DUKE GEOLOGICAL LABORATORY

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

TRIPS ON THE ROCKS

Guide 24: Geology of the Great Falls, Watchung, and Palisades Ridges, New Jersey

Trip 41: 14 September 1997

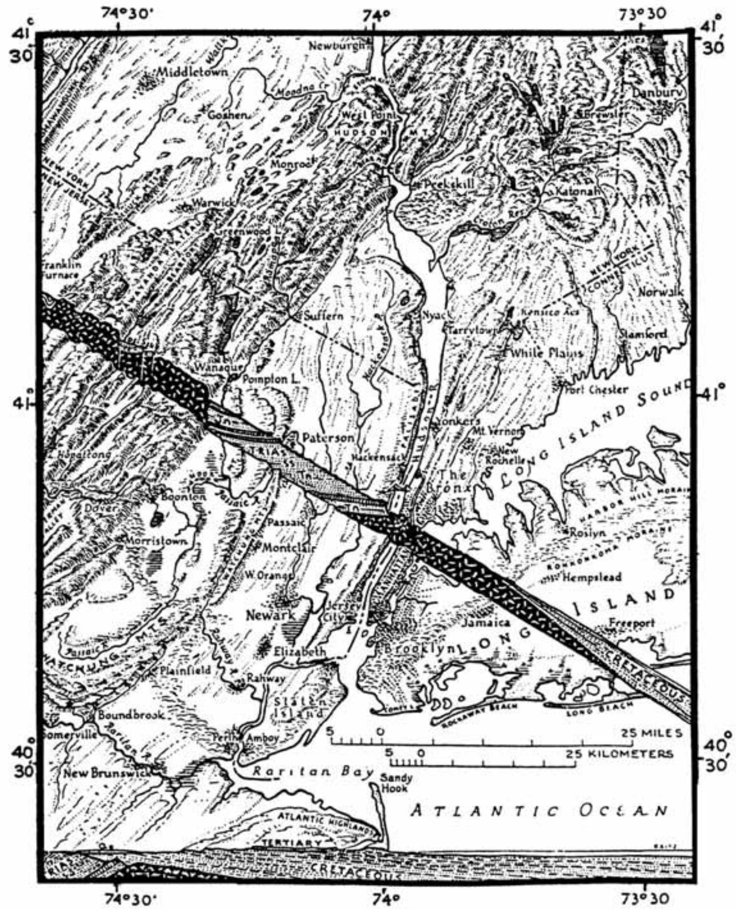


Figure 1. Physiographic map of the northern Newark Basin. (Drawing by. Erwin Raisz.)

Field Trip Notes by:

Charles Merguerian and John E. Sanders

CONTENTS

DUKE GEOLOGICAL LABORATORY

TRIPS ON THE ROCKS

Guide 24: Geology of the Great Falls, Watchung- and Palisades Ridges, New Jersey

Trip 41: 14 September 1997

Logistics:
Departure from 92nd Street Y: 0830
Return to 92nd Street Y: 1800
Bring lunch, including drinking water or other beverages.

INTRODUCTION

The centerpiece of today's field trip, Great Falls on the Passaic River in Paterson, New Jersey (Figure 1), is a miniature version of the world-famous Victoria Falls in SE Africa (Figure 2). Victoria Falls is located near the town of Livingstone on the Zambesi (alternate spellings: Zambezi or Zambeze) River, along the boundary between Zambia and Zimbabwe, about 300 km SW of Lusaka, the capital of Zambia, at approximately 18° S Latitude and 25.5° E Longitude. At both waterfalls, the water tumbles over an extended fracture in a sheet of volcanic rock and flows away laterally in a gorge formed along the fracture. The physiographic setting present at these two waterfalls resulted from the solidification, burial, tilting, and re-exposure of an ancient lava flow. The ancient former lava flow at Paterson is the lowest of three sheets whose tilted edges form the curving Watchung ridges in north-central New Jersey. (See Figure 1.)

Other features of interest that we shall examine today are those found at the base of the Palisades intrusive sheet under the George Washington bridge (GWB) on the west side of the Hudson River. We shall discuss the evidence by which geologists are able to tell whether a sheet of igneous rock is of intrusive- or of extrusive origin and apply these lessons to the resistant ridges forming the Watchungs. We shall examine evidence by which geologists infer the existence of faults. Finally, we shall study the changes that can be observed within the sedimentary strata as one approaches the basin-marginal Ramapo fault.

Because of the prevailing NE-SW strike and NW dip of the strata forming the filling of the Newark basin in the central part of the trip area, as we drive northwestward during the course of today's trip, we encounter successively younger layers. (See cut-away slice on Figure 1.) Geologists refer to traverses across the strike of strata starting with older layers and encountering successively younger ones as "traversing up section" (the "section" referring to the succession of strata, and the "up" to the progression from older layers to younger). By contrast, the reverse situation, that is, a traverse progressing from younger strata to older, is known as "traversing down section."

Our first stop will be at the western footing of the GWB to examine the contact relationships at the base of the Palisades sheet and to study the formation it intruded, the fine-textured, generally dark-colored sedimentary strata of the Lockatong Formation.

We continue with summaries of today's objectives, the general geologic setting of the local geologic record, the drainage history, list of localities to be visited, and desciptions of the features at each of our trip stops.

Figure 2. Map of southeastern Africa showing location of the Zambesi River and Victoria Falls. (National Geographic Society, December 1990 with a few labels added by JES.)

OBJECTIVES

(1) To study the minerals-, structure, and contact relationships of the Palisades sheet and the Lockatong Formation it has intruded.

