DUKE GEOLOGICAL LABORATORY

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TRIPS ON THE ROCKS

Guide 14: Stokes State Forest, New Jersey

Trip 17: 19 May 1991; Trip 35: 20 May 1995

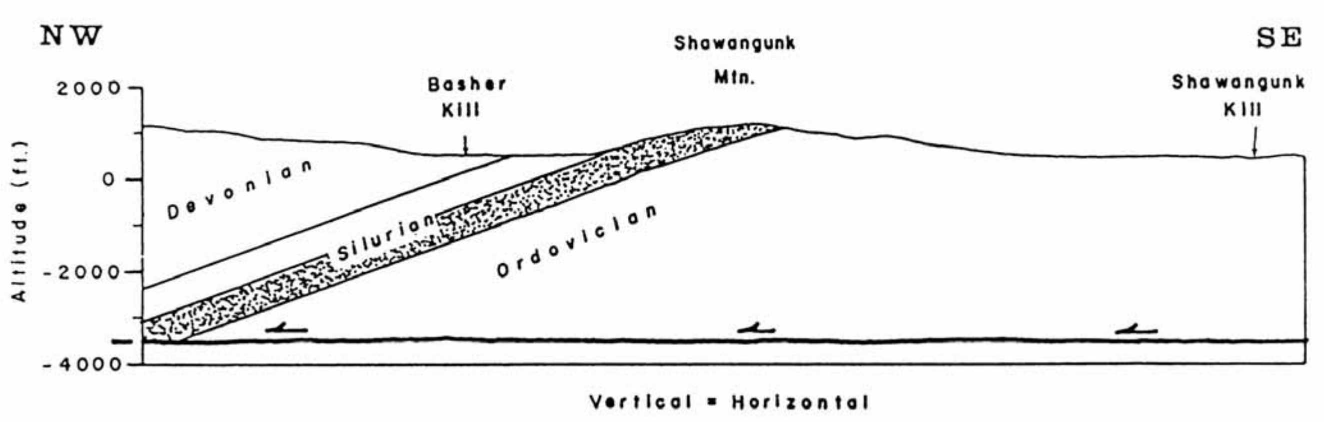

Figure 1 – Profile section across the Shawangunk ridge based on seismic data showing northwest-dipping strata abruptly truncated against a horizontal surface.

Field Trip Notes by:

Charles Merguerian and John E. Sanders

CONTENTS

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Guide 14: Stokes State Forest, New Jersey

Trip 17: 19 May 1991
Trip 35: 20 May 1995

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

INTRODUCTION

Trip 35 takes us to Stokes State Forest in New Jersey, a lovely site on Kittatinny Mountain, which forms the northwest boundary of the Appalachian Valley and Ridge Province (Figure 2). Kittatinny Mountain is a strike ridge in which the thick, resistant Shawangunk Formation (Lower Silurian) dips NW toward the Pocono-Catskill Plateau, which adjoins the Appalachians on the NW. Today's trip will focus on three general problem areas of Appalachian geology: (1) the kinds of faults present particularly among the major morphotectonic belts (are they normal? low-angle thrusts? or of the strike-slip variety?); (2) effects on sedimentary strata of deformation; and (3) the possible age(s) of post-Grenville episodes of deformation.

Our objective is to view these problems in a plate-tectonic context. But in order to do that, we need to summarize the geologic relationships that have been demonstrated, even if such demonstration was presented by geologists who had never heard of plate tectonics. In other words, our summary includes all of what we regard as the significant contributions, whatever their dates of publication. We do not stigmatize our sagacious predecessors simply because they antedated 1965.

We highlight these three special subjects in appropriate sections under the heading of GEOLOGIC BACKGROUND. The major heading in this section include Physiographic Setting, Bedrock Units, Geologic Structure--A Primer, Structural geology of Northwestern New Jersey, Layer VII: Quaternary Sediments, and Drainage History. Other first-order headings include OBJECTIVES, LIST OF LOCALITIES TO BE VISITED, ROAD LOG AND DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS"), ACKNOWLEDGEMENTS, and REFERENCES. Tables and figures referred to in the text follow the reference section.

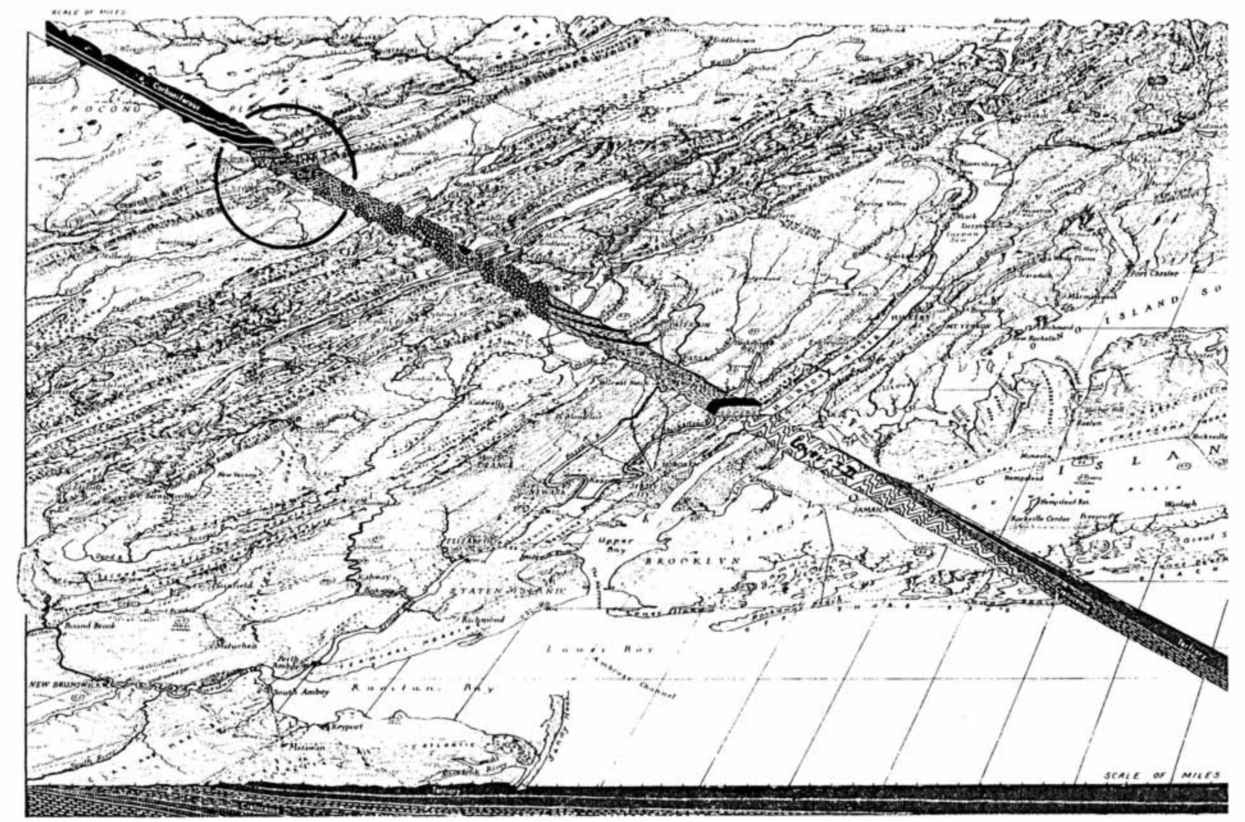


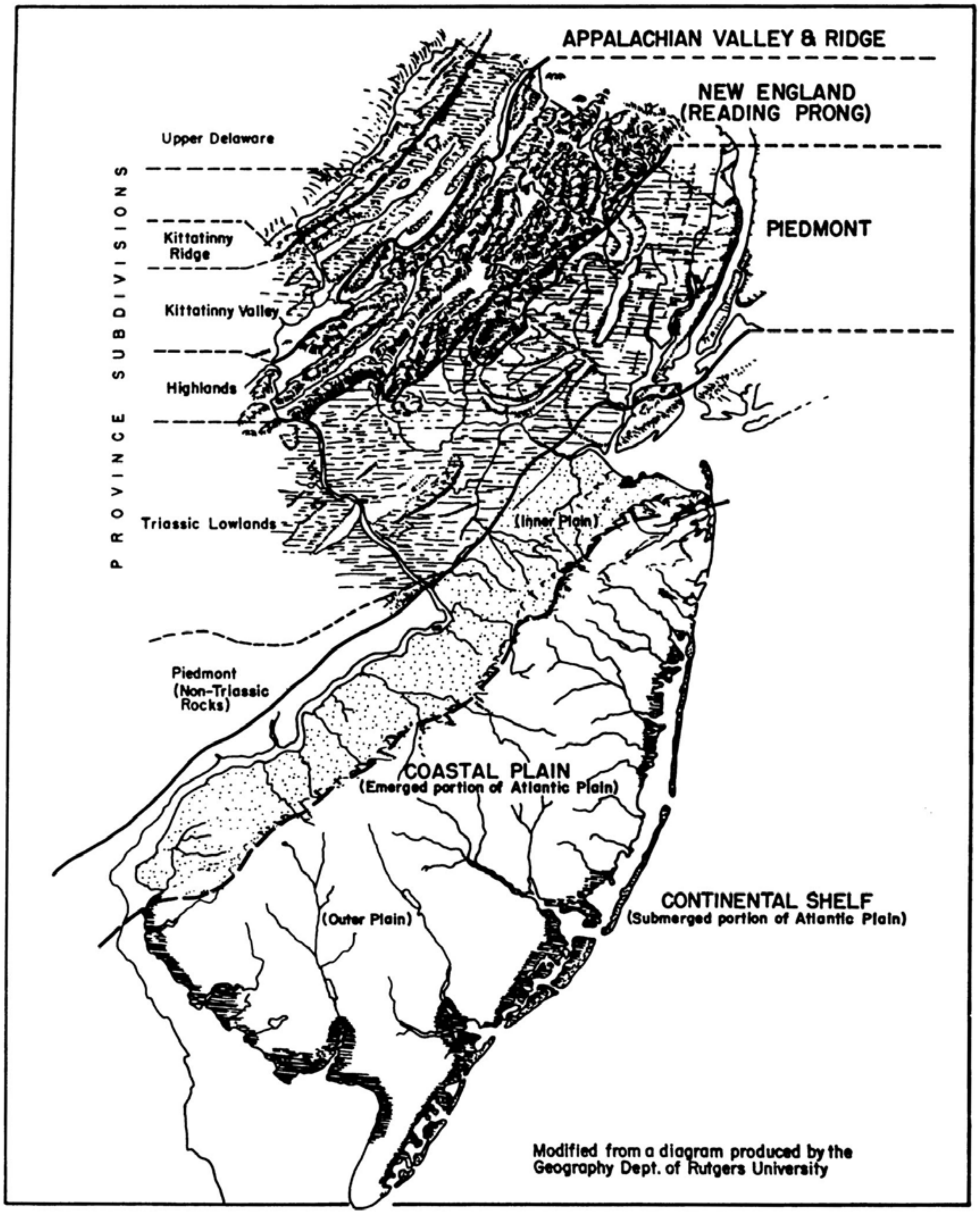
Figure 2. Oblique bird's-eye-view physiographic diagram of the Appalachians, Newark Basin, and Atlantic Coastal Plain [NY, NJ, PA], with vertical slice oriented NW-SE to show geologic structure. (E. Raisz).

GEOLOGIC BACKGROUND

Under this heading, we discuss the Physiographic Setting; Bedrock Units; Geologic Structure, with major subheadings of Low-angle Thrusts, Effects on Rocks of Deformation, and Determining Age of Deformation; Structural Geology of Northwestern New Jersey; Pleistocene Glacial Deposits; and the Drainage History of the area that our field-trip route crosses.

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 New England Upland-Manhattan Prong-Piedmont (Figure 3). Today, we focus on the Appalachian Valley and Ridge Province and vicinity, specifically the boundary between the Appalachian Great Valley and the Appalachian Plateau (here, the Pocono Plateau). Refer back to Figure 2 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.



Modified from a diagram produced by the Geography Dept. of Rutgers University

Figure 3. 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 4; also See Figure 2.) 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, a basal substrate of Proterozoic 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 open folds whose axes trend NNE-SSW. Erosion of these folds has produced a landscape of elongate ridges and -valleys. The ridges are underlain by gneisses, schists, or quartzite, and the valleys, by a thick carbonate unit, the Inwood Marble.

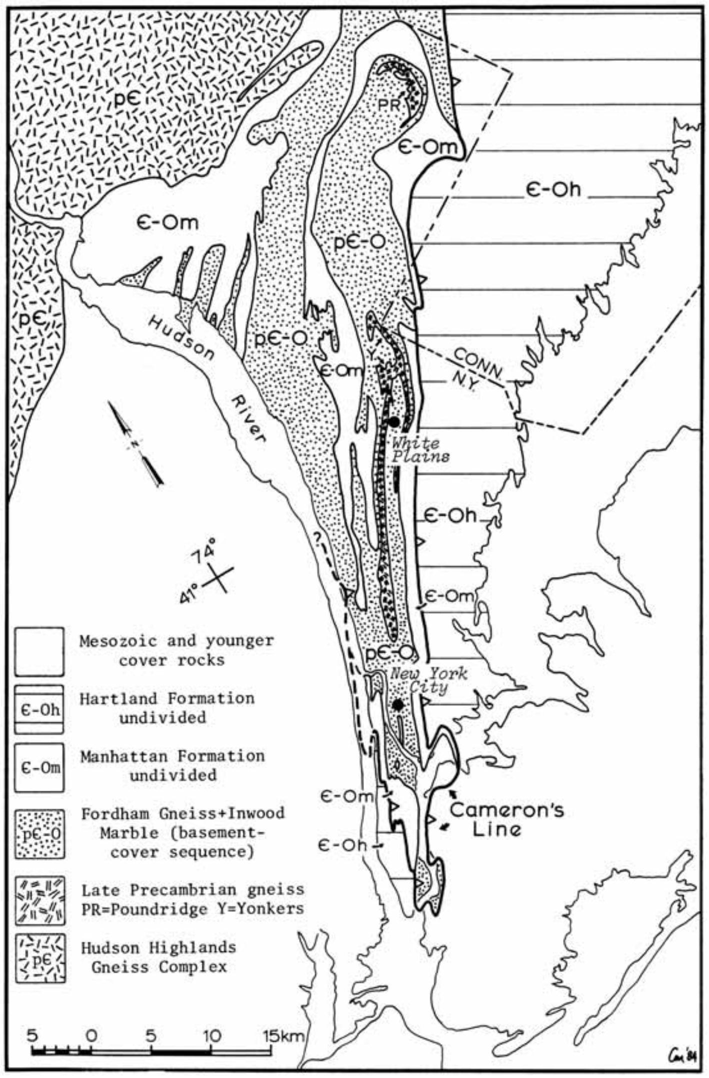


Figure 4. Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted. (Douglas G. Mose and Charles Merguerian, 1985, fig. 1, p. 21.)

Newark Lowland

The Newark Lowland refers to the territory underlain by the Newark basin-filling strata. These strata, originally horizontal, now dip more-or-less uniformly NW about 12°. (See cutaway slice across middle of Figure 2 and Figure 5.) 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 four 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).

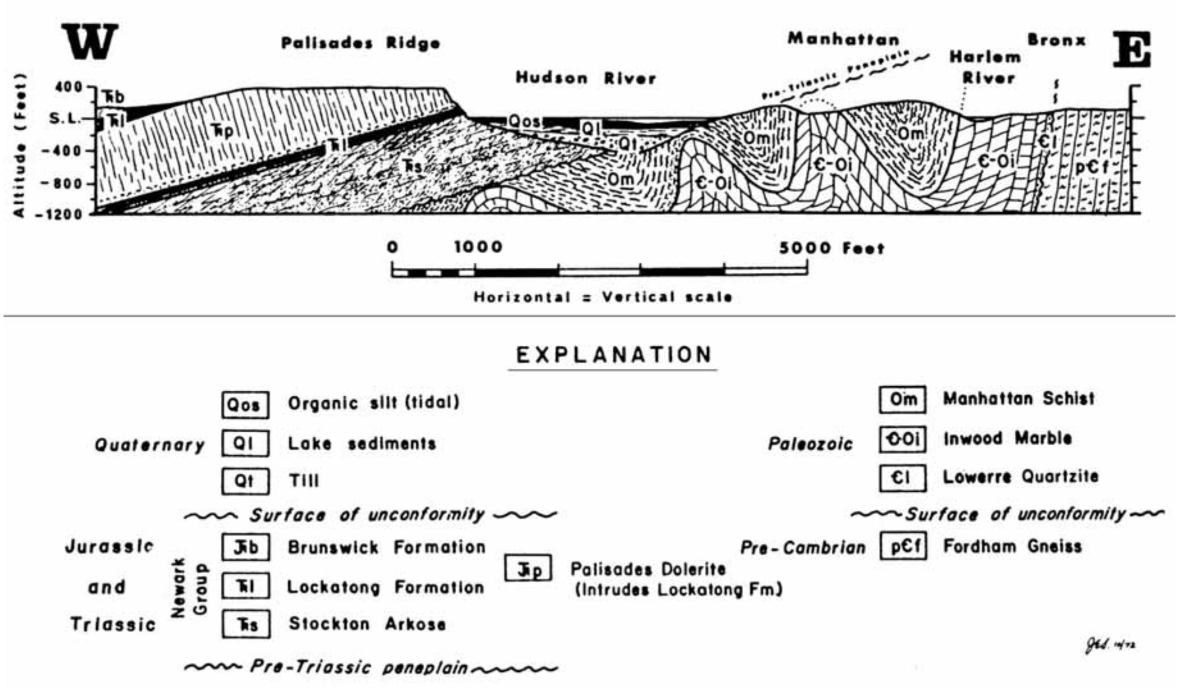


Figure 5. Profile-section across Hudson River at George Washington Bridge. Topography from U. S. Geological Survey Central Park 7.5-minute quadrangle. (J. E. Sanders, 1974a, fig. 3, p. 11.)

The sedimentary rocks generally underlie lowlands that have been blanketed by thick 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 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 faulted margin of the Ramapo Highlands. 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.

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 2.) The highlands are underlain by resistant Proterozoic rocks, mostly various gneisses, but locally including 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 2, 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. (See section entitled Geologic Structure--A Primer for definitions of horst and graben.) Collectively, these highland areas 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 displaced en masse over the Paleozoic rocks along one or more low-angle thrusts (Figure 6; See also section entitled Geologic Structure--A Primer.), the subject of the regional relationships of the rocks in northwestern New Jersey has been unsettled. We discuss the implications of Isachsen's idea in a following section entitled Structural Geology of Northwestern New Jersey.

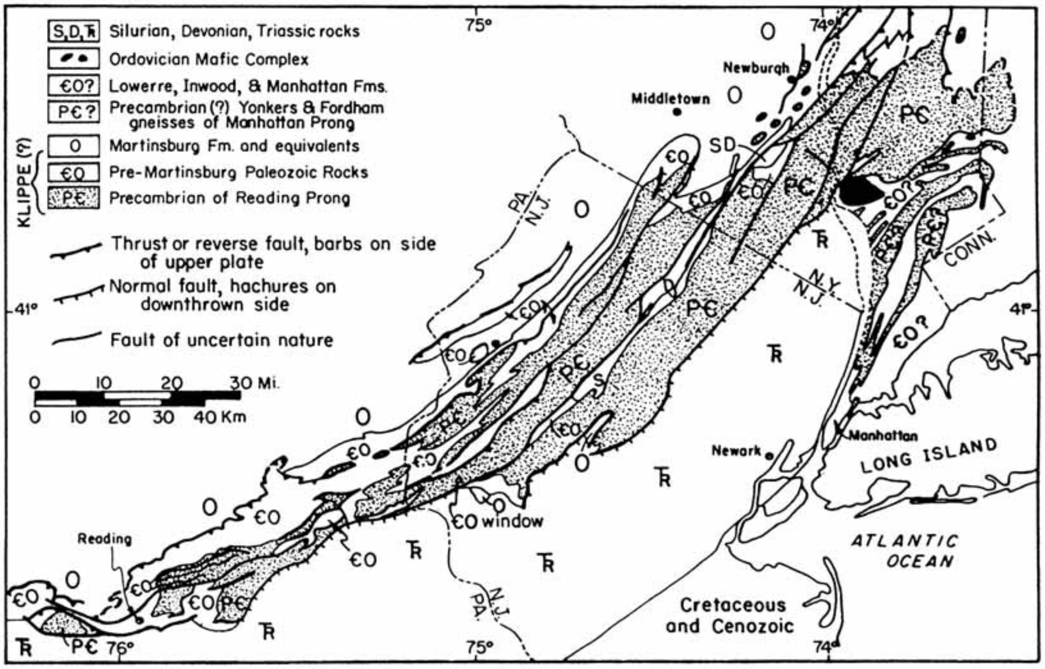


Figure 6. Sketch map showing extent of Reading Prong klippe [stippled areas]. (Yngvar W. Isachsen, 1964, fig. 5, p. 821.)

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 disposed in large folds (plunging anticlines and synclines). Deep erosion of these folded strata has created a pronounced linearity to the landscape consisting chiefly of elongate valleys and elongate ridges. Resistant formations, usually of sandstone, quartzite, or metaconglomerate underlie the ridges. Weaker formations, usually shales or carbonate rocks, underlie the valleys (Figure 7). Folds are not the only major geologic structural features found in this province; low-angle thrusts and high-angle faults are also present.

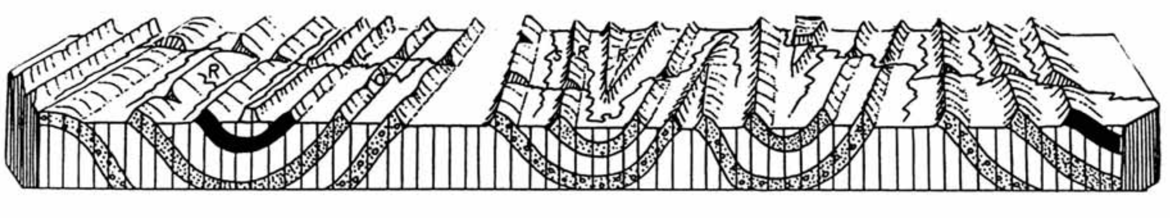


Figure 7. Schematic block diagram through eroded anticlines and -synclines showing how resistant layers form linear ridges and weak layers, linear valleys. The relationships shown here are common in the Appalachian Valley and Ridge Province of central Pennsylvania. (A. K. Lobeck, 1939, fig. on p. 588.)

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 7.)

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 the 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. Stokes State Forest is situated on Kittatinny Mountain.

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 local 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, 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 physiographic boundary between the Appalachian Valley and Ridge Province and the Appalachian Plateau.

BEDROCK UNITS

As usual, when we begin a trip from the New York Academy of Sciences, it is our habit to express a few thoughts about the rocks beneath our van tires. We shall encounter representatives of Layers I and II (Table 2) in two distinctive geographic- and geologic settings. Accordingly, we discuss these layers under two subheadings.

Layers I and II of Manhattan Prong

Originally, the New York City strata of Early Paleozoic ages were, in part, deposited on the complexly deformed sequence of layered feldspathic- and massive granitoid gneiss, amphibolite, and calc-silicate rocks of uncertain stratigraphic relationships known as the Fordham and Yonkers Gneiss (Layer I). These complexly deformed rocks are of Proterozoic age, but can be assigned to the U. S. Geological Survey's alphabetical-letter designation scheme of Proterozoic rocks. Present in SE New York are representatives of Proterozoic Y and Z. These are inferred to represent the ancient pre-Paleozoic continental crust of proto-North America.

Early in the Paleozoic Era, this region became the trailing edge of the North American plate, along what was the passive southern margin of the continent (Figure 8). During this interval, the New York region was situated in tropical latitudes. This tectonic setting persisted until the Taconian orogeny (age span: Middle to late in the Ordovician Period). Interestingly, except for the tropical location and ocean basin to the south instead of to the east, 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] is generally analogous to that of Early Paleozoic time.

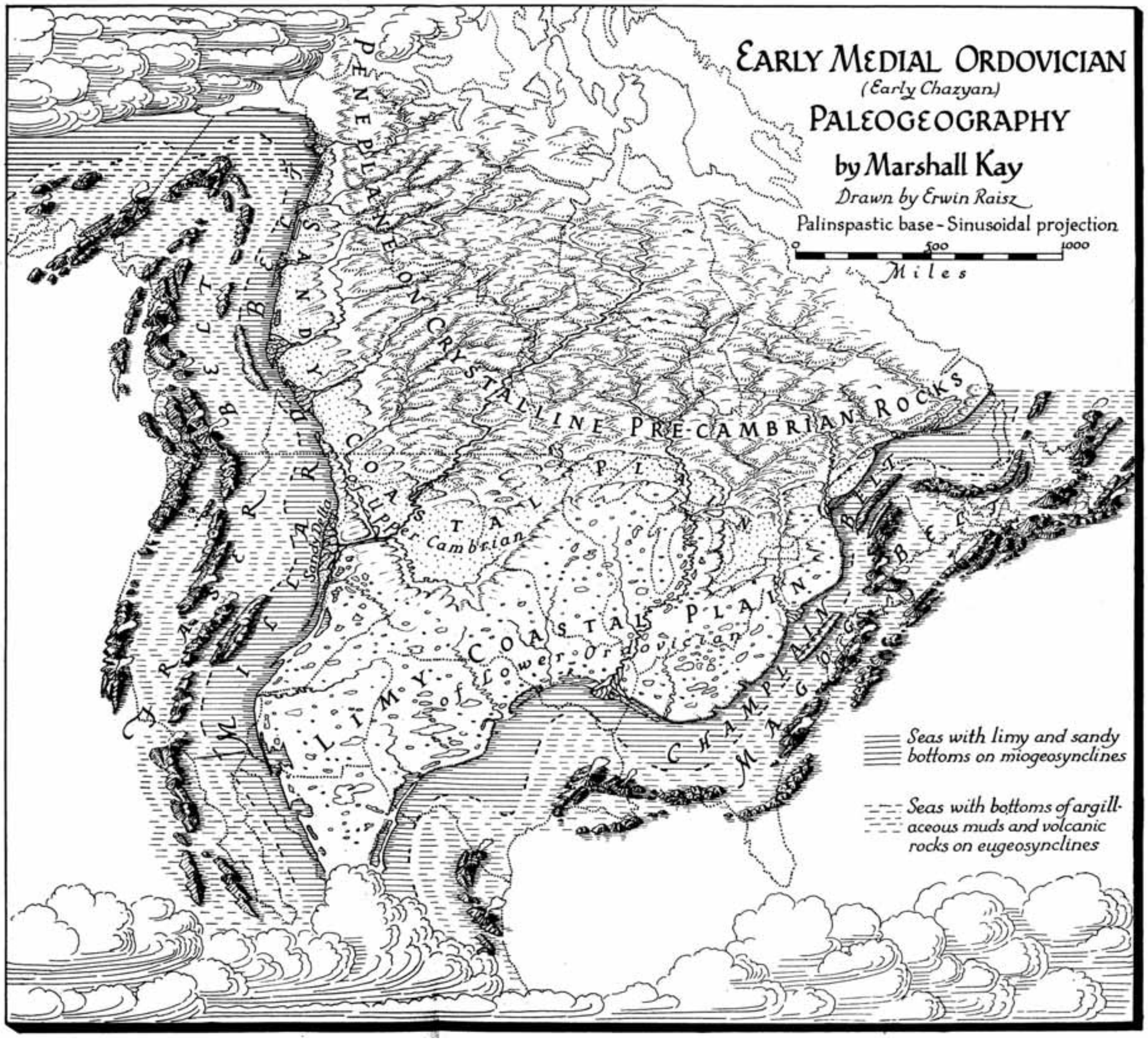


Figure 8. Paleogeographic reconstruction of North America as it is inferred to have existed during the Cambrian Period. Not shown are paleolatitudes and position of the Early Paleozoic Equator, which extended across what is now North America passing through Oklahoma, Kansas, and the Dakotas such that what is now east in the Early Paleozoic was south. (G. M. Kay, 1951, pl 1, facing p. 1.)

The Cambrian and Ordovician bedrock units (Layer II) underlying the Manhattan Prong and adjacent parts of western Connecticut consist of sedimentary- and igneous rocks that formed near the Earth's surface. They began their geologic lives approximately 550 million years ago as thick accumulations of both shallow- and deep-water sediments adjacent to the Early Paleozoic shores of proto-North America. (See Figure 8.)

