe may remain. (See Figure 29.) Both klippen and windows (or fensters) produce similar map-scale outcrop patterns. The difference is that the thrust surface typically dips toward the center of a klippe (a remnant of the allochthon) and away from the center of a window (which shows a part of the underlying autochthon).

Bedding-plane thrusts are more-localized features but are geometrically the same as thrust faults in that they involve layer-parallel shortening of strata and produce low-angle imbrication of strata. They can easily be "missed" in the field but result in overthickening of strata and can produce anomalous stratigraphic thickness in sedimentary units. The field geologist can identify them by careful bed-by-bed examination of known sequences based on duplication of key- or marker beds and by identification of highly veined rocks adjacent to- or zones of gouge or slickensides along the surfaces of dislocation.

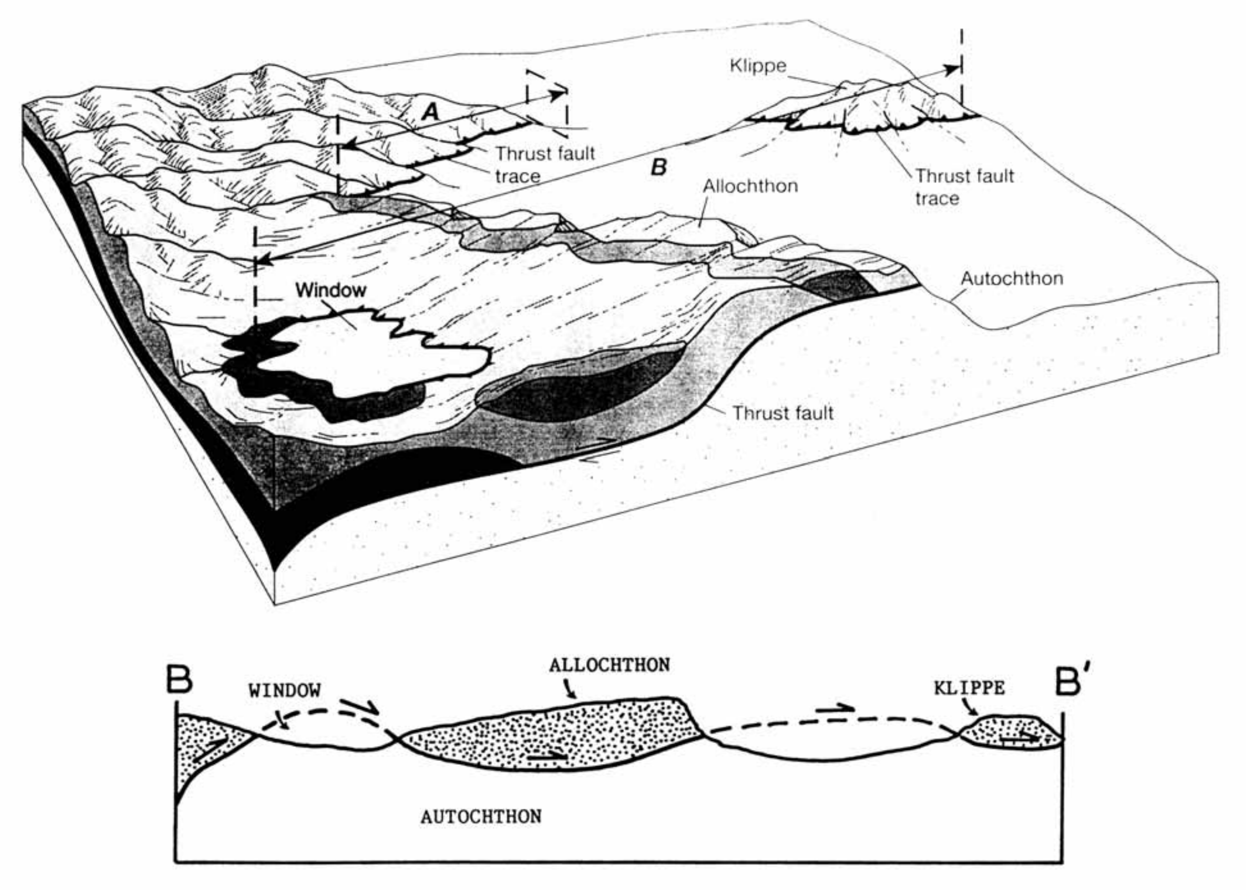


Figure 29. Block diagrams illustrating the relationships among major components of low-angle thrust sheets, including allochthons, autochthons, klippen, and windows. (R. J. Twiss and E. M. Moores, 1992, Fig. 6.4, p. 99; section B-B' drawn by CM.)

During episodes of mountain building associated with continuous subduction and/or collisions near continental margins, thrusting is typically directed from the ocean toward the continent. Accordingly, one of the large-scale effects of such periods of great overthrusting is to impose an anomalous load on the lithosphere which causes it to subside and form a foreland basin. These basins receive tremendous quantities of sediment which fill the basin with debris derived from erosion of uplifted areas within the active collision zone. In the late stages of convergence, forces transmitted from the collision zone into the developing foreland basin create a diachronous secondary stage of folding and continent-directed overthrusting of the strata filling the foreland basin. Thus, a thrust may override debris eroded from it (Sanders, 1995).

Strike-slip Faults

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 20 (c).] On a strike-slip-fault plane, slickensides are oriented subhorizontally and again may provide information as to which direction the blocks adjoining 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 20 (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.

Distinctive Fault Rocks

Tensional-, compressional, or strike-slip faulting results in brittle deformational response at crustal levels above 10 to 15 km. Such faulting is episodic and accompanied by seismicicity and the development of highly crushed and granulated rocks called fault breccias and cataclasites (including fault gouge, fault breccia, and others). Figure 30 lists brittle- and ductile fault terminology as adapted from Sibson (1977) and Hull et al. (1986). Begining at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallization during ductile 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. (See Figure 30.)

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.

Effects on Sedimentary Strata of Deformation

The most-obvious effect of deformation on sedimentary strata is change of attitude: originally horizontal strata are no longer horizontal. Apart from such changes, other indicators of deformation include displacement of strata, disruption of strata, and rock cleavage (Figure 34).

Where two sets of cleavage have been superimposed upon each other (or more than two sets of cleavage on one another), the rocks tend to break into wedge-like, triangular shapes or into long, slender faceted "pencils." This property of shape is further promoted if the deformed rocks contain a planar parting parallel to bedding.

In regions where several episodes of deformation intense enough to form rock cleavage have been superimposed, it may be very difficult to unravel the relative ages of cleavage. If deformation has beem along subparallel trends, tlhis problem may become acute. Normally, cleavage direction parallels the axial surface of folds. That is, the layer-type minerals whose parallelism causes the cleavage are oriented parallel to the plane of maximum compression. (See Figure 31.)

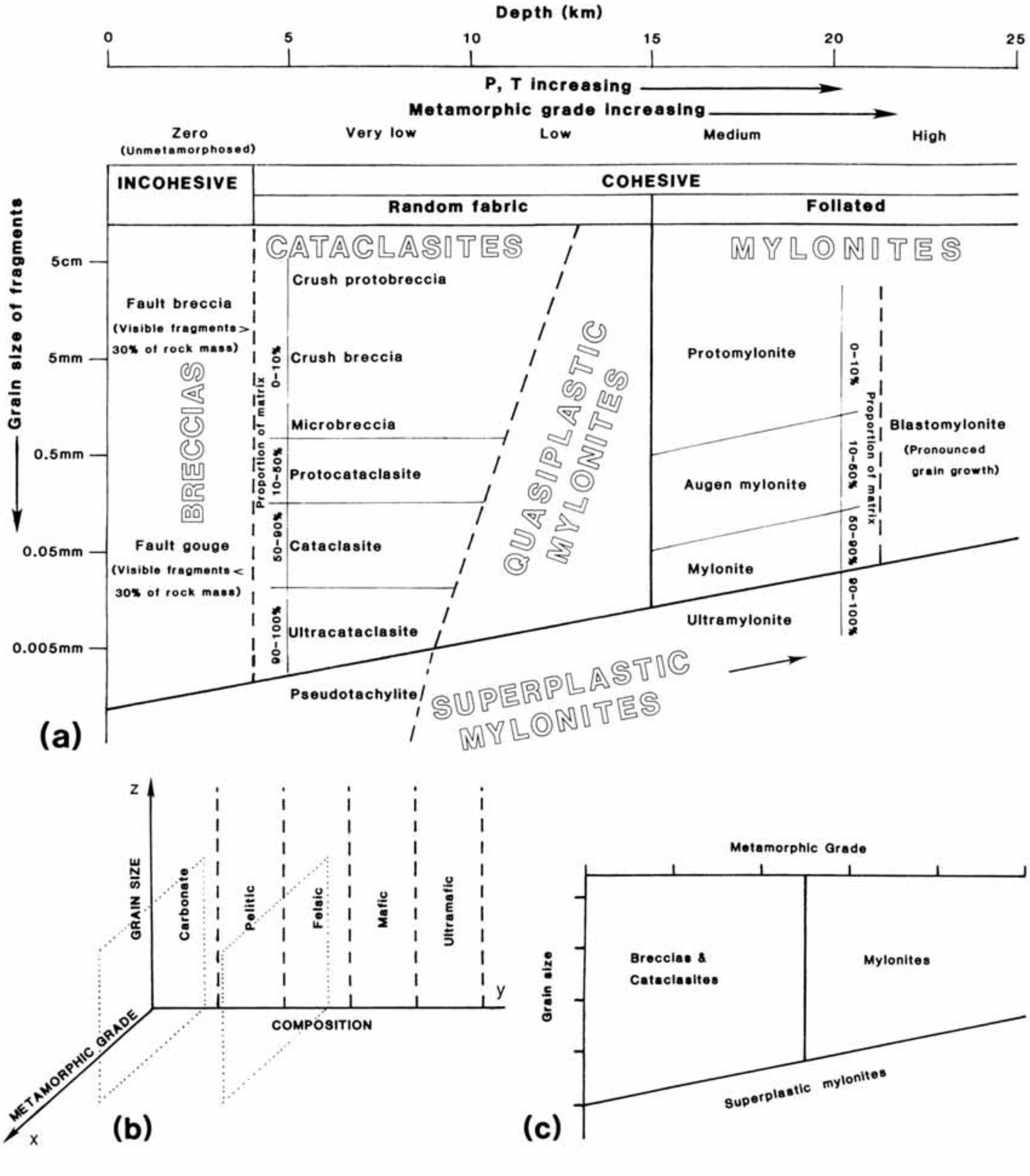


Figure 30. Fault-rock terminology. (a) Classification of fault rocks that have been derived from quartzo-feldspathic lithologies (e. g. granite). (Adapted from R. Sibson, 1977.) (b) The particle size - metamorphic grade - lithologic composition grid used for classifying fault rocks. (After J. Hull, R. Koto, and R. Bizub, 1986.) (c) Fault-rock diagram for marl showing expanded mylonite (sic) and superplastic mylonite fields as compared to those shown on the diagram for granite in (a) (Gautam Mitra and R. Stephen Marshak, 1988, fig. 11-23, p. 227.)

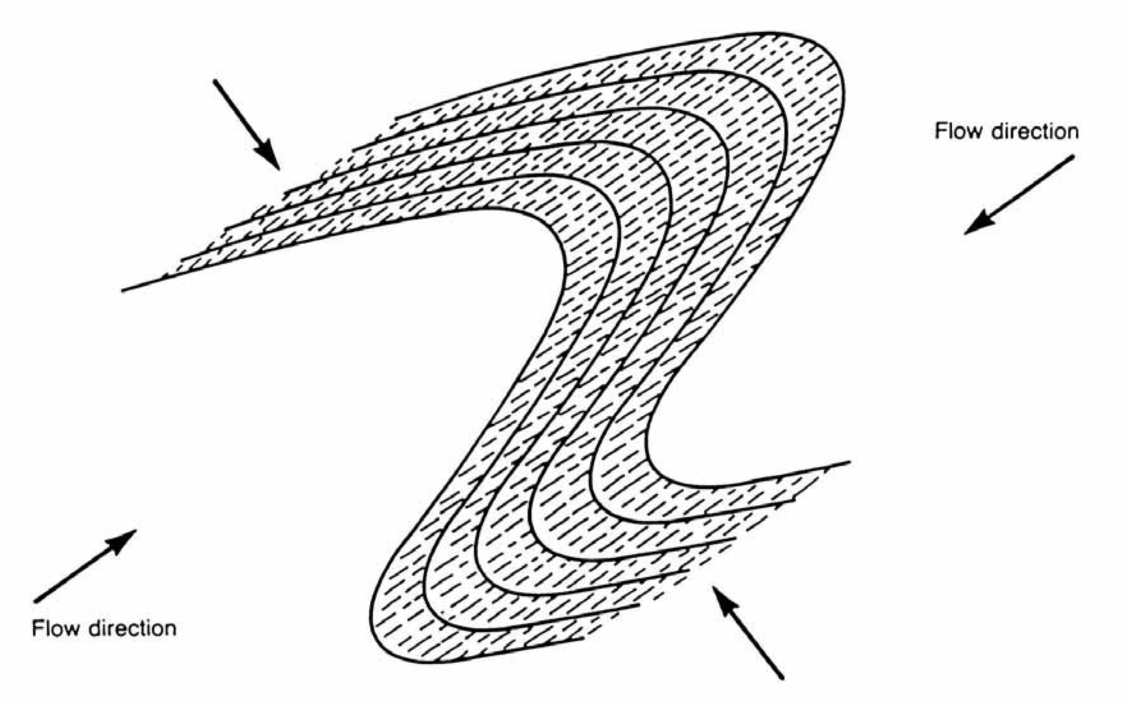


Figure 31. Sketch of slaty cleavage oriented parallel to axial plane of folds. (R. D. Hatcher, Jr., 1990, fig. 15-22, p. 335.)

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.

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 penetrative metamorphic fabrics are called foliation, if primary, and schistosity, if secondary. Minerals can also become aligned 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 tight- to isoclinal (high amplitude-to-wavelength aspect ratio) with limbs generally parallel to axial surfaces, a penetrative foliation produced during regional dynamothermal metamorphism will generally be parallel to 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.

Tectonostratigraphic Units

In metamorphic terranes, tectonostratigraphic units can best be described as large-scale tracts of land underlain by bedrock with similar age range, protolith paleoenvironment, and structure. Such terranes are generally bounded by ductile-fault zones (mylonites), surfaces of unconformity, or brittle faults. Unravelling the collisional plate-tectonic history of mountain belts is greatly facilitated by identifying former cratonic (ancient crustal), continental-margin, continental-slope-, and rise, deep-oceanic, and volcanic-island tectonostratigraphic units. The major distinction in unravelling complexly deformed mountain belts is to identify former shallow-water shelf deposits (originally deposited on continental crust) and to separate them from deep-water oceanic deposits (originally deposited on oceanic crust). The collective adjectives miogeosynclinal (for the shallow-water shelf deposits) and eugeosynclinal (for the deep-water oceanic deposits) have been applied to the products of these contrasting depositional realms.

Geologic Dating of Episodes of Deformation

Geologists use many methods to establish the geologic date of deformation. These include analysis of surfaces of unconformity, obtaining the dates on formations containing pebbles- or inclusions of deformed rock, relationships to associated plutons, and radiometric ages on minerals that grew as a result of deformation.

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 32), such surfaces represent mysterious intervals of geologic time where the local evidence contains no clues 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.

Surfaces of unconformity resulting from erosion can be classified into three categories: (a) surfaces of angular unconformity, (b) surfaces of nonconformity, and (c) surfaces of disconformity (Figure 33). Along surfaces of angular unconformity (such as that James Hutton saw exposed in the banks of the River Jed), dipping strata below the surface have been truncated and thus angular discordance is present between the strata below- and above the surface of erosion. A surface of nonconformity separates sedimentary strata above from eroded igneous- or metamorphic rocks below. Surfaces of disconformity are the most-subtle variety; the separate subparallel sedimentary strata. They are commonly identified by paleontologic means, by the presence of channels cut into the underlying strata, or by clasts of the underlying strata in their basal part. The strata above a surface of unconformity may or may not include clasts of the underlying strata in the form of a coarse-textured, often bouldery basal facies.