(2) To learn to distinguish a sill from sheet of extrusive igneous rock solidified from an ancient lava flow.

(3) To examine the evidence indicating that the paleoflow direction of the Palisades magma was from SW to NE and not from NW to SE.

(4) To evaluate the evidence bearing on the state of lithification (or lack of it!) of the sandstones in the Lockatong Formation at the time the Palisades sheet was intruded and from this evidence to estimate the depth of intrusion.

(5) To examine pillows--the products of the extrusion of hot lava under a cover of water.

(6) To examine the characteristics of the Newark sedimentary strata and to notice the contrast between sediments deposited well away from the Ramapo fault at the northwest basin margin and those deposited close to this basin-marginal fault.

(7) To study the composition of boulders in the basin-marginal rudites (general name for any coarse sediment composed chiefly of gravel-size debris).

(8) To study the evidence for postdepositional faults.

GENERAL GEOLOGIC SETTING: COMPONENTS OF THE GEOLOGIC RECORD

The three components of the geologic record of any area are: (1) the bedrock; (2) the regolith; and (3) the shape of the Earth's surface (Longwell, Flint, and Sanders, 1969).

BEDROCK

Under the heading of bedrock, we summarize the three major kinds of rocks, present a primer on geologic structure, review nature's "rock-making machinery" (named geotectonic cycles), by which major bedrock units are formed and then relate three of the four major units that compose the local geologic framework to such processes.

Three Major Rock Groups: Igneous, Sedimentary, and Metamorphic

Geologists classify rocks into three major groups: (1) igneous; (2) sedimentary; and (3) metamorphic. But after one has learned the names of these three rock groups, so what? Why have geologists organized rocks into these three groups and on what basis did they do so? Rocks don't wear union labels, so how can one look at a rock and decide to which group it belongs? This decision is important; its importance will become apparent from our discussion of the origins of rocks.

Bases for Classifying Rocks into Three Major Groups

In classifying rocks, geologists use two major factors: (1) process(es) and (2) place(s), generalized into two categories: (a) at the Earth's surface and (b) inside the Earth (Figure 3). As a first approximation, within each major rock group, one of these factors prevails throughout, and thus becomes a unity factor. The other factor typically is variable, and thus becomes a diversity factor. Among igneous rocks, process (cooling from a molten state) is the unity factor and place (where the cooling happens) is the diversity factor. Among sedimentary rocks, it is necessary to consider these two factors in two stages: (a) stage 1 is the formation of the sediments, and (b) stage 2 is the conversion of the sediments into sedimentary rocks. Among the sediments of stage 1, place (the surface of the Earth) is the unity factor and process is the diversity factor. By contrast, in stage 2, the conversion of sediments into sedimentary rocks, place is once again the unity factor (but not the same place as with sediments; the place where lithification happens typically is inside the Earth rather than at the Earth's surface) and various processes become the diversity factor.

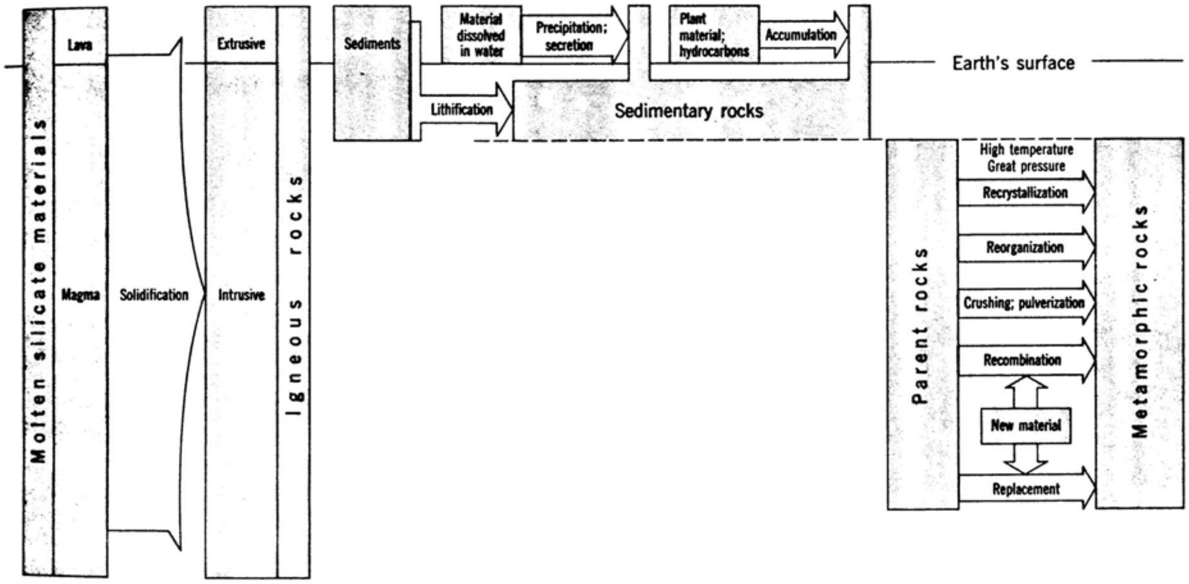


Figure 3. Factors of process and place as bases for classifying rocks into three major groups; schematic profile through a segment of the Earth's lithosphere. Boxes represent materials; arrows, processes. Arrows showing metamorphic processes are arranged arbitrarily without depth significance. Further explanation in text. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 4-5, p. 81.)