Layer II can be divided into two sub-layers, IIA and IIB. The older of these, IIA, represents the ancient passive-margin sequence deposited in an ancient open 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. The nearshore-shelf facies, the Sauk Sequence [Layer IIA(W)], was deposited in shallow water 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). The local representatives of the Sauk Sequence are the Lower Cambrian Lowerre Quartzite and Cambro-Ordovician Inwood Marble in New York City (Cheshire Quartzite and Stockbridge Marble in western Connecticut and Massachusetts).

Farther offshore, fine-textured terrigenous time-stratigraphic equivalents of the shallow-water strata (shelf sequence) were deposited as turbidites, contourites, and deep-water shales on oceanic crust [Layer IIA(E)]. This sequence is also of Cambrian to Ordovician age and the facies equivalent of the Sauk Sequence, is known as the Taconic Sequence in upstate New York and adjacent parts of Massachusetts and Vermont. It is present in units Ꞓ-Om and Ꞓ-Oh of the Manhattan Schist(s) (Figure 9). In western Connecticut, it includes the Waramaug and Hartland formations, respectively.

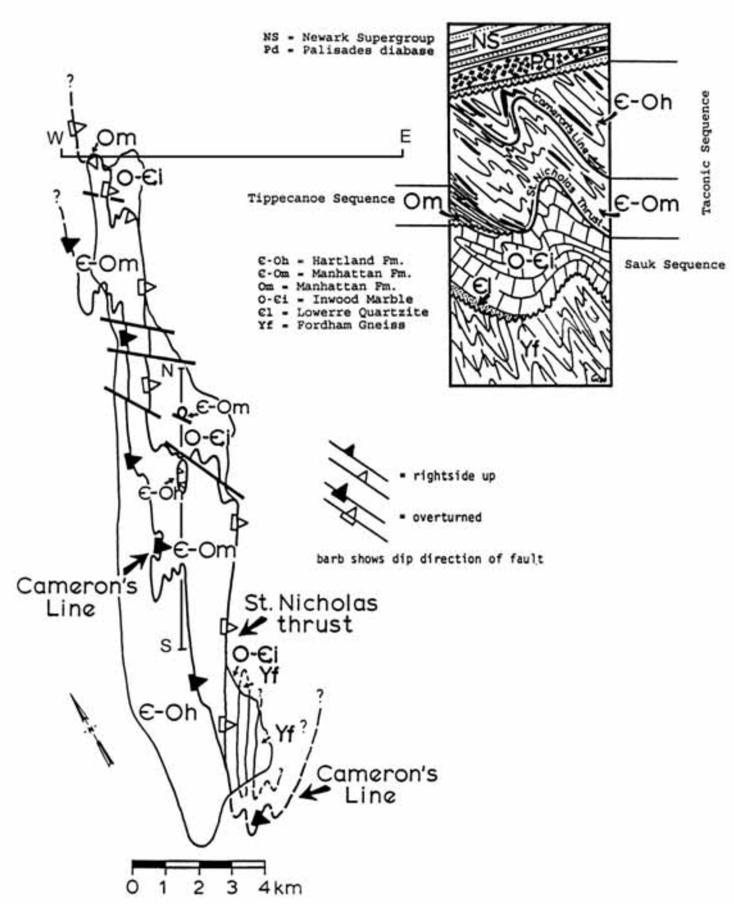


Figure 9. Geologic map of Manhattan Island showing a new interpretation of the stratigraphy- and structure of the Manhattan Schist. (Drawn and mapped by C. Merguerian.)

Layer IIB consists of younger, mostly terrigenous, strata, the Tippecanoe Sequence that was deposited in a foreland basin unconformably above the Sauk Sequence. In eastern New York State, the metamorphosed equivalents of these foreland-basin terrigenous rocks of the Tippecanoe Sequence are mapped as the Walloomsac Schist, Annsville Phyllite, and Manhattan Formation. (See Table 2.)

All of the schists originally named as the Manhattan Schist were thought to belong to units we now assign to the Tippecanoe Sequence, that is, to units entirely younger than the Inwood Marble of the Sauk Sequence. As a result of CM's mapping, large parts of the "Manhattan schist" are now recognized as rock units belonging to the Taconic Sequence (the same age or older than Manhattan Schist unit Om of the Tippecanoe Sequence and the Inwood Marble of the Sauk Sequence. (See Figure 9.) According to CM, at Inwood Hill Park in Manhattan (Merguerian and Sanders, 1991b), 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 thus belongs in the Tippecanoe Sequence, which is younger than the Sauk Sequence, as all of the "Manhattan schist" was formerly presumed to do.

Two other units, CM's Manhattan units Ꞓ-Om and Ꞓ-Oh, do not belong in the Tippecanoe Sequence, but rather in the Taconic Sequence, whose age spans that of the Sauk Sequence. This realization creates a nopersonsclatorial dilemma: What should be done with respect to the venerable- and well-known name "Manhattan Schist?" Should it continue to be applied to all the schists on the Island of Manhattan, as originally mapped? Or should it be restricted only to the schist that demonstrably belongs to the Tippecanoe Sequence, as originally interpreted? Or should the name be dropped altogether? CM and JES argue that the name Manhattan should be preserved as originally interpreted, namely for the schists in the Tippecanoe Sequence that are younger than the Inwood Marble. All other schists on Manhattan Island that have been previously mapped as belonging to the "Manhattan Schist" should be reassigned to their appropriate formations, such as Hartland or Waramaug.

During middle Ordovician time, roughly 450 million years ago, and prior to the main events of the Taconian orogeny, the passive-margin phase ended. A convergent-margin regime supplanted it. Great thrusts developed. The rocks forming the outboard zone of the former shelf province (underlain by thickened parts of the Sauk Sequence, with or without slices of the underlying felsic Proterozoic basement rocks) were driven landward across the floor of the Appalachian foreland basin in which the terrigenous sediments of the Tippecanoe Sequence were accumulating. Eventually, the Taconic Sequence (the older southern, deep-water formations), were driven landward into positions above the Inwood Marble (Sauk Sequence) and the younger overlying schist (the Tippecanoe Sequence; all of the Manhattan Schist as originally conceived, but only Manhattan Schist unit Om, according to CM). In other words, the Taconic allochthon (Merguerian and Sanders, 1991b; 1992a; Merguerian, 1995), extends into New York City.

After this great low-angle thrust had repeated the Taconic strata and shifted them up onto the former continental shelf, the New York City rocks were complexly folded together (Figure 10) and metamorphosed under amphibolite-facies conditions. This can be inferred from the presence of such "indicator" minerals as kyanite, sillimanite, and garnet.

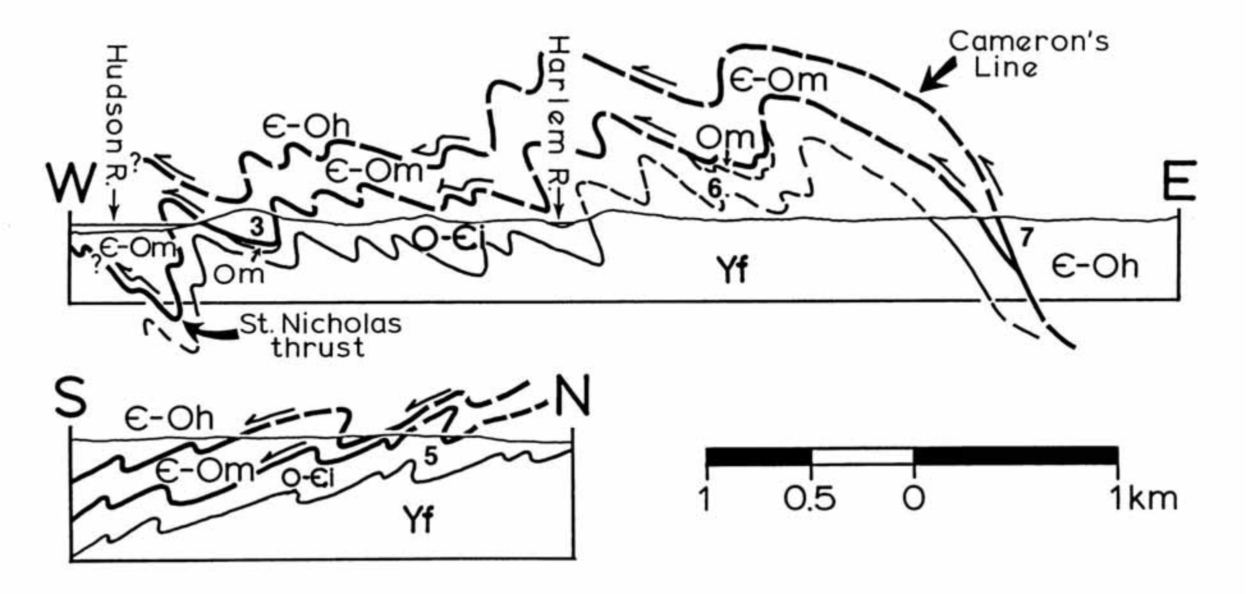


Figure 10. Folded overthrusts, Manhattan Island. Symbols defined on Figure 9. (Charles Merguerian, unpublished data.)

The thrusts imply that virtally all of the bedrock in New York City is allochthonous. The root zone of the thrusts involving the rocks of the Taconic Sequence 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 (Merguerian, 1983, 1995).

The presence of the diagnostic metamorphic minerals mentioned above suggests that rocks now exposed at the present land surface of New York City formerly were at depths of 20 to 25 km. If this is correct, it indicates that enormous uplift and pervasive 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 line at the George Washington Bridge (GWB) is shown in Figure 5. The overturned anticlines and -synclines of the New York City metamorphic rocks are nonconformably overlain by the west-dipping strata of the Newark Supergroup (Layer V, Table 2). The surface of nonconformity 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.

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

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

These rocks have been studied in great detail in a few selected localities by researchers interested in learning about the exact mineralogic composition of individual specimens and petrologic interpretations based thereon. They mapped outcrops in great detail and carried out extensive laboratory investigations. Examples include the studies by Dodd (1965) in the Popolopen Lake quadrangle and by Jaffe and Jaffe (1973, 1989) in the Monroe area and Puffer (1980) in northern New Jersey. Only Offield (1967) and Drake (1984) have tried to aggregate the outcrop information into mappable formations and thus to infer a stratigraphic succession. Both of these contrasting kinds of investigations are necessary. The greatest progress has always come about when these are carried out by the same investigator.

In a few localities, the Proterozoic rocks clearly are allochthonous. Isolated hills composed of Proterozoic rocks in their high parts display Paleozoic rocks, typically the Martinsburg Formation (Layer IIB, Table 2), in their lower elevations (Figure 11). 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 overthrust sheets (klippen, auf Deutsch; see Jaffe and Jaffe, 1973, 1989). A few examples include the Woodcock Hill klippe, Museum Village klippe, and Goose Pond Mountain, west of Monroe.

Elsewhere, the allochthonous relationship is not particularly obvious from study of the exposed rocks, but is strongly suggested by geophysical surveys, notably from aeromagnetic data (Henderson, Tyson, and Wilson, 1958; Henderson and Smith, 1962; Henderson, Andreasen, and Petty, 1966; Harwood and Zeitz, 1974), from gravity data (Urban, Bromery, Ravetta, and Diment, 1973), and from continuous seismic-reflection profiles (COCORP results; Cook and others, 1979; Cook, Brown and Oliver, 1980; Cook and Oliver, 1981; Ando and others, 1983; L. D. Brown and others 1983; Ando and other others, 1984).

Allochthonous or autochthonous, some of the Proterozoic rocks of the Reading Prong are famous throughout the world. An example is the remarkable suite of minerals uncovered in the zinc mines at Franklin and Sterling Hill, New Jersey (Metsger, 1980; Frondel and Baum, 1974; Frondel, 1972; Baker and Buddington, 1970; Metsger, Tennant, and Rodda, 1958; Hague, Baum, Herrmann, and Pickering, 1956; Palache, 1929, 1935; Spencer, Kümmel, Wolff, Salisbury, and Palache, 1908). (See our On-The-Rocks guidebook for Trip 12 to Franklin, New Jersey and vicinity, Merguerian and Sanders, 1990.)

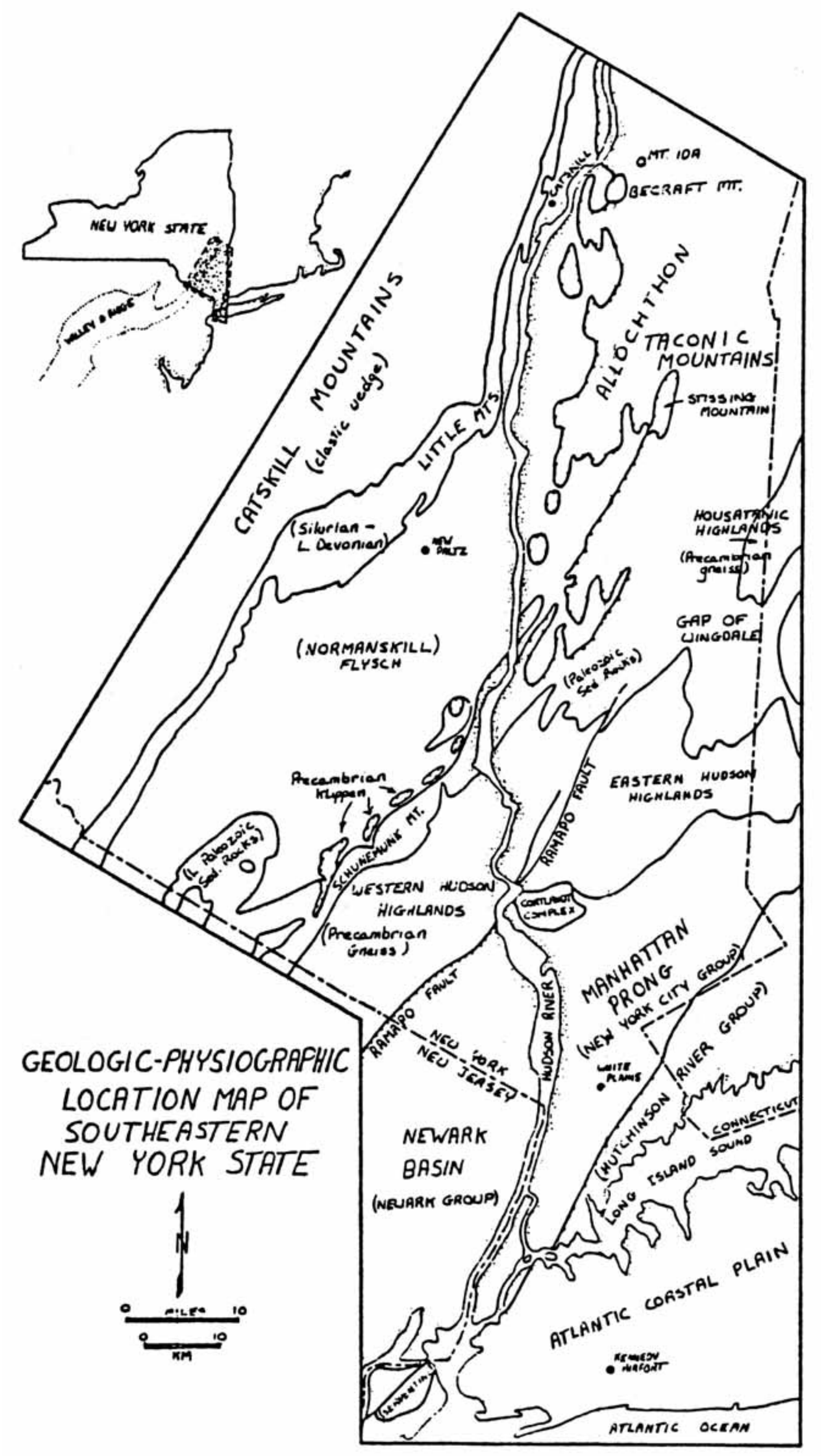


Figure 11. Tectonic sketch map of southeastern New York State showing klippen of Proterozoic rocks lying NW of Schunnemunk Mountain. This linear belt of klippen lies between the main belt of Proterozoic rocks of the Hudson Highlands and the NE-plunging anticline south of Middletown, NY. (Terry Engelder, from guidebook to solution-cleavage field trip.)

Layer II: Cambro-Ordovician Strata Northwest of the Hudson Highlands

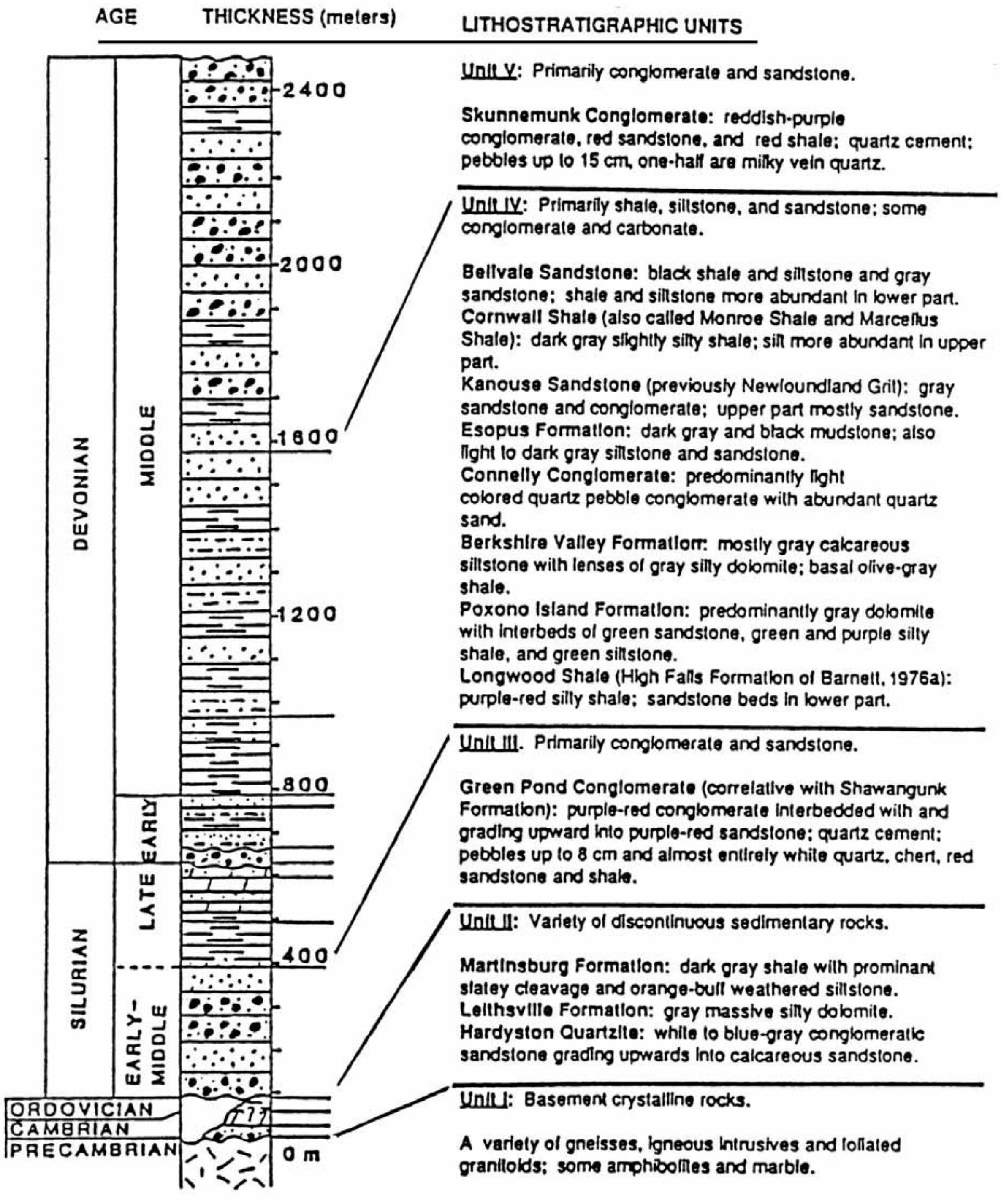
We have mentioned the rocks of Layer II in the Manhattan Prong, where they have been subjected to Taconic overthrusting and high-grade metamorphism. In the belts northwest of the Hudson Highlands, these rocks have been folded and faulted, but have never been subjected to the temperatures that thoroughly recrystallize rocks. Moreover, throughout most of the Appalachian Great Valley, no Taconic klippen are present. The same general twofold subdivision of predominantly Sauk Seqeunce carbonates below and predominantly terrigenous rocks of the Tippecanoe Sequence 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 (forming the Sauk Sequence, Cambro-Ordovician carbonates equivalent to the Wappinger of New York and also to the Inwood-Stockbridge marbles), surface of regional unconformity, Jacksonburg Limestone (equivalent to the New York Balmville), and the Martinsburg Formation (of the Tippecanoe Sequence, 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.).

The carbonate rocks in the Sauk Sequence display 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, rounded quartz particles mixed with varying proportions of carbonate sand whose particles included intraclasts of the adjacent muddy sediment. In addition, algal stromatolites are prominent. Chert is abundant. Finally, as a result of deep burial, all layers have been subjected to the effects of pressure dissolution, as is evidenced by the numerous stylolites on several scales. (Tada and Siever, 1989, summarize pressure dissolution.)

In the region of our field trip, these rocks were folded and eroded several times. Initially, the Sauk Sequence (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, including Proterozoic "basement" (Finks and Raffoni, 1989, p. 116-118).

Layer III: Silurian and Devonian Strata

The rocks of Layer III are at center stage on this trip. We will examine them in their western outcrop belt. The stratigraphic succession that has been established in the eastern belt (Layer IIIE, Table 2) begins with the Lower Silurian Green Pond Conglomerate and ends with the Middle Devonian Schunnemunk Conglomerate. A recent version of the succession at the southwestern end near Green Pond Mountain, NJ is shown in Figure 12.



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 12. 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).

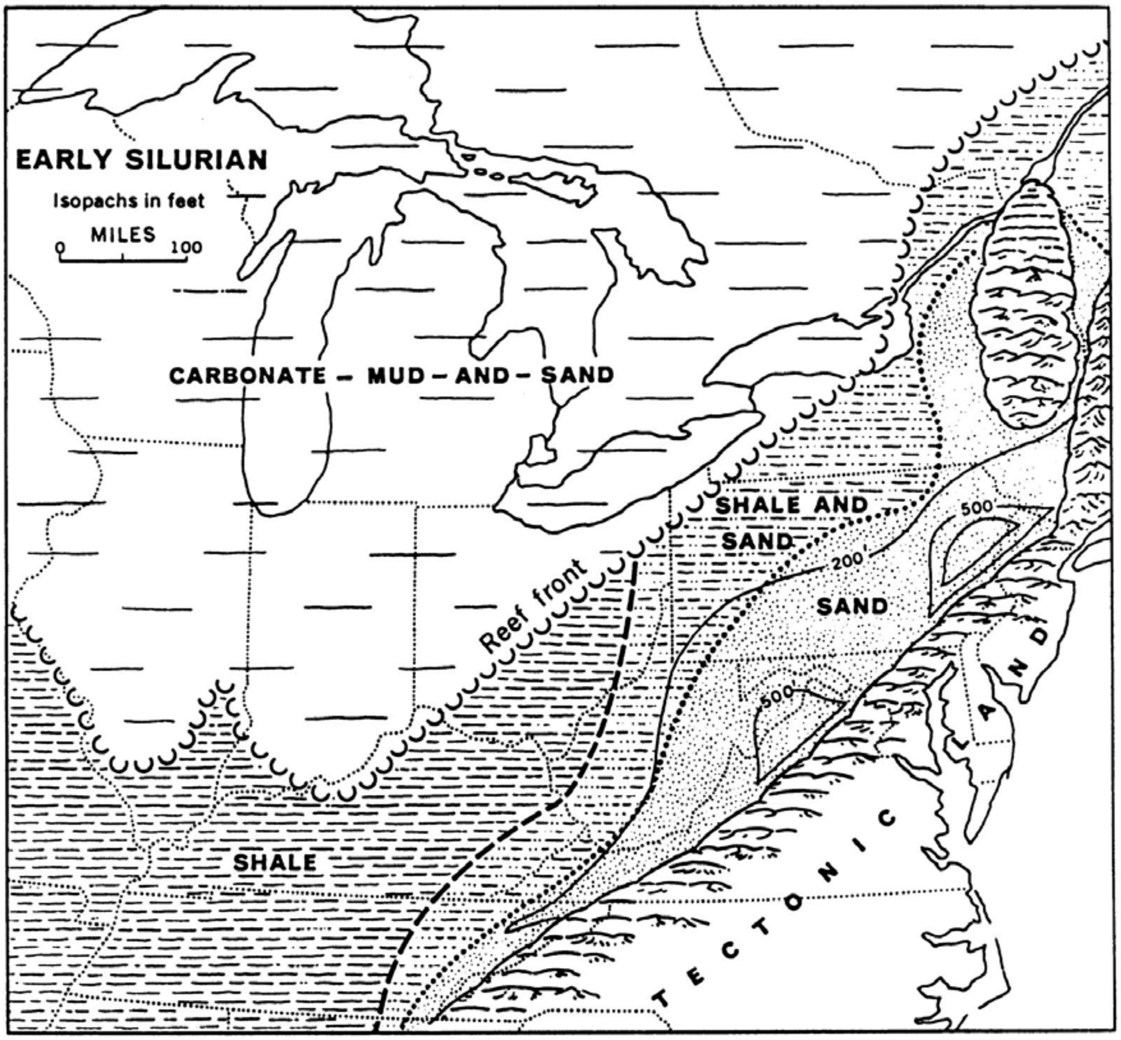


Figure 13. Map of parts of east-central United States showing extent of Lower Silurian sand (now sandstone after deep burial and cementation by quartz) and relationships to mud and reef-carbonate belt. Numbered lines show thicknesses in feet. (G. M. Kay and E. H. Colbert, 1965, fig. 10-12, p. 192.)

Along the northwest side of the Appalachian Great Valley, this formation forms a wall-like ridge in which the strata dip to the NW. The younger strata share this direction of dip, but in the overlying rocks, 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 by many (but not by us) to mean that the strike ridge marks the NW limit of deformation in the Appalachian chain. Granted the possibility of large-scale overthrusts of Late Paleozoic age, then this NW dip may result from a ramp-related anticline and be the NW limb of such a structure (Figure 14). 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 (Figure 1, cover). We think that this profile confirms the existence of low-angle thrusts and that the interpretation of the NW dips as part of a ramp-related anticline is correct.