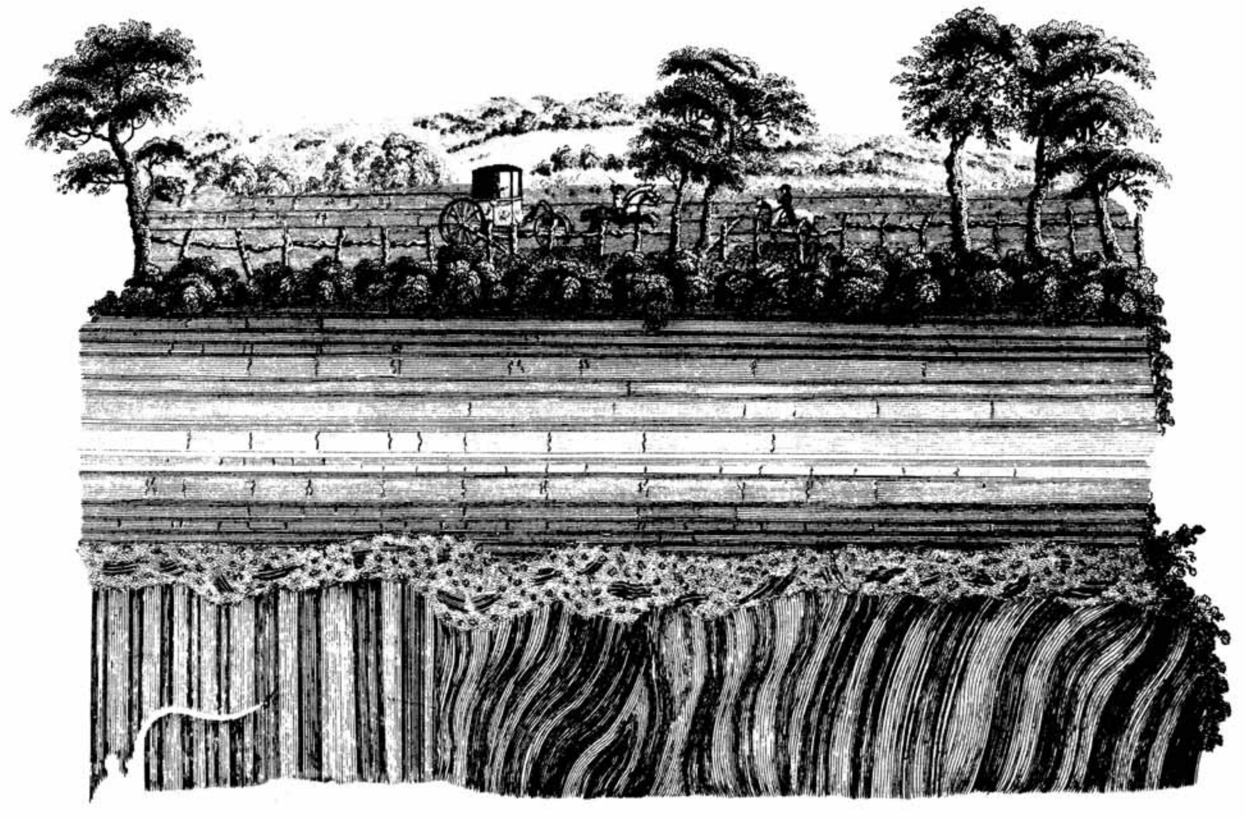


Figure 32. Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. [James Hutton, "Theory (sic) of the Earth", 1795.]

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.

Dating Formations That Contain Pebbles- or Inclusions of Deformed Rock

In certain situations, it is possible to find pebbles- or inclusions of deformed rock in another formation that can be dated. The date of the formation containing the pebble or inclusion places an upper limit on the date of deformation indicated by the pebble. For example, pieces of Martinsburg slate have been found as inclusions in the Late Ordovician igneous rocks in northwestern New Jersey. This proves that the age of the slate is pre-Late Ordovician. In other cases, pebbles of mylonite might be found in a datable conglomerate and the age of the conglomerate thus marks an upper limit on the age of the mylonite.

Relationships to Associated Plutons

Commonly orogenic episodes are accompanied by plutonic activity. Where a pluton cuts a fault, for example, the pluton clearly is younger. The date on the pluton thus sets an upper limit on the age of the fault. Plutons can be dated directly by a radiometric age on minerals, a whole-rock age, or indirectly by crosscutting relationships with formations of the country rock or by finding pebbles of the pluton in younger formations.

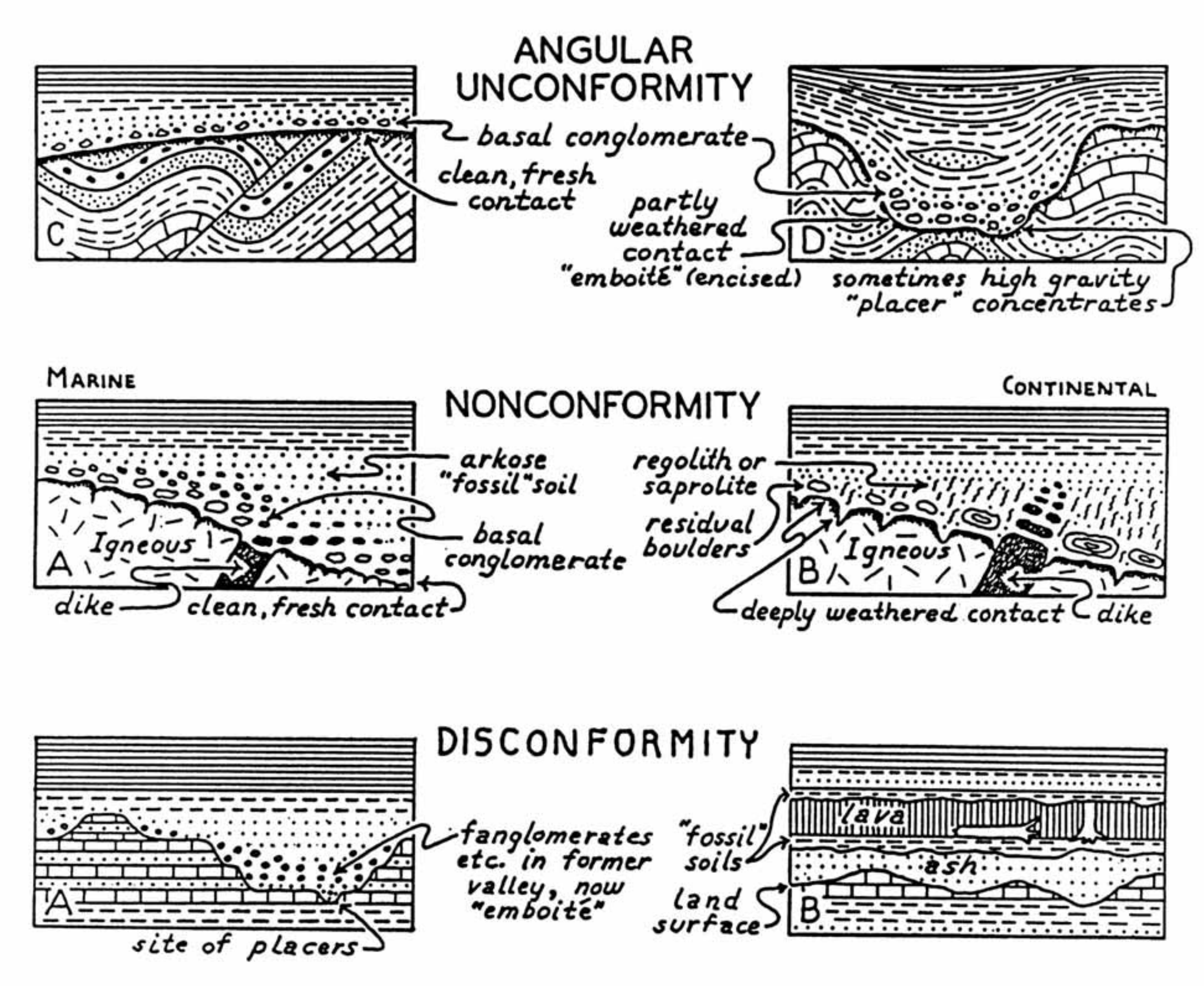


Figure 33. Varieties of geologic relationships along surfaces of unconformity, which mark gaps in the geologic record. (Drawings by Rhodes W. Fairbridge.)

Radiometric Ages on Minerals that Grew as a Result of Deformation

Dating deformation by radiometric ages on minerals that grew as a result of deformation is analogous to obtaining radiometric ages on minerals from a deformation-associated pluton, but need not always involve a pluton. In some cases, micas or other minerals recrystallized as a result of deformation and the radiometric date yields the date of recrystallization. Other kinds of minerals may grow in veins whose emplacement accompanied an episode of deformation.

BEDROCK UNITS

Layers I and Metamorphosed Parts of Layer II: "Basement Complex" (Proterozoic and Lower Paleozoic)

As we begin Trip 36 from the New York Academy of Sciences, let us express a few thoughts to the rocks beneath our feet. The crystalline bedrock of New York City is part of a physiographic province known as the Manhattan Prong (See Figures 5 and 6.) that widens northward into the New England Upland physiographic province of the Appalachian mountain belt. The Manhattan Prong is underlain by an important sequence of metamorphosed Proterozoic- to Lower Paleozoic rocks. Originally, the New York City strata of Early Paleozoic ages were, in part, deposited on the complexly deformed sequence of layered feldspathic and massive granitoid gneiss, amphibolite, and calc-silicate rocks of uncertain stratigraphic relationships known as the Fordham [Y] and Yonkers Gneiss [Z] (Layer I). These complexly deformed rocks are of Proterozoic age, but can be assigned to the alphabetical-letter scheme of Proterozoic rocks adopted by the U. S. Geological Survey. Present in SE New York are representatives of Proterozoic Y and Z. These are inferred to represent the ancient continental crust of proto-North America.

Early in the Paleozoic Era, this region became the trailing edge of a continental plate, a passive continental margin. This tectonic setting persisted until the Taconan orogeny late in the Ordovician Period. Interestingly, the current plate-tectonic passive-continental-margin setting of eastern North America [deformed Paleozoic and older basement covered by essentially nondeformed Mesozoic and younger sediments that were (and continue to be) deposited as the margin subsides toward an ocean basin to the east; Figure 34] more or less duplicates that of Early Paleozoic time but with two major differences. First of all, during the Early Paleozoic, this part of North America lay within the tropical zone of Southern Hemisphere. Secondly, the open ocean formerly lay to the south rather than to the east, as it does today.

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

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

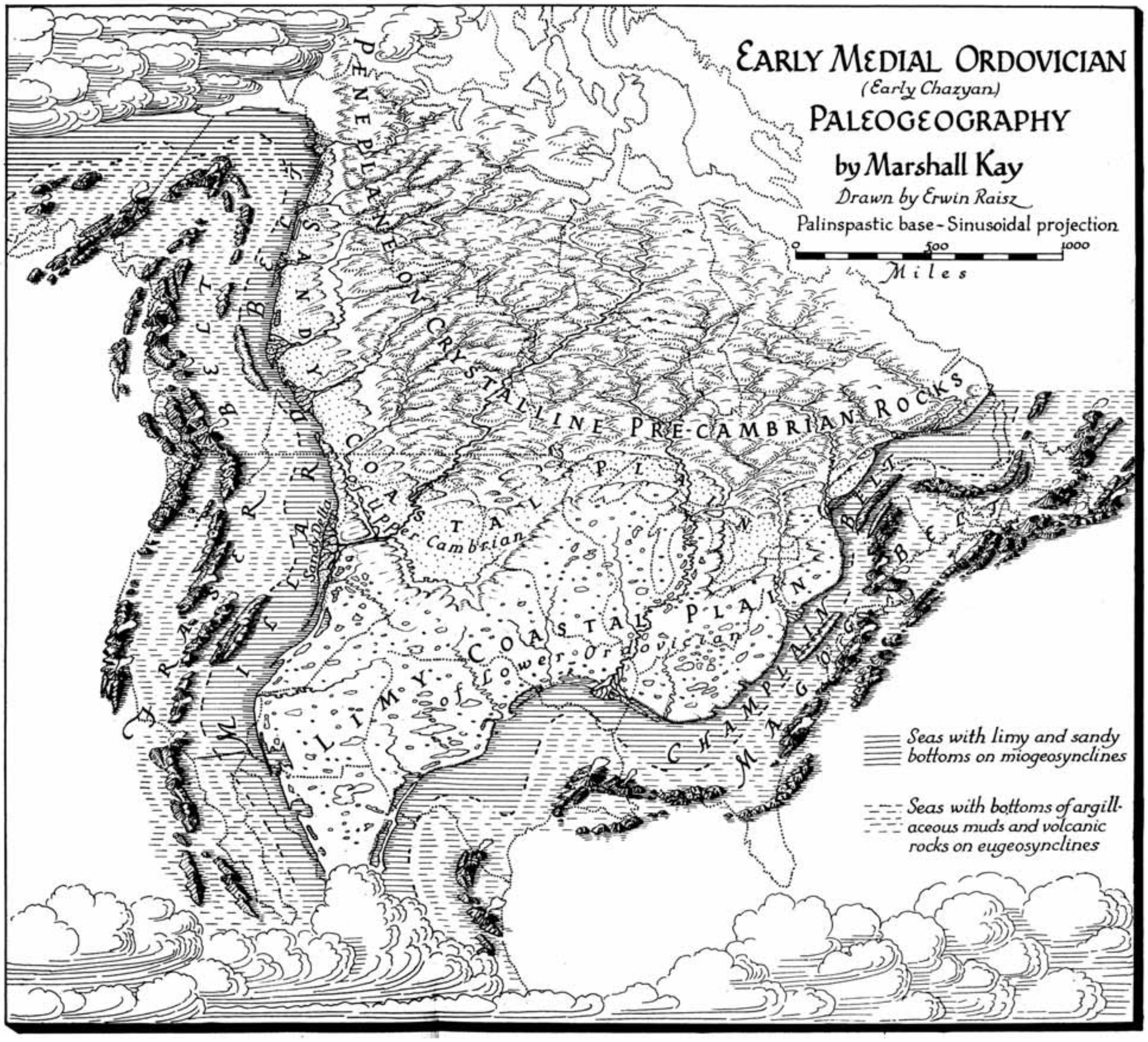


Figure 34. Paleogeographic reconstruction of North America as it is inferred to have existed during the Cambrian Period. Not shown are paleolatitudes and position of the Early Paleozoic Equator, which extended across what is now North America passing through Oklahoma, Kansas, and the Dakotas such that what is now east in the Early Paleozoic was south. (G. M. Kay, 1951, plate 1, facing p. 1.)

Farther offshore, fine-textured terrigenous time-stratigraphic equivalents of the shallow-water strata (shelf sequence) were evidently deposited under deep water on oceanic crust [Layer IIA(E)]. This sequence is also of Cambrian to Ordovician age and is known as the Taconic sequence in upstate New York, as units Ꞓ-Om and Ꞓ-Oh of the Manhattan Schist(s). (See Figure 6.) In western Connecticut, it includes the Waramaug and Hartland formations, respectively.

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

The schists originally named as the Manhattan Schist were thought to be entirely younger than the Inwood Marble (Layer IIB). If this presumed arrangement were true, then the schists would have formed from metamorphism of strata belonging entirely to the Tippecanoe Sequence. As a result of CM's mapping, large parts of this body of schist are now recognized as rock units that are the same age or older than Manhattan Schist unit Om and the Inwood Marble. According to CM (Merguerian, 1983b, 1995; Merguerian and Baskerville, 1987; Merguerian and Sanders, 1988, 1991b), at Inwood Hill Park in Manhattan, this Manhattan schist Unit Om is demonstrably interlayered with the Inwood Marble and at its base, contains thin layers of calcite marble (Balmville equivalent). Such field evidence is used to indicate that unit Om of the Manhattan Schist is in place where found and is therefore younger, or the same age as, Manhattan units Ꞓ-Om and Ꞓ-Oh.