Among most metamorphic rocks, place (inside the Earth) is the sole unity factor, but two diversity factors are involved: (a) pre-existing- or precursor rock (known as the protolith) and

(b) various processes. (Impact metamorphism associated with the arrival of a meteorite is an exception to place as a unity factor in metamorphic rocks; impact metamorphism happens only at the Earth's surface.) In the following paragraphs, we summarize how these factors are expressed in classifying rocks into the three major groups.

Igneous Rocks: One Process Operates in Two Places

As mentioned, all igneous rocks result from one process: the cooling- and solidification of a molten liquid. But geologists have established two major categories of igneous rocks depending on the place (or location) where the cooling took place. Extrusive igneous rocks form at the Earth's surface by the cooling- and solidification of a molten liquid known as lava. By contrast, intrusive igneous rocks form within the Earth by the cooling- and solidification of a mixture of molten liquid + dissolved gases, collectively known as magma. Three important reasons can be cited for explaining why geologists make a major distinction among igneous rocks based on the place where the cooling happens.

(1) Beneath the Earth's surface, the pressure enables the gases to remain dissolved within the molten liquid (magma). As soon as the magma reaches the Earth's surface where it can be seen, geologists change its name from magma to lava. But, something else happens, too. The dissolved gases escape. In its simplest form, then, we can consider lava as being degassed magma.

(2) Place generally affects the rate of cooling. As Sir James Hall [1761-1832], a friend of the founder of modern geology, James Hutton [1726-1797], discovered, rate of cooling determines the sizes of the growing crystals. Therefore, any factor that affects the rate of cooling has to be considered a first-order factor in understanding igneous rocks. As a general rule, cooling at the Earth's surface is a fast process involving days to months, whereas cooling that takes place inside the Earth is a slow process that required hundreds- to thousands of years.

(3) Place determines how the heat escaping from the molten liquid will affect its surroundings. A body of lava cooling at the Earth's surface heats only the materials over which it flows. A body of body of magma cooling underground heats its surroundings on all directions: top, bottom, and sides (Figure 4).

Sediments and Sedimentary Rocks: Many Processes Operate in One of Two Places

As mentioned, because sedimentary rocks result from the lithification of sediments, geologists recognize two stages: (a) the origin of the sediments, and (b) lithification of sediments to form sedimentary rocks. In our discussion, we treat stage (a), the sediments at greater length than the stage (b), the processes of converting sediments to sedimentary rocks.

As mentioned, the unity factor among sediments is place: they all form at the Earth's surface, although in many different environments. The diversity factor is process: many processes are involved in the origin of sediments. In the lithification of sediments, the unity factor is generally place (but not the same place as with sediments, but within the Earth; however this place is not a hard-and-fast generalization because some sediments are lithified at the Earth's surface); many processes constitute the diversity factor.]

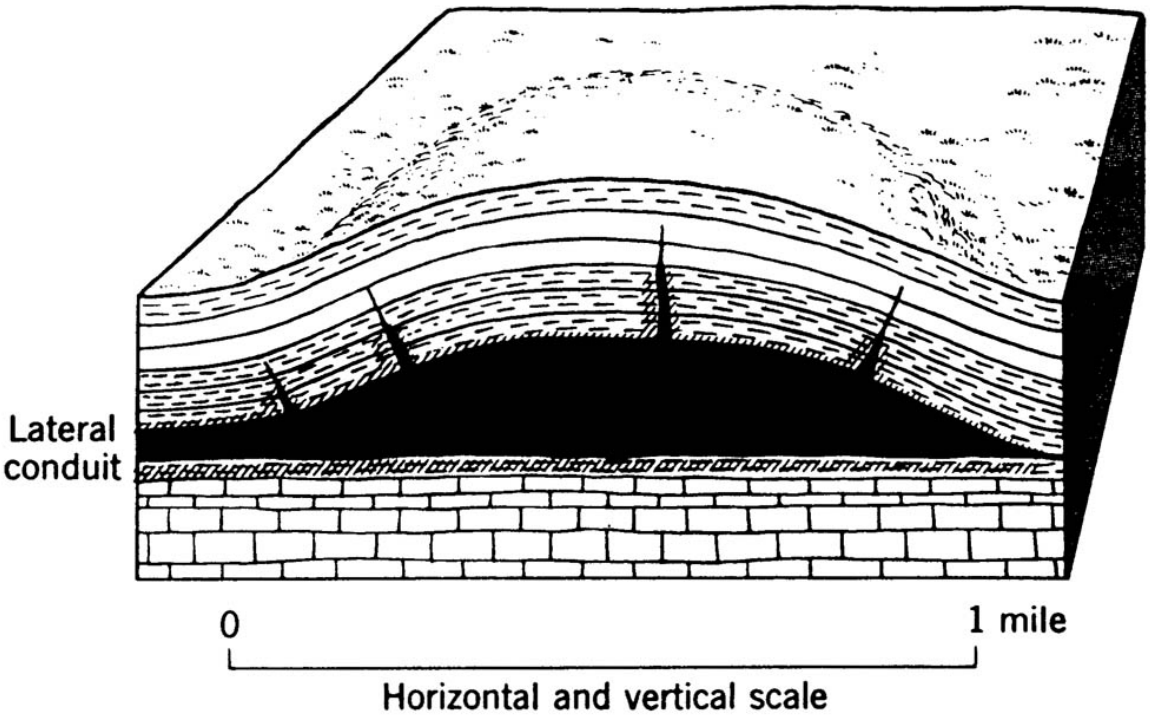


Figure 4. A body of magma (black) cooling underground releases heat to the country rock on all sides; schematic. Effects of heat shown by short parallel diagonal lines. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 20-8, B, p. 496.)