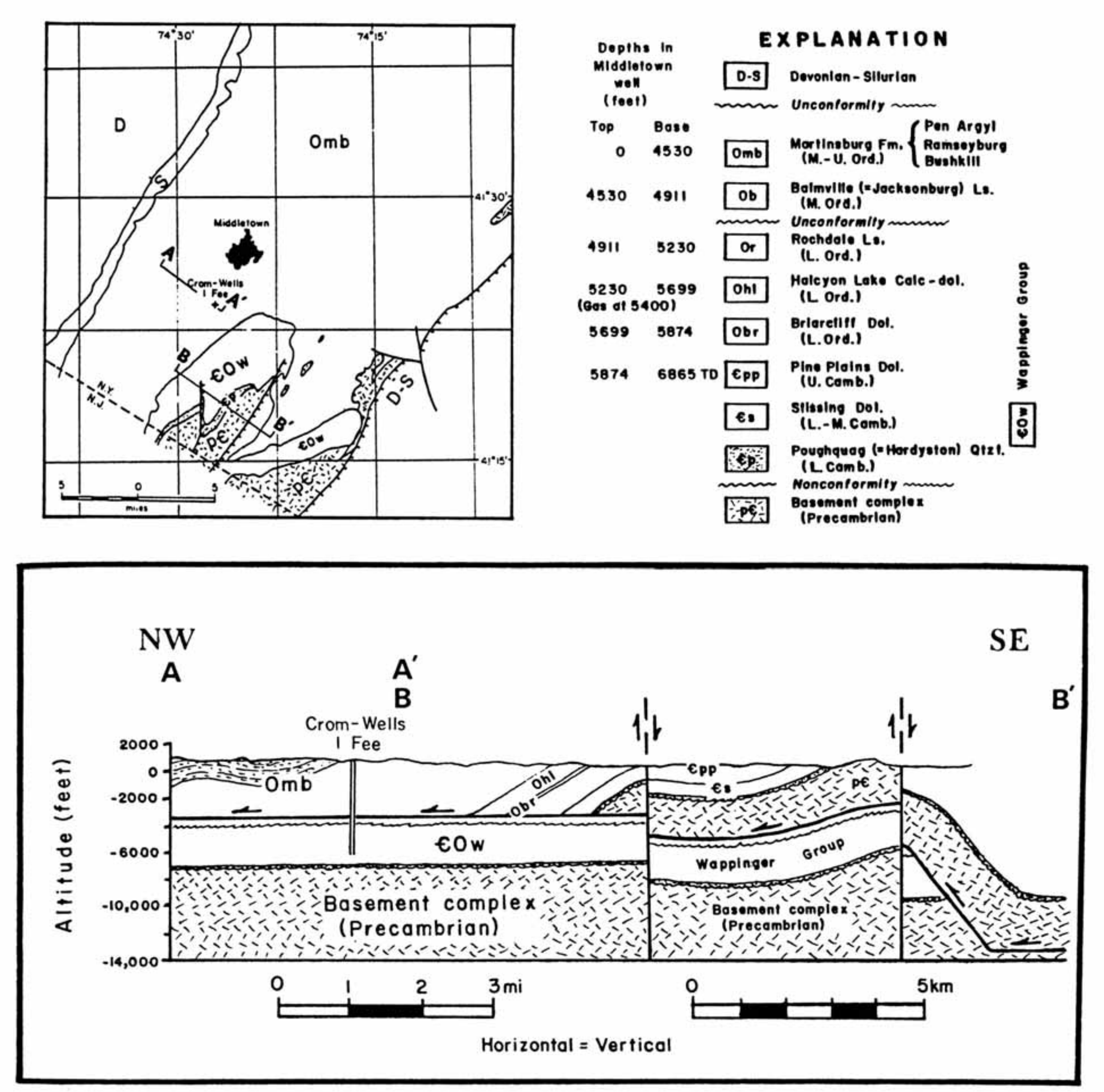


Figure 14. Geologic setting of Middletown gas well (Crom-Wells 1 Fee), Orange County, NY.

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.).

A notable feature of the terrigenous sediment, especially during the Early and Medial parts of the Silurian Period, was an enormous abundance of quartz, ranging in size from pebbles to silt. Although deep burial doubtless contributed to the dissolution of easily dissolved minerals, such as feldspar and carbonate, it is still remarkable that so much quartz of sand size and coarser was spread throughout such a vast area and to the thickness of many tens of meters. The sheet of Silurian sand extends unbroken from New York to Tennessee and has been found in the subsurface as far west as eastern Ohio. (See Figure 13.) 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 subjects of ongoing research.

Layer IV: Coal Measures and Related Strata

On this trip, we will not be examining any of the rocks of Layer IV. We mention them briefly and refer the interested reader to Table 2 because they are significant factors in the debates about the age(s) of the episodes of deformation. The important points about the rocks of Layer IV are that they are thick and coarse; possibly the conglomerates mark episodes of Late Paleozoic deformation. In addition, they contain coal beds that locally have been metamorphosed to anthracite grade. The anthracite district is near Scranton, Pennsylvania. After about a century of extensive mining, the district's reserves have been largely exhausted.

Layer V: Newark Basin-Filling Strata

The tilted- and eroded remnants of the Newark strata are exposed along the west side of the Hudson River, from Stony Point south to Staten Island. As shown on the diagonal cut-away slice in Figure 2, the Newark strata generally dip about 12° to 15° to the northwest. (See also Figure 5.)

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 the ridges known as the Watchungs. The age of the sedimentary units beneath the oldest extrusive sheet, the Orange Mountain Basalt (First Watachung) is Late Triassic. The remainder of the formations are of Early Jurassic age.

The Newark sedimentary strata were deposited in a fault-bounded basin to which the sea never gained access. In this basin, the filling strata were deposited in various nonmarine environments, including subaerial fans, streams, and shallow- and deep lakes. Lake levels varied according to changes in climate. After the Newark strata had been deeply buried, they were elevated and tilted, probably during a period of mid-Jurassic tectonic activities. They were then eroded and truncated to form a surface upon which the Upper Cretaceous and younger coastal-plain strata were deposited.

GEOLOGIC STRUCTURE--A PRIMER

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. 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 then examine some mechanical aspects of rock deformation. From there, we work our way upward through geologic structures such as folds and faults to lithosphere plates. Then follows a discussion of the effects on rocks of deformation and how one can determine when deformation took place.

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 15). 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 Nicholas 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.

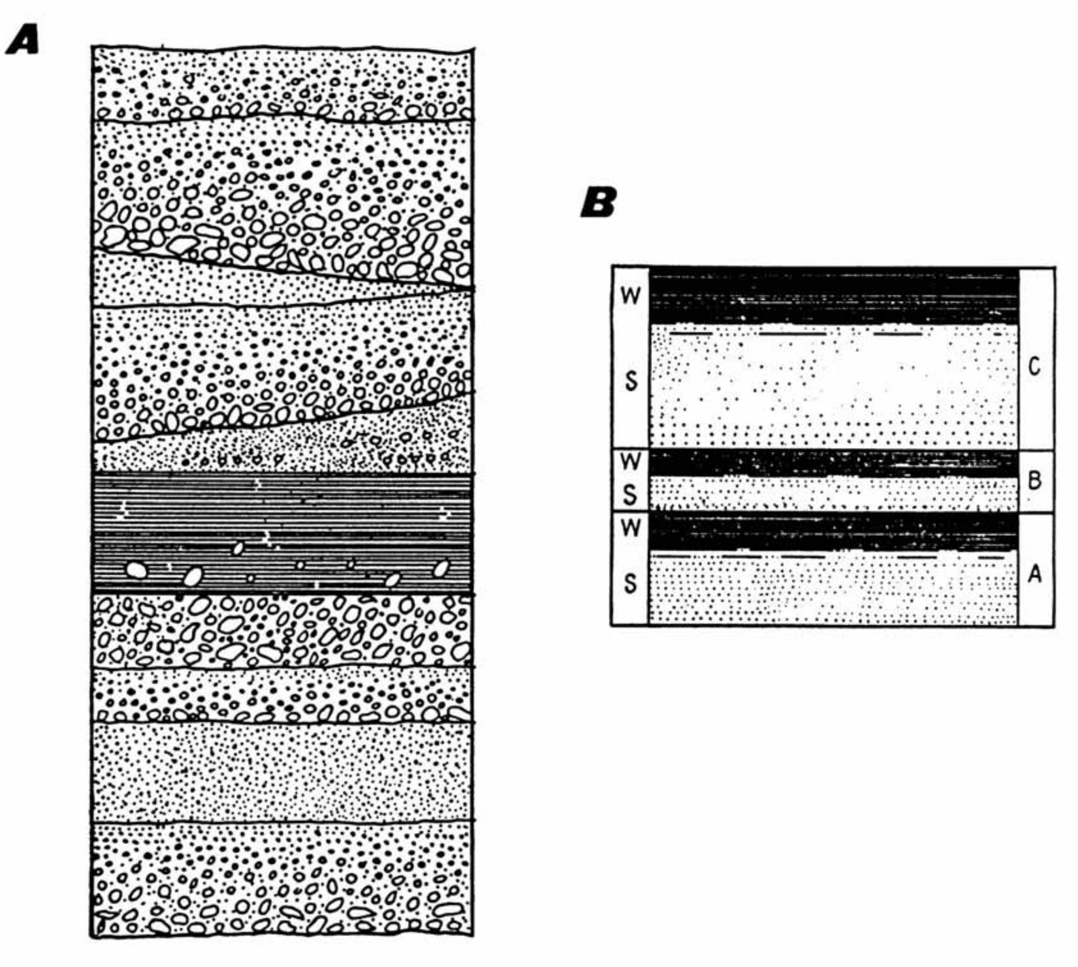


Figure 15. Contrasting kinds of sediments showing internal upward-fining grading.
A. Conglomeratic layers, some graded, some uniform, interbedded with shale containing scattered pebbles. Nonmarine Wamsutta Formation, (Pennsylvanian), E side of Great Pond, Braintree, MA. (R. R. Shrock, 1948, fig. 43, 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)

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)

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 16) 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.)

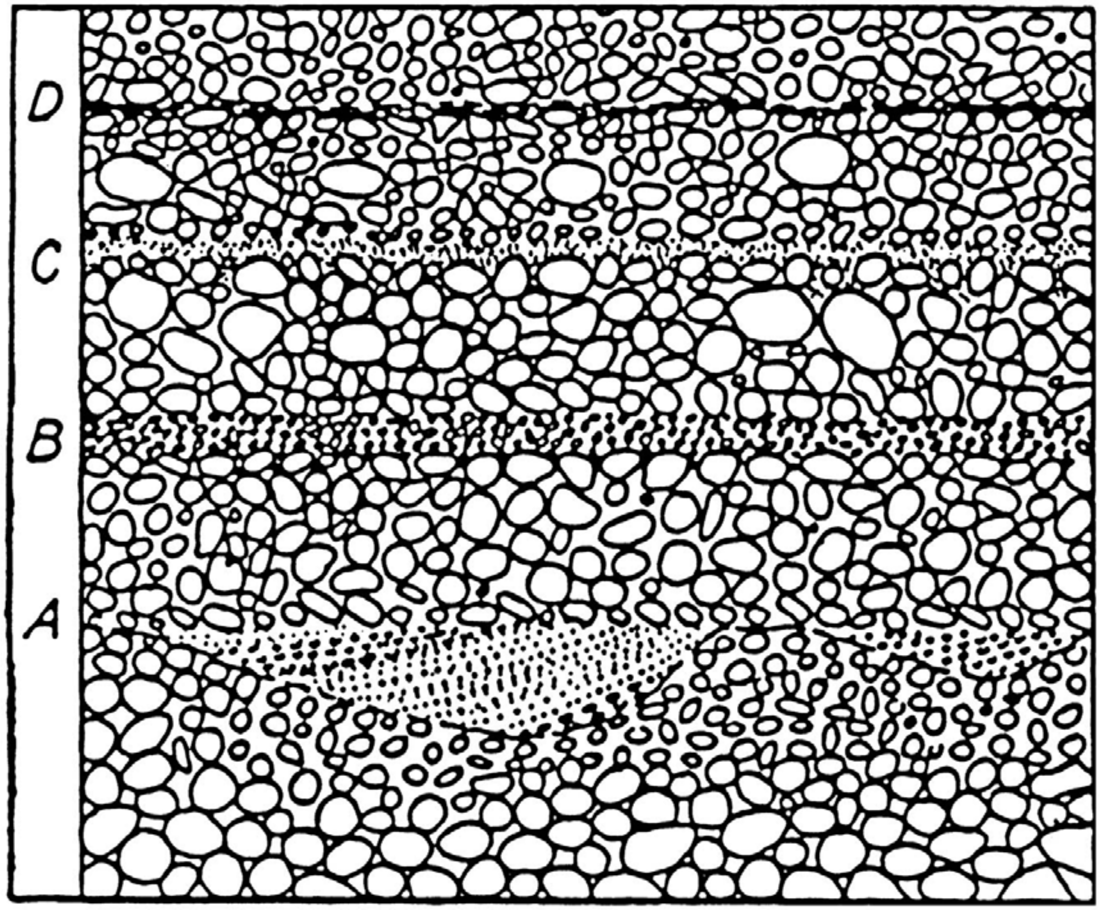


Figure 16. Sketch of gravel (or conglomerate) showing how bedding is revealed by finer sediment in planar layers (such as B, C, and D) or in lenses (as in A). (R. R. Shrock, 1948, fig. 3, p. 12.)

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 17), aligned shells of invertebrates, differences in degree of cementation, or whatever.

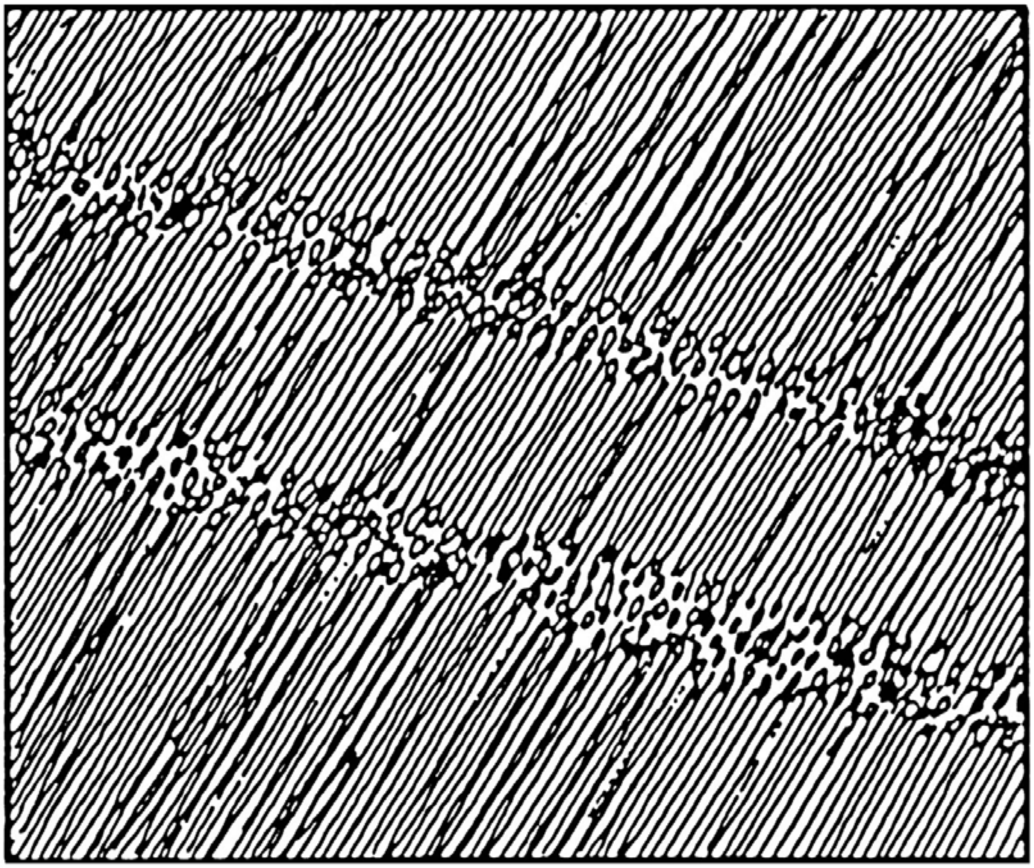


Figure 17. Sketch of slate (dark color) with prominent parting (slaty cleavage) dipping steeply to the left; two layers composed of silt-size sediment (stipple) show that bedding dips gently to the right. (R. R. Shrock, 1948, fig. 7, p. 15.)

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, a moving current reacts with the sediment it is transporting 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 18). 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 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 18, A.) If the crests of the bed forms are sinuous and concave downcurrent, then downcurrent migration creates trough-type cross strata. (See Figure 18, B.)

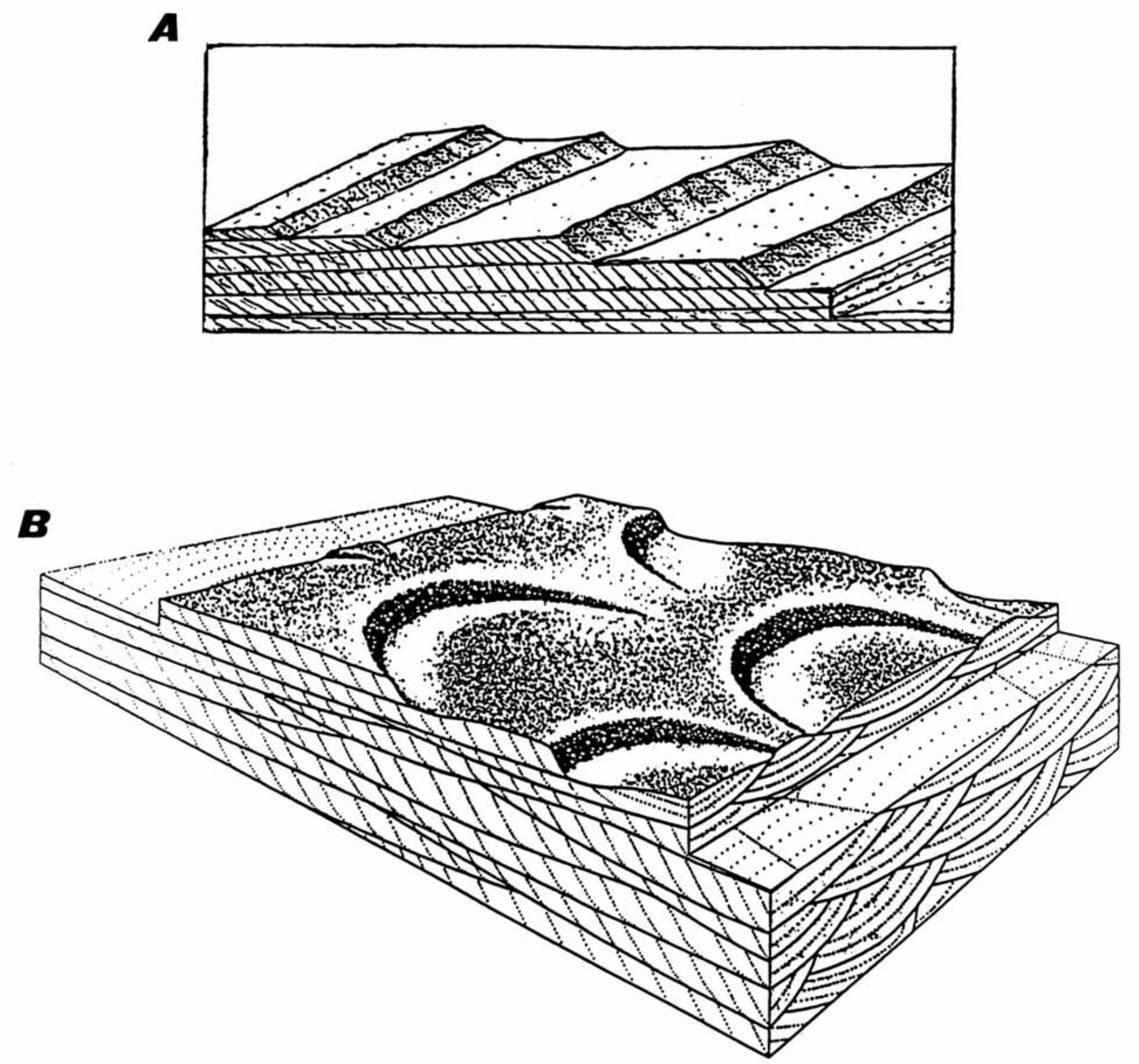


Figure 18. Sketches of contrasting shapes of bed forms created by a current flowing from left to right and cross strata resulting from their downcurrent migration.
A. (new) Linear bed forms create planar cross strata. (G. M. Friedman, J. E. Sanders, and D. C. Kopaska-Merkel, 1992, fig. 5-19, A, p. 166.)
B. (old fig. 26) 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 (as in Figure 19, 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 19, B). In other places, cross strata are deposited at the fronts of sediment embankments where water currents encounter 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 19, C and E).

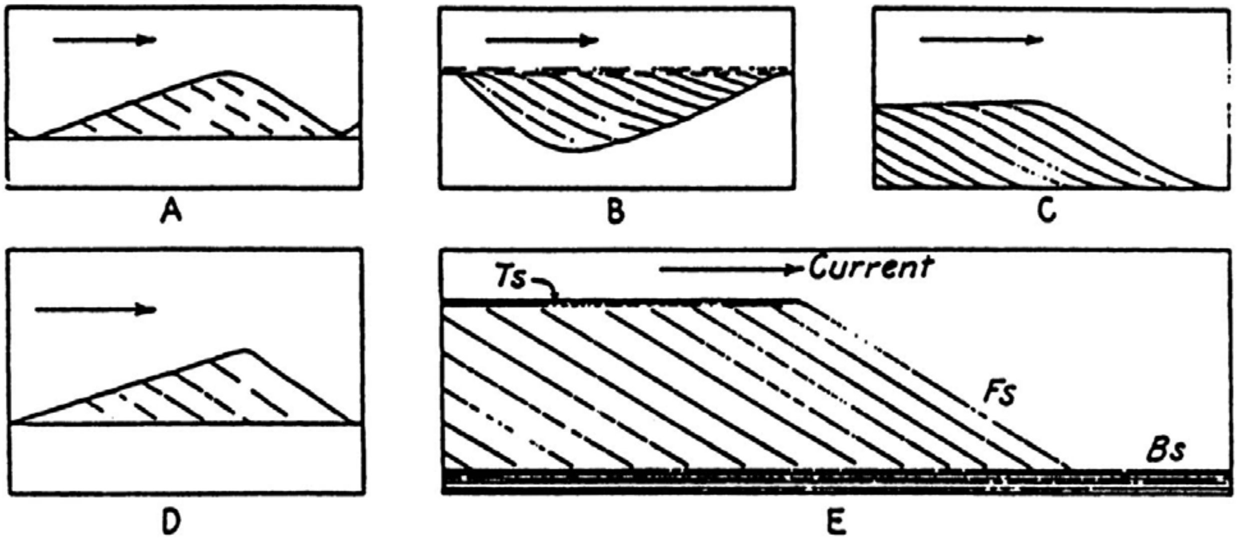


Figure 19. Sketches showing various settings in which cross strata dipping to the right can be deposited by a current flowing from left to right.
A and D, Longitudinal profiles through individual bed forms that have migrated to the right (downcurrent) by at least one wavelength, thus preserving as internal 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 20, 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 20, B).

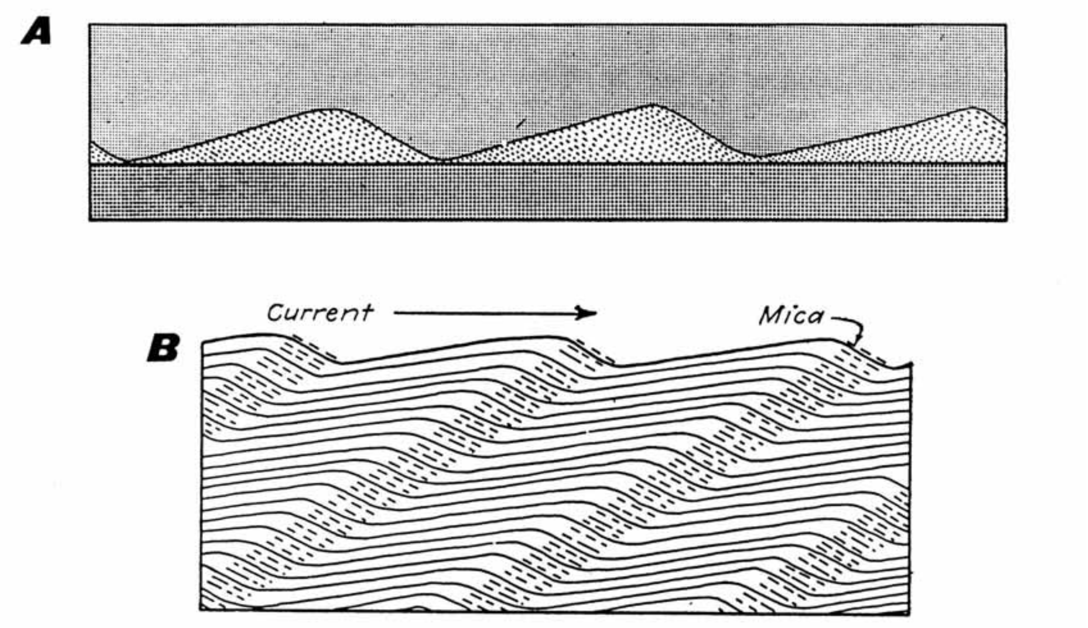


Figure 20. Sketches of ripple cross laminae formed under varying conditions of sediment supply.
A. Cross laminae formed by migration of ripples from left to right when no new sediment is added from the current. (R. R. Shrock, 1948, fig. 57, p. 103.)
B. Climbing-ripple laminae formed when sediment falls 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 21).

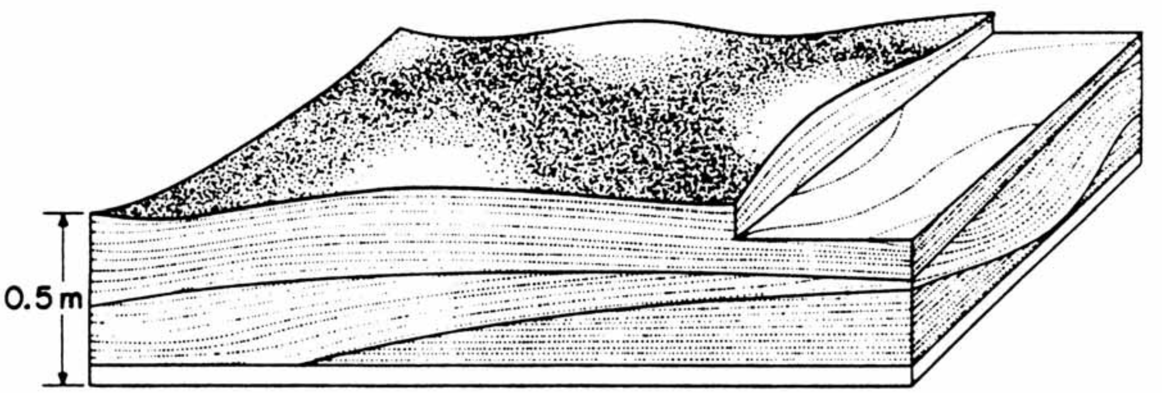


Figure 21. Sketch of hummocky strata. (R. H. Dott, Jr. and Joanne Bourgeois, 1982, fig. 1, p. 663.)

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 22).

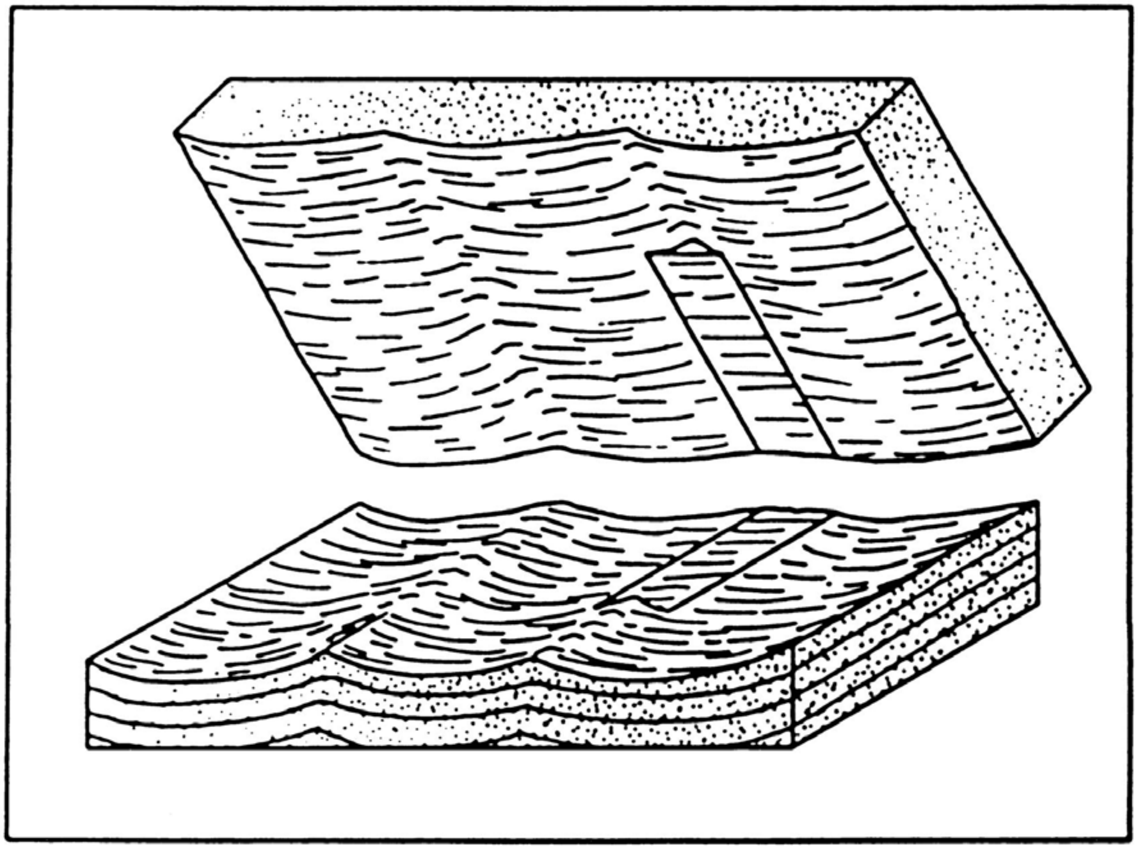


Figure 22. Sketch of symmetrical ripples showing appearane of laminae formed when pointed crests and rounded troughs are superimposed and shape of bottom of covering layer. (G. M. Friedman and J. E. Sanders, 1978, fig. 13-13, p. 415, based on R. R. Shrock, 1948, fig. 71, p. 114 and 81, A, p. 120.)