During the middle part of the Ordovician Period, roughly 450 million years ago, and prior to the main events of the Taconic orogeny, these older eastern, deep-water formations [Layer No. IIA(E)], were overthrust into a position above the Inwood Marble and the younger overlying schist (all of the Manhattan Schist as originally conceived, but only Manhattan Schist unit Om, according to CM; Figure 35). In other words, the Taconic allochthon (units Ꞓ-Om and Ꞓ-Oh) extends into New York City (Merguerian, 1995a, b; Merguerian and Sanders, 1989a, 1992a).

After this great thrust took place, the New York City rocks were complexly folded together (Figure 36) and metamorphosed under amphibolite-facies conditions. This can be inferred from the presence of such "indicator" minerals as kyanite, sillimanite, and garnet.

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

The presence of the diagnostic metamorphic minerals mentioned above suggests that rocks now exposed at the present land surface of New York City formerly were at depths of roughly 20 km. If this is correct, it indicates that enormous uplift and vast erosion took place between the middle of the Paleozoic Era, the time of the last great metamorphism, and late in the Triassic Period, when these metamorphic rocks began to be covered by the sedimentary strata filling the Newark basin. A simplified geologic section showing the relationships between the folded New York City rocks, at the former land surface, and the Newark Supergroup drawn along an east-west at the George Washington Bridge (GWB). (See Figure 7.) The overturned anticlines and -synclines of the New York City metamorphic rocks are unconformably overlain by the west-dipping strata of the Newark Supergroup (Layer V, Table 2). The unconformity surface projects out of the Hudson River over Manhattan. On the W side of the Hudson River, this surface dips westward at the same angle as the overlying strata of the Newark Supergroup.

It may not have occurred to you in these terms, but as you observe outcrops in New York City, you are doing two contrasting things. First, you are vicariously walking backward in time. And second, you are figuratively descending deep within a former mountain zone.

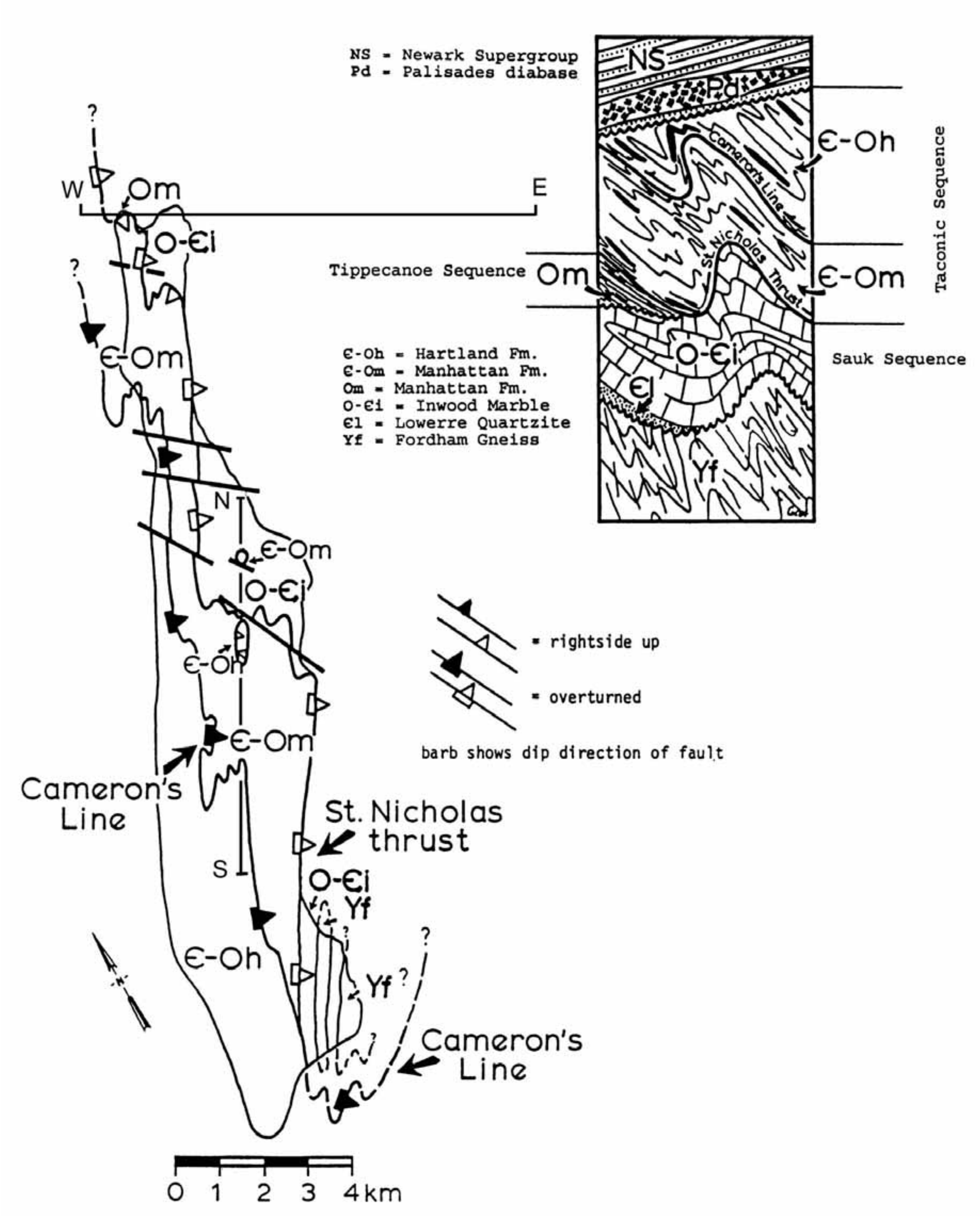


Figure 35. Geologic map of Manhattan Island showing a new interpretation of the stratigraphy- and structure of the Manhattan Schist. (Drawn and mapped by C. Merguerian.)

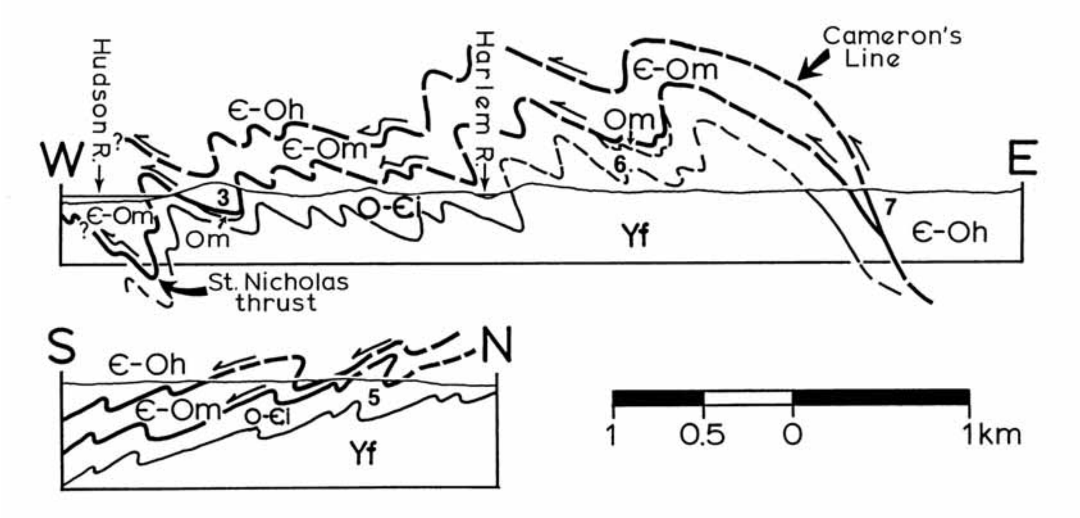


Figure 36. Folded overthrusts, Manhattan Island. Symbols defined on Figure 35. (Charles Merguerian, unpublished data.)

Layer I of Hudson Highlands-Reading Prong

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

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

In a few localities, the Proterozoic rocks clearly are allochthonous. Isolated hills composed of Proterozoic rocks in their high parts display Paleozoic rocks, typically the Tippecanoe sequence [Martinsburg Formation (Layer No. IIB, of Table 2)], in their lower regions. Both the structural relationships and the composition of the Proterozoic rocks (commonly graphitic phyllite or graphitic quartzite) demonstrate that these isolated hills are remnants of formerly more-extensive low-angle thrust sheets (klippen, auf Deutsch). (See Jaffe and Jaffe, 1973, 1989; and Figure 25.). A few examples include Woodcock Hill klippe, Museum Village klippe (in which all contacts between the Proterozoic and adjacent rocks are nearly horizontal and Goose Pond Mountain, west of Monroe (in which the contacts on the NW sides are nearly horizontal, whereas those on the SE sides dip steeply and are best interpreted as the result of post-overthrust high-angle "normal" faults).

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

Allochthonous or autochthonous, some of the Proterozoic rocks of the Reading Prong are famous throughout the world. An example is the remarkable suite of minerals uncovered in the zinc mines at Franklin and Sterling Hill, New Jersey (Metsger, 1980; Frondel and Baum, 1974; Frondel, 1972; Baker and Buddington, 1970; Metsger, Tennant, and Rodda, 1958; Hague, Baum, Herrmann, and Pickering, 1956; Palache, 1929, 1935; Spencer, Kümmel, Wolff, Salisbury, and Palache, 1908). (We expect to include a visit to Franklin Mineral Museum and vicinity on our next On-the-Rocks trip, No. 37.) These mineral deposits are associated with granitic pegmatites that have intruded the Franklin Marble, a coarsely crystalline calcite marble that we shall examine at Stop 5.

Details are yet to be determined, but a likely possibility is that within the Proterozoic rocks of the Grenville suite a still-more-ancient continental margin was involved, with shallow-water carbonates giving way to deep-water terrigenous pelites and volcanics, as in the Early Paleozoic (Merguerian and Sanders, 1991).

Layer II Northwest of the Hudson Highlands

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

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

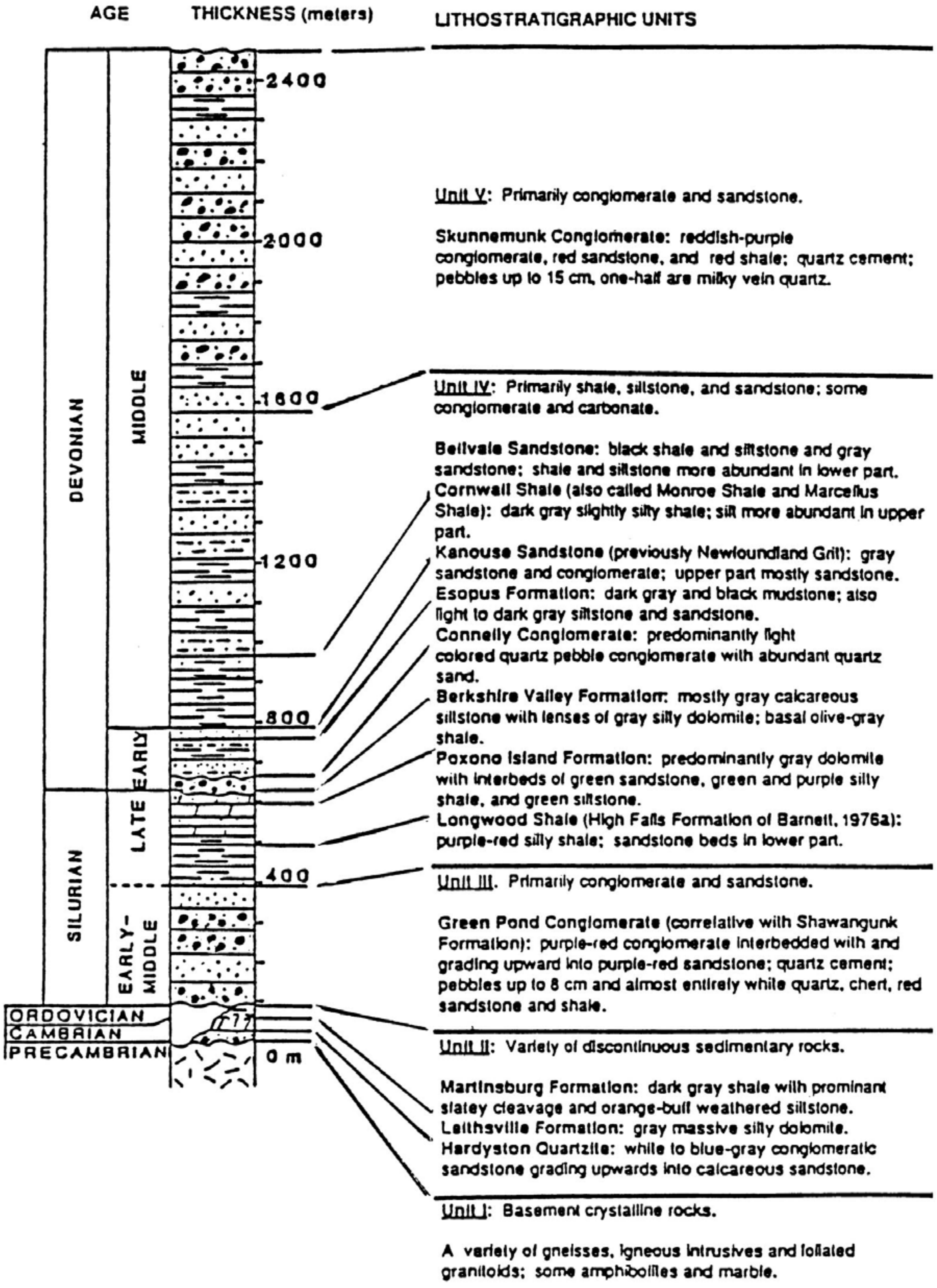
We will examine the slates of the basal member (=Bushkill Member) of the Martinsburg Formation west of Warwick (Stop 4), and one of the coarse members (Ramseyburg Member in middle? or High Point Member at the top?) at the ramps to I-84 at Smith's Corners (Stop 6).

Depending on the progress of our trip, we may be able to visit Stop 8, a roadcut SW of Hamburg, New Jersey, where the Upper Cambrian part of the Cambro-Ordovician carbonate succession displays numerous features made by a peritidal environment. Present are dolomitic rocks that formed from what were originally calcium-carbonate muds and -sands. The originally sandy layers feature ooids and rounded quartz particles mixed with varying proportions of carbonate sand whose particles included intraclasts of the adjacent muddy sediment. In addition, algal stromatolites are prominent and chert is abundant. Finally, as a result of deep burial, all layers have been subjected to pressure solution, as is evidenced by the numerous stylolites on several scales. (Tada and Siever, 1989, summarize pressure solution.)

Layer III: Silurian and Devonian

The rocks of Layer III are at center stage on this trip. We will examine them in both their southeastern- and northwestern outcrop belts. The stratigraphic succession that has been established in the southeastern belt (Layer No. IIIE, Table 2, p. 26) begins with the Lower Silurian Green Pond Conglomerate and ends with the Middle Devonian Schunnemunk Conglomerate. Two recent versions of the succession at opposite ends of the southeastern belt are shown in Figure 37 (for the southwestern end near Green Pond Mountain, NJ) and Figure 38 (near Schunnemunk Mountain, NY). Differences result from actual changes in the strata and also from contrasting perceptions of the stratigraphic succession based on available exposures, the purposes of the studies, and backgrounds of the investigators. More of the Sauk (Cambro-Ordovician) carbonates are exposed near Schunnemunk Mountain than at Green Pond Mountain.