Sediments are classified according to the origin of their constituents. Four major categories are:

(1) Particles (or clasts), derived from the breakdown of some pre-existing rock (Figure 5, A) and the physical transport, as individual solid objects, of the breakdown products to the site where they are deposited. [Many names are in use for sediments composed of such breakdown products that were transported as individual solids. Among these are terrigenous sediment, extrabasinal sediment, detritus (or detrital sediment), clastic sediment, and siliciclastic sediment. Each geologist displays a marked preference for using one of these several terms. No consensus has ever existed nor is ever likely to.]

(2) Biocrystals secreted by organisms (Figure 5, B) using ions dissolved in the water. Some geologists use the term skeletal debris for solid materials secreted by organisms.

(3) Crystals (Figure 5, C) precipitated chemically from ions dissolved in the water, usually as a result of evaporation of the water. (Accordingly, all geologists refer to such crystals as evaporites)

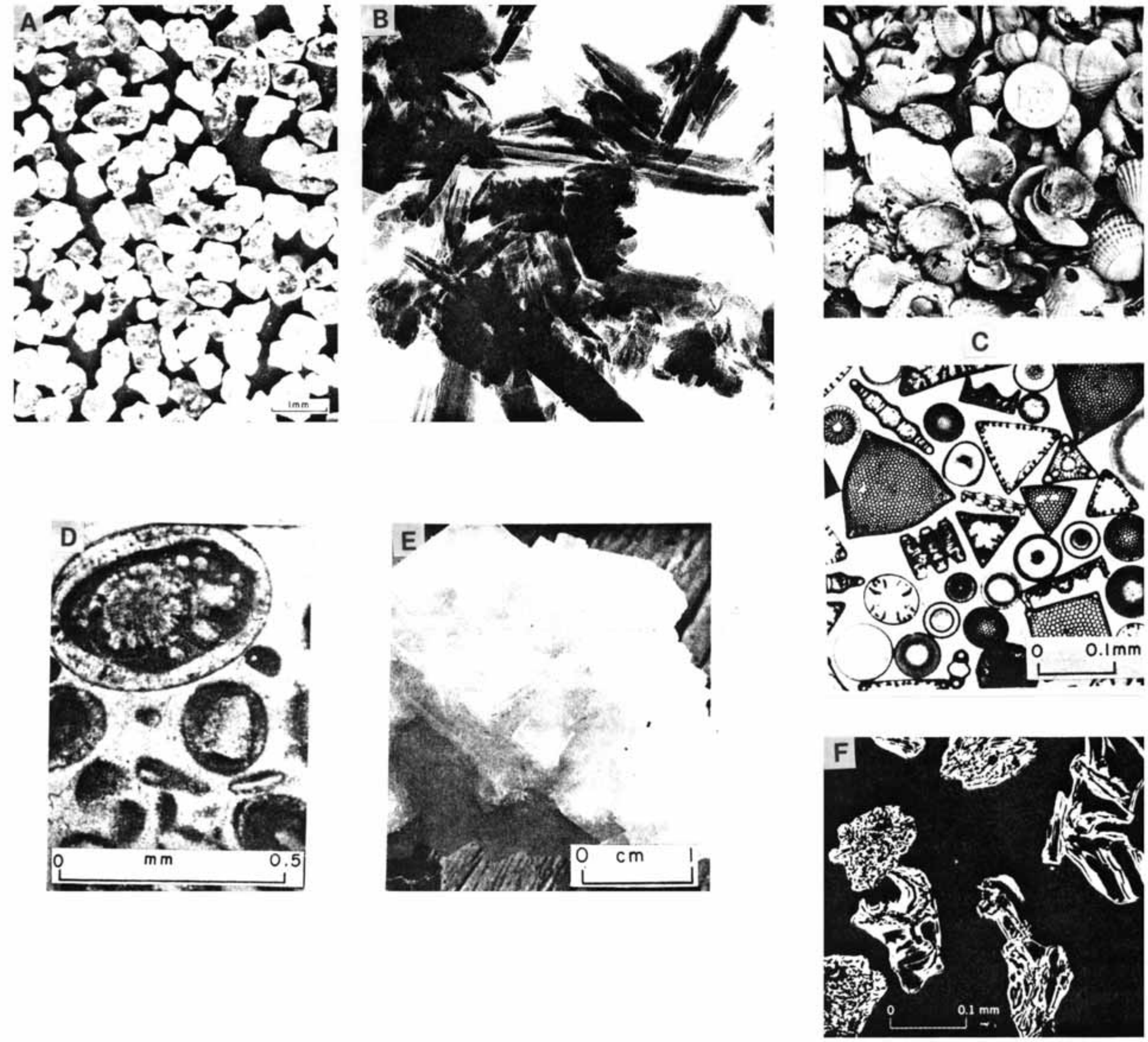


Figure 5. Major constituents of sediments and sedimentary rocks. (J. E. Sanders, 1981, figs. 8.2 and 8.3, p. 200; figs. 8.4 and 8.5, p. 201; and fig. 8.6, p. 202.)

A. Quartz and feldspar from breakdown of pre-existing rock.

B. Clay minerals, a typical product formed during chemical weathering of feldspars.

C. Biocrystals (calcareous mollusk shells, above; siliceous diatoms in greatly enlarged view, below)

D. Ooids seen in microscopic view of petrographic thin section.

E. Cubic crystals of halite precipitated from a highly concentrated brine.

F. Tephra consisting of glass shards.

(4) Ooids, distinctive spherical objects (Figure 5, D) that result from the combination of crystal growth by evaporation and agitation of the water in which such growth takes place.