A current carrying sand in suspension that crosses a substrate composed of cohesive fine sediment 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 23).

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 24 is a composite diagram illustrating common sedimentary structures.

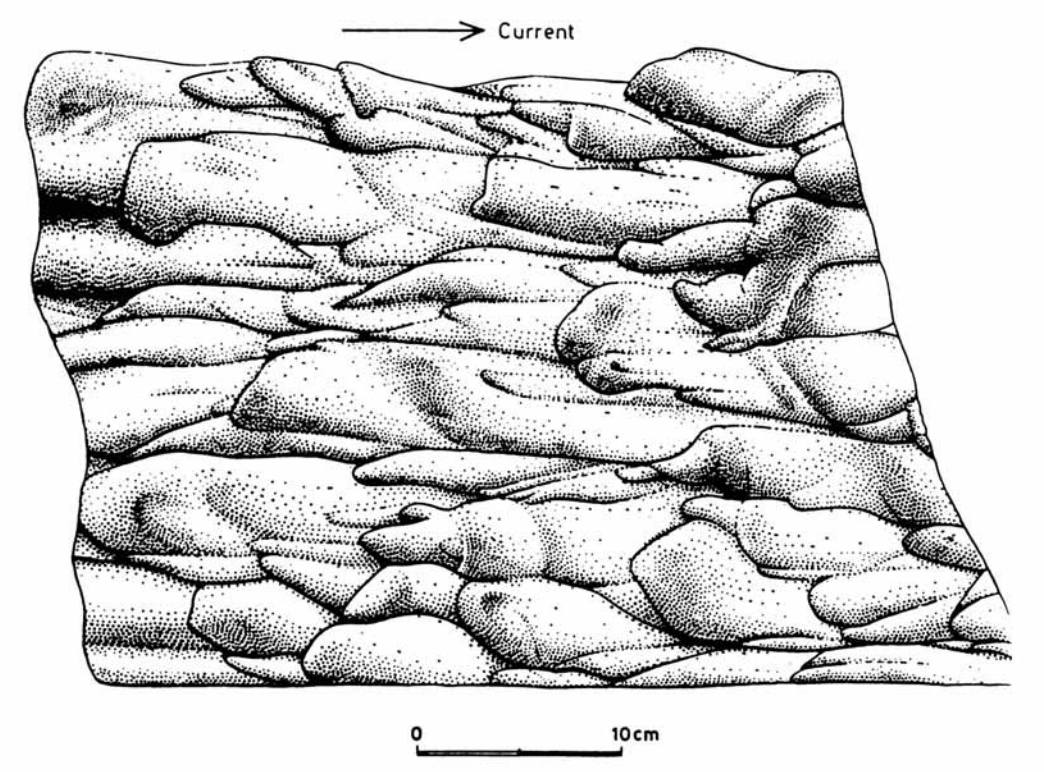


Figure 23. Sketch of counterparts of flutes, sole marks on base of Miocene sandstone bed, Apennines, Italy. (P. E. Potter and F. J. Pettijohn, 1977, fig. 5-2, p. 160, from E. ten Haaf, 1959, fig. 12.)

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 unraveled 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 folds and faults after a brief lead-in discussion concerning the mechanical aspects of deformation and the strength of materials.

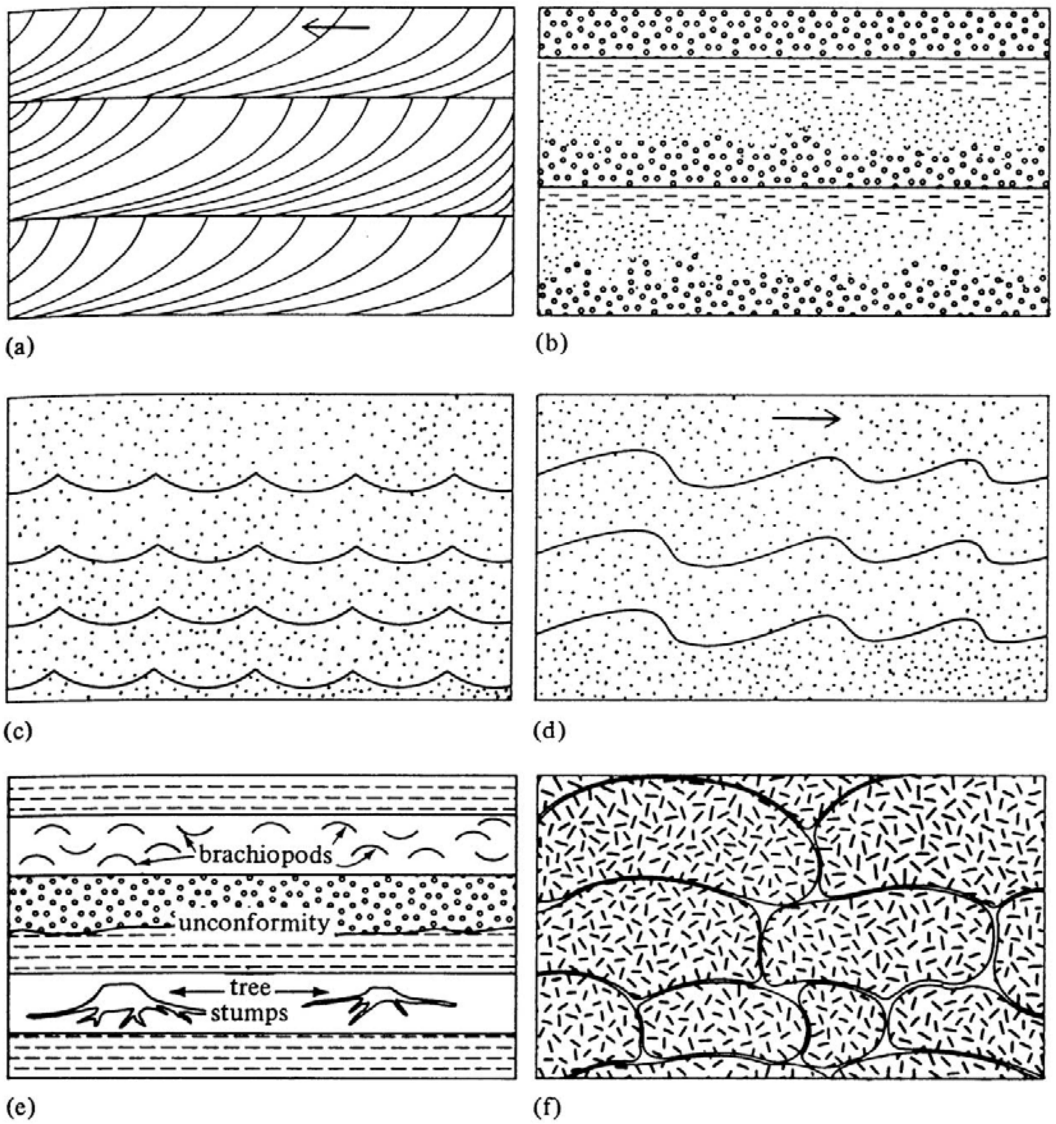


Figure 24. Diagrammatic sketches of primary sedimentary structures (a through e) and cross sections of pillows (f) used in determining topping (younging) directions in layered rocks.

Mechanical Aspects of Deformation

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.

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 states 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 field observation and inference than from rock-squeezing data to gain a feel for the complex nature of how rocks are deformed in nature.]

Despite the limitations of the experimental work, measurements in the laboratory on specimens being deformed provide some fundamental definitions. One key definition is the elastic limit, which is the point at which a test specimen no longer returns to its initial shape after the load has been released. Below the elastic limit, the change of shape and/or volume (which is known as strain) is proportional to the stress inside the specimen. Above the elastic limit, the specimen acquires some permanent strain. In other words, the specimen has "failed" internally. Irrecoverable strain manifests itself in the 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 S_1 and S_0) 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 S_0 (or surface number zero) as it is commonly overprinted by S_1 (the first foliation). To use this relative nomenclature to describe the structural history of an area, for example, one might write: "During the second deformation (D_2), F_2 folds formed with the development of an L_2 mineral lineation. An axial-planar S_2 schistosity developed and crosscut both an early foliation (S_1) and bedding (S_0). These features were produced under progressive M_1 metamorphic conditions."

Folds

If layers are folded into convex-upward forms we call them anticlines. Convex-downward fold forms are called synclines. In Figure 25, note the geometric relationship of anticlines and synclines. Axial planes (or axial surfaces) physically divide folds in half. Note that in Figure 25, 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 25, 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.

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.

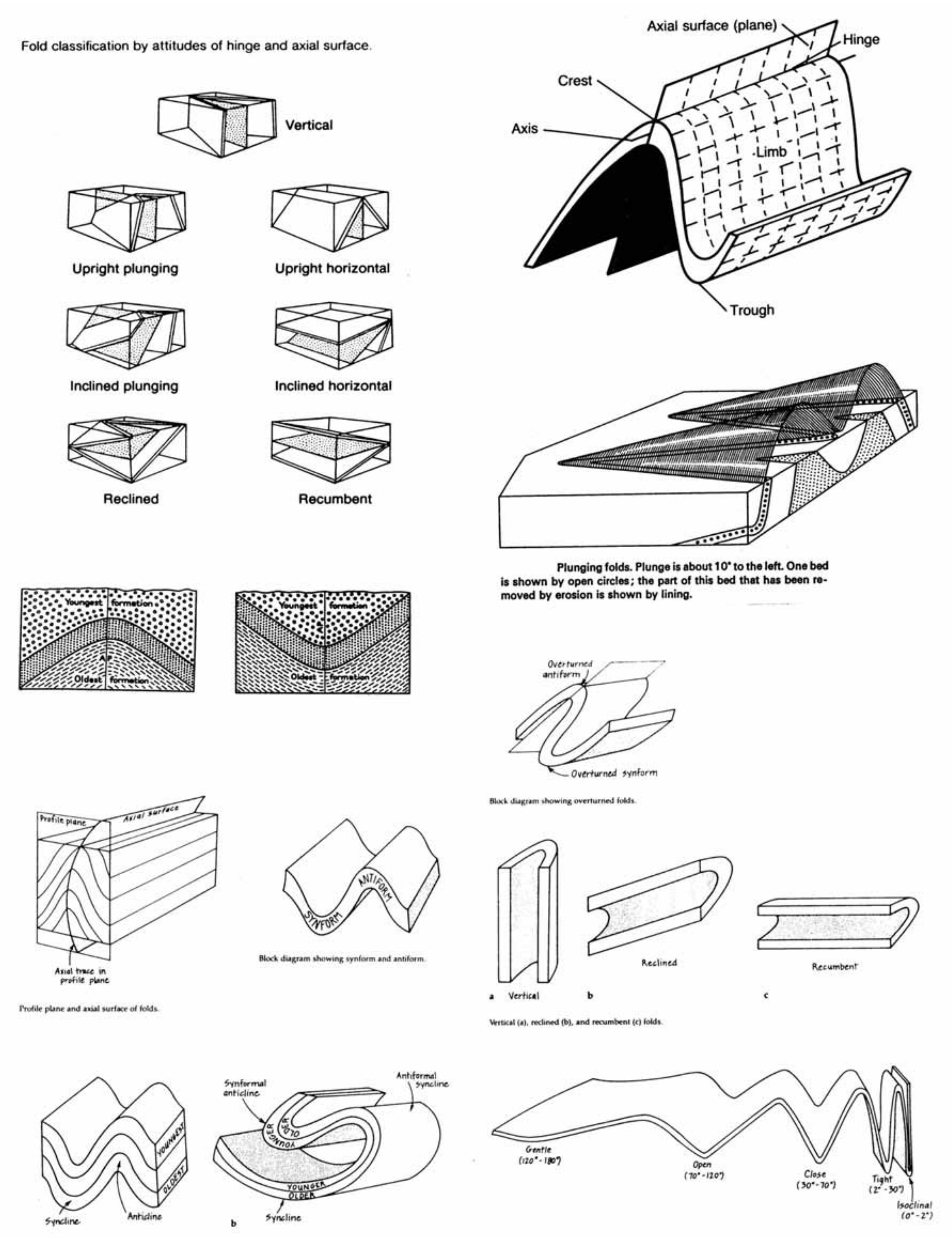


Figure 25. Composite diagram from introductory texts showing various fold styles and nopersonsclature (non-sexist terminology) as discussed in the text.

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 25.) It is also possible for an axial surface to be vertical but for the orientation of the fold axis to range from horizontal to some angle other than 0° (thus to acquire a plunge and to produce a plunging fold). Possible configurations include plunging anticlines (or -antiforms) or plunging synclines (or -synforms). Vertical folds (plunging 90°) are also known; in them, the terms anticline and syncline are not meaningful. In reclined folds, quite common in ductile 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 26, 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.

Normal- and Reverse Faults

Imagine subjecting a block-like portion of the Earth's crust to extension or compression. Extensional force causes the hanging-wall block to slide down the fault plane producing a

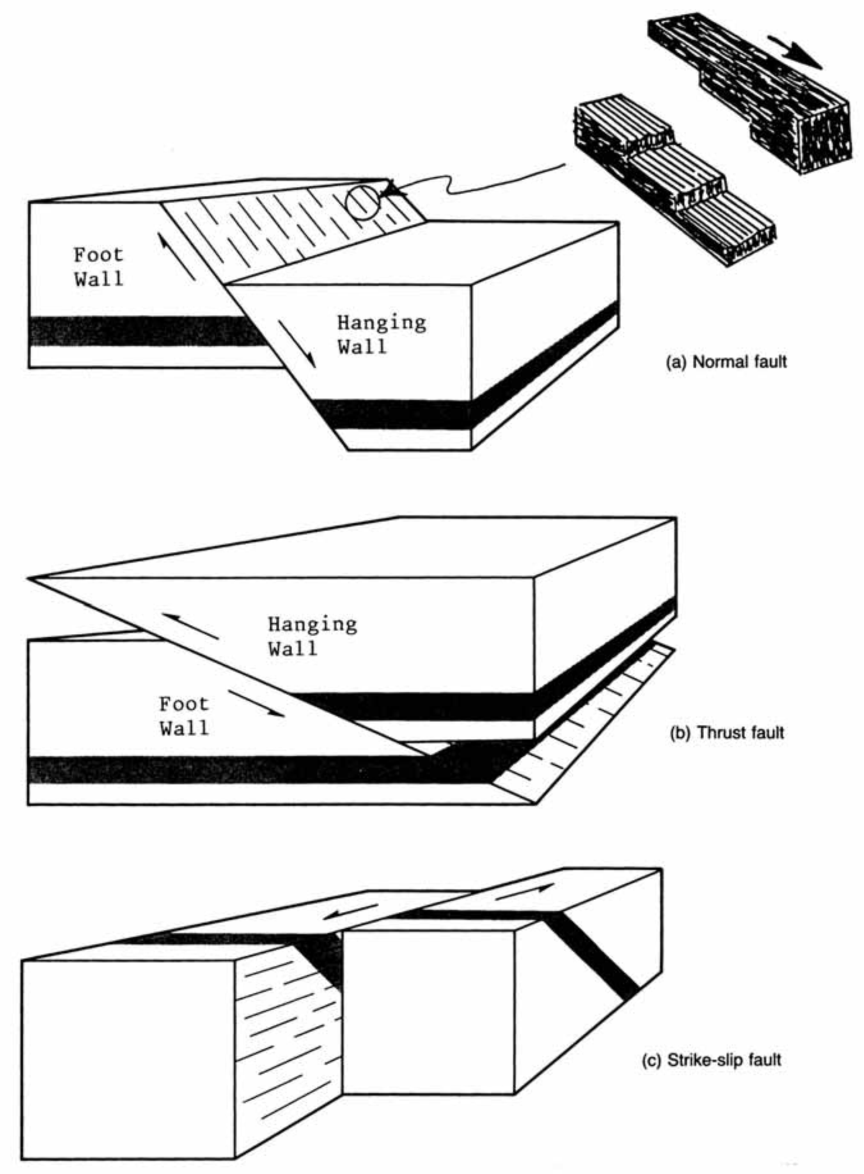


Figure 26. The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (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 fault. [See Figure 26 (a).] Compressive forces drive the hanging-wall block up the fault plane to make a reverse fault. A reverse fault with a low angle (<30°) is called a thrust fault. [See Figure 26 (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 (1966) 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 27) 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 28).

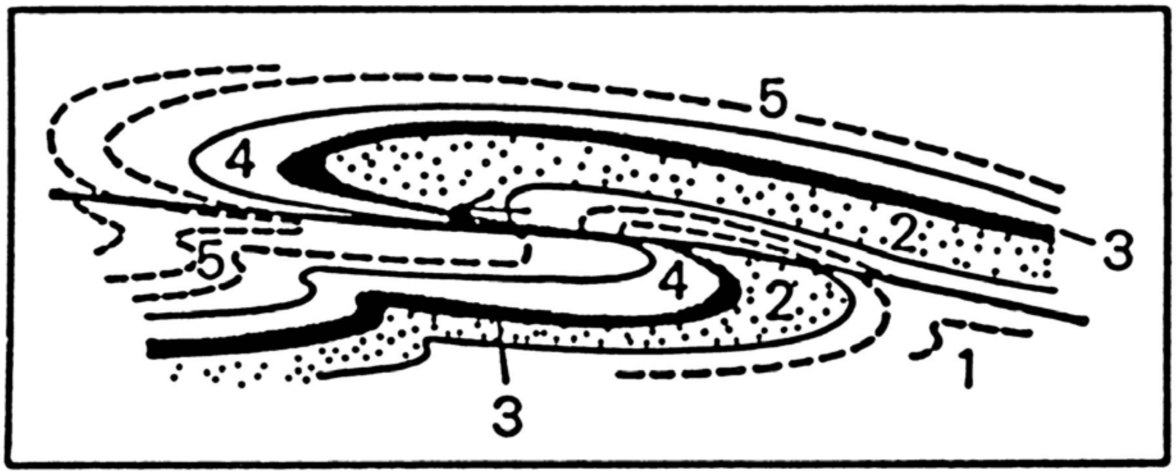
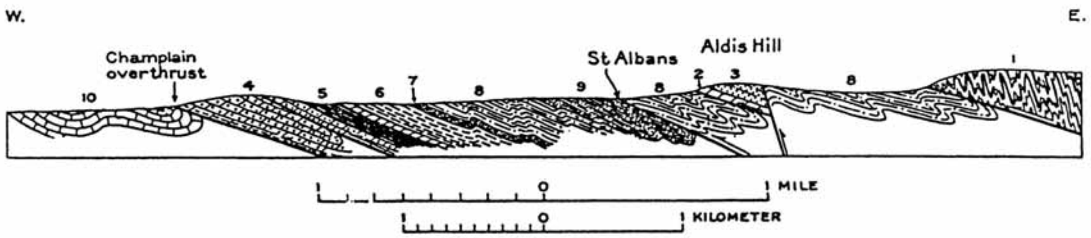


Figure 27. Overturned fold broken by a low-angle thrust fault, schematic profile section. Units are numbered in order of decreasing age, from 1 (oldest) to 5 (youngest). (J. E. Sanders, 1981, fig. 16.14, p. 398.)



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

Studies in the Appalachians led John L. Rich (1934) to propose the concept of "bedding thrusts." By this term, he referred to overthrusts along which two contrasting segments can be recognized: (1) segments that are parallel to the bedding; and (2) segments that cut across bedding at steep angles (Figure 29). (These segments that cut bedding at steep angles have subsequently been named ramps.) What was totally different about Rich's analysis is the relationship between thrusts and folds. Because of the geometric arrangement of the ramps and the beds, any forward displacement causes the strata of the upper block to be folded. As the strata are pushed against the ramp, they become parallel to it, forming one limb of a ramp-related anticline. Where the strata that have been displaced past the ramp return to the next bedding-parallel segment of the thrust surface, they dip downward toward this surface, thus forming the second limb of the ramp-related anticline. Where later deformation has not obscured the relationships, Rich's mechanism creates flat-topped anticlines whose widths are direct functions of the amount of displacement on the overthrust and intervening flat-bottom synclines whose widths are determined by the spacing between adjacent ramps.

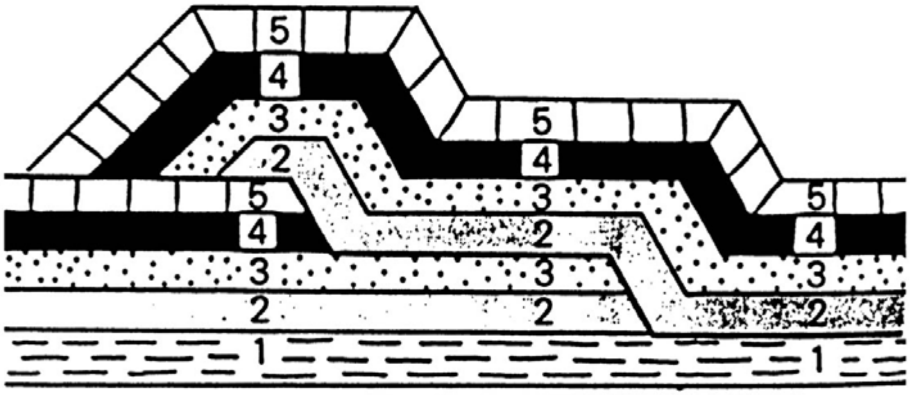


Figure 29. Folds formed by movement on a bedding-plane thrust according to the mechanism proposed by J. L. Rich; schematic profile section with units numbered in order of decreasing age from 1 (oldest) to 5 (youngest). (J. E. Sanders, 1981, fig. 16.1e, p. 390.)

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.

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 duplicated by low-angle thrusts. They believed that deformation on a scale that creates low-angle thrusts would destroy any petroleum present in the strata. Therefore, thrust belts ranked high on the list of places to avoid. Much to everybody's surprise, major discoveries were made by drilling through low-angle thrusts 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 provide 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 had been thrust over the strata. (See Figure 6.) 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 30). 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).

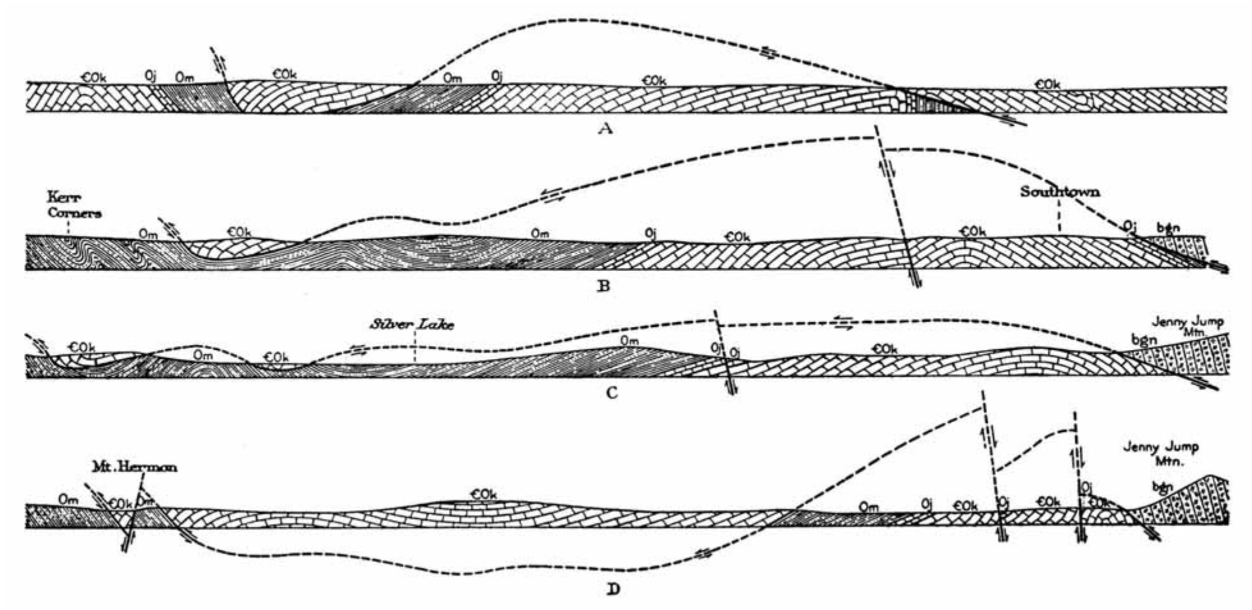


Figure 30. Geologic sections illustrating the vast thrust sheets of Cambro-Ordovician strata in the Kittatinny Valley and klippe composed of Proterozoic rocks at Jenny Jump Mountain. (J. V. Lewis and H. B. Kümmel, 1915, fig. 3, p. 58.)

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. (See Figure 11.) 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 31).

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. (See Figure 14.) 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 1 (on the cover). 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.

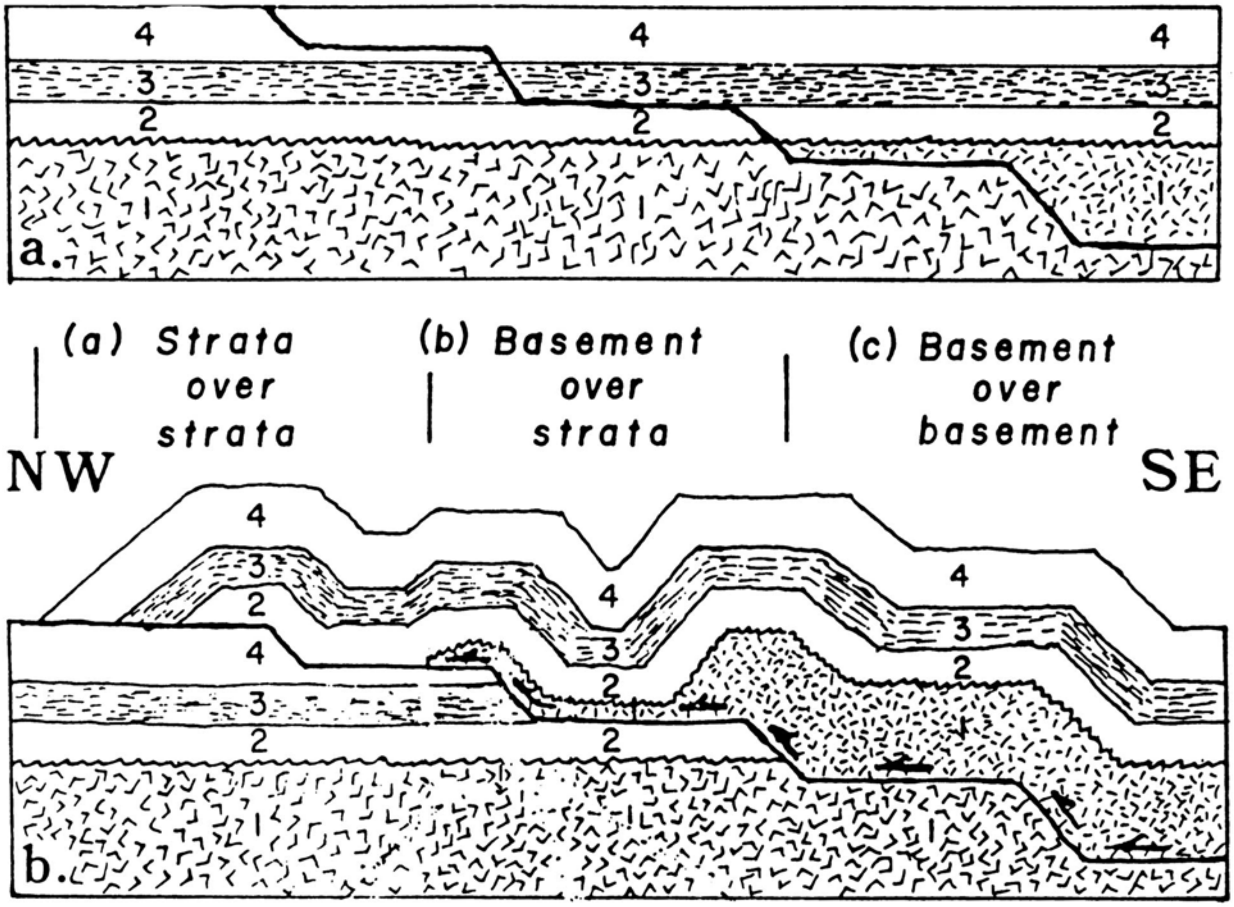


Figure 31. "Bedding thrusts" as described by J. L. Rich (1934), but extended downward so as to includes sheets of basement rock, schematic profile-section with no erosion. Where basement rocks move over other basement rocks, the cause of the separation is probably thermal, as argued by Armstrong and 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.)