A renewed interest in the structural-geologic relationships of the rocks within the southeastern belt of Layer No. III has developed on the part of investigators studying the features made as the rocks were deformed (i.e. strained). The latest wrinkle is that "flower structures" (Figure 39) are present along the SE side of the Reservoir fault zone, which forms the border of the western belt of the Green Pond outlier in NW New Jersey and which has been inferred to display significant right-lateral strike-slip movement. Latest movement on the Reservoir Fault has been inferred to be of Late Paleozoic age, although the constraints listed range from post-Mid Devonian to Triassic (Malizzi and Gates, 1989b, p. 84-86). We find this evidence for right-lateral strike-slip movement of more than casual interest in view of our "minority" interpretation of the strike-slip offsets on the Hopewell- and Flemington faults that cut the Newark- and associated strata in the Delaware River Valley and adjacent areas (Sanders, 1962b; Merguerian and Sanders, 1993b, 1994b). Geologic credulity does not need to be strained so much as were the rocks to connect the Flemington fault (with its JES-inferred 19 km of right-lateral strike-slip displacement (Figure 40) accompanying a dip-slip shift of approximately 3 km) and the Reservoir fault. If this intuitive leap by JES proves to be correct, then the age of the deformation on the Reservoir fault becomes Mid-Jurassic. And the combined Hopewell-Reservoir fault assumes a big-league status not heretofore imagined. The rocks of Layer IIIE are discussed further under the descriptions of Stops 2 and 3.



Unit V: Primarily conglomerate and sandstone.

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

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

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

Unit III. Primarily conglomerate and sandstone.

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

Unit II: Variety of discontinuous sedimentary rocks.

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

Unit I: Basement crystalline rocks.

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

Figure 37. Stratigraphic column in the Green Pond outlier, NW New Jersey, according to J. P. Mitchell and R. D. Forsythe, 1989 (their fig. 2, p. 53, slightly modified.)

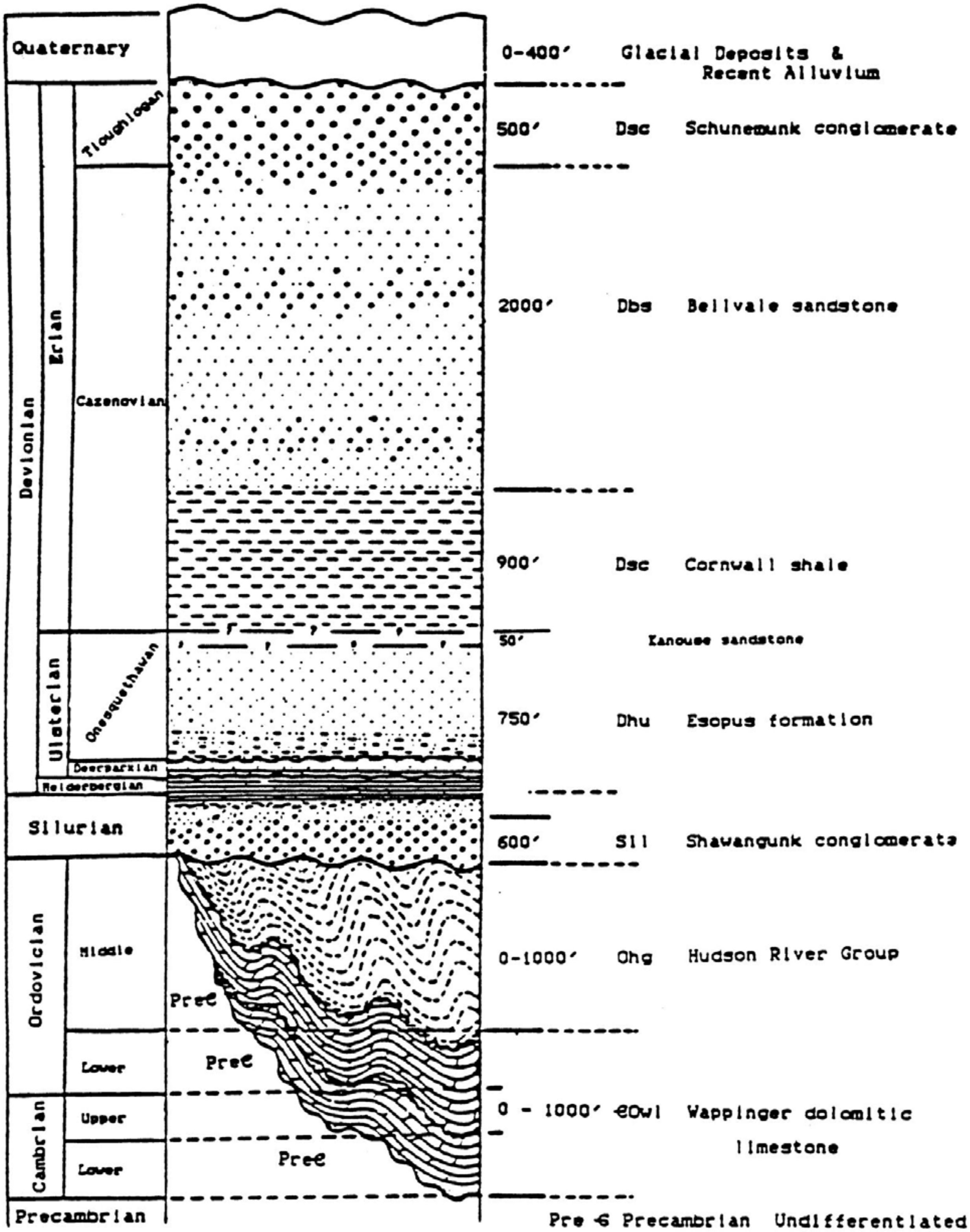
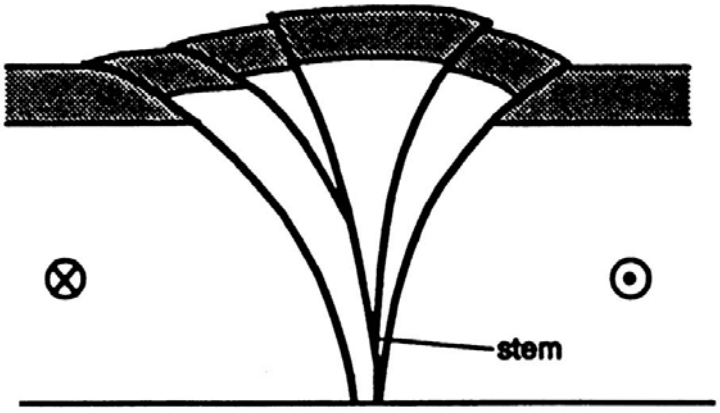
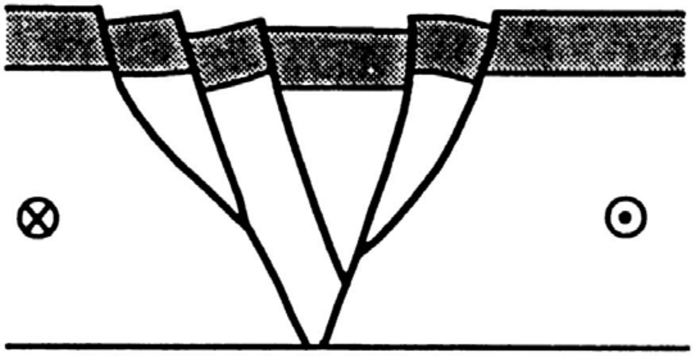


Figure 38. Stratigraphic column in the vicinity of Schunnemunk Mountain, SE New York. (K. R. Kothe, 1960 ms.; used by W. J. Tucci and Robert Kalin, 1989, as their fig. 2, p. 144.)



POSITIVE FLOWER STRUCTURE



NEGATIVE FLOWER STRUCTURE

Figure 39. Sketches of "flower structures," upward-diverging faults associated with a strike-slip fault. (N. H. Woodcock and C. Schubert, 1994, fig. 12.13, p. 259.)

The most-prominent unit of Layer IIIW is the ridge-making Shawangunk Formation (conglomerate and sandstone), of Early Silurian age. Along the northwest side of the Appalachian Great Valley, this formation forms a wall-like ridge in which many parts of the strata dip to the NW. The younger strata share this direction of dip, but at higher stratigraphic levels, the dip becomes less and less. Beneath the Catskill and Pocono plateaus, the strata are essentially horizontal. This NW dip grading northwest into horizontal strata has been taken to by many geologists to mean that the Kittatinny strike ridge marks the NW limit of deformation in the Appalachian chain. Granted the possibility of large-scale thrusts of Late Paleozoic age, then this NW dip may result from a ramp-related anticline and be the NW limb of such a structure. (See Sanders, 1983, Figure 8, p. 176 and p. 177-178; and Figure 27). JES has seen a seismic-reflection profile shot along NY Route 17 in which the NW dips of the Shawangunk Formation terminate abruptly downward and at greater depth, the reflectors are horizontal. (See Figure 28.) JES and CM think that this profile confirms the existence of overthrusts and that the interpretation of the NW dips as part of a ramp-related anticline is correct.

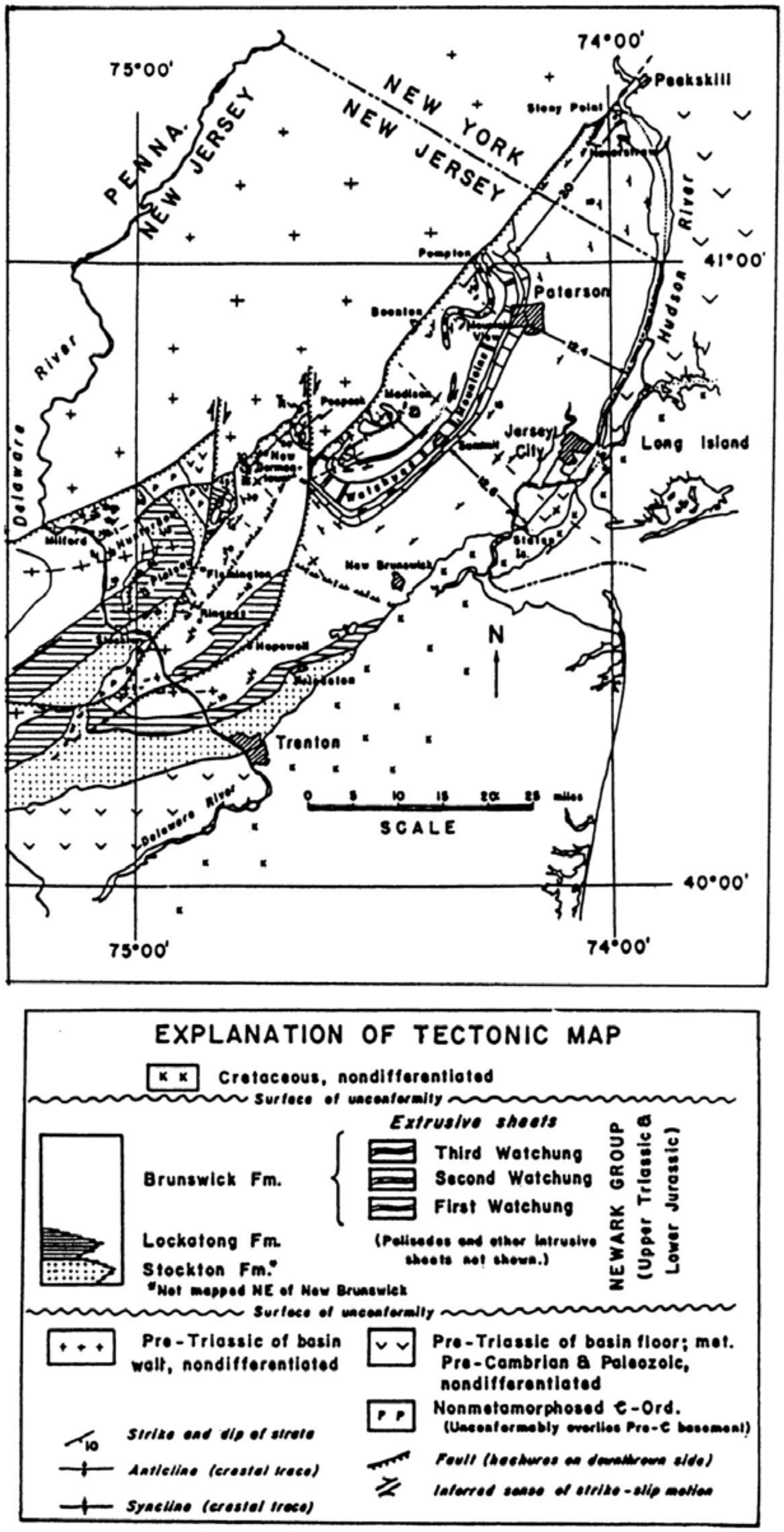


Figure 40. Tectonic map of Newark basin in New Jersey, with Hopewell and Flemington faults shown as displaying significant right-lateral strike-slip offsets, according to JES. If these faults are correctly shown here, then they probably extend to the north, and perhaps curve around to become parallel to the NE-SW trend of the Appalachian structures. On the EXPLANATION, the pre-Olsen stratigraphic usage is shown.

Another noteworthy aspect of the Silurian strata is their thinning toward the northeast (Figure 41). To the NE, Shawangunk Mountain disappears because the basal Shawangunk Conglomerate-Sandstone ends by stratigraphic overlap against what was a comparatively high area on the Silurian sea floor. This former high part of the Silurian sea floor implies that a transverse basement high crosses the Appalachian region, possibly centered on Albany, NY. North of Rosendale, NY, where the Shawangunk Formation is absent, the "big" mountains of the central Appalachians give way to the "Little Mountains east of the Catskills" (Merguerian and Sanders, 1990b, 1994c). Between Rosendale and Albany, the thickness of the Silurian strata is only a few meters. The Devonian strata underlying the Catskill Plateau are virtually in contact with the Ordovician beds.

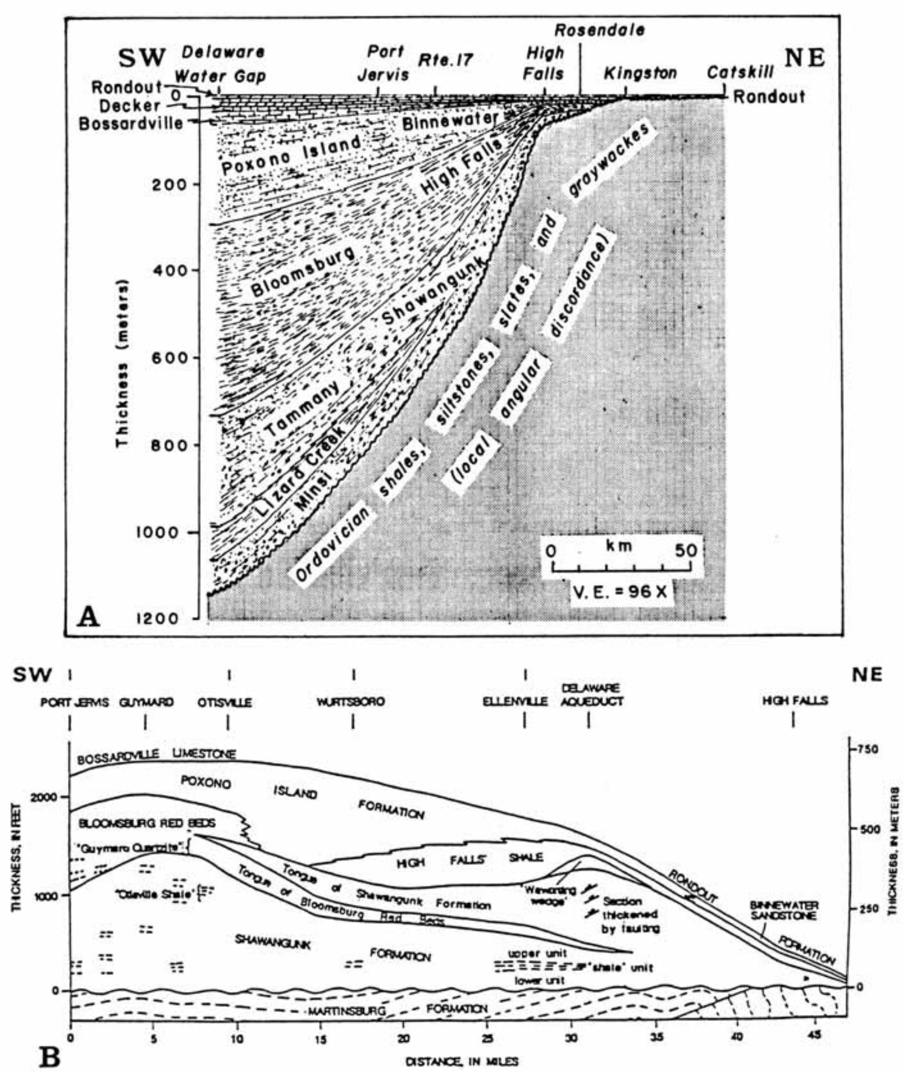


Figure 41. Two contrasting presentations of the northeastward, along-strike thinning of the Silurian strata, Kittatinny-Shawangunk Mountain belt.