(5) Tephra, commonly referred to as volcaniclastic sediment, is material blown out of volcanoes (Figure 5, E).

The diagnostic feature of all extrabasinal particles is evidence of abrasion during their physical transport as individual solid objects. Any initial sharp edges become rounded. Untimately, no matter what they looked like when they were first broken loose from the bedrock, they may become smooth and spherical.

In addition, after they have formed, biocrystals secreted by organisms, crystals precipitated by evaporation, and ooids formed by combined evaporation and agitation, are also subject to being transported physically as individual solid objects. Accordingly, these objects may also display evidence of breakage and abrasion and are organized into layers and display features formed as a result of deposition by physical processes.

Metamorphic Rocks: Unity of Place but Double Diversity of Protolith(s) and Process(es)

In most metamorphic rocks, the unity factor is place (within the Earth); but not one but two diversity factors must be considered: (a) pre-existing rock (the protolith) and (b) metamorphic process(es). Some major metamorphic processes are heat acting alone, deformation by shearing, and shearing deformation plus heat acting in combination. Rearrangement of minerals during deformation gives rise to distinct rock fabrics in which layer-lattice silicate minerals such as micas become preferentially oriented.

GEOLOGIC STRUCTURE – A PRIMER

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

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

Strata

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

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

The particle sizes within a stratum may be uniformly distributed across the bed or may display grading in which larger particles are present at the base of a particular layer and the sizes diminish or "grade" upward into finer particles (Figure 6). A graded layer is the result of a kind of a "lump-sum distribution" from a current carrying a wide range of particles and depositing them within a short time span, largest first and progressively smaller ones later. A common kind of current that deposits layers showing size grading is a gravity-induced turbidity current that flows down a subaqueous slope and crosses a flat part of the basin floor.

Fundamental principles about strata were recognized in the 1660s by Nicolaus Steno [1631-1687]. 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 or gravitational adjustment.

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. These are features that Robert R. Shrock [1904-1994] named geopetal criteria (Shrock, 1948).