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).

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 thrust sheets of strata that have been folded after they had been duplicated by a low-angle thrust. 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 32). By contrast, if most of the upper plate has been eroded, only a remnant outlier or klippe may remain. (See Figure 32.) 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.

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 low-angle thrusting 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 low-angle thrusts of the strata filling the foreland basin. Thus, a thrust may override debris eroded from it (Sanders, 1995).

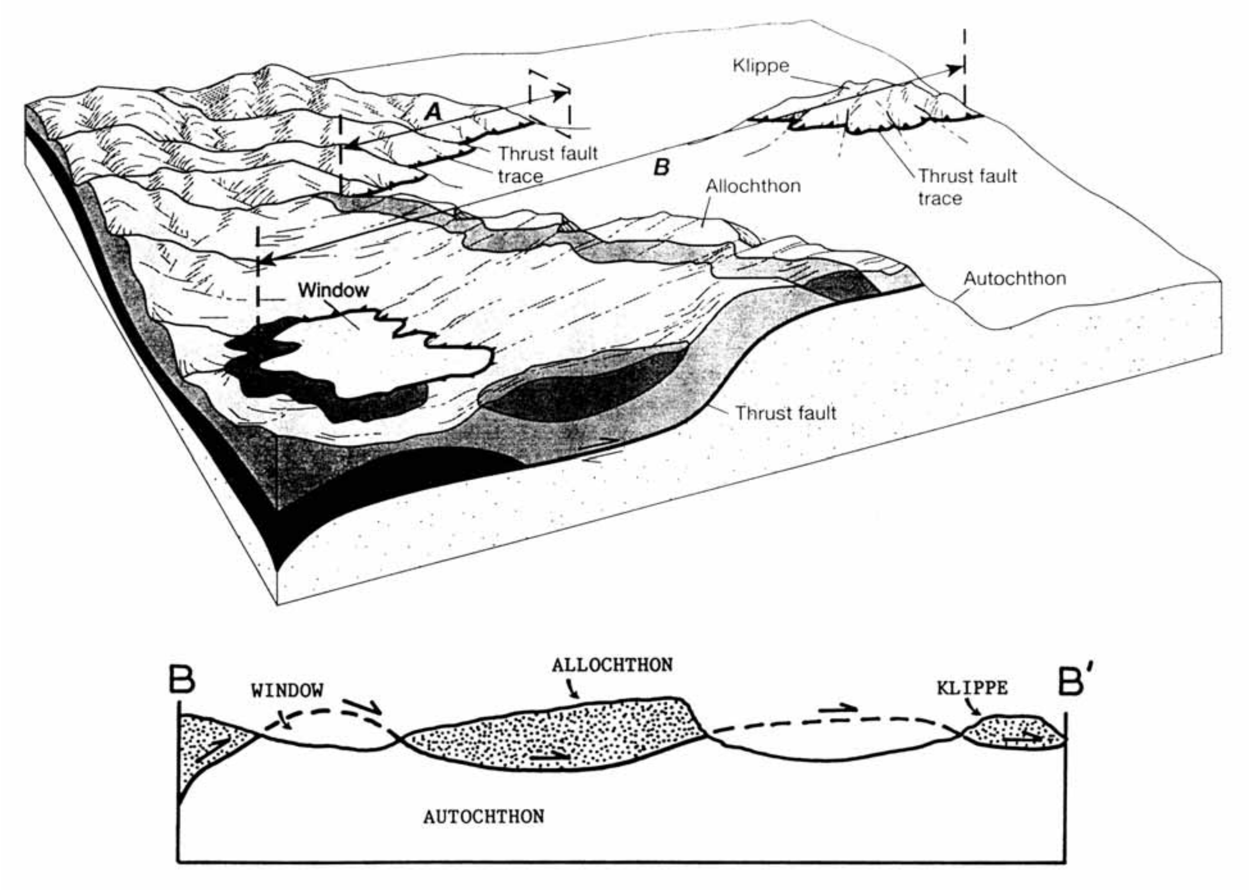


Figure 32. Block diagrams illustrating the relationships among major components of low-angle thrust sheets, including allochthons, autochthons, klippen, and windows. (R. J. Twiss and E. M. Moores, 1992, fig. , p. 99; section B-B' drawn by CM.)

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

Two basic kinds of shearing couples and/or strike-slip motion are possible: left lateral and right lateral. These are defined as follows. Imagine yourself standing on one of the fault blocks and looking across the fault plane to the other block. If the block across the fault from you appears to have moved to the left, the fault is left lateral [illustrated in Figure 26 (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 33 lists brittle- and ductile-fault-rock 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 33.)

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 or more sets of cleavage have been superimposed upon one another, the rocks tend to break into wedge-like, triangular shapes (Stop 3) or into long, slender faceted "pencils" (Stop 4). 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 34.)

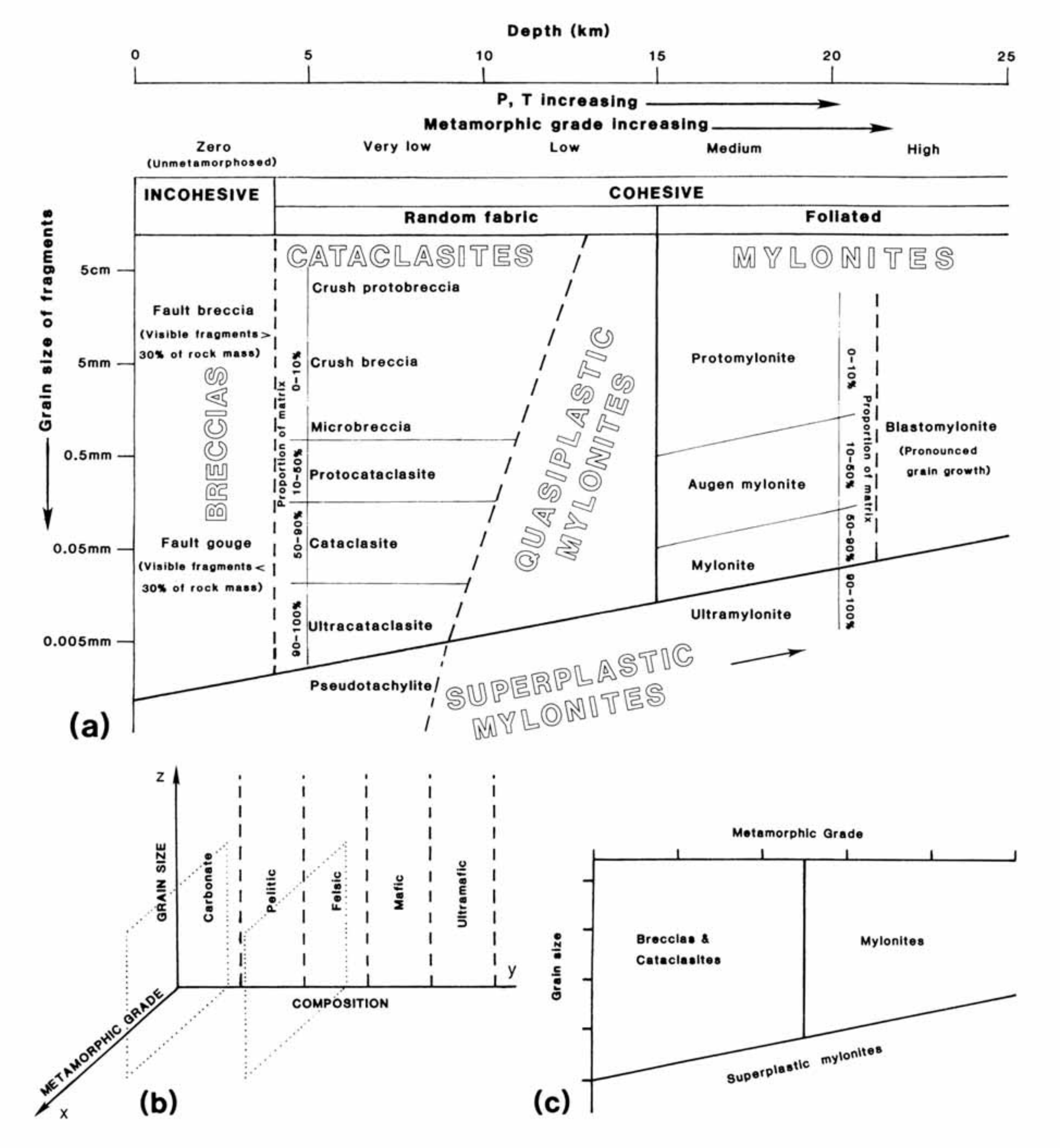


Figure 33. Fault-rock terminology. (a) Classification of fault rocks that have been derived from quartzo-feldspathic lithologies (e.g. granite). (Adapted from R. Sibson, 1977, fig. xx, p. yyy.) (b) The particle size - metamorphic grade - lithologic composition grid used for classifying fault rocks. (After J. Hull, R. Koto, and R. Bizub, 1986, fig. p. .) (c) Fault-rock diagram for marl showing expanded mylonite and superplastic mylonite fields as compared to those shown on the diagram for granite in (a) (R. Stephen Marshak and Gautam Mitra, 1988, fig. , p. .)

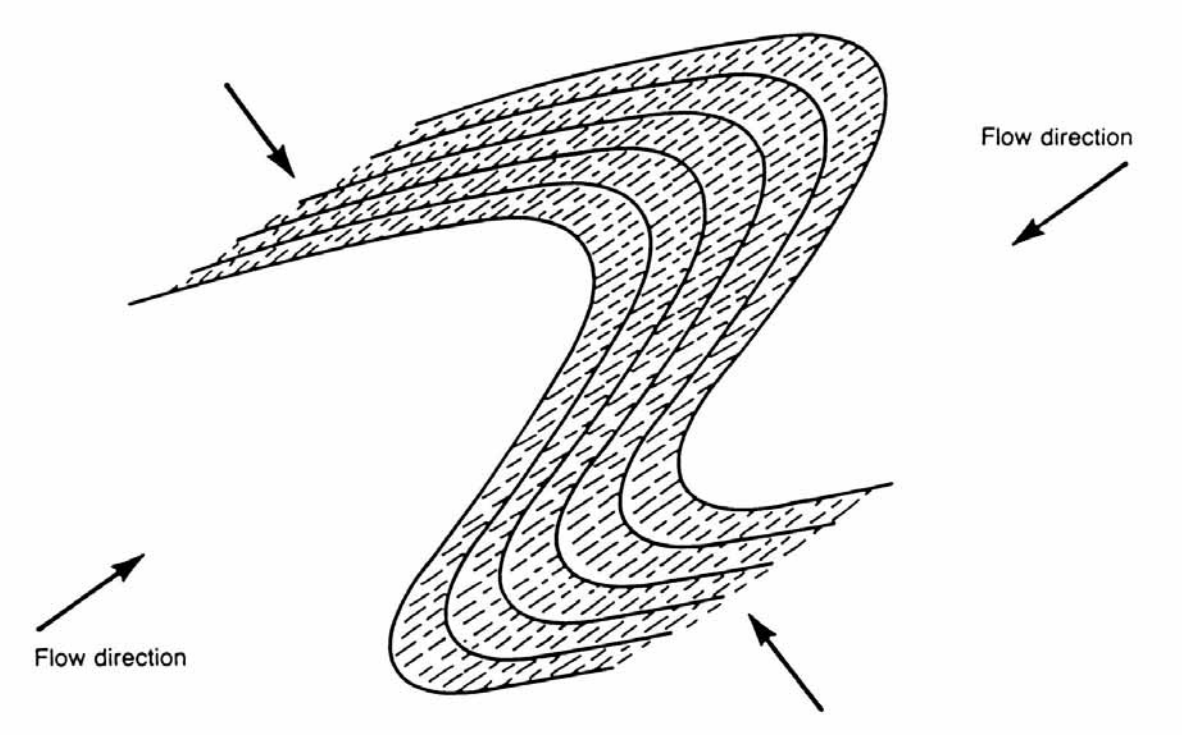


Figure 34. Sketch of slaty cleavage oriented parallel to axial plane of folds. (R. D. Hatcher, Jr., 1990, fig. 15-22, p. 335.)

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. Commonly such uplift and erosion are 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 35), 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 36). 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.

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

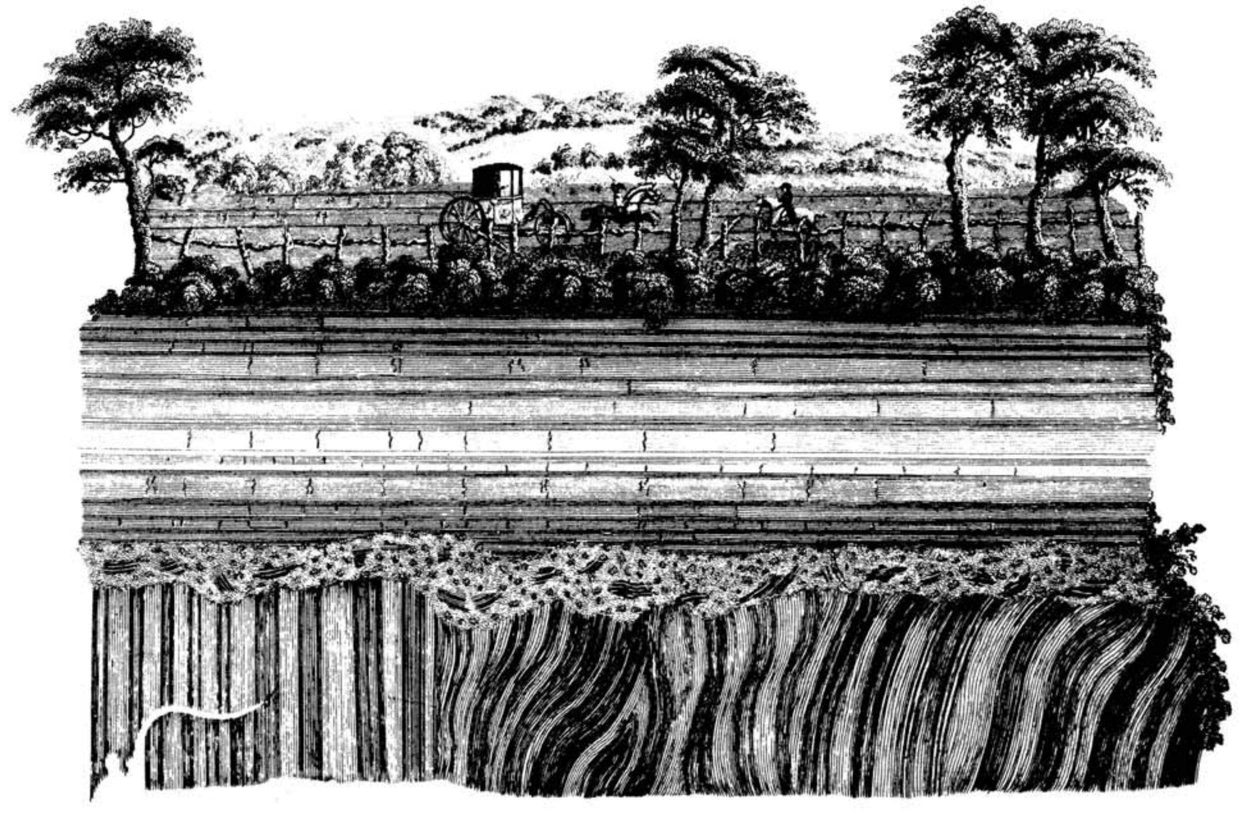


Figure 35. Unconformity with basal conglomerate along the River Jed, south of Edinburgh, Scotland. [James Hutton, "Theory (sic) of the Earth", 1795.]

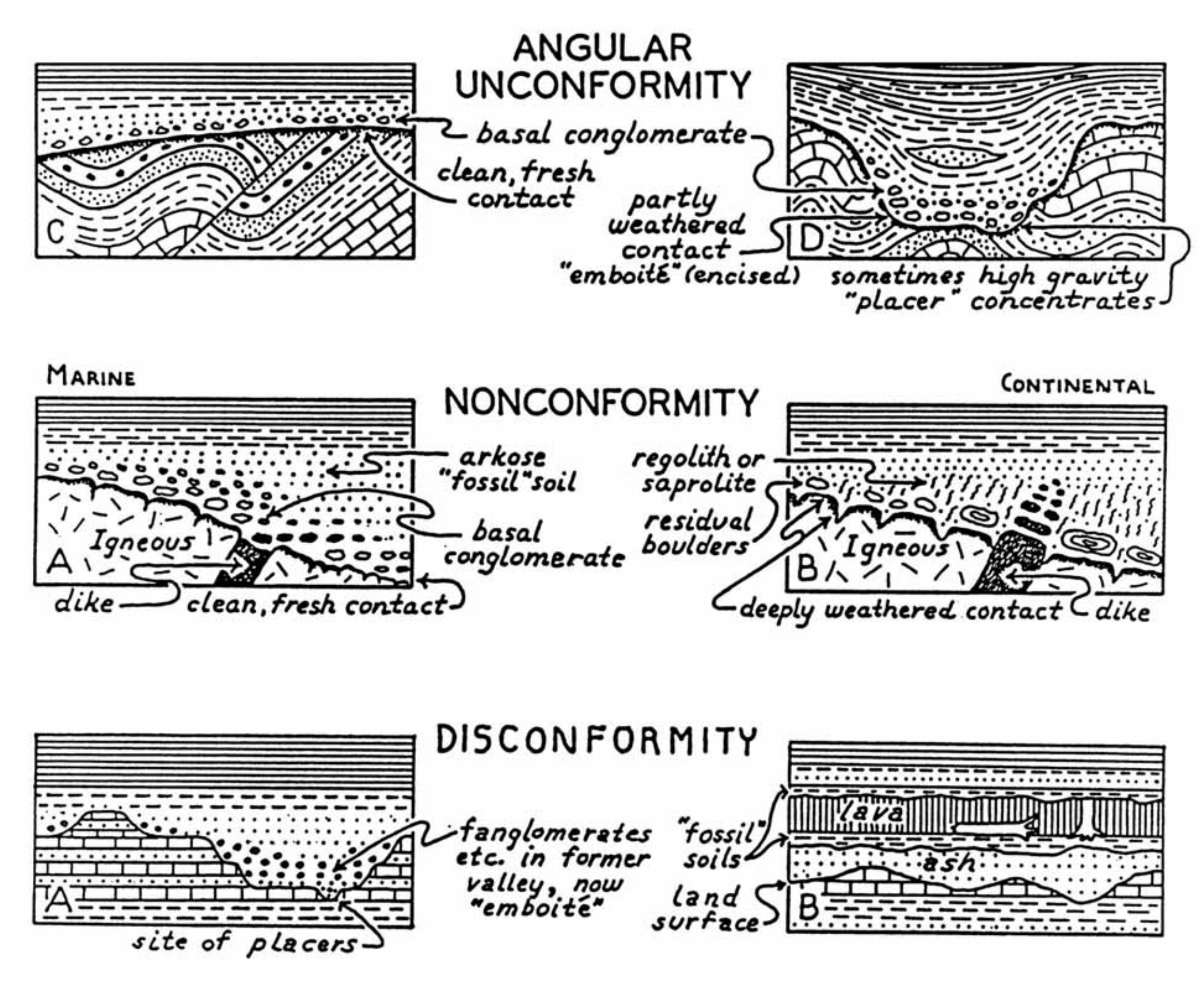


Figure 36. Varieties of geologic relationships along surfaces of unconformity, which mark gaps in the geologic record. (Drawings by Rhodes W. Fairbridge.)

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 plutons. 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 or indirectly by crosscutting relationships with formations of the country rock or by finding pebbles of the pluton in younger formations.

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.

STRUCTURAL GEOLOGY OF NORTHWESTERN NEW JERSEY

Under this heading, we describe the relationships among the various physiographic provinces (or morphotectonic belts) that trend NE-SW across northwestern New Jersey. Refer back to Figure 2 for the following discussion. Our headings in this section are: Distinctive Features of Appalachians in New Jersey, Boundaries of Morphotectonic Zones, Some Ideas (Some "Orphaned") Based on New Jersey Geology, and Age(s) of Paleozoic orogenies.

Distinctive Features of the Appalachians in New Jersey

From the Hudson River northwestward are six major morphotectonic belts (these are more or less the same things that we referred to as physiographic provinces in an earlier section). These belts are: (1) Newark basin (rocks of Upper Triassic-Lower Jurassic ages); (2) Southeastern part of New Jersey Highlands (Ramapo block; Proterozoic basement complex); (3) Green Pond-Bellvale-Schunnemunk belt (complexly folded and faulted Silurian-Devonian strata); (4) Northwestern part of New Jersey Highlands (Wawayanda-Franklin-Pochuck block; Proterozoic basement complex); (5) Appalachian Valley and Ridge Province (Wallkill Valley and vicinity); and (6) the Kittatinny monocline-fold belt.

Four peculiarly distinctive features of the New Jersey segment of the Appalachians contrast with those found in the segment of the Appalachians in eastern New York State and elsewhere. These are: (1) lack of a high-standing Blue-Ridge type of boundary on the SE side of the Appalachian Valley; (2) Proterozoic rocks lying above Paleozoic sedimentary strata along low-angle thrusts; (3) virtual absence of Taconic-type rocks; and (4) presence of a wide remnant of the Newark basin-filling strata. In the following paragraphs we elaborate briefly on these four points.

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

(2) The Proterozoic rocks of the Reading Prong are known in at least two places to lie above the Paleozoic rocks along one or more low-angle thrust faults. These two places are (a) the Musconetcong tunnel built by the Lehigh Railroad through Musconetacong Mountain in the mid-19th century and (b) Jenny Jump Mountain.

(3) The near absence of any Taconic-Sequence rocks in the NW New Jersey Appalachians contrasts decidedly with the great abundance of such rocks in eastern New York State. In New Jersey, the only place known to JES where Taconic rocks are exposed is around the town of Jutland, where a transverse anticline of mid-Jurassic age brings up the pre-Newark rocks in a small area. Typical purple-, red-, and green slates, diagnostic Taconic rocks, are well exposed in new roadcuts and building excavations (Sanders, 1962a). From this small area, one can infer that a belt of outcrop of Taconic rocks crosses NW New Jersey, but is mostly concealed because it has been buried beneath the Upper Triassic-Lower Jurassic strata filling the Newark basin. Other Taconic-type rocks may be present in New Jersey but are not easy to recognize as such because they have been metamorphosed (as in New York City).

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

Boundaries of Morphotectonic Zones

The boundaries of most of the morphotectonic zones are faults of one kind or another. Two exceptions are: (a) the basin-filling strata of the Newark-basin belt nonconformably overlap the pre-Newark metamorphic rocks of the Manhattan Prong and (b) the Kittatinny monocline-fold belt disappears to the NW by a change in dip of the strata from steep to horizontal.

Our main emphasis is on the kinds of fault boundaries and implications of the thrusting of the Proterozoic rocks. The Ramapo fault between the Newark basin-filling strata and the Proterozoic rocks of the Ramapo Highlands block is a real "old timer;" it has been active intermittently for 1.1 billion years (Ratcliffe, 1971). This fault and those connected with it are steep brittle faults in contrast with many of the low-angle faults characterized as ductile shear zones (Ratcliffe, 1980). According to JES, the Ramapo fault zone has been displaced by the Hopewell and Flemington faults, which he considers to be two post-Newark strike-slip faults (Sanders, 1962a).

As mentioned in a previous section, Isachsen's (1964) concept of massive low-angle thrusting of the Proterozoic rocks over the Paleozoic sedimentary strata involves at least three implications relative to the structural geology of northwestern New Jersey. The first and most far-reaching of these implications is that these basement rocks of the Ramapo Highlands belt (the eastern belt of the Highlands province) and of the northwestern Highlands belt (the Wawayanda-Franklin-Pochuck block) do not extend indefinitely downward, as drawm in the cutaway slice in Figure 2. Instead, if they are part of a great thrust sheet, the "basement rocks" extend downward only to one or more low-angle thrust faults. And below the low-angle thrusts are more Paleozoic rocks [and still deeper, of course, more Proterozoic rocks rocks (but probably of kinds not like those on the upper thrust sheet)]. Instead of being parts of elevated blocks, as suggested in the cutaway slice of Figure 2, therefore, the Proterozoic rocks of these two belts of the Reading Prong are just the opposite. The regional structure is not an anticlinorium, as described by Rodgers (1971) but rather that of a synclinorium. In other words, deeper erosion of these highland blocks would probably not expose more and more Proterozoic rocks, but conceivably could remove all of the Proterozoic rocks, as has nearly happened in the klippe belt of SE New York State near Monroe. (See Figure 11.)

A second implication of Isachsen's thrust interpretation is that some of the areas underlain by Paleozoic rocks within the New Jersey Highlands, rather than being parts of downdropped graben blocks as shown on Figure 2, could be fensters. (See Figure 32.)

A third implication deals with the relationships of the Silurian-Devonian rocks of the Green Pond-Bellvale-Schunnemunk belt to the Proterozoic rocks. According to Finks (1968) and Finks and Raffoni (1989), within this belt, the Lower Silurian Green Pond Formation overlaps onto Proterozoic basement rocks. Finks and Raffoni inferred that this relationship resulted from an episode of pre-Silurian uplift and erosion to strip away the Paleozoic cover and expose the Proterozoic basement rocks. Another possibility is that the Proterozoic rocks are part of a great thrust sheet, as inferred by Isachsen (1964). If so, then the overlap of Lower Silurian rocks proves the Taconian age of the thrusting.

If the thrust sheets moved across the floor of the northern Appalachian foreland basin, as some did in southeastern New York (Sanders, 1995), then one can expect to find in the dark shales beneath the thrust pieces of the rocks from the thrust sheet. This would be an inevitable consequence of a thrust sheet moving across the former sea floor, shedding its own debris off the front of the sheet and then advancing over it. The absence of such thrust-derived debris implies that the thrusting took place after the foreland basin had been destroyed. The age of the thrusting therefore could still be Taconian (but post-foreland basin). Overlap of the Lower Silurian onto the thrust sheet precludes a much later age (Appalachian, for example).

The JES interpretation of the structural features within the Bellvale Mountain block (See Figure 37.), implies that in this block are typical tight folds and broken folds of the Late Paleozoic Valley and Ridge deformation. If the thrust sheet containing Proterozoic rocks was already in place beneath the Lower Silurian rocks, then the Proterozoic rocks must have been so thin that they did not affect the style of folding.