A. Capping carbonates shown as horizontal. (J. E. Sanders, in G. M. Friedman, J. E. Sanders, I. P. Martini, and others, 1982, fig. 7. p. .)

B. Relationships shown with base horizontal. (A. R. Prave, M. L. Alcala, and J. B. Epstien, 19889, fig. 2, p. 123.)

Finally, a few words about the paleogeography and environments of deposition. Paleogeographic reconstructions indicate that the Silurian Equator passed through New York State. Moreover, the conditions in the equatorial sea fluctuated within a wide range. At times, great floods of sediment from the S (what is now the E) were transported by streams across fans to deltas and this sediment pushed the shoreline northward. At other times, the sea submerged the alluvial tracts. A notable feature of the terrigenous sediment, especially during the Early and Middle parts of the Silurian Period, was an enormous abundance of quartz, ranging in size from pebbles to silt. Although deep burial doubtless contributed to the dissolution of easily dissolved sedimentary minerals, such as feldspar, it is still remarkable that so much sand-size and coarser quartz was spread throughout such a vast area and to the thickness of many tens of meters. A unique source area undoubtedly existed to provide the quartz-rich parent from which these sediments were weathered and eroded. The identification of this source remains one of the unanswered questions in Appalachian geology. We address this point farther in our Taconic guidebook (Merguerian and Sanders, 1992b). The sheet of Silurian quartzose sand extends unbroken from New York to Tennessee and has been found in the subsurface as far west as eastern Ohio (Figure 42).

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

A point for investigators of such subjects to keep in mind is that within the equatorial tropical zones, the prevailing winds undergo seasonal reversals. This happens as the equatorial zone of rising, heated air (the "thermal equator" or Intertropical Convergence Zone (ITCZ of meteorologists) moves northward and southward with the seasons.

When the ITCZ is at the Earth's Equator, the air moving northward toward it from the Southern Hemisphere constitutes the southeast trades (because of the left-deflection rule of the Coriolis effect in the Southern Hemisphere). However, once the ITCZ has migrated northward away from the Equator, at least some of the winds blowing toward it from the south are no longer in the Southern Hemisphere. Instead, they are in the Northern Hemisphere. Accordingly, as they flow northward toward the ITCZ, they follow the right-deflection rule of the Coriolis effect in the Northern Hemisphere and veer to their right and become southwesterlies. An example is along the Arabian coast, where Arab sailors long ago recognized that they could be blown downwind to India by the southwest winds during May-July, and blown downwind back again at other times. Their term for these reversing winds was "monsoon," which means "season." Not only does the wind shift, but its effect on the water reverses. Thus, the coastal downwelling off Arabia associated with the prevailing northeast winds becomes coastal upwelling during the southwest monsoons (Gentilli, 1967a, b).

In a recent analysis of the sedimentology of the Silurian strata on the western belt (Prave, Alcala, and Epstein, 1989), the direction of currents inferred from dips of the cross strata was found to be bipolar. From this observed bipolarity, these investigators inferred that the reversing currents were the result of tidal action and thus that the environment of deposition had been intertidal. Bipolarity of inferred current-flow directions alone does not necessarily demonstrate that the same currents reversed, as do tidal currents. Such bipolarity could also result from the seasonal reversal of the wind belts, as in the equatorial regions.

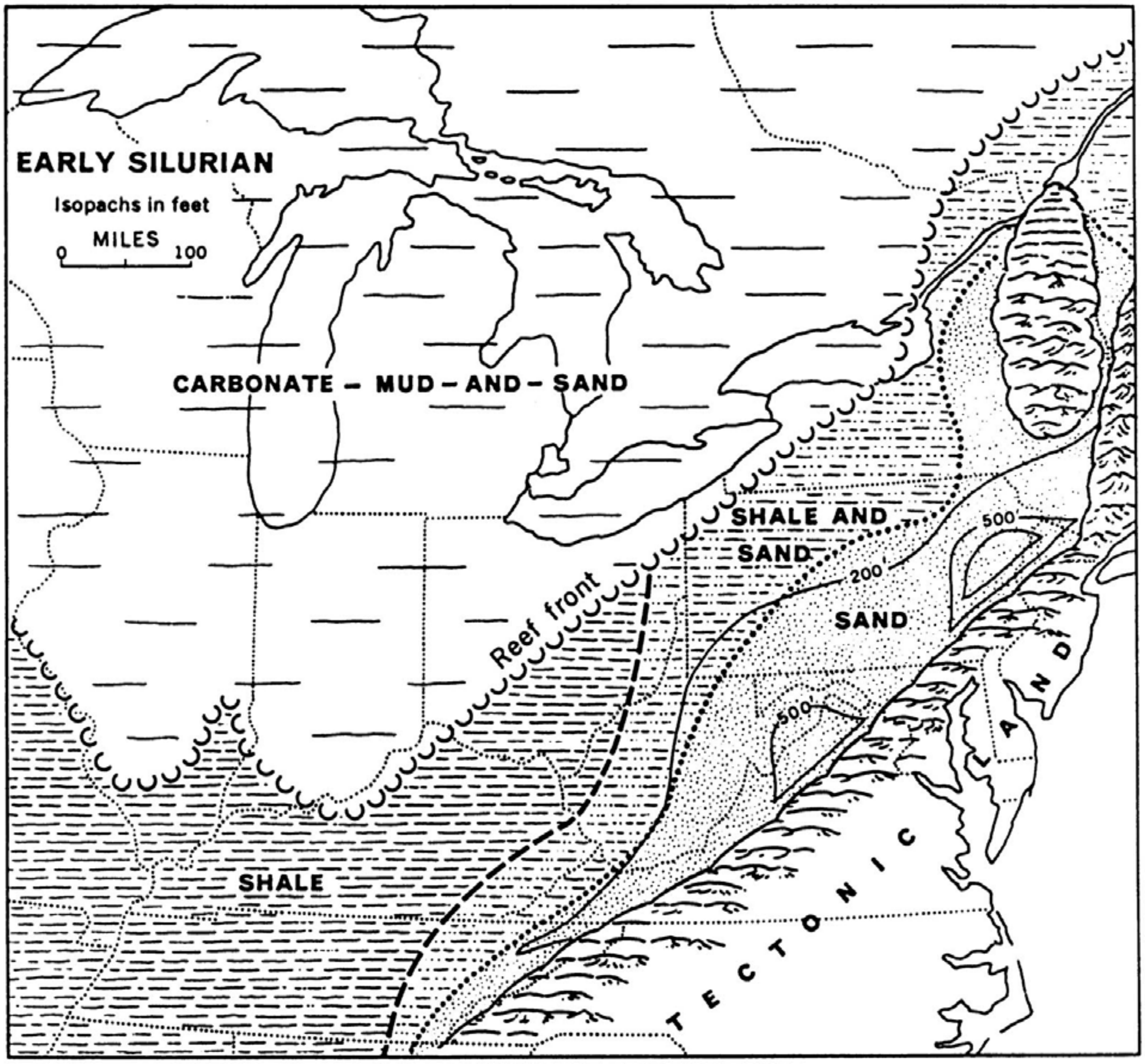


Figure 42. Map of parts of east-central United States showing extent of Lower Silurian sand (now sandstone after deep burial and cementation by quartz) and relationships to mud and reef-carbonate belt. Numbered lines show thicknesses in feet. (G. M. Kay and E. H. Colbert, 1965, fig. 10-12, p. 192.)

Layer V: Newark Basin-Filling Strata

The tilted- and eroded remnants of the Newark strata are exposed along the west side of the Hudson River, from Stony Point south to Staten Island. As shown on the diagonal cut-away slice in Figure 1, the Newark strata generally dip about 15ø to the northwest.

The formal stratigraphic name for the Newark strata is Newark Supergroup. Included are various sedimentary formations, of which the basal unit is the Stockton Arkose. Above it is the Lockatong Formation, the unit into which the Palisades sheet has been intruded. Higher up are other sedimentary units and three interbedded sheets of mafic extrusive igneous rock (ancient lava flows), whose tilted edges are resistant and underlie ridges known as the Watchungs. The age of the sedimentary units beneath the oldest extrusive sheet is Late Triassic. The remainder of the formations are of Early Jurassic age.

The Newark sedimentary strata were deposited in a fault-bounded basin (See Figure 3, p.10, on which the Newark strata are labeled "Triassic Lowlands") to which the sea never gained access. In this basin, the filling strata were deposited in various nonmarine environments, including subaerial fans, streams, and shallow- and deep lakes. Lake levels varied according to changes in climate.

After the Newark strata had been deeply buried, they were elevated and tilted, probably during a period of mid-Jurassic tectonic activities (Merguerian and Sanders, 1993a; 1994a, b; 1995). They were then eroded and truncated to form a surface upon which the Upper Cretaceous- and younger coastal-plain strata were deposited.

GLACIAL DEPOSITS

As mentioned under the description of Layer No. VII, the Quaternary sediments in Table 2, p. 4, glacial deposits include several contrasting varieties. We will be especially interested in the characteristics of till and outwash. Till is a general name for any sediment deposited directly by the flowing ice of the glacier. Typically, till is not stratified and contains a wide range of particle sizes, from boulders to clay. Outwash is a general term for any sediment deposited by water melted from a glacier. Outwash includes such contrasting sediments as stream sands/gravels and lake clays. The key point about recognizing outwash is the stratification that resulted from the action of water.

An important point to be determined in studying a glacial deposit is which way the glacier flowed. Because glaciers create scratches and even large grooves on solid bedrock, it is usually a straightforward matter to infer ice-flow direction. It is along the trend of the linear grooves, striae, and other elongate features. Direction of flow may also be inferred by studying provenance; that is, the source of the particles in the deposits. Because glaciers can transport stones long distances, one commonly finds a collection of glacial particles unlike the bedrock on which the glacial deposits rest. Such stones are known as erratics. If an erratic can be traced to a distinctive source, it becomes an indicator stone. Use of striae and indicator stones shows that glaciers flowed across the New York region from several directions.

The distribution of erratics derived from as far away as the anthractite district in eastern Pennsylvania and pebbles of the distinctive maroon-matrix, white pebble rock in the Green Pond Formation (Lower Silurian--the "Braunschweiger-sausage rock" of the late Barnard biology Professor Donald Ritchie) in the red- brown tills and -outwashes in New York City lends strong support to the interpretation that the striae and other directional indicators oriented NW-SE indicate regional ice flow from that direction, rather than SE deviation locally of a glacier whose main axis of flow was from NNE to SSW.

The stratigraphy of glacial deposits is worked out by noting the relationships among till, outwash, and sediments that have nothing at all to do with a glacier and, in fact, were deposited under a climate regime that is nonglacial. In a coastal area such as New York City, glacial deposits are interstratified with marginal-marine deposits. This has resulted from the relationship between growth of continental ice sheets and the volume of water in the ocean basins. Professor R. A. Daly, of Harvard, once described this relationships between glacial ice and the water of the oceans as one of "robbery and restitution." By robbery, he meant the locking up of the water in the glaciers. By restitution, he meant the return of the water to the oceans when glaciers melted. Although the exact climate settings involved in these changes are not as well known as one might suppose, it has been firmly established that when the glaciers reached their maximum extents, the sea was at its lowest stand, a level around 90 to 150 m lower than now.

The most-critical sections showing the relationships among various Pleistocene glacial deposits are exposed at Croton Point Park, Westchester County, NY. There, a gray till containing erratics of ultramafic rocks from the Cortlandt Complex decayed granitic stones is overlain by a red-brown till that is, in turn, overlain by gray varved lake deposits containing isolated dropstones. Farther north along the shore of the Hudson River, two red-brown tills are separated by red-brown outwash. The upper red-brown till is overlain by a yellowish-brown till shaped into a drumlin having a long axis trending N-S (Merguerian and Sanders, 1990a, 1992c; Sanders and Merguerian, 1991, 1994b).

In addition to ripping up individual fragments from the material over which it passes, a glacier may also deform the strata it over-rides. One of the Pleistocene glaciers profoundly affected some of the Upper Cretaceous strata: it stripped several large thin slabs (up to 0.5 km in one dimension and a few tens of meters thick) away from their pre-glacial positions and incorporated them as great thrust slices in the till, one on Staten Island displaying recumbently folded Cretaceous strata (Sanders, Merguerian, and Okulewicz, 1995a, b).

Another aspect of glacial deposits dear to the heart of those who are Pleistocene geologists is use of sediments to infer the positions of the margin of a melting, retreating glacier. In many places, records of deglaciation are extensive; numerous ice-margin positions during the retreat can be established. The deglacial record in the Wallkill Valley has recently been revised by Connally, Sirkin, and Cadwell (1989). Several glacial lakes left bottom deposits subsequently covered by peat. The flat areas underlain by peat are used to grow onions on a large scale. We will pass many onion fields en route from Warwick to Pine Island. The digging of the drainage ditches in these flat bottom lands has on occasion revealed mastodon bones (Averill, Pardi, Newman, and Dineen, 1980). Numerous sand pits have been opened in the sandy-gravelly outwash.

DRAINAGE HISTORY

Modern rivers are flowing in lowlands some of which have been in existence for hundreds of millions of years, and others of which are only a few tens of thousands of years old. Discussed here are the peculiarities of the Ramapo, Wallkill, and Siluro-Devonian strike-valley drainage networks (including the Delaware River), all of which are of postglacial age.

The headwaters of the Ramapo River are in Central Valley, which occupies the divide between the south-flowing Ramapo River and the north-flowing Woodbury Creek. The headwaters of the Wallkill are southwest of Sparta, NJ. The waters flow northeastward and are augmented by waters from the Shawangunk Kill and other NE-flowing tributaries. East of Rosendale, the Wallkill is joined by another drainage network having headwaters in the Catskills, but flowing northeastward in the Siluro-Devonian strike valley (the Rondout network, whose major tributary from the Shawangunk Mountains is named, of all things, the Sanders Kill). The combined Wallkill-Rondout flow drains into the Hudson River at Kingston. There, it forms a barbed tributary (tributary entering the main stream with the acute angle between them on the downstream side, with reference to the flow direction of the main stream). Barbed tributaries are distinctly rare. The usual arrangement is for the acute angle to be on the upstream side.

JES has not read all the literature on these drainage networks, but comments in blissful ignorance of what predecessors may have thought or proved, that some non-glacial-isostatic neotectonic movements must be involved. The drainage from the melting glacier was generally southward. Moreover, the isostatic rebound from the melting glacier has caused areas to the north to be elevated, thus creating a slope toward the south. If nothing else were at work, then, both the residual effects from the meltwater channels and the isostatic rebound should have established a regional drainage toward the south. How about an active syncline pitching toward the northeast as a mechanism for explaining the direction of the Wallkill drainage?