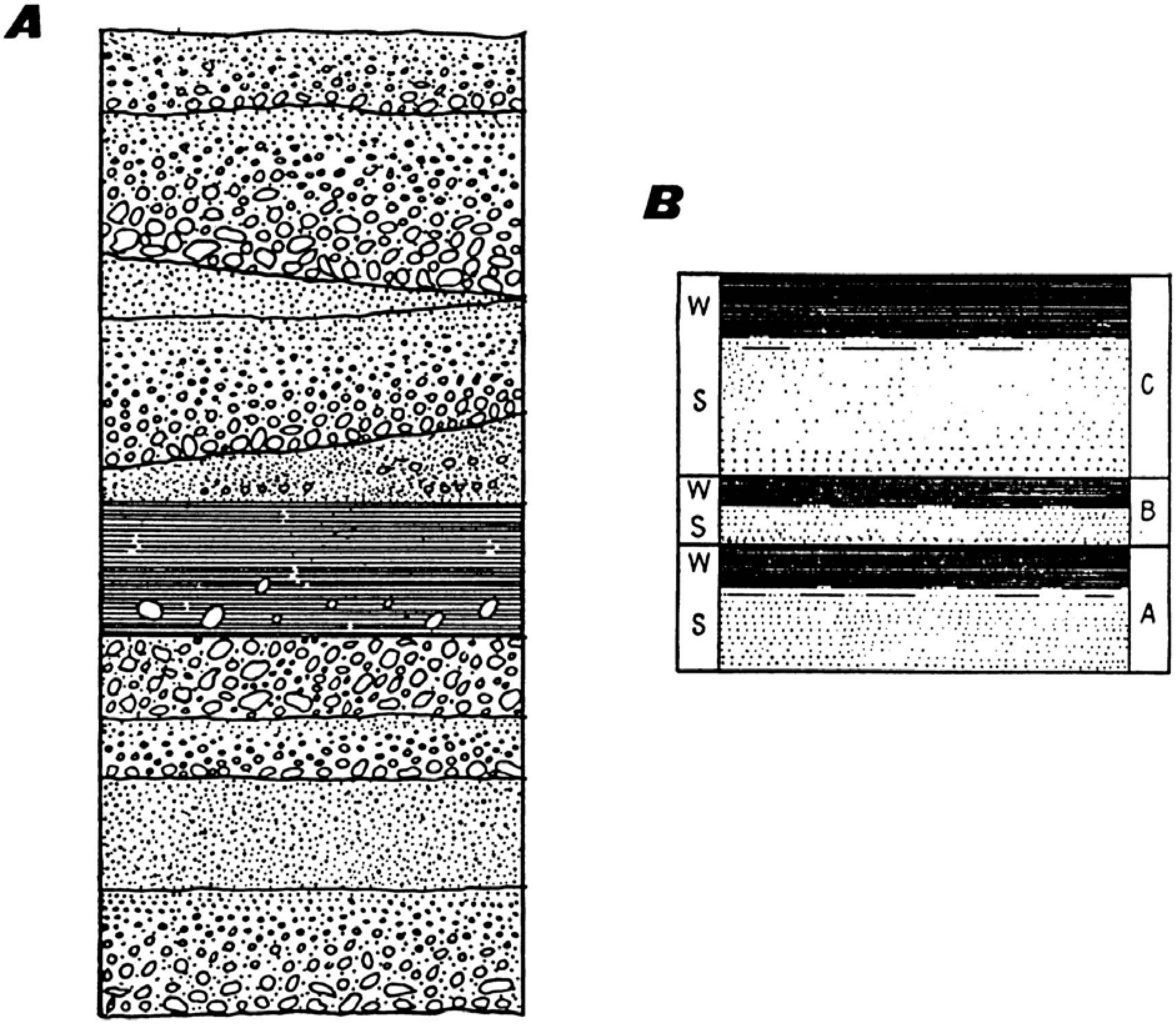


Figure 6. Contrasting kinds of sediments showing internal upward-fining grading.
A. Conglomeratic layers, some graded, some uniform, interbedded with shale containing scattered pebbles. Nonmarine Wamsutta Formation, (Pennsylvanian), E side of Great Pond, Braintree, MA. (R. R. Shrock, 1948, fig. 43, p. 84)
B. Schematic view of varved silt and -clay deposited in a proglacial lake showing light-colored, coarser graded silty layers deposited during the short summer season when lake is free of ice (marked with S) alternating with dark-colored clay layers deposited during the much-longer winter season when the lake surface is frozen over (marked with W). (R. R. Shrock, 1948, fig. 44, p. 85.)

Strata are such fundamental reference surfaces that we emphasize the importance of being able to recognize strata. Where all the particles are about the same size, bedding may not be so easy to identify. This is especially true with uniformly fine sediments (silt size, for example) or with uniformly coarse sediments (boulder gravel). In some cases, such recognition is self evident: materials of contrasting composition or -particle size (Figure 7) 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.)

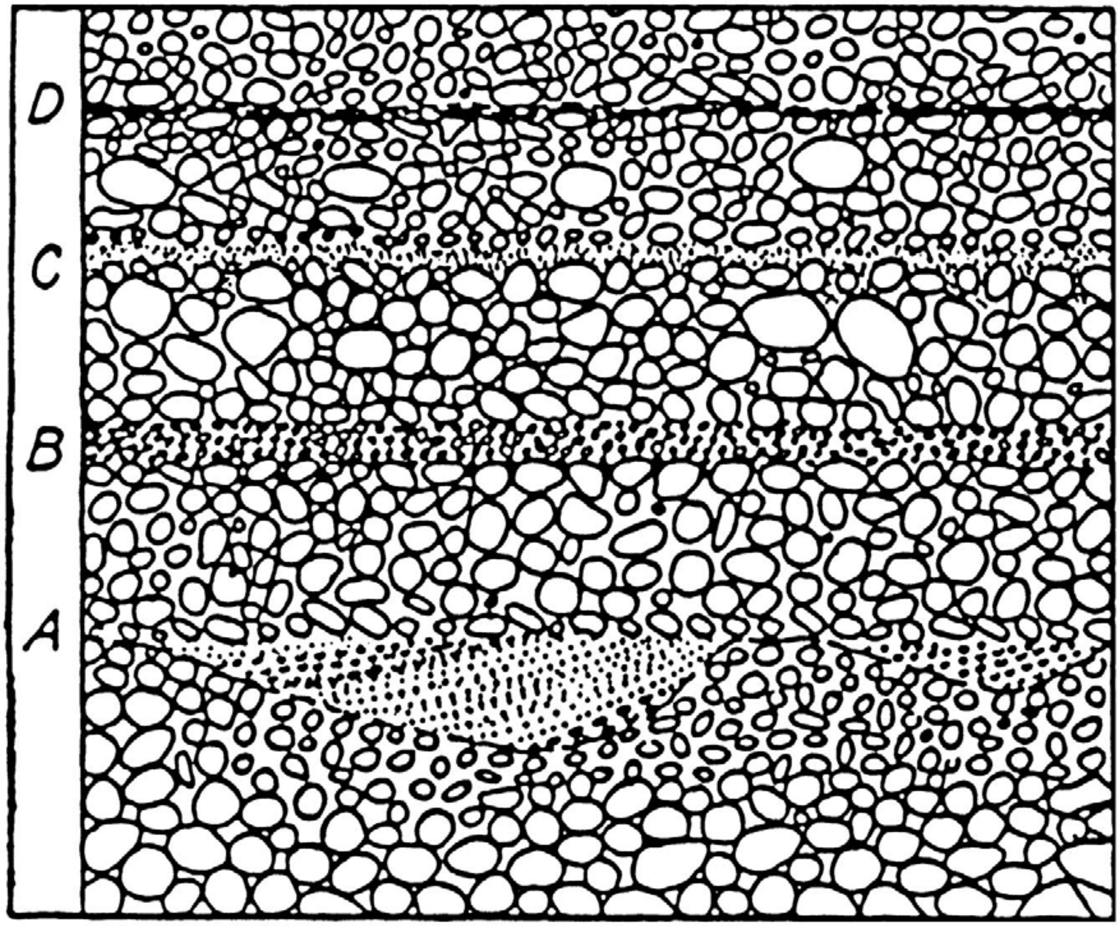


Figure 7. Sketch of gravel (or conglomerate) showing how bedding is revealed by finer sediment in planar layers (such as B, C, and D) or in lenses (as in A). (R. R. Shrock, 1948, fig. 3, p. 12.)

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 8), aligned shells of invertebrates, differences in the degree of cementation, to name a few.