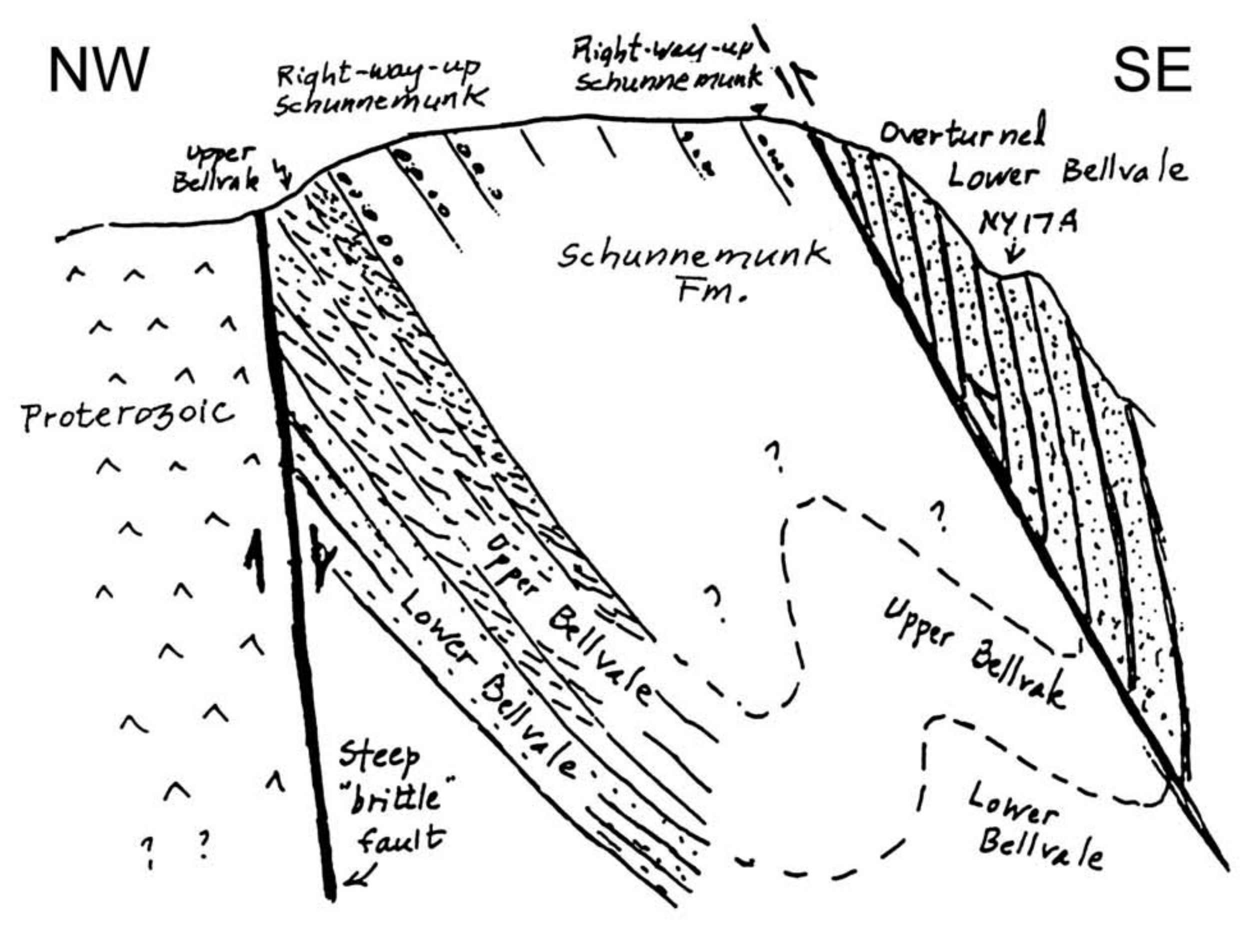


Figure 37. Schematic profile-section through Bellvale Mountain along NY Route 17A, showing inferred thrust fault breaking across the fold axis and displacing the overturned limb against the normal limb. (JES, based on results of student mapping in August 1981 in the "ad-hoc" Barnard summer field camp based in Monroe, NY.)

A renewed interest in the structural geology of the Green Pond-Bellvale-Schunnemunk belt 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" (Harding, 1985; Figure 38) are present along the SE side of the Reservoir fault zone, which forms the border of the western belt of the Green Pond outlier in NW New Jersey and which has been inferred to display significant right-lateral strike-slip movement. Latest movement on the Reservoir Fault has been inferred to be of Late Paleozoic age, although the constraints listed range from post-Medial Devonian to Triassic (Malizzi and Gates, 1989). JES finds this evidence for right-lateral strike-slip movement of more than casual interest in view of the JES "minority-of-one" interpretation of the strike-slip offsets on the Hopewell and Flemington faults that cut the Newark and associated strata in the Delaware River Valley and adjacent areas (Sanders, 1962a). Not much straining of geologic credulity is required to connect the Flemington fault (with its JES-inferred 19 km of right-lateral strike-slip displacement accompanying a dip-slip shift of approximately 3 km) and the Reservoir fault. If this intuitive leap by JES proves to be correct, then the age of the deformation on the Reservoir fault becomes mid-Jurassic. Thus, the combined Hopewell-Reservoir fault assumes a big-league status not heretofore imagined.

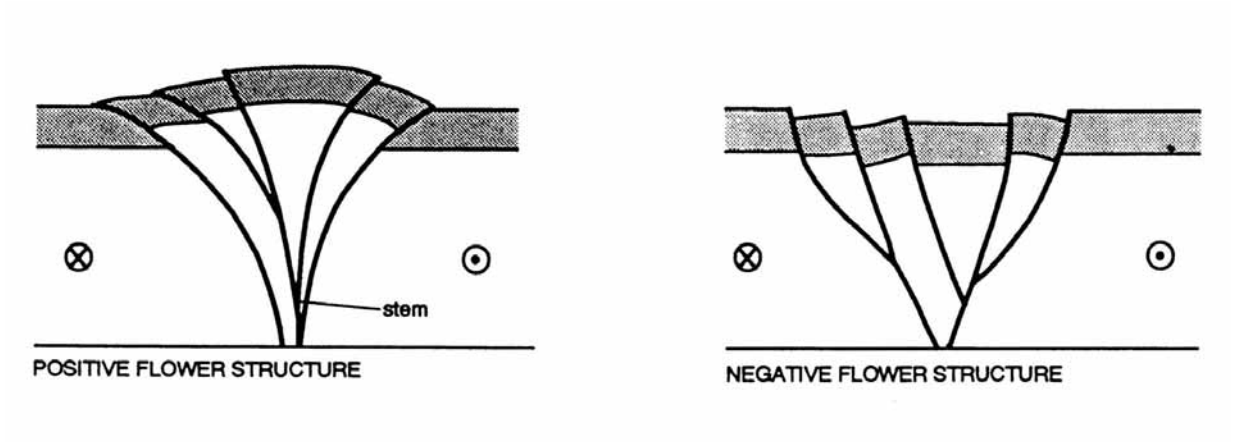


Figure 38. Sketches of "flower structures," upward-diverging faults associated with a strike-slip fault. (N. H. Woodcock and C. Schubert, 1994, fig. 12.13, p. 259.)

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

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

(2) The geological footprints left behind by the Taconic orogeny in NW New Jersey are less obvious than in eastern New York state. We think that the "big one" from the Taconic orogeny in NW New Jersey was the massive low-angle thrusting to the NW of Proterozoic basement rocks over the Paleozoic strata, as inferred by Isachsen (1964). Moreover, these thrusts sheets may have moved across the floor of the foreland basin in which the Martinsburg

strata were accumulating. Thus, the conditions for the origin of the slaty cleavage, as visualized by J. C. Maxwell (1962) can be invoked with confidence and we think, assigned to the Taconian orogeny. (The foregoing remarks are not in any way meant to suggest that we deny the evidence showing that overthrusts also took place during the Late Paleozoic Appalachian orogeny.)

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

Age(s) of Paleozoic Orogenies

The rocks of the Appalachians have experienced at least three Paleozoic orogenic episodes. These were originally named Taconian (Late Ordovician), Acadian (Medial Devonian), and Appalachian (Late Paleozoic). The last was viewed as the grandest of them all and its premier status signalled by the name of Appalachian Revolution. We first review the status of the term Appalachian in light of Woodward's proposal to downgrade it. Thereafter, we take up the evidence bearing on the ages of the Paleozoic orogenic deformation.

H. P. Woodward's Proposal to Downgrade the Appalachian Revolution to the Alleghenian Disturbance

In 1957, H. P. Woodward proposed the interpretation that in the northern Appalachians, the last "significant" deformation had taken place in medial Devonian time. Moreover, Woodward (1957a, b) specifically rejected the "classical" viewpoint that the Appalachian "Revolution" (a supposedly terminal Appalachian event) marked the orogenic climax in the Appalachians. Woodward was convinced that the basis for the Appalachian "Revolution" lay somewhere between trivial and non-existant. Accordingly, he proposed the ultimate trivialization of the "good-old" "Appalachian Revolution:" he supplanted Appalachian with "Alleghenian" and "Revolution" with "disturbance."

Woodward's proposal has been accepted by large numbers of Appalachian geologists. Geologists studying the Appalachians kept on calling themselves Appalachian geologists after the geographic name of the mountain chain. In effect, they restricted their use of "Appalachian" to the name of the mountain chain and followed Woodward in referring to the Late Paleozoic deformation as the Alleghenian "disturbance." (We shall start a new trend by referring to these folks as Alleghenian geologists).

What has been happening since Woodward's proposal is that more and more evidence has been compiled to show that the Late Paleozoic deformation was considerably more vigorous than Woodward visualized. In other words, the "Alleghenian" is being upgraded. That situation strikes us as being absurd. If the evidence supports the conclusion that the Late Paleozoic deformation was not a ho-hum affair (as we might paraphrase the Woodward viewpoint), then why not reject the upstart term, Alleghenian "disturbance" and bring back the "good-old" Appalachian orogeny?

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

But, as is explained subsequently, certain geologic ideas are like cats (they have 9 lives) or a pendulum (they swing back and forth). The swinging has been back and forth has been between late in the Paleozoic Era (the Appalachian orogeny) and Medial Devonian (the Acadian orogeny). Our brief review of previous ideas about the age of Appalachian deformation illustrates these changes.

Some Previous Ideas About the Age of Appalachian Deformation

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

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

The current fashion is to base one's belief about this age question on various structural considerations. A few of the possibilities in this department include: (a) sizes of folds, (b) trends of folds, and (c) structural "style." The following paragraphs take up these topics and such other matters as structural fabric and radiometric ages of minerals. We close this section with some remarks about plate-tectonic considerations.

Age of Deformation Based on Sizes of Folds

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

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

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

As far as we are concerned, nothing that has appeared in the geologic literature in the past 26 years requires any change in the foregoing paragraph.

Age of Deformation Based on Trends of Folds

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

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

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

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

Age of Deformation Based on Style of Deformation

The concept that each orogeny is characterized by a distinctive style of deformation is another slippery sort of business that has prompted large amounts of geologic arm waving. The idea seems sound enough but is not always easy to apply. In the case at hand, because no agreement exists on what structures are Acadian and what structures, Appalachian, how can "style" be resolved? JES has no idea what should be considered Acadian style, but the regional evidence amassed from Pennslvania southward and now creeping into New York, is that Appalachian style involves large-scale bedding thrusts (J. L. Rich, 1934). JES discovered such thrusts in the Little Mountains in 1969; they are now popular topics of research (Marshak, 1986; Marshak and Tabor, 1989; Merguerian and Sanders, 1991a).

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

Structural Fabrics

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

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

Radiometric Ages on Minerals

In some situations, a radiometric age on one- or more minerals may yield numerical information that assists in dating orogenic events. Examples include minerals, such as micas and feldspars, that recrystallized during an episode of deep burial and regional metamorphism (as the 420-ma dates on rocks from the northern Manhattan Prong and 365-ma dates on rocks from most other parts of the Manhattan Prong). Recently, radiometric ages have been determined by the U. S. Geological Survey on the lead-bearing minerals from the old mineral prospect pits in the Shawangunk district. A mid-Mesozoic age is indicated (J. D. Friedman, personal communication to JES in 1994).

Plate-tectonic Considerations

Students of the plate-tectonic history of the Appalachians have not reached total agreement about the relative effects of- and about the circumstances involved in the changes from a given long-established plate-tectonic regimen to a contrasting regimen. What is generally agreed upon, however, is that the passive-margin regimen that became established in the middle of the Jurassic Period, when the Atlantic Ocean began to open, more or less duplicates a previous such regimen that became established during the Cambrian Period and persisted until the middle of the Ordovician Period.

Nearly all those who have ventured a point of view on the subject of the relationship of the Newark basin and the Atlantic-Ocean episode advocate the concept that the Newark basin is a product of regional extension-type tectonics and that this episode of extension was associated with the beginning of spreading at the Mid-Atlantic Ridge.

As we have recently explained (Merguerian and Sanders, 1994b; 1995) we disagree totally with this "party-line" dogma that Newark extension equals Atlantic spreading. We think that the "party-line" view starts off wrong and then goes steadily downhill from there. We ascribe the growth-, filling-, and destruction of the Newark basins to non-extensional tectonic events that entirely preceded the start of opening of the Atlantic Ocean. In our view, the Newark should not be relegated to an insignificant position as a byproduct of the Atlantic cycle, but rather assigned to a highly significant episode of rapid plate readjustments (and associated paleomagnetic changes) that took place after the Appalachian episode had been completed and before the Atlantic cyle got started.

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

LAYER VII: PRODUCTS OF QUATERNARY GLACIAL EPISODES

Our discussion of the products of Quaternary glacial episodes includes not only the Pleistocene deposits made by continental glaciers that formerly flowed across the region and various bodies of outwash that were deposited when the glaciers melted but also the kinds of features eroded on the bedrock surfaces affected by glacial ice. The important subject of which way the now-vanished glaciers flowed can be determined by features eroded on the bedrock by the ice and by glacial sediments, such as directions of displaced indicator stones and the orientations of the long axes of drumlins. We begin with diretional features eroded on the bedrock.

Directional Features Eroded on Bedrock by Glacier Ice

Glaciers create several kinds of features on bedrock that enable a geologist to infer the direction of glacial flow. These include linear scratches and even large grooves, crescentic marks, and elongate features such as roche moutonnées, "roche-moutonnée structures," and rock drumlins.

The linear features are easy to use: the ice flowe along the trend of the linear grooves, striae, and other elongate features.

In some places, the ice created various crescentic marks (Flint, 1971, p. 95; G. K. Gilbert, 1906; S. E. Harris, 1943; P. MacClintock, 1953). The use of crescentic marks for inferring the direction of ice flow is based on the asymmetric longitudinal profiles through the centers of the crescents. The ice came from the gently dipping side. The direction of concavity is not reliable. Crescentic gouges are convex in the direction of flow. Lunate fractures are concave in the direction of flow (Figure 39).

Glaciers also sculpt larger-scale asymmetric relief features in the bedrock known as roche moutonnées (Figure 40). These are smooth and broadly rounded; they dip gently toward the side from which the ice flowed. (This is a result of the glacier's grinding on an obstruction to flow.). By contrast, they are jagged, irregular, and steep on the side toward which the ice flowed [a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction. (See Figure 23.)]

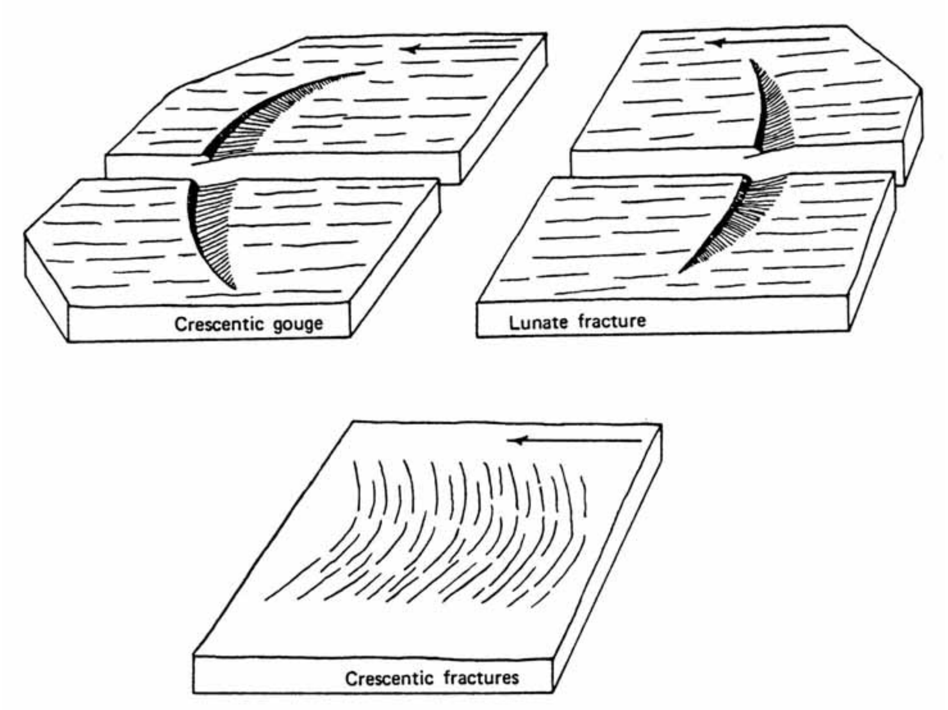


Figure 39. Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

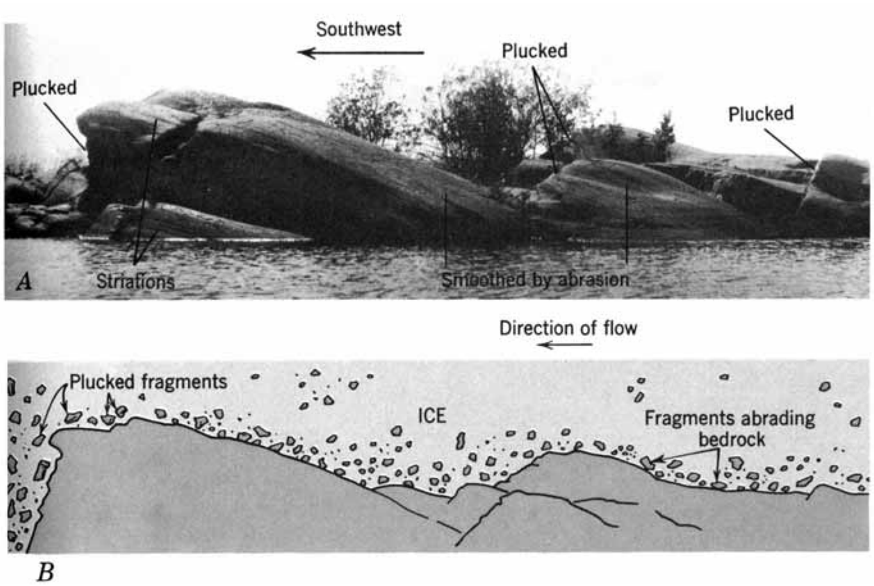


Figure 40. Roche moutonnées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of a roche moutonnée sculpted in Proterozoic granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnée beneath a restored, now-vanished glacier.

Ice-flow Direction Inferred From Glacial Sediments

Direction of flow may also be inferred by studying certain aspects of glacial sediments. These include provenance (the source of the particles in the deposits) and the orientations of the long axes of elongate streamlined hills known as drumlins.

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.

Drumlins are asymmetric, elongate features fashioned by a glaciers. The long axes of drumlins are parallel to the flow direction of the ice; the steeper side is toward the direction from which the ice came. Drumlins consist of till, of bedrock, or of some combination of till and bedrock. The term used by itself implies a feature composed of till. A rock-cored drumlin is one containing both till and of bedrock. A rock drumlin consists only of bedrock. (JES does not know why a glacier forms a rock drumlin instead of a roche moutonnée or vice versa.)

Implications of Our Results

We have studied the topics of flow directions of former Quaternary glaciers in the New York City region by recording the orientations of striae, crescentic marks, directions of asymmetry of roche moutonnées, the directions of displacement of indicator stones, and the orientations of the long axes of drumlins. We think that all this evidence shows that more than one glacier flowed across the New York region. Moreover, the flow indicators prove that the ice came from not one but rather from several directions.

Figure 41 shows a map of North America with what was for a long time the standard view of how the Pleistocene ice covered Canada and northern United States. Notice that New York is within the flow pattern shown for the Labrador Ice Sheet.

Given the concept that ice from the Labrador center should have been present in New York City, then the expected direction of such glacier flow is from the NNE to the SSW, a direction that is parallel to the Hudson River. However, in Manhattan and on the top of the Palisades Ridge, striae are oriented from about N20°W to S20°E, or even more toward the NW-SE direction. A previous generation of glacial geologists adopted the view of deviated flow from a central lobate glacier (Figure 42).

According to this concept, the main flow of the latest (and, according to many, the only Wisconsinan) glacier was concentrated down the Hackensack lowland, but the ice deviated to its left and crossed the Palisades ridge and New York City on a NW-to-SE course. This concept of a single glacier flowing in a direction that is parallel to the Hudson Valley was reinforced by the results of thousands of engineering borings through the thick bodies of sediment underlying the Hudson, Hackensack, and other valleys that trend NE-SW. These borings show bedrock overlain by a fresh till that is in turn overlain by outwash (sands/gravels and/or lake clays and -silts) that is overlain by estuarine deposits. By contrast, the borings from valleys that trend NW-

SW display a more-complicated succession of sediments. JES infers that these complex sediments in the fillings of valleys that trend NW-SE are products of glaciers that flowed from NW to SE that that would tend to deepen valleys having orientations parallel to their direction of flow. Any sediments that were deposited in valleys trending NW-SE would tend to be preserved from destruction by ice flowing from NE to SW. By contrast, any such complex deposits that may have been deposited in valleys trending NE-SW would have been especially vulnerable to total removal by a glacier flowing from NE to SW.

Figure 41. Reconstruction of North American Pleistocene Ice Sheets with Keewatin center and Labrador center shown as attaining simultaneous maxima. Further explanation in text. (U. S. Geological Survey).

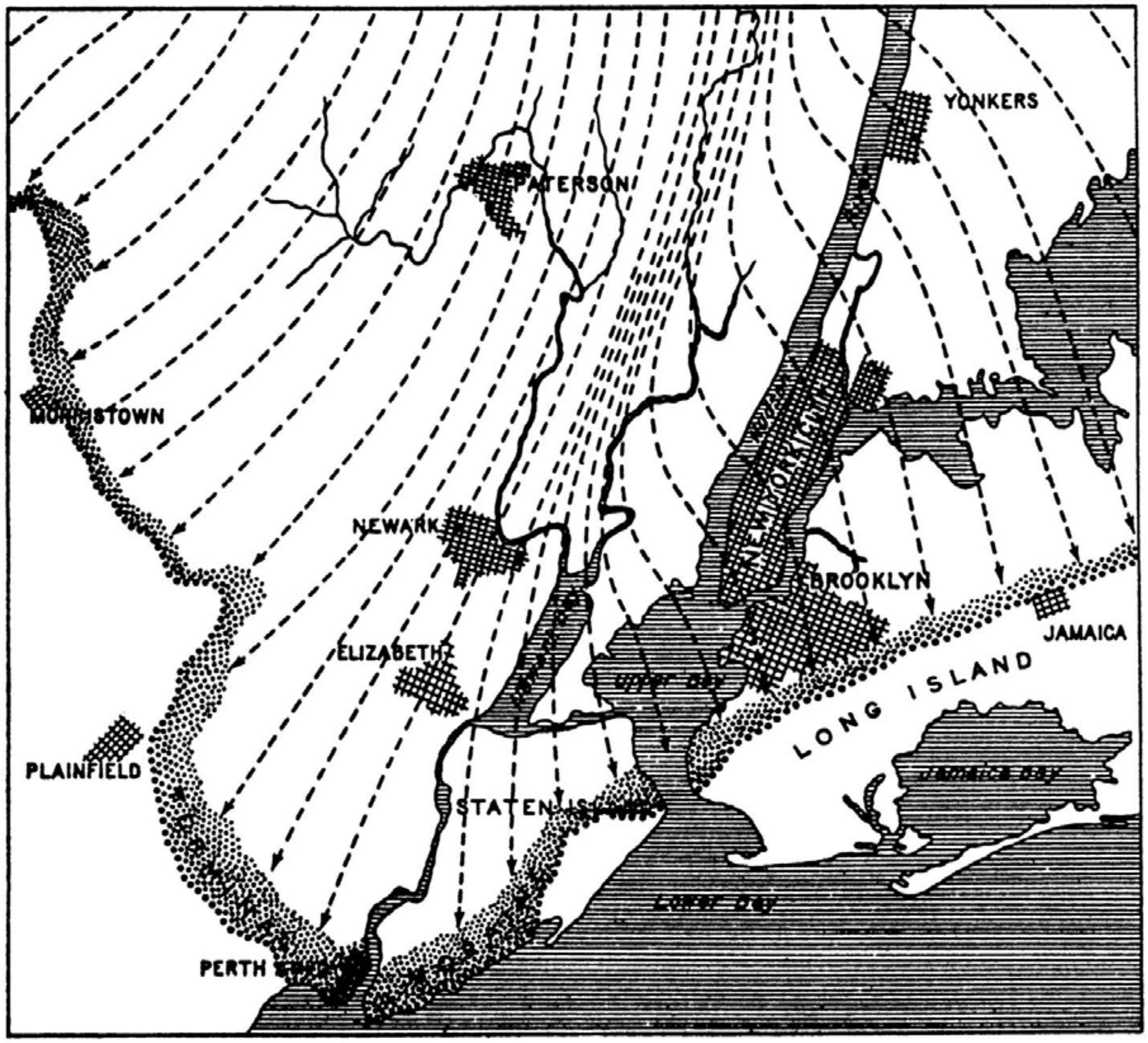


Figure 42. Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (U. S. Geological Survey, Passaic Folio, No. 157, Figure 11, 1908, rendering of R. D. Salisbury).

From studying the stratigraphic relationships, provenance, grooves and crescentic gouges on bedrock surfaces, directions of asymmetry of roche moutonnée and of drumlins, we propose an alternative view. In our scheme of things, the flow indicated in Figure 42 is not the product of one glacier, but of more than one (two, possibly more). Figures 43 and 44 show how we interpret the glaciers in the same area of Figure 42. In Figure 43, the ice flowed rectilinearly from NW to SE, across the highest ridges and across the Hudson Valley without deflection. This suggests a thick ice sheet whose flow pattern was governed by the gradient on the top of the glacier. Figure 44 shows the flow from NNE to SSE as resulting from a later glacier. According to us, the two prominent moraine ridges on Long Island resulted from ice flowing as in Figure 43. The latest glacier, shown in Figure 44, did not reach much of Long Island. It covered parts of Queens and Brooklyn, Manhattan, and Staten Island. What its terminal moraine was like is not yet known.

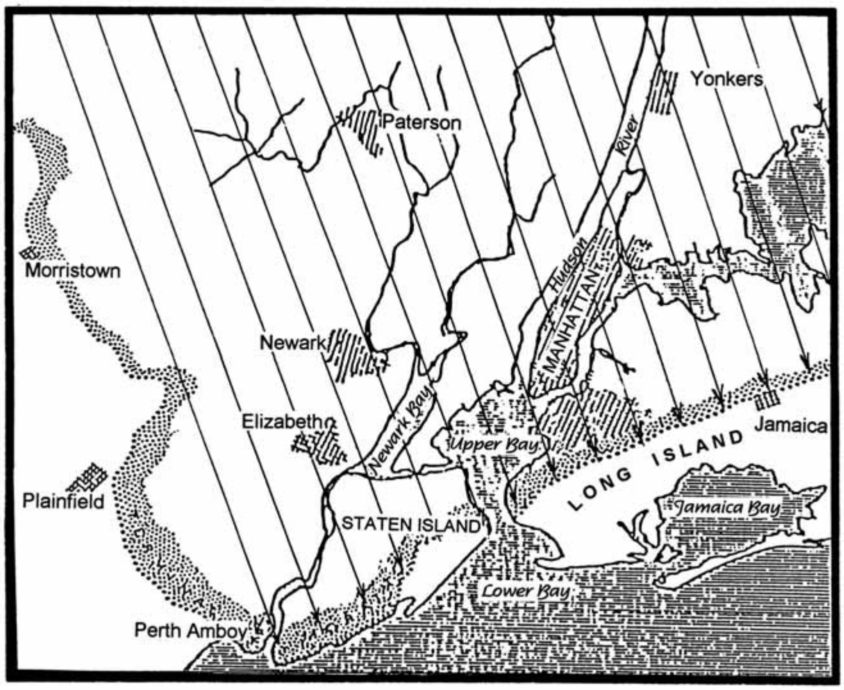


Figure 43. Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. (J. E. Sanders).