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

OBJECTIVES

1) To study the four major bedrock units exposed in the trip area. From top downward, these are: Layer V, Newark strata; Layer III, Silurian and Devonian; Layer II, where not metamorphosed; and Layer I, Proterozoic of the Ramapo block-Reading Prong. We will start with the oldest unit and study progressively younger units, but see Layer V only in passing.

2) To study the geologic structure, on scales both large and small, with particular emphasis on features found in the post-Taconian strata.

3) To examine the geologic relationships of the local valley-and-ridge type morphology associated with the downdropped Silurian and Devonian strata of the Green Pond-Bellvale-Schunnemunk belt.

4) To understand the relationship between slaty cleavage and bedding in folds.

5) To learn how to use slickensides to infer direction of relative movement on faults.

6) To note any flow-direction features made by glaciers or left in the glacial sediments.

DRIVING DIRECTIONS

(NYAS to High Point, NJ, via the George Washington Bridge, NJ 17 to Suffern, NJ Route 17A to Warwick, Co. roads to High Point State Park and return via NJ 23 and I-80.)

Turn L on 5th Ave. and drive south to 59th St. Turn R across 59th St. to Broadway and turn R driving northward on Broadway to 72nd St. Turn L and get on the West Side Highway northbound to the GWB westbound exit near 178th St.

To Pit Stop 1: Continue across the GWB past the toll plaza and follow signs to I-80 local, NJ 17. [Arch bridge over deep cut is Jones Road; just beyond on R, the cuts display the contact at the top of the Palisades sheet and contact-altered strata of the Lockatong Formation. Higher ground beyond the Hackensack Meadowlands is underlain by red sandstones and siltstones of the Passaic Formation, the basal member of the Brunswick Group.] Leave I-80 at Exit 69 and follow Route 17 northbound. At Mahwah, NJ, notice Mile Post 25; this is 23.3 mi from the GWB Toll Plaza. In 1.5 mi, notice large new cuts at left and ahead; these are in the Proterozoic rocks along the Ramapo fault (part of new route of I-287). Keep R for NJ 17 northbound. [Cuts along the road starting near the crossing overhead of the NYS Thruway are in the Proterozoic rocks of the Ramapo block.] Pass exit for NY17A on L and continue on NY 17 to Red Apple Restaurant [UTM Coordinates: 568.95E, 4565.5N, Sloatsburg quadrangle]. Pit stop.

To Stop 1: Use caution leaving parking lot; turn L and retrace route to NY 17A, a R turn 0.8 mi from the parking lot. After stop sign, join NY 17A and 210. Cuts on R in 0.5 mi are pullover stop 1. Cuts ahead another mile are "official" Stop 1.

To Stop 2: Continue NW on NY 17A/210. In 1.7 mi, pass Sterling Forest Ski Area Village; many cuts along the way expose Proterozoic rocks. In 1.4 mile, view ahead down the hill into the long strike-valley lowland occupied by Greenwood Lake. The first ridge beyond the lowland is Bellvale Mountain, underlain by Middle Devonian strata. In 2.3 mi, the road crosses a narrow part of Greenwood Lake. Just after the bridge, turn R on NY 71A (NY 210 branches to the L), following the sign for Warwick. In 0.1 mi, turn L on NY 17A. Follow NY 17A uphill past Jarmain Rd. on the R. After big curve to the L, 0.3 mi from Jarmain Rd., pull up and park in the open area on the left. (Walk back down NY 17A to steeply dipping L. Bellvale strata along the road; use caution. View ahead is down the strike valley occupied by Greenwood Lake. Walk back uphill to examine the rocks exposed at the big curve = Schunnemunk Fm.)

To Stop 3: Continue NW on NY 17A (careful in crossing over). In 0.4 mi, pull over to R at Kain Road and parking lot for former restaurant. View ahead (atmosphere willing); walk back uphill to cuts along NY 17A for Schunnemunk Formation and downhill on opposite side of NY 17A for upper Bellvale Formation.

To Stop 4: Turn R leaving parking lot, continue downhill on NY 17A. In 0.2 mi, Proterozoic rocks exposed on L; we have crossed a major fault with Middle Devonian (U. Bellvale) on the SE and the Proterozoic of the Reading Prong on the NW. Lowlands ahead are underlain for the most part by Paleozoic rocks, the Sauk Sequence (Cambro-Ordovician) carbonates and Tippecanoe Sequence (Martinsburg Formation). In 4.1 mi from the outcrop of Proterozoic rocks, in Warwick, jct. with NY 94. Turn R at corner. (20-minute rest stop in Warwick.)

Reassemble in vans and retrace route to jct. of NY17A and NY 94. Continue on NY 94, past cemetery and take first road on R; in 0.2 mi, join Orange Co. Route 1A. In about 1 mile, after passing cuts of the Sauk carbonates, stop at cuts on R of Bushkill Member of the Martinsburg formation, Stop 4.

To Stop 5: Continue toward Pine Island on Co. Route 1A. In about 1 mile, notice hills on R in distance (Mts. Adam and Eve; outcrops of Proterozoic granite). In another 1.2 mi, stop by large cut on R of white rock (=Proterozoic Franklin Marble), the subject for Stop 5.

To Stop 6: Continue toward Pine Island on Co. Route 1A. At crest of hill in 1.3 mi, view ahead to bottom lands underlain by peat and ditched for growing onions. In 0.8 mi, the higher land near Pine Island is underlain by Sauk Sequence (Cambro-Ordovician) carbonates. In 0.3 mi, Pine Island village; Jolly Onion Inn on L. In 0.5 mi, cross Wallkill; 0.3 mi after the bridge, turn R on Co. Route 1 (Pine Island Tpk). In 5.3 mi, junction with 284, road to Westtown. After 3.9 mi, turn L on US 6, direction of Port Jervis. After 1.1 mi, RJ at Smith Corners with Orange Co. Route 35. Follow signs on Mountain Road to I-84. Park by exit ramps. Stop 6 to study Tippecanoe Sequence [coarse middle member (Ramseyburg) of Martinsburg Formation].

To Stop 7: Drive on Mountain Road back to Smith Corners. Stop for Co. 55; cross US 6. In 0.7 mi, RJ Greenville. In 2.4 mi, cross NY-NJ state line; road becomes Sussex Co. 519. In 2.8 mi, turn R on NJ 23. Follow it to NW for 1.1 mi. to entrance of High Point State Park. Pull into first parking lot on R for pit stop and a look at Shawangunk Conglomerate in woods beyond parking lot. Drive to Monument at summit for scenic views and study of Shawangunk Formation.

To Stop 8: On leaving park, turn L into NJ 23. In 7.6 mi, RJ NW of Sussex. Cuts expose mostly Martinsburg Formation or till. Follow NJ 23 to Hamburg, another 5.7 mi to the traffic light at RJ NJ 94. Turn R on NJ 94. In 1 mi, pass roadcut on R, turn R into road at top of hill and park. Walk back to cuts. Upper Cambrian part of Sauk Sequence [Cambro-Ordovician carbonates].

To Stop 9: Turn L on NJ 94, go back to NJ 23 at light in Hamburg; turn R on NJ 23. In 4.5 mi, pass Mile Post 33 on R at Franklin. In 0.6 mi, large cuts in till behind new Franklin Shopping Center. After 6.4 mi, much of it in the Proterozoic (1989-90 NYAS On-the-Rocks Field Trip No. 9, p. 37). pass Mile Post 26 on R. Pass village of Newfoundland. In 5.2 mi from MP 26, pull up on R for anticline in Green Pond Fm., Stop 9.

Back to NYAS: Continue SE on NJ 23. After 6.6 mi, pass more large new cuts in Proteroizoic rocks along Ramapo fault as part of new right of way for I-287, at Pequannock. Continue on NJ 23, to I-80. Join I-80 and return to GWB. From GWB, take Harlem River drive S and local streets to NYAS.

DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

STOP 1- Proterozoic Gneiss Exposures on NY Route 17A, Tuxedo, New York. [UTM Coordinates: 567.8E / 4564.6N, Sloatsburg quadrangle.]

Our first stop today is just a quick stop to examine rocks of Layer I, Proterozoic gneiss of the Hudson Highlands. These gneisses are predominantly felsic; their layering and foliation are distinct and they contain variable percentages of the mafic minerals pyroxene, amphibole, and biotite. Other rock types include thin, dark layers of amphibolite gneiss and discordant bodies of granitic pegmatite. Locally, the pegmatite is internally foliated as well. This indicates that the granitic magma was emplaced before a phase of penetrative deformation had been completed. Ample evidence for granitization comes in the form of wispy pegmatite-felsic gneiss contacts, and partly digested gneissic xenoliths.

Here, the gneissic layers are subvertical and they have been cut by numerous brittle faults. Although CM and JES were not able to determine the relative ages of the faults (at 40 mph), we are convinced that both high-angle- and low-angle faults exist in this exposure. Both of these sets of structures dip eastward. As argued later, and on other On-The-Rocks field trips, the significance of low-angle faults within the Proterozoic rock is that they may be related to major dislocations within the basement (Layer I). The absolute age(s) of such displacement(s) is (are) unknown. Based on regional evidence, the possibilities include: Proterozoic (Grenville), mid- and/or Late Ordovician (Taconic), mid-Devonian (Acadian), Late Paleozoic (Appalachian), and mid-Jurassic. As a first order approximation of the age of deformation, we can use the kind of features formed. For example, ductile-fault textures would have resulted from deformation a great depth and at elevated temperatures (thus possibly the Grenville-, Taconic-, Acadian-, or Appalachian events). By contrast, brittle-fault textures characterize deformation at shallower depth and at lower temperatures (thus possibly indicating Appalachian- and mid-Jurassic events).

The high-angle faults are responsible for major-, abrupt-, lithologic changes across the strike of the Appalachian fold belt. Along some of these faults, rocks of Proterozoic- (Layer I), Cambro-Ordovician- (Layer II), and Siluro-Devonian (Layer III) ages are in structural contact with one another. In the literature, isolated blocks of Proterozoic gneiss have been interpreted both as inliers and outliers. An inlier interpretation would suggest that the isolated hills composed of Proterozoic rocks are erosional remnants (monadnocks) of the basement, now found poking through the Paleozoic cover rocks formerly deposited around them. As pointed out by Offield (1967), however, no coarse detritus from the Proterozoic has been found in the adjacent sedimentary strata, and the formational contacts among the Paleozoic formations do not "wrap around" the Proterozoic blocks. Rather, the contacts are straight and locally show evidence for brittle faulting.

The preferred (at least by Offield, JES, and CM) interpretation of the isolated blocks of Proterozoic gneiss is that they are outliers. That is, structurally transported slices that rest physically above the Paleozoic sedimentary strata. (See Figure 25.) The northwestern margins of the blocks are thus thrust above the Paleozoic cover and the southeastern margins have been cut by steep brittle faults. Based on their orientations, Offield argued that the age of the steep brittle faults may be Mesozoic in age. He also stated that the actual age control on the faults is based on the fact that they cut rocks as young as mid-Devonian. Offield thought that the cross faults (See Figure 25.), which offset the isolated blocks, came about during readjustments when the Siluro-Devonian blocks were downfaulted.

Alternatively, according to JES, these northwest-trending cross structures might possibly be mid-Jurassic strike-slip faults. In the vicinity of New York City, CM has found ample evidence for northwest-trending faults. The movement histories of these faults are complex and include an early component of strike-slip movement. CM suggests that these faults, which are on line with transcurrent faults of the Atlantic Ocean basin, are active today because of readjustments of the oceanic lithosphere during contemporary sea-floor spreading and, therefore, are potential seismically active faults.

STOP 2 - Middle Devonian Strata, eastern crest of Bellvale Mountain. [UTM Coordinates: 560.2E / 4566.3N, Greenwood Lake quadrangle].

Topics: characteristics of steeply dipping graywackes of the lower Bellvale and coarse, quartzose Schunnemunk Conglomerate; plant debris and sedimentary structures in the graywackes; upward-fining cycles in the Schunnemunk; evidence for original top direction of steeply to overturned dipping strata; "technicolor" slickensides; and inferred direction of fault movement.

Our interpretation of the relationships at STOP 2 are based on the results of the 1981 "ad-hoc" Barnard summer geologic "field camp," during which JES instructed a hardy band of 6 (including 3 Barnard junior geology majors) in the fundamentals of field observations and geologic mapping and investigations by Merguerian's legions of structural geology classes from Hofstra University after 1993. The mapping projects started at STOP 2 and progressed northeastward and southwestward along the crest of Bellvale Mountain, with emphasis on three units: the graded graywackes of the lower Bellvale, the coarsely cross-bedded graywackes of the Upper Bellvale, and the quartzose, pebbly Schunnemunk Conglomerate.

What the student mappers discovered was that the lower Bellvale strata along the road are overturned, but are nearly in contact with layers of Schunnemunk Conglomerate oriented N30°E, 74°SE. The dip of both units is nearly the same but the lower Bellvale lithic wackes trend N37°E and dip 66° SE. They exhibit thick cross strata, graded beds, rip-up clasts and plant debris. As noted along the road on the eastern slope of Bellvale Mountain, the lower Bellvale strata are overturned (i. e., "bottoms up") but the Schunnemunk strata are in normal order (i. e., "tops up," or original depositional tops to the SE). Furthermore, the thick upper Bellvale is not present. The SE, overturned limb of this large syncline has been faulted against the right-side-up limb where a brittle reverse fault (oriented N32°E, 68°SE) cuts out some of the strata (the upper

Bellvale). Steep and colorful (the result of chlorite+quartz mineralization on red rock), nearly dip-slip slickensides plunge 62° into N85°E. As we shall see at STOP 3, the upper Bellvale strata, missing from the SE, overturned limb, are present on the NW limb, in normal order underlying the Schunnemunk Conglomerate. An interpretive section through Bellvale Mountain as shown in Figure 44. Compare the section with Offield's (Figure 45).

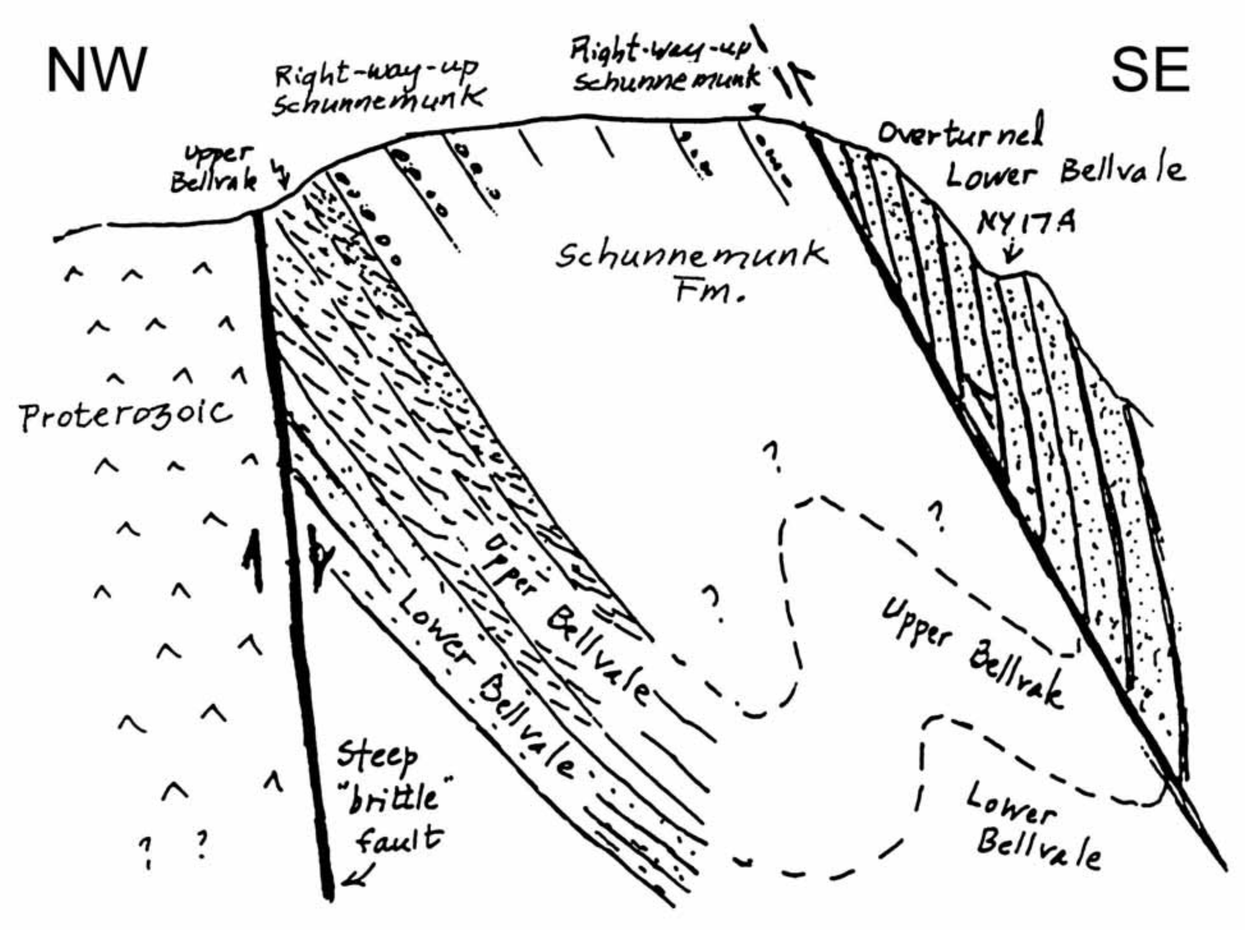


Figure 44. Schematic profile-section through Bellvale Mountain along NY Route 17A, showing inferred thrust fault breaking across the axis of the asymmetric overturned fold and displacing the overturned limb against the normal limb. (J. E. Sanders, based on results of student mapping in August 1981 in the "ad-hoc" Barnard summer field camp based in Monroe, NY.)