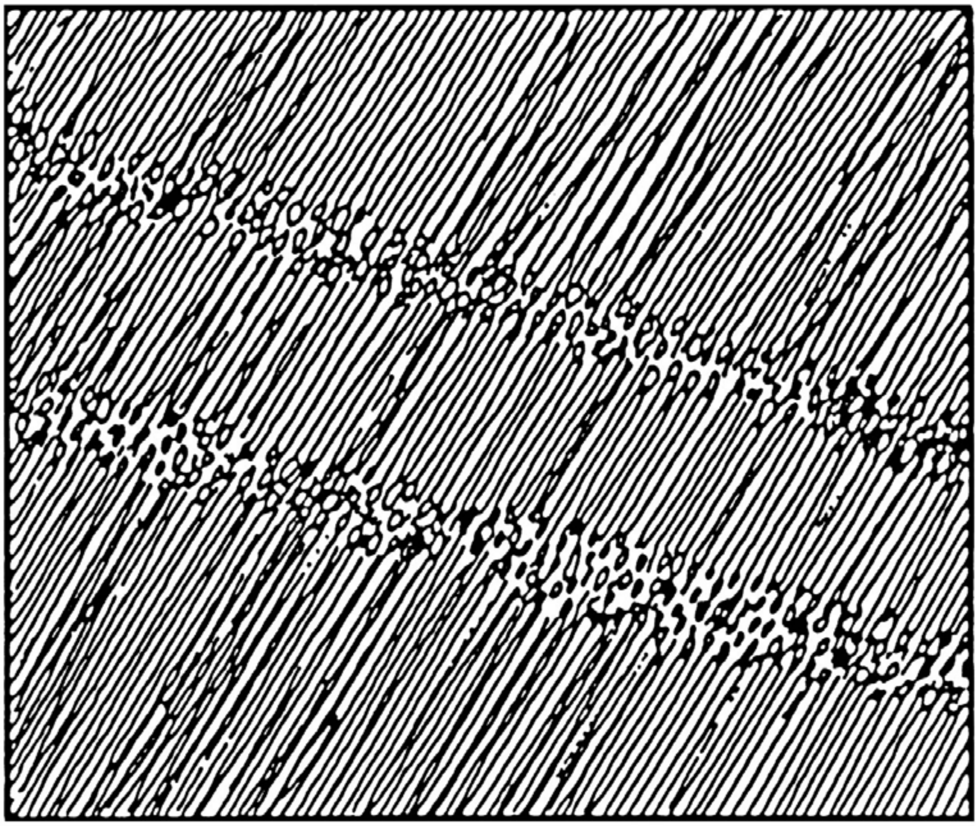


Figure 8. Sketch of slate with closely spaced prominent partings (slaty cleavage) dipping steeply to the left; two layers composed of silt-size sediment (stipple) show that bedding dips gently to the right. (R. R. Shrock, 1948, fig. 7, p. 15.)

Sedimentary Structures

Primary- and secondary sedimentary structures can develop above-, below-, and within strata during deposition in a variety of environments. During high-energy transport of sand-size or coarser particles (defined as cohesionless sediment), a moving current reacts with the sediment it is transporting and over which it is flowing to create repeating patterns of linear- or curvilinear relief features having long axes that may be transverse to- or parallel with the direction of the current. These are collectively designated as bed forms (Figure 9). In many cases, the tops of sandstone beds display such bed forms, which are named ripples if their relief and crestal-separation distances are measured in centimeters or up to a few tens of centimeters or dunes, if their dimensions measure in meters, tens of meters, or even kilometers. Many bed forms are asymmetric; they slope gently into the current on their upcurrent sides and steeply downcurrent on their downcurrent sides. The shearing-drag effect of the current on the cohesionless-sediment substrate causes these bed forms to migrate downcurrent. They migrate bodily as sediment is eroded from their upcurrent sides and added to their downcurrent sides. The result is a distinctive kind of internal cross strata in which the layers are concave up, tangential at their bases, and truncated at their tops. If the crests of the bed forms are linear, then downcurrent migration creates planar cross strata. (See Figure 8, A.) If the crests of the bed forms are sinuous and concave downcurrent, then downcurrent migration creates trough-type cross strata. (See Figure 9, B.)