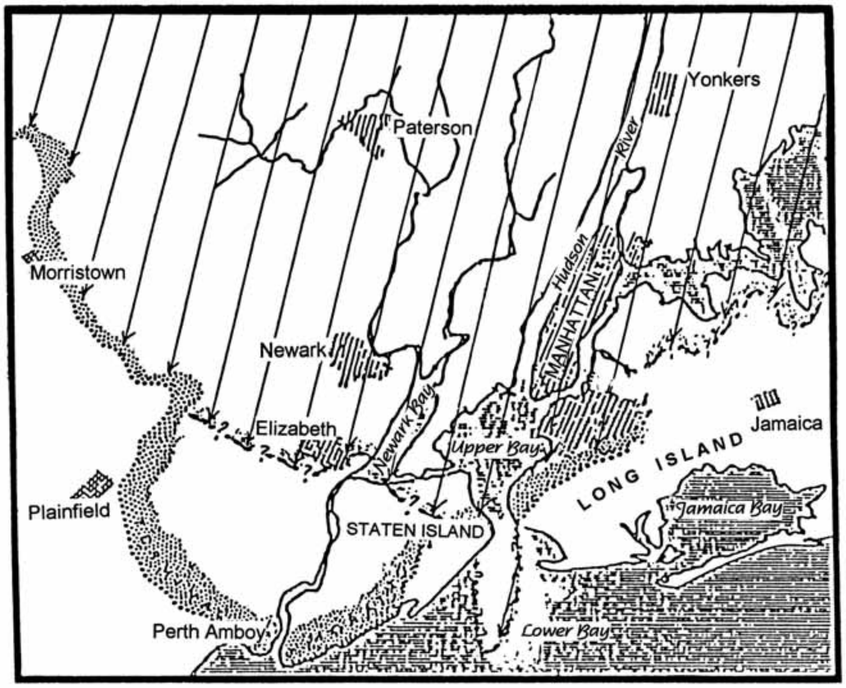


Figure 44. Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

The distribution of erratics derived from as far away as the anthractite district in eastern Pennsylvania (Figure 45) in the red-brown tills and -outwashes in localities east of the Hudson River (as in New York City and Westchester County, New York) lends strong support to our interpretation shown in Figures 43 and 44, as contrasted to Figure 42. The finding by JES of natural erratics of anthracite in the red-brown till in the Hudson Valley suggests that the fossiliferous pieces of Carboniferous material found in the Country Club Road excavations in the Bronx are glacial erratics and not indicators of a buried Carboniferous basin, as suggested by Zen and Mamay (1968).

Evidence for glacial flow from the NW to the SE is not confined to the territory near New York City. Figure 46 shows examples based on swarms of drumlins near Charlevoix, Michigan (northwestern part of southern peninsula) and on indicator stones in New England.

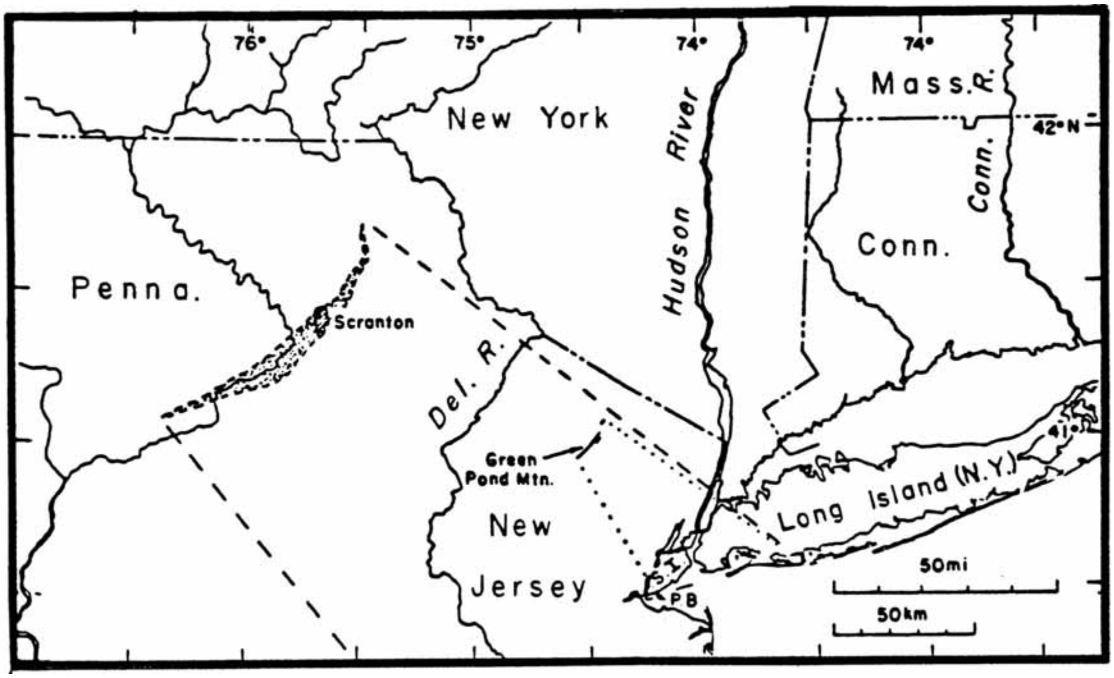


Figure 45. Map of distinctive indicator stones found in till in New York City, (1) anthracite from northeastern Pennsylvania, and (2) Green Pond Conglomerate from northern New Jersey, support interpretation of rectilinear flow of glacier from NW to SE. Stippled area, outcrops of anthracite coal; S. I. = Staten Island; P. B. = Princess Bay. (G. M. Friedman and J. E. Sanders, 1978, Figure 2-1, p. 27.)

Pleistocene Deposits

The Pleistocene sediments consist of several contrasting varieties deposited either directly by now-vanished continental glaciers or as a consequence of the melting of these glaciers. We will be especially interested in the characteristics of till and outwash and the stratigraphic relationshiops of these two kinds of glacial sediments with themselves and with other kinds of sediments.

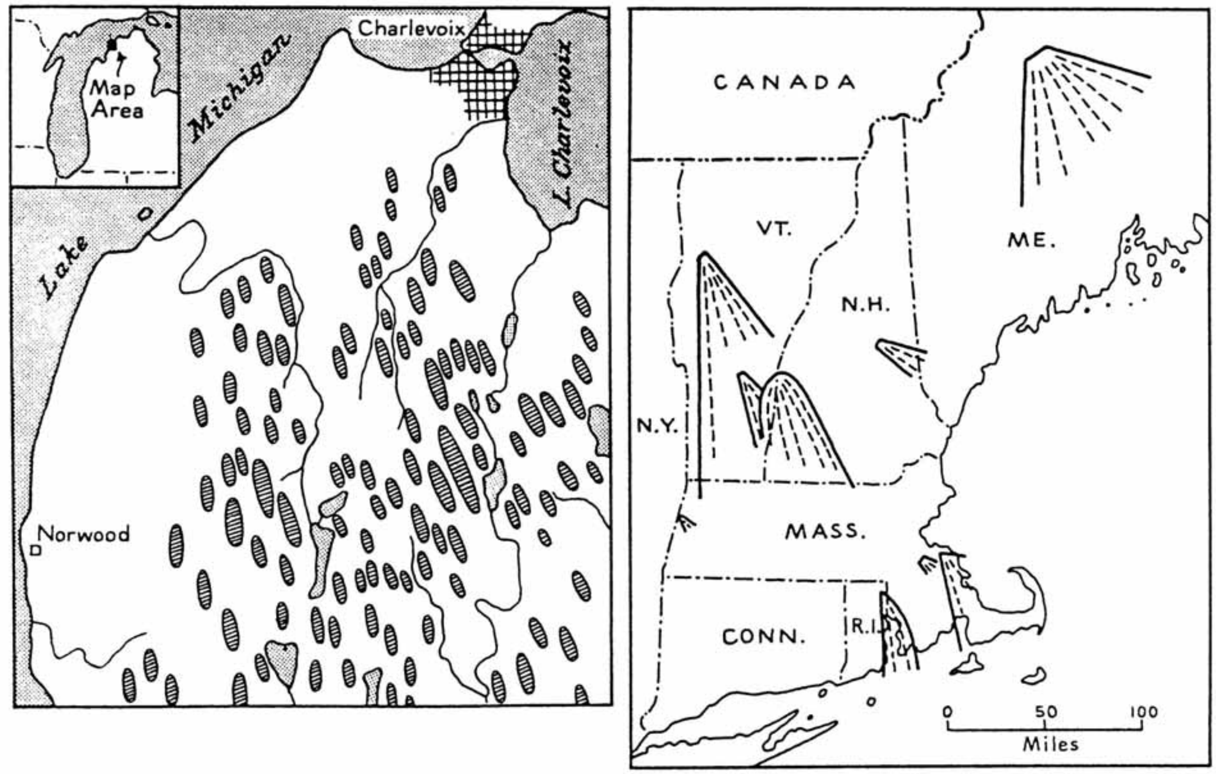


Figure 46. Sketch maps showing other regions in the United States where glacier flow was from NW to SE.
A. Swarm of drumlins south of Charlevoix, Michigan. (Frank Leverett, and F. B. Taylor, 1915, p. 311; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-20, p. 188.)
B. Boulder trains in New England, all products of regional glacier flow from NW to SE. (J. W. Goldthwait, in R. F. Flint, 1945; redrawn by L. D. Leet and Sheldon Judson, 1965, fig. 13-22, p. 190.)

Till

Till is a general name for any sediment deposited directly by the flowing ice of a glacier. Typically, till is not stratified and contains a wide range of particle sizes, from boulders to clay.

In addition to ripping up individual fragments from the material over which it passes, a glacier may also deform the strata it overrides. The Pleistocene glacier that deposited the Harbor Hill Moraine on Staten Island 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 (Sanders, Merguerian, and Okulewicz, 1995a, b).

Outwash

Outwash is a general term for any sediment deposited by water melted from a glacier. Outwash includes such contrasting sediments as stream sands and lake clays. The key point about recognizing outwash is the stratification that resulted from the action of water.

In the region of today's trip, most of the outwash has been submerged; it lies beneath the estuarine sediments deposited by the rising sea. But, no account of the geologic history of the New York City region would be complete without a discussion of the freshwater lakes that occupied the Hudson valley from the time when the last glacier disappeared (about 13,000 years ago) until the sea invaded the area (about 11,000 years ago).

When the most-recent of the Wisconsinan glaciers (the Woodfordian, reaching a maximum about 14,000 yr ago, and beginning its rapid disappearance starting about 13,000 yr ago), had attained its southernmost limit, it completely covered the basins now occupied by the Great Lakes. By 13,000 yr ago, the retreating ice had uncovered the south end of today's Lake Michigan basin and much of the basin of modern Lake Erie. The only outlet available was situated at Chicago, via the Illinois River into the Mississippi and Gulf of Mexico. By about 10,500 yr ago, the ice had melted out of the basins of Lake Michigan, Lake Erie, and Lake Ontario, but still covered the eastern part of the basin of Lake Superior and the northern part of the basin of Lake Huron. The St. Lawrence outlet was plugged; hence, the water drained out of Lake Ontario into the Mohawk, then eastward to a large lake that occupied the Hudson Valley and adjacent lowlands. Counts of varves (sediments deposited in a year) in the proglacial-lake clays at Little Ferry, New Jersey (Reeds, 1926, 1927, 1933) showed that this arrangement lasted for at least 2,550 years. The south end of this narrow lake was formed by the natural dam of the Harbor Hill moraine. Two factors, dates not well known, contributed to the demise of this Hudson Valley lake: (1) the dam burst at The Narrows, and the surge of water is thought to have eroded the Hudson Shelf Valley; (2) the ice melted out of the St. Lawrence lowland, making possible the modern-day discharge route into the Gulf of St. Lawrence, Canada.

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. Many onion fields are present between Warwick and Pine Island. The digging of the drainage ditches in these flat bottom lands has, on occasion, revealed mastodon bones.

Hogwash

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

Stratigraphy of Pleistocene Sediments

The stratigraphy of glacial deposits is worked out by noting the relationships among till, outwash, and sediments that have nothing at all to do with a glacier and, in fact, were deposited under a climate regime that is nonglacial. In a coastal area such as New York, glacial deposits are interstratified with marginal-marine deposits. This has resulted from the relationship between growth of continental ice sheets and the volume of water in the ocean basins. Professor R. A. Daly, of Harvard, once described this relationships between glacial ice and the water of the oceans as one of "robbery and restitution." By robbery, he meant the locking up of the water in the glaciers. By restitution, he meant the return of the water to the oceans when glaciers melted. Although the exact climate settings involved in these changes are not as exactly known as one might suppose, it is well established that when the glaciers reached their maximum extents, the sea was at its lowest stand, a level around 75 m lower than now.

Long Island's two world-famous terminal-moriane ridges, the southern and older Ronkonkama and northern and younger Harbor Hill moraines figure prominently in most interpretations of the glacial geology of New York City and vicinity. The "standard" view [and the one adopted by the New York State Geological Survey in its recently published surficial geologic map of New York State (Cadwell, 1986, 1988)] follows the T. C. Chamberlin (1883) interpretation that Long Island's moraines were deposited by a single glacier. Although Fuller (1914) accepted the view that a single glacier had deposited these two moraines, he assigned them to the Early Wisconsinan. Starting in the mid-1930's (Fleming, 1935; MacClintock and Richards, 1936) the ages assigned to these two moraines changed from Early Wisconsinan to Late Wisconsinan (a substage now known as the Woodfordian)

Our field studies made in connection with preparation of guidebooks for these On-The-Rocks trips (recently summarized in Sanders and Merguerian, 1994a, b; 1995) have turned up evidence that is completely at odds with the prevailing "one-glacier (or possibly at the most, two)" view of the Pleistocene sediments in New York City and vicinity and, we think, totally disproves the interpretation that the Harbor Hill Moraine was deposited by the Woodfordian glacier.

Our argument about the age of the Harbor Hill Moraine is based on provenance. We have found abundant evidence consistent with what Woodworth (1901a) found Long Island City (Queens), where this moraine consists of distinctive reddish-brown sediments resting on a glaciated bedrock surface displaying striae oriented N20°W-S20°E. Clearly this moraine was deposited by ice that flowed across the Newark basin and arrived on Long Island following a path oriented about S20°E.

[By contrast, we think that the latest glacier, the Woodfordian, which flowed down the Hudson Valley, did not reach most of Long Island, but rather left its end moraines along the south coast of Connecticut (Flint and Gebert, 1974, 1976; the situation depicted in Figure 44)].

If we are correct that the Harbor Hill moraine is of pre-Woodfordian age, then the interstratification of glacial- and nonglacial sediments found in the borings in the general vicinity of Jones Beach assumes critical importance. Here, sandy strata interpreted as outwash deposited during times of emergence are interbedded with fossiliferous marginal-marine strata deposited during a submergent episode (Rampino, 1978 ms.; Rampino and Sanders, 1976, 1980, 1981a, b).

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

Our newly proposed correlations are summarized in Table 3. Notice that except for the age assignment of the Ronkonkoma Moraine, we support Fuller and reject all those who themselves rejected Fuller.

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 Catskill, 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

The objectives of today's On-The-Rocks field trip include:

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

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

3) Taking a leisurely walk through a part of Stokes State Forest for a detailed look at folds and superposed cleavage.

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

5) Looking for glacial features and indicator stones to develop ideas on superposed glaciation for this part of northwestern New Jersey, and,

6) To get to all of our intended stops for the day (we think we have a good chance at this one, for a change!).

LIST OF LOCALITIES TO BE VISITED

Stop 1: Scenic overlook, Kittatinny Mountain.
Stop 2: Sunrise Mountain.
Stop 3: Tillman Ravine, Stokes State Forest.
Stop 4: Martinsburg Slates, Hampton Township.
Stop 5: Jenny Jump Thrust, Newton County Mall.

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

Begins at NE corner Fort Washington Avenue and 179 Street, Manhattan, by Holy Rood Episcopal Church. Refer to the road map (Figure 47) for the field-trip route and positions of localities ("stops") discussed below.

Figure 47. Road map showing field trip route and stops (AAA).

0.0 Bear L for ramp to George Washington Bridge, upper level.
1.5 Passing tollgate on L; keep L for I-80 and I-95.
2.1 Bear R for I-80 local.
2.3 Take ramp on L to I-80 local.
2.7 Jones Road overpass; upper contact of Palisades sill exposed on R.
2.9 Top of sill at road level. Note contact-metamorphosed Lockatong Formation. Ahead is the strike ridge underlain by a sandstone in the Passaic Formation.
4.4 Leave Central Park quadrangle, enter Weehawken quadrangle.
4.5 Pass exit on R for Main St., Bogota.
4.8 Bear R for Exit 69 to I-80 local (Paterson).
5.8 Red sandstones and shales of Passaic Formation exposed on R.
6.2 More Passaic sandstones exposed on R.
6.3 Ramp on R for traffic entering on R.
6.5 Bridge over Hackensack River.
6.8 Pass Exit 66 on R.
7.6 Pass Exit 65 on R.
7.8 Leave Weehawken quadrangle, enter Hackensack quadrangle.
8.0 Pass Exit 64B on R. Exit 64B is for N.J. 17 South; move left one lane.
8.2 Pass ramp on R for Exit 64A, to N.J. 17 North
8.5-8.6 More Passaic strata dipping NW exposed on R.
9.4 Pass ramp on R for Exit 63.
9.7 More Passaic strata exposed on R.
10.0 Passing ramp on R for incoming traffic on R.
10.6 MP 63 on R.
11.0 Pass ramp on R for Exit 62, Garden State Parkway.
11.6 MP 62 on R.
12.0 Passing ramp on R for entering traffic from R.
12.6 Passing Exit 61 on R; to N.J. 507.
12.7 Leave Hackensack quadrangle; enter Paterson quadrangle.
13.1 Bridge over Passaic River; leave Bergen Co., enter Passaic Co.
13.2 Passing Exit 60 on R (to N.J. 20 North; move L one lane).
13.4 Passing ramp on R for Exit 59 to Market Street, Paterson; U.S. 46 and N.J. Route 20.
13.7 MP 60 on R.
14.3 Passing ramp on R for Exit 58B, Madison Avenue, Paterson.
14.4 View ahead to contact between top of red Passaic Formation and base of overlying Orange Mountain Basalt (= First Watchung of pre-Paul Olsen terminology).
14.5 Passing Exit 58A, Madison Ave., Clifton, on R.
14.9 Passing ramp on R for traffic entering on R.
15.9 Large cut on L of Orange Mountain Basalt showing columnar joints cut by five sub-vertical faults.
16.5 Passing Exit 56 ramp on R; Squirrelwood Rd., W. Paterson.
17.4 Bridge over Passaic River.
18.4 Pass ramp on R for Exit 55B.
18.7 Pass ramp on R for Exit 55A, Union Blvd., Little Falls.
18.9 MP 55 on R.

19.4 Passing through belt of outcrop of Preakness Basalt (Second Watchung Ridge, here cut by the gap through which the Passaic River flows).
20.1 Pass ramp on R for Exit 53, U.S. 46 and N.J. Route 23.
20.2 Leave Paterson quadrangle; enter Pompton Plains quadrangle.
21.1 Bridge over Passaic River (again); Leave Passaic Co., enter Essex Co.
21.5 Pass ramp on R for Exit 52, Lincoln Park. View ahead to Third Watchung Basalt Ridge (underlain by Hook Mountain Basalt).
22.0 MP 52 on R.
22.5 Start big curve to left.
23.0 MP 51 on R; start big curve to left.
25.1 Leave Pompton Plains quadrangle; enter Caldwell quadrangle.
25.7 Bridge over Passaic River; entering Montville Township.
26.2 MP 48 on R; pass ramp on R for Exit 48.
26.4 Cuts of Hook Mountain (3rd Watchung) Basalt.
27.7 Pass ramp for Exit 47 on R to U.S. 46 (Westbound) toward Parsippany.
28.0 Road divides. Keep L for I-80, do not veer R to I-287 (Morristown).
28.2 Leave Caldwell quadrangle, enter Morristown quadrangle.
31.3 MP 43 on R.
31.4 Pass ramp on R for U.S. 202.
33.1 Exposures on L of subvertical Proterozoic gneiss.
33.4 Interlayered mafic and felsic gneisses (See guidebook by John Puffer; also Avery Drake); MP 41 on R.
33.8 Leave Morristown quadrangle, enter Boonton quadrangle.
34.4 MP 40 on R.
35.0 Passing Exit 39 on R (Denville) to U.S. 46 and N.J. Route 59.
35.7 Ramp on R for entering traffic from R.
36.4 Leave Boonton quadrangle, enter Dover quadrangle.
36.5 MP 38 on R.
36.8 Entering Rockaway Township.
36.9 Pass ramp on R for Exit 37 for Co. Hwy. 513, Hibernia and Rockaway.
37.5 MP 37 on R; Proterozoic gneisses in cuts, both sides.
39.0 Pass Exit 35B ramp on R. (to Mt. Hope).
38.5 MP 36.
39.3 Pass Exit 35A ramp on R. (road to Dover).
40.2 Take Exit 34B ramp on R for N.J. Route 15 (North) to Sparta.
41.0 Traffic light. Road for trucks to Picatinny Arsenal.
42.1 Entering Jefferson Township. In lowland just ahead is the marginal fault between the Proterozoic gneisses on the SE and the Silurian and Devonian strata of the Green Pond belt.
42.4 Traffic light by powerline parallel to road.
42.6 MP 4 on R.
43.0 Pass road junction with Taylor Road (no light).
43.5 Exposure on R of steep-dipping quartzite (Green Pond Formation, Silurian).
44.0 Proterozoic mafic gneiss in cut on R.
44.1-44.2 Felsic Proterozoic gneisses.
44.55 Traffic light.
44.6 MP 6 on R; mafic gneisses with felsic plutons.

45.0 Leave Morris Co., enter Sussex Co.
45.6 MP 7; passing exit on R for 181 N.
45.8 Great exposure of Proterozoic gneisses repeated on S-dipping reverse faults.
46.0 Leave Dover quadrangle, enter Franklin quadrangle.
46.3 More deep cuts; mafic gneisses; steep foliation; low-angle faults cut rock into meter-scale blebs.
46.7 Large deep cuts on both sides of highway.
46.9 W end of cut; steep brittle fractures and quartz veins.
47.1 More Proterozoic gneisses; steep foliation; N.J. 15 curves to L and goes downhill; leave Franklin quadrangle; enter Newton East quadrangle.
47.3 Gneisses in large cut on L; small cut on R.
47.5 Sign for Sparta.
47.6 MP 9 on R; more mafic gneisses.
48.1 End of big cuts in this series; more ahead.
48.3 Xenoliths of mafic gneiss in felsic gneiss.
48.6 MP 10 on R.
48.8 Cut made for exit ramp; road not yet built; felsic gneisses exposed in this no-road roadcut.
49.0 Pass exit on R for N.J. 181.
49.5 Mostly felsic Proterozoic gneisses in roadcut.
49.6 MP 11; interlayered mafic gneiss and felsic dikes.
49.9 Proterozoic rocks with steep foliation.
50.6 MP 12.
50.9 Bridge over local road; Sparta.
51.2 Passing exposure on Sauk Sequence (Cambro-Ordovician) carbonates on left; Stop 1 of Franklin Trip.
51.6 MP 13.
51.7 Proterozoic Grenville marble and -gneiss in cuts on L.
52.1 Opposite entrance ramp on L side for southbound entry to N.J. 15 where new highway commences.
52.0 Proterozoic gneisses in cuts on L.
53.8 Blinker light; Woodruffs Gap; road on L goes to Limecrest (no such locality shown on the topographic map; would you believe Sparta Junction or Sussex Mills?).
54.0 Another RR crossing, just before Germany Flats.
54.6 Sauk Sequence carbonates exposed on R; dip is to NW.
54.7 More of same.
55.1 Entering Lafayette Township.
55.2 Ordovician Martinsburg slate (Tippecanoe Sequence) exposed on R.
55.6 More slates exposed on both sides of road.
55.7 Traffic light; N.J. 94 to Newton on L; continue on N.J. 15.
58.4 Traffic light at Ross Corner; end of N.J. 15; highway continues as U.S. 206; continue NW on U.S. 206.
58.9 Leave Newton East quadrangle, enter Branchville quadrangle.
59.5 Old RR crossing at Augusta.
60.4 MP 116 on R.
60.5 Traffic light; stay on U.S. 206 to bypass Branchville; pass Co. Rte 630 to Branchville on R.
60.9 Traffic light; junction of road to Beemerville.

61.1 Leave Branchville quadrangle; enter Culvers Gap quadrangle
61.5 Five Star Diner on R. [PIT STOP and last chance to pick up lunch fixings!].

61.6 MP 117 on R.
61.8 Ordovician slates exposed on L; bedding/cleavage dip gently to NW.
62.2 Road junction Co. 630 on R.
63.2 Blinker light.
63.5 Bridge for walkway overhead; looks like old RR bridge (but no old RR shows on topo map).
64.1 Culvers Lake on R.
64.4 Road junction Co. 521 on L.
64.7 MP120 on R.; just beyond Culvers Lake, enter Culvers Gap in Kittatinny Mountain.
64.9 Enter Sandyston Township.
65.1 Turn R onto Sunrise Mountain Road Sussex Co. 636.
65.2 Road junction, keep straight ahead (on 31 March 1991, this road became one way in the direction we are traveling).
65.9 Passing Coursen Trail on L.
66.7 Tower Trail crosses Sunrise Mountain Road.
67.6 Stonybrook Trail on L; we walked in the woods looking for the erratics of Beemerville igneous rocks but found none.
67.9 Leave Culvers Gap quadrangle, enter Branchville quadrangle.
68.9 Passing Tinsley Trail.
69.0 Park at Overlook on L for scenic view.

STOP 1 - Scenic overlook from Kittatinny Mountain westward to the strike ridges and Pocono/Catskill Plateau. UTM Coordinates: 522.19E, 4562.00N; Branchville 7-1/2' quadrangle.

A general view of the roads and trails through Stokes State Forest is reproduced in Figure 48. The strike valley underlain by the Devonian shales and Helderberg limestones lies northwest of Kittatinny Mountain. Figure 1 (cover) shows strata dipping NW but ending downward against horizontal strata below (proof of bedding-type thrust in which the beds on the upper block are dipping back down to intersect the fault surface, maintaining the same angle with the fault as deeper down where the steep fault cuts horizontal beds. Now the result is a horizontal fault and dipping beds). A more-generalized structure section is shown in Figure 49. Here, bedding strikes N48°E and dips 40°NW. Glacial grooves and crescentic gouges suggest glacial ice flow directions from N80°E but we had problems with our Brunton compass and do not believe this measurement.

Depending upon time and interest level, we may opt to take a short walk down Tinsley Trail (note trailhead above at 68.9) for about a mile or so in search of an unusual glacial boulder of nepheline syenite on the way to a boulder field as shown in Figure 50. Our reputations as "Pleistocene Boulder Chasers" precedes us so keep an open mind for a possible "fabulous discovery" of a potentially important indicator stone. Because Upper Ordovician carbonatite-alkalic rocks of the Beemerville Complex (Ratcliffe, 1981) crop out to the northeast of this area, the identification of nepheline syenite and related rocks may provide much-needed evidence for SSW-directed (meaning originally from the NNE) glacial flow.