We think that the tight, overturned syncline (plus possible complex of two synclines and an intervening anticline) and subsequent reverse fault that broke parallel to the axial surface, shifted the strata of the overturned limb against those of the normal limb. This implies that folding took place above a basement that could yield downward and that the strata being folding were detached from the basement. Such relationships were widespread along the Appalachians during the Late Paleozoic deformation suggesting that the Bellvale folding and overthrusting were part of a regional pattern. The steep fault on the NW side is inferred to be of post-fold, possibly mid-Jurassic, age. The new evidence for reverse faulting across the broken syncline suggests that Offield's passive "drape" hypothesis is not applicable.

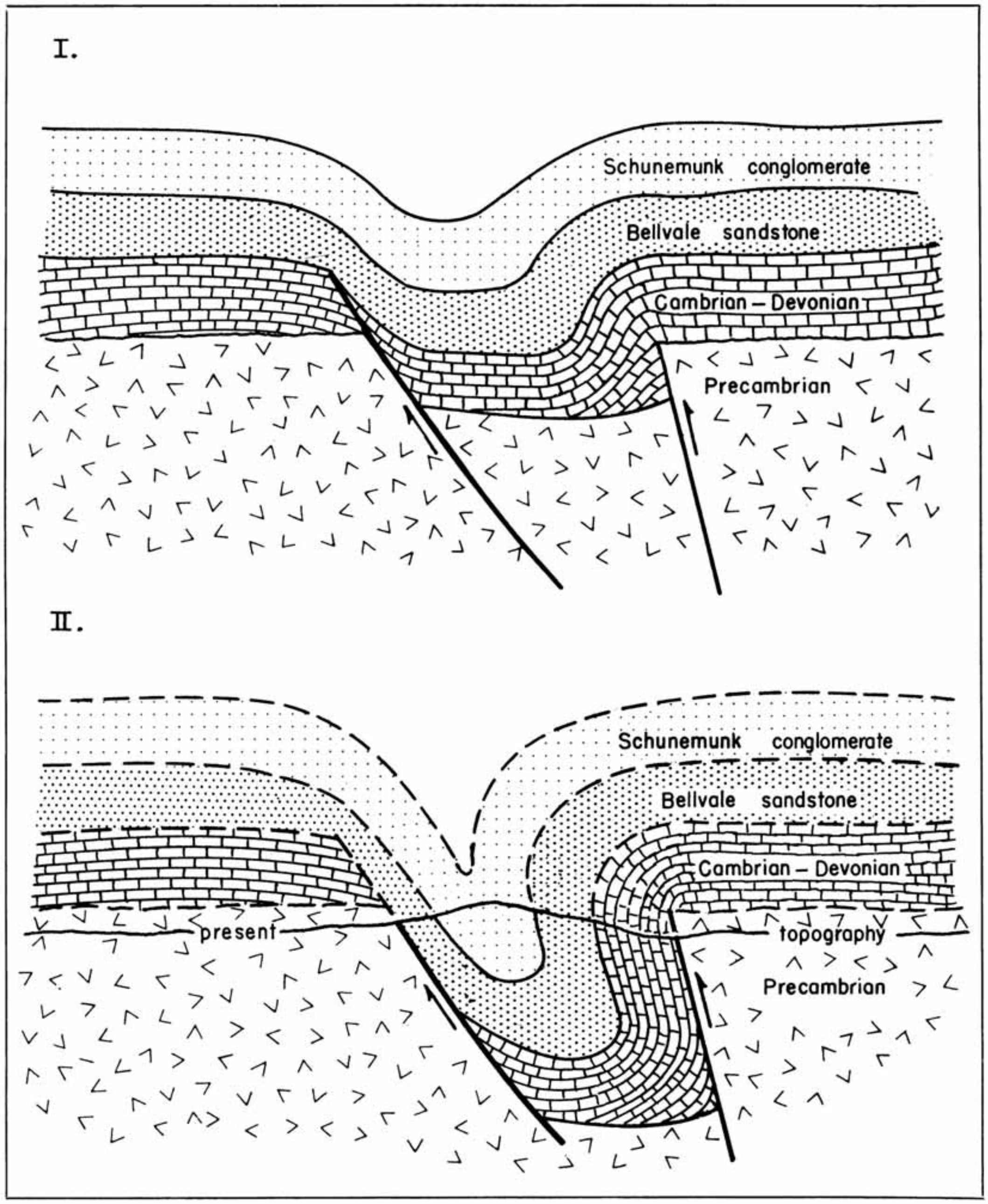


Figure 45. Development of syncline of Bellvale Mountain, NY, according to the interpretation that the fold grew by compression from rising basement blocks on each side. This is the "drape hypothesis" of Offield, who recognized the overturned strata of the SE limb of the syncline, but did not discover the steep thrust fault that has cut out the upper Bellvale. (T. W. Offield, 1967, fig. 33, p. 63; also text on p. 62.)

By hiking southward from Route 17A at the crest of Bellvale Mountain along the Appalachian trailhead, various facies of upper Bellvale and overlying Schunnemunk can be found, often in glaciated exposures. South of the powerline crossing, red shales and pebbly conglomerates dominate the exposures. About 1.5 miles south of the trailhead, notice the panoramic view along the length of the glaciated strike valley now occupied by Greenwood Lake. This is a typical aspect of the Appalachian Valley and Ridge Province elsewhere. Keep in mind that glaciers did not descend south of Pennsylvania thus producing a southward change in the geomorphology of the chain. Such morphology is not common hereabouts except in the Green Pond-Bellvale-Schunnemunk belt of complexly folded strata that include units which are topographically resistant (such as massive sandstones or conglomerates) interbedded with those that are topographically weak (such as shales, and in humid climates, carbonate rocks).

STOP 3 - Schunnemunk Conglomerate and Upper Bellvale Formation, NY 17A, western crest of Bellvale Mountain. [UTM Coordinates: 559.6E / 4565.9N, Greenwood Lake quadrangle.]

At STOP 3, we hope to begin with the scenic panorama to the NW into a region underlain by folded Sauk and Tippecanoe rocks. In view are resistant isolated knobs composed of Proterozoic rocks (klippen or horsts?), the Appalachian Great Valley, Schunnemunk Mountain (to the NE), and the Shawangunk-Kittatinny ridge in the far distance. Compare the distant view with the "bird's-eye" physiographic diagram on the cover of the guidebook (Figure 1).

The rocks north of the birding station here are typical Schunnemunk, with upward-fining cycles starting with pebbles at the base and grading upward into shale. Beddind is roughly oriented N36°E, 65°SE and channels plunge obliquely ~54° into S23°E. Notice the irregular channelized bases of the pebbly layers, the clasts of red slate (as well as of white “Shawangunk?” quartz), and the coarse cross strata. Two cleavages are present here. As usual, the slaty cleavage is best developed in the fine-textured strata. Notice what becomes of the cleavage in the coarser layers.

If time permits, we shall cross the road and walk downslope a short distance to see the Upper Bellvale. This unit usually displays coarse cross strata and irregularly pebbly coarse sandstone or even conglomerate. Just a bit farther downhill are outcrops of the Proterozoic rocks against which the Devonian strata have been downdropped. (This assertion is supported by evidence from slickensides. In light of the possibility that some of the Proterozoic rocks may have been overthrust, an outcrop of the Proterozoic does not necessarily indicate the bottom of everything. Quite the contrary, it may come from the "top," that is, from the block formerly above the overthrust (Merguerian and Sanders, 1989b, 1991a). Such Proterozoic rocks from above an overthrust could well be preserved in a graben, and not represent horsts, as would be the case were no overthrusts involved.)

STOP 4 - Tippecanoe Sequence (Martinsburg Slate), County Route 1, west of Warwick, New York. [UTM Coordinates: 592.8E / 4568.3N, Warwick quadrangle.]

The purpose of this stop is to demonstrate the relationship between slaty cleavage that is parallel to the axial plane of a fold and the bedding, and also to examine the Bushkill Member of the Martinsburg Formation. Notice from the south side of the road that bedding is rounghly horizontal but undulating along the length of the exposure. Bedding strikes N45°W and dips 10°NE while the axial surface slaty cleavage cuts bedding at a steep angle (See Figure 31.) and is oriented N42°E, 90°. The bedding cleavage intersection provides an obvious lineation plunging 10° into N44°E, thus defining the plunge of regional folds. Clearly we are in the axial part of the fold and it must be a syncline as we just drove past older rocks of the Sauk carbonates on the way to this stop and Sauk carbonates are exposed to the west. On the limbs of an isoclinal fold, however, cleavage and bedding may be parallel. On an overturned limb, the dip of the cleavage is less than that of the bedding.

STOP 5 - Franklin Marble (Grenville Proterozoic), Orange County Route 1A, between Warwick and Pine Island, New York. [UTM Coordinates: 551.2E / 4569.1N, Pine Island quadrangle.]

In sharp contrast to the felsic Proterozoic gneisses exposed at Stop 1, the Grenville here consists of massive graphite-bearing carbonate rocks. In fact, this entire exposure might be considered a single crystal of calcite but we suspect that significant heating and recrystallization have taken place. In fact, CM and JES are of the opinion that we are looking at "igneous" carbonate here that was thoroughly molten and then crystallized at depth to form such large crystals (more than 5- to 10 cm in size). At this stop, mineral enthusiasts will be happy to collect beautifully twinned calcite, graphite, quartz, calcic plagioclase, amphibole, diopsidic pyroxene, phlogopite, muscovite, idocrase(?), and a few specimens of red-colored idontknowite and leverite. These minerals are typical of skarn deposits (contact-metamorphic rocks). If the skarn interpretation is correct, then a buried intrusive lurks in the vicinity.

These massive carbonate rocks lie along strike with and thus are considered to be correlative with the massive Franklin Marble and identical marbles exposed at Sparta, New Jersey. Likewise, their mineralogic composition is identical with Grenville-aged Proterozoic marbles mapped throughout the Adirondack massif of northern New York State. Many of you apply lime to your lawns from the Limecrest Quarry which is located in this marble belt (look for the Limecrest trademark next time you shop!).

Nearly all mineral collectors are very familiar with the mineral deposits of Franklin-Sterling Hill, which boast about 400 species of minerals, many of which are not found elsewhere in the world. Thus, these areas contain roughly 20% of ALL the minerals known to science! Of additional interest, nearly sixty of the Franklin-Sterling Hill minerals are wildly fluorescent and phosphorescent under the influence of both short- and long-wave ultraviolet light. The Franklin Museum (part of our next On-The-Rocks trip, No. 37!) offers a spectacular display of the fluorescent minerals and an opportunity to collect minerals from a mine dump site. Long known as a source for zinc, iron, and manganese, the "mines" were first found by Dutch settlers in the 1600s, and possibly earlier by aboriginal diggers. Price wars with the Japanese and other foreign markets resulted in the closing, in 1986, of the last operating "Franklin" mine, in Ogdensburg, New Jersey. A rich history and mineralogic discussion of the Franklin district can be found in Palache (1935) and Frondel (1972).

Because the Highlands gneisses are now situated as much as 9,000 feet higher in elevation than the basal Proterozoic gneisses encountered in the Middletown well, Offield (1967) argued that significant uplift to the east has occurred to allow the Hudson Highlands Grenville basement rocks to become exposed. CM argues that we may be viewing totally different

"Grenvillian" basement terranes that may, in fact, have been duplicated along low-angle thrusts early in their geologic histories. CM would thus separate the thick marble-rich Grenville Proterozoic belt as found through Franklin and Sparta, New Jersey, from the easterly, dominantly volcanogenic and plutonic Grenville basement as exposed in the Pochuck-Hudson-Fordham belt. As such, we may infer a major buried thrust fault between these belts as thus have evidence for regional displacement of eugeosyncline over miogeosyncline in the basement Proterozoic rocks.

STOP 6 - Coarse-textured Tippecanoe Sequence - either the Ramseyburg (M. Ord.) or the High Point (U. Ord.) Members of the Martinsburg Formation. Cuts in Ramps at I-84 interchange at Mountain Road and Smith Corners. [UTM Coordinates: 532.3E / 4579.1N, Unionville quadrangle.]

At STOP 6, we approach the NW side of the Appalachian Great Valley and its bounding strike ridge underlain by NW-dipping Lower Silurian conglomerate/sandstone. Along this side of the Great Valley, the dips of Ordovician and Silurian strata typically are the same; we are outside the belt of Taconian folds.

The coarse Martinsburg strata here display the features of what geologists refer to as a "flysch." The coarse layers commonly show grading; their bases are sharp and may display indications that the current which deposited the coarse sediment interacted with the muddy bottom over which it flowed. The various features found on the bases of such coarse layers are known as "hieroglyphs" or sole markings. One common kind of current mark is a flute, which is a "streamlined" rounded, asymmetric feature having a deeper pointed end on the upcurrent side and that flares out and becomes shallower on the downcurrent side. (See Figure 17.) Flutes were scoured out of the underlying cohesive sediment, but we most always study them as relief features (counterparts or molds--not "casts" as geologists who are not rigorous in their use of terms have been known to call them) on the bottoms of the overlying sandstone. This follows from the fact that the sand becomes cemented and thus holds its shape, whereas the silty-clayey layer crumbles and is easily eroded, thus not preserved.

See how many features you can find that were made by currents, either now preserved as counterparts on the bases of the sandstone beds or within them, and what conclusions you can draw about the direction of flow of the currents on the upper Ordovician sea floor.

STOP 7 - Shawangunk Formation, High Point State Park, New Jersey. [UTM Coordinates: 528.35E / 4574.25N, Port Jervis quadrangle.]

STOP 7 is another rocks-plus-scenic-vista locality. The Shawangunk and underlying Martinsburg here have been closely folded together, an arrangement that is not typical of the monoclinal strike ridge to the NE and SW. [See Fink and Schuberth, 1962, for a geologic map and discussion of the structure here (Figure 48) and Drake, 1991, for the description- and naming of the High Point Member of the Martinsburg Formation.] Similar relationships were found by Merguerian's Fall 2004 Structure class at Sunrise Mountain. (Stokes Forest Trip). Our visit to High Point will be too brief to enable us to appreciate the complexity of the folds. Our purpose is to examine the massive sandstone/conglomerate and to relate this resistant formation to its topographic expression.