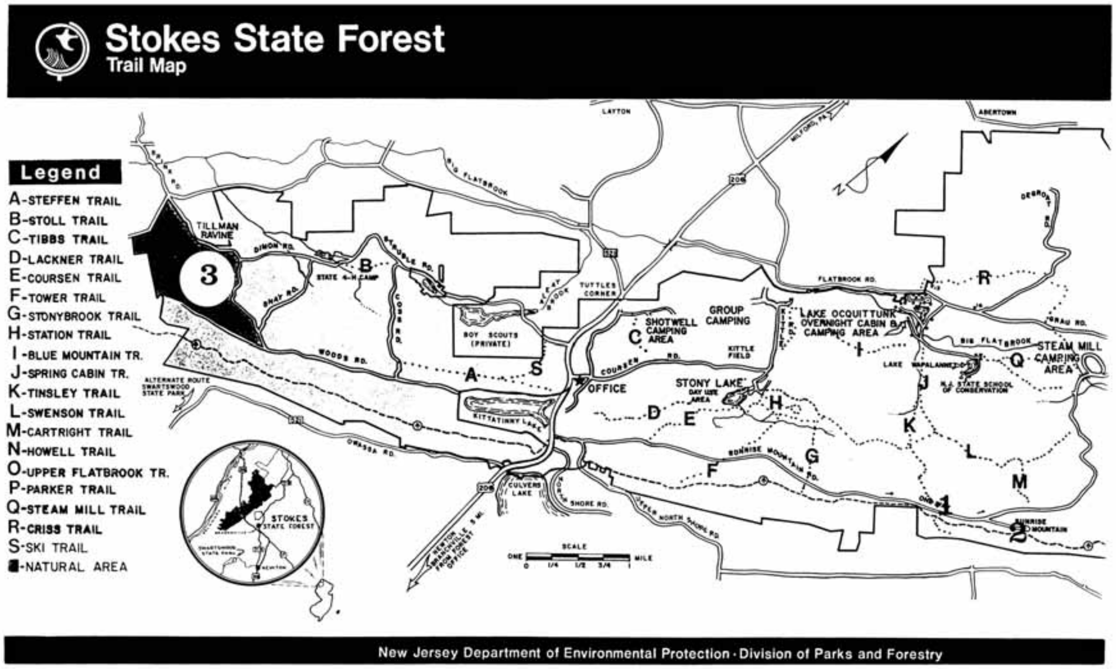
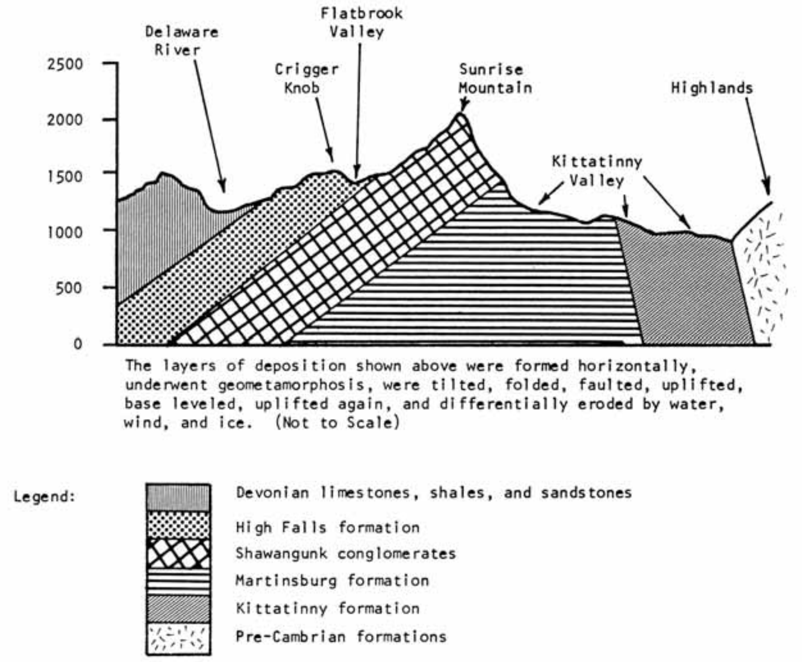


Figure 48. Map showing trails and roads in Stokes State Forest and our Stops 1 through 3. (Stokes State Forest Guide.)



The layers of deposition shown above were formed horizontally, underwent geometamorphosis, were tilted, folded, faulted, uplifted, base leveled, uplifted again, and differentially eroded by water, wind, and ice. (Not to Scale)

Figure 49. Generalized NW-SE structure section across Sunrise Mountain. (Stokes State Forest Guide.)

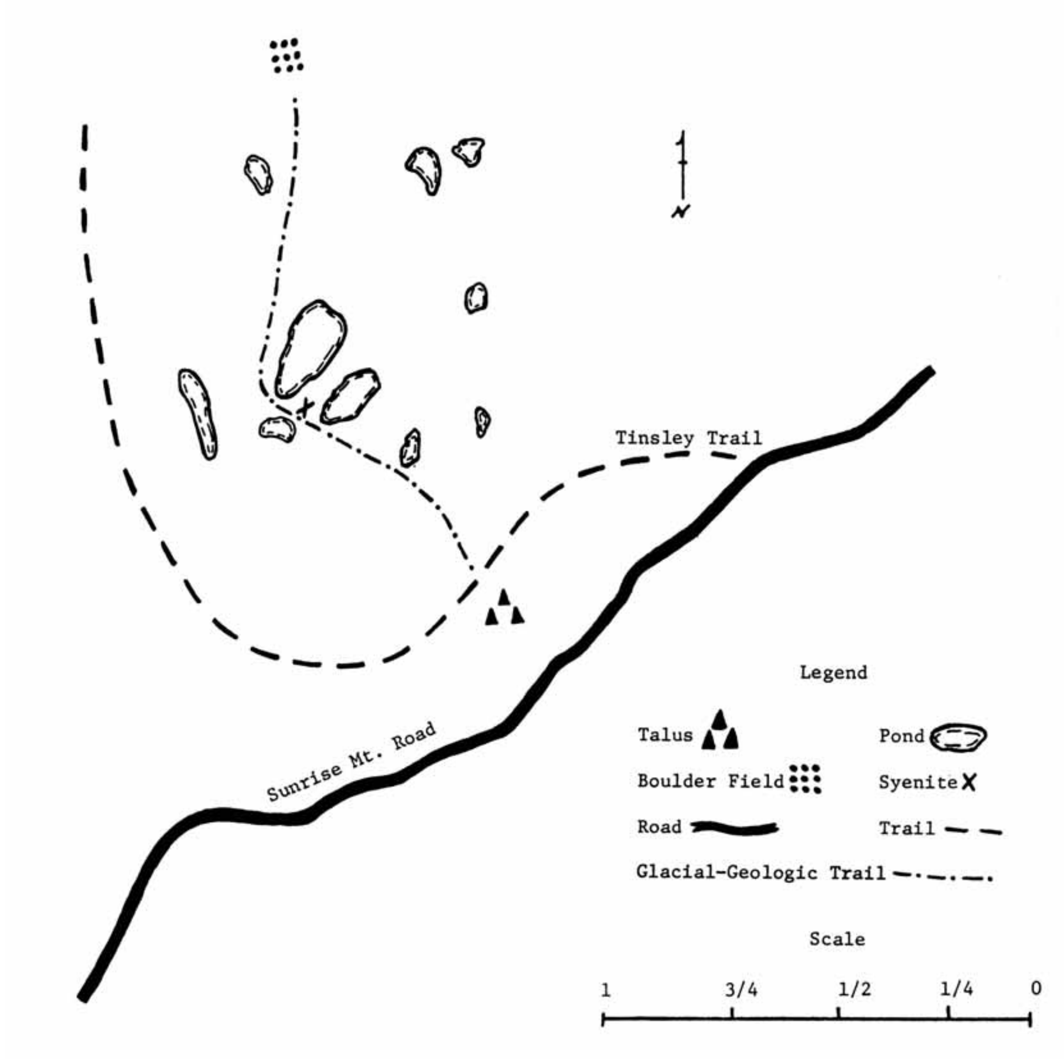


Figure 50. Sketch map showing position of erratic boulders on Tinsley Trail near Stop 1. (Stokes State Forest Guide.)

69.0 Continue ahead; given the one-way traffic flow, we can't do anything else.
69.3 Bear R for 2-way road to crest of Sunrise Mountain.
70.6 Parking lot at end of road by rest rooms. Try to find the United States Geological Survey benchmark for altitude 1653' at top.

STOP 2 - Sunrise Mountain. UTM Coordinates: 523.35E, 4562.77N; Branchville 7-1/2' quadrangle.

At the breathtaking elevation of 1653' above sea level, we here stand on the Shawangunk-Kittatinny Conglomerate near a portion of the Appalachian Trail. Look out toward the east for a panoramic vista of the Great Valley (underlain by Tippecanoe slates and Sauk carbonates) and the Proterozoic crystalline massifs of the Reading-Hudson Highlands of New Jersey and New

York. Figure 49 shows a generalized west-east structure section. We wonder, upon looking at the Proterozoic massifs in the distance, how many of them were "punched up" through the Paleozoic cover as horsts, or "dropped down" from above as grabens, or left as erosional outliers along low-angle thrusts as klippen. High Point State Park, the highest elevation in New Jersey, may be seen toward the north depending on the amount of vegetation in the way. Note that the local mountain peaks (including those of Stop 1) are all approximately the same height. Such summit accordance is indicative of prolonged erosion and development of a planation surface. Sunrise Mountain is a natural drainage divide where rainfall on the east side flows toward the Hudson River and rain falling to the west works its way into the Delaware River.

According to a 31-page booklet entitled "A Guide to Stokes State Forest", published by the New Jersey Department of Environmental Protection, Division of Parks and Forestry, State Park Service, CN 404, Trenton, NJ 08625, we are standing on a ridge of great natural significance. The harsh climate and thin soil promote the growth of hardy (and laurel?) strains of vegetation, including scrub oak, pitch pine, wild blueberry, and, you guessed it, mountain laurel. Monarch butterflies and hawks use the Shawangunk-Kittatinny Ridge as a part of their seasonal migratory flight by utilizing warm-air updrafts against the eastern edge. In addition, the largest rattlesnake den in New Jersey is located at the base of Sunrise Mountain but these critters tend to stay at lower elevations and should pose no threat to our On-The-Rocks Stokes Forest wilderness experience. Ask JES to tell the joke about the rattlesnake bite and two husky geologists.

The pavilion at the summit was built in the late 1930's by the Civilian Conservation Corps with materials transported to the summit by a steam-powered rail system. Atop the ridge on the west side of the parking area the attitude of bedding in the conglomerate is N54°E, dip 34°NW but we will recheck this measurement as this was the place where CM's compass seemed to give spurious readings in 1995. Note the spectacular tabular cross beds in the conglomerate outcrops. They indicate tops to the northwest, a right-side-up sequence! The trail from the SE corner of the lot leads over some rounded glaciated knolls showing crescentic gouges and grooves. We recorded N36°W to S36°E glacial flow here. Elsewhere glacial striae are oriented N35°E and roche-moutonnée structures are oriented N15°E. Locally, glacial polish and related grooves show N25°W to S25°E orientation. By the bench, the glacial striae are parallel to the strike of the ridge and more crescentic gouges show strike-parallel glacier flow (we measured a bearing of N75°E for the striae and that the bedding is N80°E and vertical.

On a Fall 2004 Structural Geology field trip to this area, Merguerian and students found something important by climbing down over the eastern edge of the escarpment (Wills, Bigolski, and Merguerian, 2005). Here, bedding changes rapidly from NW dips recorded elsewhere to subvertical and overturned and we measured a maximum overturned orientation of N84°E, 74°SE. We found the reason for this deflection and curling up of the strata in the form of localized concentric folds. The folds plunge 29° into S75°W and we measured the axial surface at N50°E, 52°NW. Bedding plane slip lines are corrugated about the fold axes but trend roughly 72° into S35°E.

On the topographic map, the trend of Kittatinny Mountain and most of the surrounding ranges and beds is about N45°E with NW dips, thus the 40° eastward divergence in strike and overturning of the Shawangunk strata is noteworthy. WSW-plunging concentric folds with NW dipping axial surfaces and SE plunging slip lines could have been produced by right-lateral shearing and we suggest that such shearing may be related to oroclinal bending of the entire Appalachian belt, as best exemplified to the south in Pennsylvania. Taken together, the Newark, Gettysburg, and Culpepper basins are distributed in a broad Z-fold and show geometrically similar oroclinal bending as do the Pennsylvania Valley and Ridge section of the Appalachians. Such observations force us to suggest that post-Newark (mid-Jurassic?) right-lateral shearing along the typical Appalachian trend (N45°E) may have caused the observed map-scale deformation of the Newark strata and oroclinal bending of the Appalachian chain in Pennsylvania and to a small degree at Sunrise Mountain in NW New Jersey. Could the eastern Shawangunk escarpment be locus of such strike-slip offset?

70.6 Reboard vans, retrace route down the hill.
71.3 Sharp R turn onto the one-way road.
72.2 Cartwright Trail.
72.8 Howell Trail.
73.4 Swenson Trial.
73.9 Road junction; road on L.
74.0 Crossing tributary of Big Flat Brook; two-way traffic now. On the topo map, this is shown as Crigger Road.
74.3 Parker Trail on R.
74.4 Crossing another tributary of Big Flat Brook.
74.5 Road junction; turn L onto Skelliger Road (topo map name); sign indicates to U.S. 206.
75.4 Cross Criss Trail. [Say that ten times fast!].
75.5 Pass road on L to Lake Wapalanne.
75.6 Leave Branchville quadrangle, enter Culvers Gap quadrangle.
77.1 Road bends R where Stonybrook Trail is on L.
77.3 End of Skelliger Road; turn L onto Flat Brook Road following sign to U.S. 206.
78.4 Road junction U.S. 206; stop and then turn L.
79.2 Tuttles Corner; Sussex Co. 560 (road to Dingmans Bridge on Delaware River) enters from R; bear L, following U.S. 206.
79.4 Sign for Stokes State Forest.
79.9 Struble Road on R (we will drive down this road, either now or after a short visit to the Ranger's Office of Stokes State Forest. If we go to the Ranger's Office, then continue on U.S. 206 for another 0.5 mi).
80.4 Turn L on Coursen Road to entrance of Stokes State Forest.
80.5 Check-in stop; [Pit stop (if not pitted out at Five-Star Diner)].
80.5 Leave Park office, turn L.
80.6 After stop, turn R on U.S. 206 and Co. 521 (N).
80.7 MP 121 on R.; highway goes downhill and curves to R; prepare for upcoming left turn.
81.0 Turn L onto secondary road (Struble Road).
81.3 At sharp curve to R, pass entrance to Scout Camp on L.
81.35 Crossing outlet to Lake Ashroe; road curves left and goes uphill. Boulders alongside the road are from Bloomsburg redbeds (L. Silurian formation overlying the Shawangunk Conglomerate).
82.0 Curve R by house; view of lake ahead and to L.

82.6 Passing pond on L (private; houses).
83.1 Intersection of Coss Trail on L (jeep track).
83.4 Curve to L; trail on R is continuation of Struble Rd.; by following the blacktop road around the curve to the L, we picked up Dimon Rd. (no sign tells this to a stranger).
83.7 Nearly flat strata of "Bloomsburg" redbeds exposed alongside road.
83.75 Entrance on R for 4H Club camp on Lake Shawanni.
84.0 Junction with Stoll Trail.
84.4 Junction with "Shay Road;" another jeep track.
85.0 Turn R; road shown as Brink Road; topo map labels the rough trail to the L as Brink Road.
85.3 Pass parking lot on L for upper falls.
85.6 Turn L into parking lot for lower falls. Leave vans for STOP 3.

STOP 3 - Tillman Ravine, Stokes State Forest. UTM Coordinates: 511.40E, 4556.03N; Culver's Gap 7-1/2' quadrangle.

The rocks exposed in Tillman Brook (See Figure 48.) are reddish sandstones, shales, and siltstones of the Silurian Bloomsburg Formation (equivalent to the High Falls Formation of previous On-The-Rocks trips - See Table 2). These sediments were deposited roughly 400 Ma (Million years ago) in a broad fan-delta complex and are essentially non-fossiliferous excepting a few preserved remains of fish and plant fossils. The strata have been folded and display many aspects of cleavage. The obvious folds here plunge 27° into S50°W with a N54°E, subvertical axial surface. Three cleavages were measured as N20°E, N24°E, and N63°E, all vertical. [What is the age of these cleavages? Are they regional? Or controlled by local folds? If it is anything like the cleavage relationships at the Delaware Water Gap in this same formation, then it is regional and probably Appalachian. If so, then this cleavage deals a fatal blow to the Woodward et al. flock that wants to downplay the Late Paleozoic Appalachian orogeny to some miniscule "Alleghanian" something or other.]

Tillman ravine is a youthful feature illustrating the erosive effects of rapid downcutting by post-glacial streams. Just before the lower falls a tributary enters; from the trail, one gets a clear view of its V-shaped cross-valley (or transverse) profile indicating a youthful stream. Such a profile is indicative of stream action and not glaciation. Here, the course of the main stream is controlled by the steep fracture cleavage, a structural weakness in the rocks.

At the Lower Falls-Teacup area (the Teacup is a large pothole), red siltstones are exposed. In the red siltstones, it is not easy to ascertain the attitude of the bedding but greenish-gray interlayers of siltstone give a faint hint of the orientation. We tried one measurement and found N32°W, 17°SW, with prominent steep cleavage at N62°E, 68°SE. The orientation of a secondary cleavage is N55°E, 54°SE. Here, the intersection of the cleavages forms splinter-like wedges in the siltstone.

The foot trail follows an upstream surface that may be the dip slope of the bedding and may also conform to the hinge area of a plunging fold. This is confirmed by the exposure on the opposite side of the creek. Thus the stream cuts through the axis of an anticlinal fold that plunges toward the SW. The cleavage/bedding intersection trends S45°W and plunges 17°.

At the footbridge over the creek (near Council Chamber) is exposed a crest of an anticline with the cleavage parallel to the axial plane. The cleavage is refracted; that is, its orientation in the red siltstones differs from that in the overlying sandstone. The base of the sandstone is slightly irregular and its lower part displays planar cross strata. The creek is flowing along the strike of the hard strata here. Cross strata are also visible near the bridge footing. Some small bedding- parallel displacements of the strata appear to postdate the cleavage.

Walk out to the upper parking area (rest rooms here) and follow road down hill back to lower parking area and vans.

85.6 Turn R out of parking lot and retrace road to U.S. 206.
86.1 Turn L on blacktop road (Dimon Road).
87.3 Passing 4H Club entrance on L.
87.3 Road bends to R; now it is Struble Road.
88.4 Coss Trail on R; crossing low drainage divide. Just beyond is a sign for Deer Lake (name of small pond not labeled on topo map).
89.4 Crossing causeway at N end of Lake Ashroe.
89.8 Passing entrance to Boy Scout Camp on R.
90.1 Road ends against U.S. 206; after stop, turn R (also Sussex Co. 521).
90.3 Passing MP 121 on R.
90.4 Passing road on L to Park Office, Stokes Forest.
90.8 Cove Rd. on R.
91.1 Sign advertises Sussex Co. 636 on L; Sunrise Mountain Road.
91.6 Passing Kittatinny Lake on R.
92.1 MP 120 on R.
92.2 Culvers Lake on L.
92.9 Flea Market on R. (Optional stop for shoppers.)
93.1 MP 119 on R.
93.3 Footbridge above highway (the one that looks like a RR bridge but is not).
94.1 MP 118 on R.
95.3 Five-Star Diner on L. (Haven't we been here before?)
95.7 Traffic light; road to Beemerville.
96.1 Traffic light; Sussex Co. 630 to Branchville on L.
96.2 MP 116 on R. (Note surveyor's error from odometer.)
97.1 Old RR crossing at Augusta.
97.7 Leave Branchville quadrangle, enter Newton East quadrangle.
98.1 Traffic light at Ross Corner; turn R on U.S. 206 to Newton at intersection where N.J. 15 begins.
98.25 Crossing Paulins Kill (stream flows NW here). MP 114.
98.8 Leave Frankford Twp.; enter Hampton Twp.
99.2 Slates exposed on L; MP 113
99.4 Old road on L by pond.
99.7 Slate exposed on L. Pull over for STOP 4.

STOP 4 - Martinsburg slates, Hampton Township. UTM Coordinates: 523.05E, 4550.55N; Newton East 7-1/2' quadrangle.

Before you is a marvelous example of an anticline in dark- colored slates of the Martinbsburg Formation. At the NW end of cut, bedding on one limb strikes N47°E and dips 18°NW and it is cut by a cleavage striking N44°E with a dip of 37°SE. Another slaty cleavage trends N58°E, 40°SE. The bedding/cleavage intersection (= plunge of folds) trends N35°E and is subhorizontal. Note the very prominent "pencil" structure here because the bedding and the cleavages break the rock into extremely long pieces.

Let's look for evidence for another (third?) slaty cleavage or two and try to find some nice slate specimens showing a high angle bedding/cleavage relationship.

99.7 Back in vans and continue south on U.S. 206.
100.2 Sussex Co. 626 on R (road to Halsey).
100.7 Junction on L with N.J. 94; continue S on U.S. 206/N.J. 94.
100.9 Slates exposed on R.
101.1 More slates exposed on R.
101.7 "Fossil" drive-in theater on R.
102.0 Entrance to Newton County Mall; turn R, then R again to go 0.1 mi. to back of stores for STOP 5.
102.1 Park here for STOP 5. Watch out for poison ivy.

STOP 5 - Sauk Sequence (Cambro-Ordovician) carbonates thrust over Martinsburg slates ("Jenny Jump thrust"), Newton County Mall. UTM Coordinates: 521.60E, 4546.60N; Newton East 7-1/2' quadrangle.

The area of this stop was described in detail by Drake and Lyttle (1980; Stop 9) and we borrow liberally from their discussion. Here a small slab of Allentown Dolostone (Upper Cambrian part of the Sauk Sequence, Table 2) lies structurally above slates of the Tippecanoe Sequence [Ramseyburg Member of the Martinsburg Formation (part of our Layer IIB)]. The contact is a thrust fault (the Jenny Jump thrust of Lewis and Kümmel (1915), and Kümmel (1940), and renamed the Grand Union thrust by Drake and Lyttle 1980). This marvelous, but somewhat non-picturesque, exposure was created during excavation for the shopping center. The thrust is oriented N50°E, 40°NW and is marked by 2 to 8 cm of gouge consisting of crushed, slickensided dolostone.

This exposure presents real challenges for separating the bedding and the fractures in the carbonates. We make the bedding to be N40°E, 40°NW and algal stromatolites indicate right-side-up for the dolostone strata. Below the thrust contact, the rocks have been isoclinally folded into "M' patterns suggesting that the thrust broke across the area of a fold hinge. Bedding in the slates adjacent to the thrust is oriented N35°E, 65°NW but is variable, going to vertical a few meters to the southeast. Drake and Lyttle (1980) describe the Ramseyburg Member as an "autoclastic m,lange" [tectonic m,lange to you, buddy] in which graywacke beds have been pulled apart and fragmented and swim as tectonic "fish" in a shaly "sea". Look for fish heads in the construction debris adjacent to the outcrop. [Send them to Sanders for his next blueberry pie.]

The slaty cleavage is roughly oriented N20°E, 35°NW but shows signs of rotation and is truncated by the Jenny Jump thrust. Drake and Lyttle (1980) suggest that "the Ramseyburg here is in the brow and upper limb of a northwest-closing recumbent fold".

Prominent fractures cutting the thrust are oriented N5°W and dip 45°NE. A normal fault parallel to the fractures offsets the W-dipping thrust and offsets it by about 1 m. The thrust contact dips NW; it is thought that the movement was from SE to NW and thus would be down the dip here. A strong down-dip extension lineation plunges 39° into N55°W. The implication is that the Jenny Jump thrust is younger that the slaty cleavage and that a post-thrust fold brought about the NW dip of the thrust surface.

102.1 Reboard vans. Return to exit from shopping center.
102.2 Turn L onto U.S. 206 and N.J. 94.
103.1 Slates exposed on L.
103.5 Traffic light; turn R on N.J. 94. MP 25 just after light.
103.7-103.9 Slates exposed on L.
104.3 Entering Lafayette Township.
104.6 MP 26; slate exposed in Road junction on hill.
105.2 Exposures of Sauk Sequence (Cambro-Ordovician) carbonates, nearly horizontal. What is their structural position? On the lower thrust block stratigraphically below the Martinsburg slates? Or on the upper block, those thrust above the slates, as at the shopping center, STOP 5?
105.6 MP 27; pass Road junction on R. (to Warbasse and Hyper-Humas Station).
105.7 Road junction for Co. 659 to Lafayette ahead; turn R on N.J. 94.
106.1 Bridge over Paulins Kill.
106.4 Traffic light; Road junction N.J. 94 and N.J. 15; rejoin N.J. 15.
106.6 Traffic light; N.J. 94 goes to L; continue ahead on N.J. 15.
106.7 More slates exposed on both sides of road.
107.1 Martinsburg slate exposed on L.
107.2 Entering Sparta Township.
107.6 Cambro-Ordovician carbonates on L; dip is to NW.
107.7 More carbonates on L; same dip; entering Germany Flats.
108.3 RR crossing, Germany Flats.
108.5 Blinker light; Woodruffs Gap; road to Limecrest on R.
109.1 RR crossing. follow signs for N.J. 15 S where divided highway begins.
110.5 MP 13; exposures of Precambrian gneiss.
110.9 Passing Cambro-Ordovician carbonates exposed on R (Stop 1 of Franklin Trip).
121.6 N.J. 15 joins I-80 eastbound. End of road log.

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

ACKNOWLEDGEMENTS

In addition to thanking our usual list of suspects (Matt Katz and his Executive Assistant (Marcie Brenner) and staff at the New York Academy of Sciences, and Jessica Levine (a geology major at Hofstra), we are grateful to Ranger Robert Sikora of Stokes Forest, Branchville, NJ for helping us by providing pamphlets and pointing out localities to visit in our pre-trip checkout.

TABLES

Table 01 - GEOLOGIC TIME CHART

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

ERA **Periods (Epochs)**	**Years (Ma)**	**Selected Major Events**
CENOZOIC		
(Holocene)	0.1	Rising sea forms Hudson Estuary, Long Island Sound, and other bays. Barrier islands form and migrate.
(Pleistocene)	1.6	Melting of last glaciers forms large lakes. Drainage from Great Lakes overflows into Hudson Valley. Dam at The Narrows suddenly breached and flood waters erode Hudson shelf valley. Repeated continental glaciation with five? glaciers flowing from NW and NE form moraine ridges on Long Island.
(Pliocene)	6.2	Regional uplift, tilting and erosion of coastal-plain strata; sea level drops. Depression eroded that later becomes Long Island Sound.
(Miocene)	26.2	Fans spread E and SE from Appalachians and push back sea. Last widespread marine unit in coastal-plain strata.
MESOZOIC	66.5	
(Cretaceous)		
	96	Passive eastern margin of North American plate subsides and sediments (the coastal-plain strata) accumulate.
	131	(Passive-margin sequence II).
(Jurassic)		Baltimore Canyon Trough forms and fills with 8,000 feet of pre-Cretaceous sediments.
		Atlantic Ocean starts to open. Newark basins deformed, arched, eroded.
(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	**Taconic orogeny.** Intense deformation and metamorphism.
	450	Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line). Arc-continent collision.
(Ordovician)		Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata. Ultramafic rocks (oceanic lithosphere) sliced off and transported above deposits of continental shelf.
		Shallow-water clastics and carbonates accumulate in west of basin (= Sauk Sequence; protoliths of the Lowerre Quartzite, Inwood Marble, part of Manhattan Schist Fm.).
(Cambrian)		Deep-water terrigenous silts form to east. (= Taconic Sequence; protoliths of Hartland Formation, parts of Manhattan Schist Fm.). (Passive-margin sequence I).
PROTEROZOIC		
	570	Period of uplift and erosion followed by subsidence of margin.
(Z)	600	Rifting with rift sediments, volcanism, and intrusive activity. (Ned Mountain, Pound Ridge, and Yonkers gneiss protoliths).
(Y)	1100	**Grenville orogeny.** Sediments and volcanics deposited, compressive deformation, intrusive activity, and granulite facies metamorphism. (Fordham Gneiss, Hudson Highlands and related rocks).
ARCHEOZOIC		
	2600	No record in New York.
	4600	Solar system (including Earth) forms.

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

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

LAYER VII - QUATERNARY SEDIMENTS

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

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

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

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

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

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

marine)	(graded layers, marine)
Bakoven Black Shale	Cornwall Black Shale
Onondaga Limestone	
Schoharie buff siltstone	Pine Hill Formation
Esopus Formation	Esopus Formation
Glenerie Chert	
Connelly Conglomerate	Connelly Conglomerate
Central Valley Sandstone	
Carbonates of Helderberg Group	Carbonates of Helderberg Group
Manlius Limestone	
Rondout Formation	Rondout Formation
Decker Formation	
Binnewater Sandstone	Poxono Island Formation
High Falls Shale	Longwood Red Shale
Shawangunk Formation	Green Pond Conglomerate

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

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

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

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

Not metamorphosed / Metamorphosed
Martinsburg Fm. / Manhattan Schist (Om - lower unit).
Normanskill Fm. / Annsville Phyllite

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

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

LAYER IIA[W] - SAUK SEQUENCE	**LAYER IIA[E] - TACONIC SEQUENCE**
Western shallow-water platform (L. Cambrian-M. Ordovician)	Eastern deep-water zone (L. Cambrian-M. Ordovician)
Copake Limestone	Stockbridge or Inwood Marbles
Rochdale Limestone	
Halcyon Lake Fm.	
Briarcliff Dolostone	(Ꞓ-Oh) Hartland Fm.
Pine Plains Fm.	(Ꞓ-Om) Manhattan Fm. (in part).
Stissing Dolostone	
Poughquag Quartzite	
Lowerre Quartzite [Base not known]	

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

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

LAYER I - PROTEROZOIC BASEMENT ROCKS

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

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

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

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

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

Table 03 – Proposed new classification of the Pleistocene deposits of New York City and vicinity
(Sanders and Merguerian, 1998, Table 2)

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

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