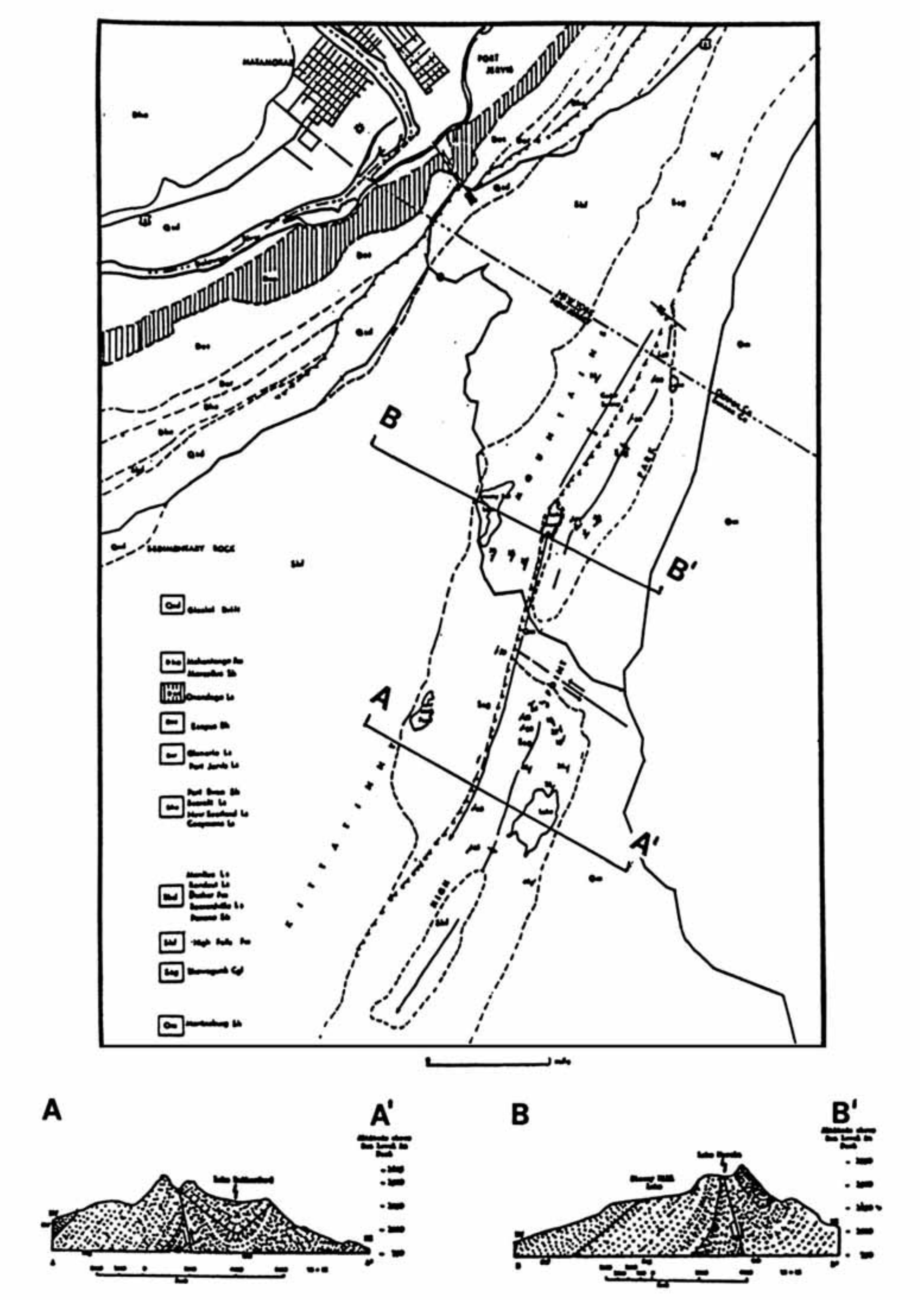


Figure 48. Geologic map and profile-sections, High Point Park and vicinity. These drawings have been much reduced from their original sizes; the scale bar at the bottom of the map marks one mile; the scales on the profile-sections are in feet. The horizontal scale of both profile sections has been changed to make it the the same as that of the map; both drawn with vertical exaggeration x4. (Sidney Fink and C. J. Schuberth, 1962; map, Pl. 6; sections, Pls. 2 and 3.)

STOP 8 - Upper Cambrian part of the Sauk Sequence (Cambro-Ordovician carbonates). Roadcut along NJ Route 94, Hamburg, New Jersey. [UTM Coordinates: 534.30E / 4455.45N, Hamburg quadrangle.]

The features to see here include the alternating coarse-fine layers and the characteristics of each, plus their mutual interpenetration along stylolite seams and the chert. Layers that consist of original sand-size sediment contain quartz, intraclasts of the former lime mud, and ooids. Cross laminae are common. The finer-textured layers are well laminated. Algal stromatolites characterize certain layers.

The repeated pattern of couplets of coarse- and fine layers has been interpreted as being the result of upward shoaling from a subtidal environment to an intertidal/supratidal environment. The pattern of sedimentation is thought to have been controlled by an abrupt submergence (relative rise of sea level), after which the shore prograded seaward and built up shoals or even mudflats. In the "deeper" waters (only a few meters' depth), the sand-size carbonate sediment was deposited. As shoaling proceeded, mud took over. The repetition of the sand-mud pairs implies many episodes of deepening and subsequent progradation to spread out the mud. In the modern language of sequence stratigraphy, each product of a rapid deepening and subsequent progradation forms a parasequence. (See discussion in Friedman, Sanders, and Kopaska-Merkel, 1992)

STOP 9 - SE-vergent anticline in the Green Pond Formation, SE of Newfoundland, NJ. Roadcut in the median of NJ Route 23. [UTM Coordinates: 547.5E / 4542.8N, Newfoundland quadrangle.]

This splendid exposure enables one to examine the crest of an anticline that is totally accessible. Trace the layers carefully and see if they are as continuous as they might seem to be. Notice the direction of asymmetry of the folds; the steep limbs are on the SE and the gentler limbs on the NW, just the opposite of most Appalachian folds. A photograph of this exposure appears in the article Molly Vaux (1983) wrote for Columbia (The Magazine of Columbia University) after going along on some of JES's Columbia geology-class field trips. Where she got the idea that the glaciers had anything to do with this fold, JES does not know (but this glacial-origin idea was expressed in at least one student report handed in before Molly discussed the idea of going on the trips!)

This area is part of the Green Pond outlier; a geologic map is shown in Figure 46. As can be seen from this geologic map, the width of the outcrop of the Green Pond belt increases so that all the strata from the Green Pond to the Schunnemunk are present. The wider outcrop belt also coincides with the localities in which the basal Silurian cuts across the older Paleozoic strata to rest on the basement (Figure 47).

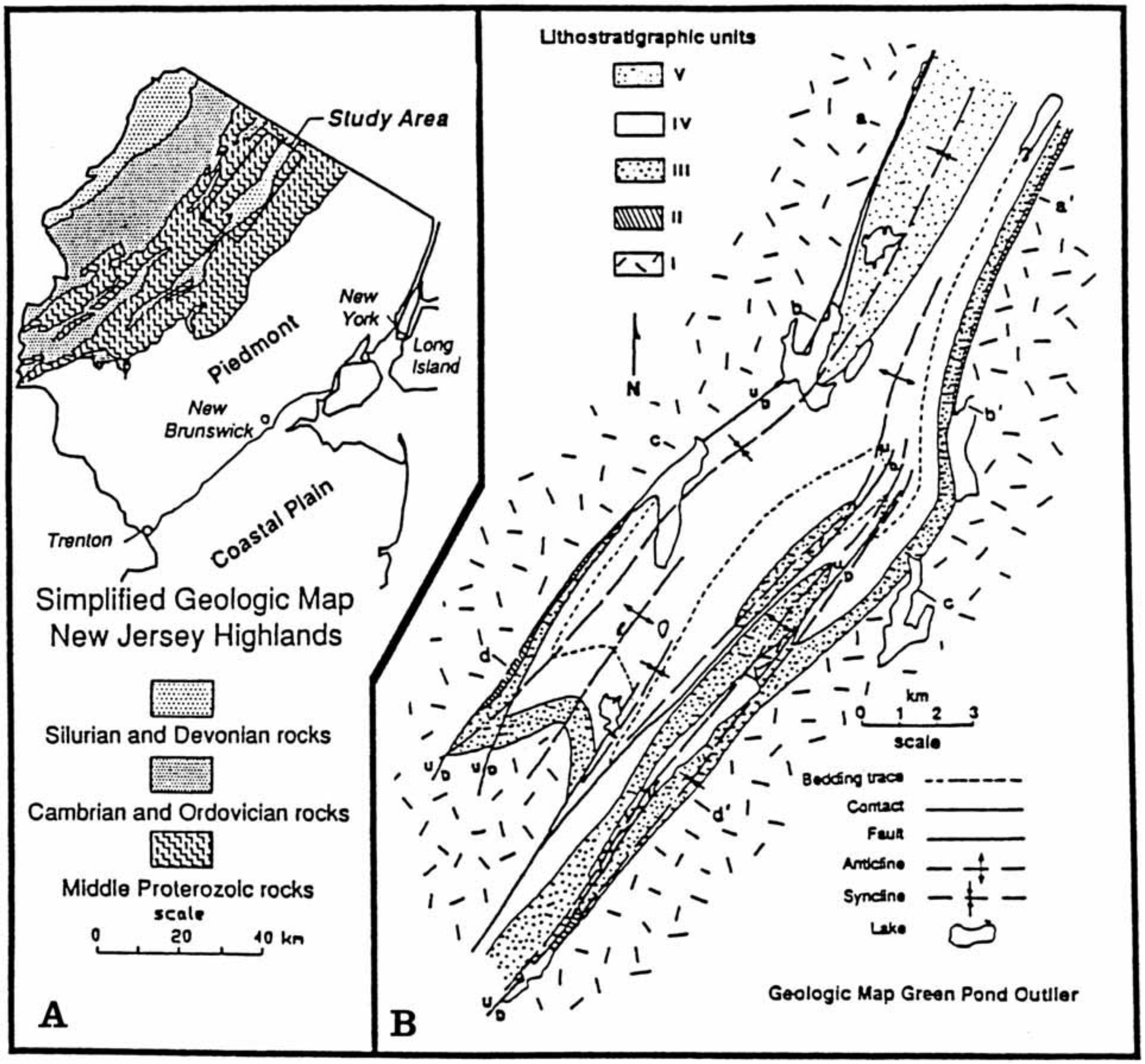
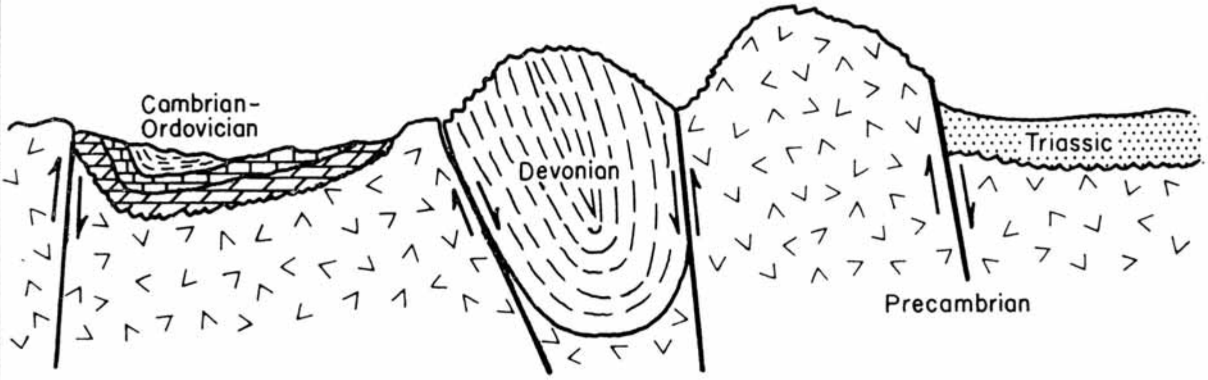


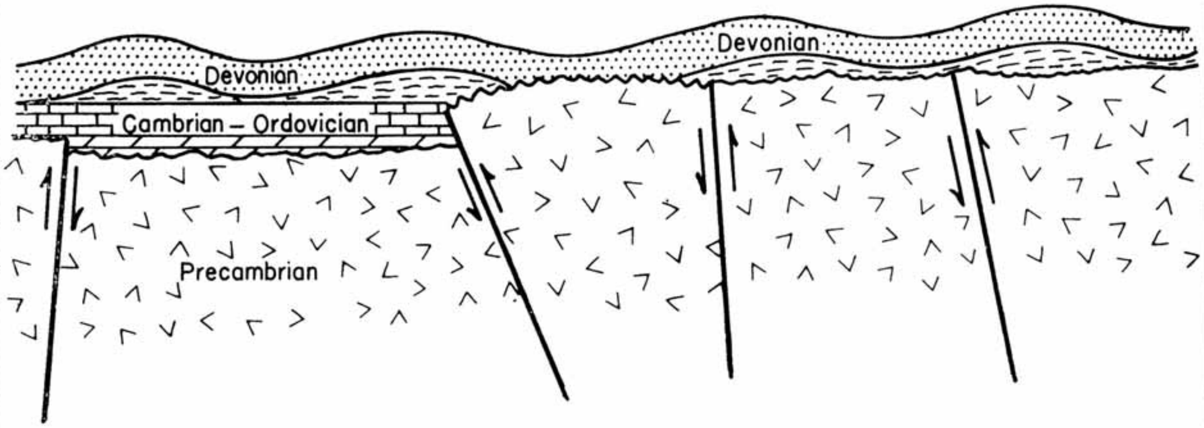
Figure 46. Geologic map of Green Pond outlier, NW New Jersey. (J. P. Mitchell and R. D. Forsythe, 1989, fig. 1, p. 52.)

A. Sketch map of Appalachians in New Jersey.

B. Geologic map. Units shown by Roman numerals are defined in Figure 12, p. 24.



B. Triassic deformation along the same lines; note reversals of movement sense owing to response to broad upwarp.



A. Pre-Triassic configuration; arrows indicate probable Allegheny, Acadian, and Taconian movement sense, which differed from inferred Precambrian movement sense.

Figure 47. Possible stages in development of Green Pond belt. (T. W. Offield, 1967, fig. 40, p. 68; also text, p. 67).

ACKNOWLEDGEMENTS

JES thanks Terry Offield, of the US Geological Survey, for conducting such instructive "cook's tours" of this region for JES in the early 1960s, while Offield was completing his field mapping of the Goshen-Greenwood Lake area. JES is also obliged to the participants in the 1981 field camp for their contributions to the geologic mapping of the northern end of Bellvale Mountain and Mr. Victor F. Tomasso, President of VAB, Inc., Farmington, CT, for financial support of the field studies. Mr. Russell Such, of Monroe, NY, introduced JES to many of the geologic features in the Monroe area and has assisted in many ways.

We also thank Matt Katz and his Executive Assistant, Marcie Brenner of the New York Academy of Sciences for their logistical support and the assistance of the staff at Duke Geological Laboratory.

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

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

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

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

LAYER VII - QUATERNARY SEDIMENTS

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

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IIA [W] - SAUK SEQUENCE

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

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

LAYER IIA [E] - TACONIC SEQUENCE

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

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

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

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

LAYER I - PROTEROZOIC BASEMENT ROCKS

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

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

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

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

In New Jersey and Pennsylvania rocks older than the Franklin Marble Belt and associated rocks include the Losee Metamorphic Suite. Unconformably beneath the Losee, in Pennsylvania, Proterozoic X rocks of the Hexenkopf Complex crop out.
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Table 03 - Silurian and Devonian formations near Highland Mills, NY
(Boucot, Gauri, and Southard, 1970)

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

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