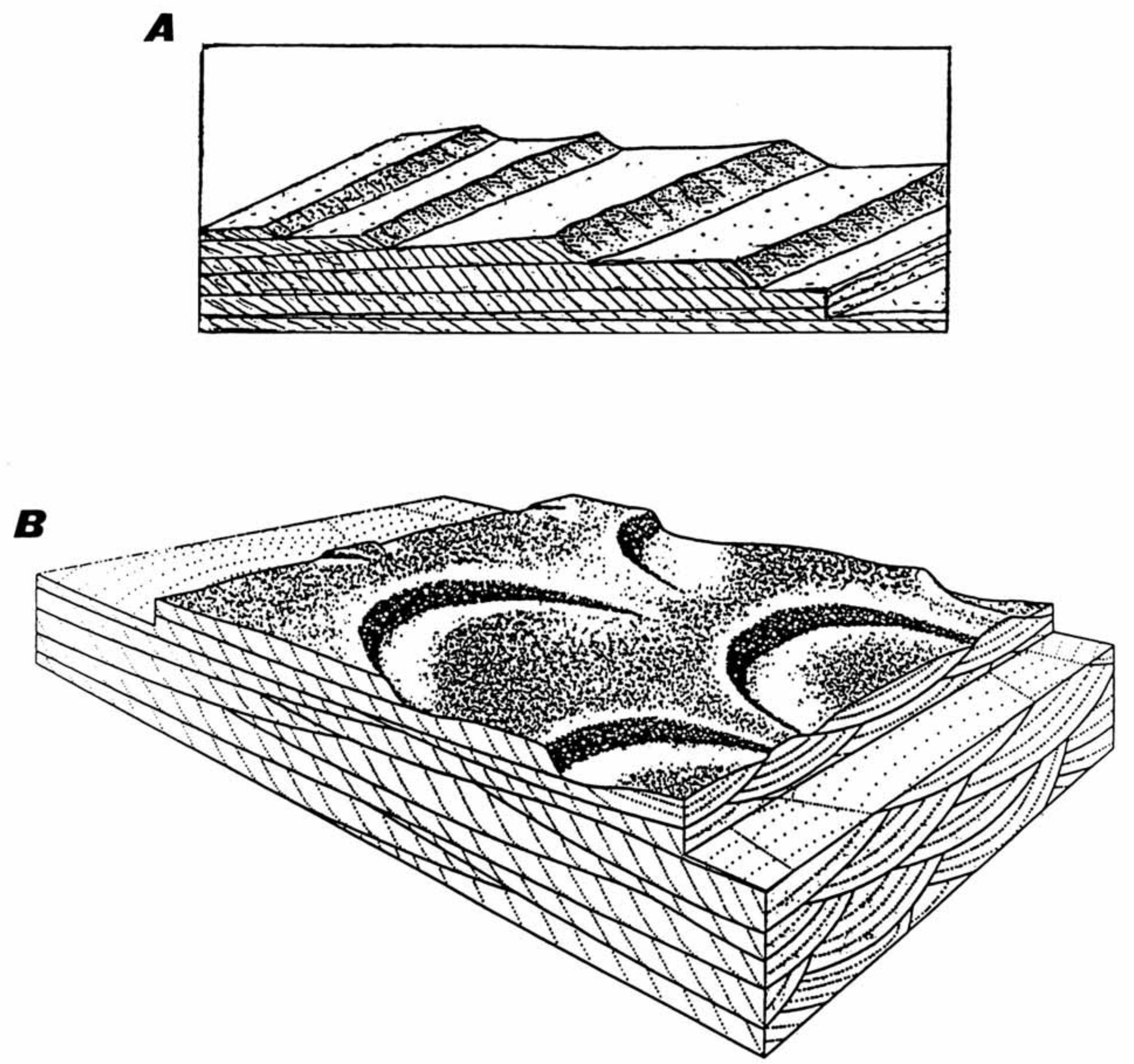


Figure 9. Sketches of contrasting shapes of bed forms created by a current flowing from left to right and cross strata resulting from their downcurrent migration.
A. Linear bed forms create planar cross strata. (G. M. Friedman, J. E. Sanders, and D. C. Kopaska-Merkel, 1992, fig. 5-19, A, p. 166.)
B. When cuspate (lunate) megaripples migrate downcurrent trough-type cross strata form. In sections that are parallel to the current, trough cross strata and planar cross strata look about alike. The difference between them is immediately apparent in sections normal to the current. (H. E. Reineck and I. B. Singh, 1980, fig. 52, p. 43.)

Not all cross strata result from downcurrent migration of rhythmic bed forms composed of cohesionless sediment (as in Figure 10, 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 10, B). In other places, cross strata are deposited at the fronts of sediment embankments where a water current encounters a deeper place. The embankment lengthens in the downcurrent direction as sediment is deposited in inclined layers (cross strata) along the growing front of the embankment (Figure 10, C and E).

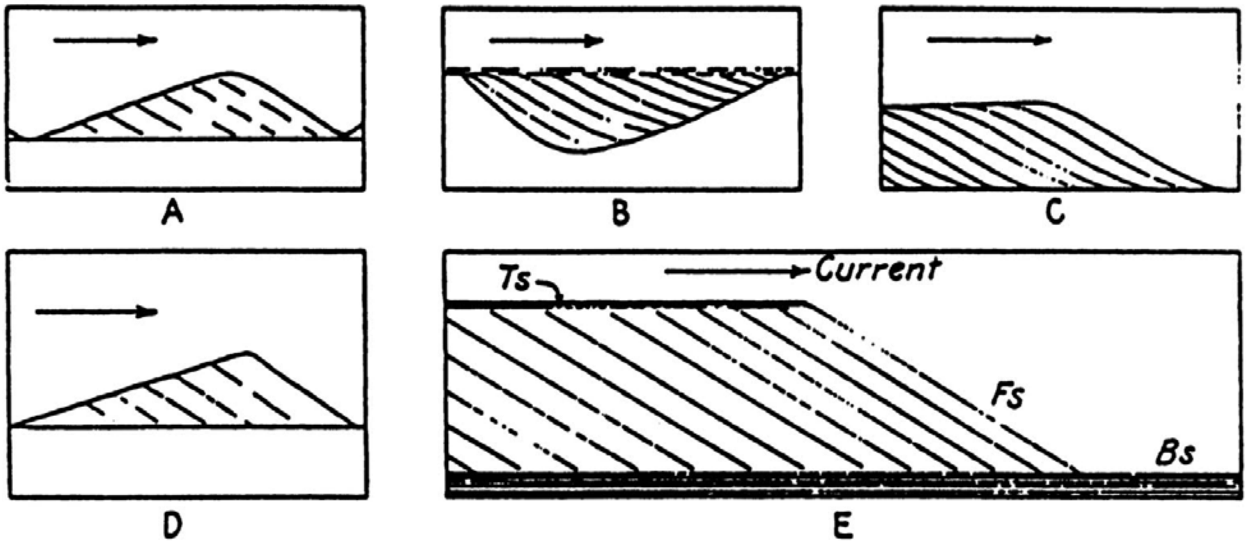


Figure 10. Sketches showing various settings in which cross strata dipping to the right can be deposited by a current flowing from left to right.
A and D, Longitudinal profiles through individual bed forms that have migrated to the right (downcurrent) by at least one wavelength, thus preserving as internal 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 11, 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 11, B).

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 12). 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 13).

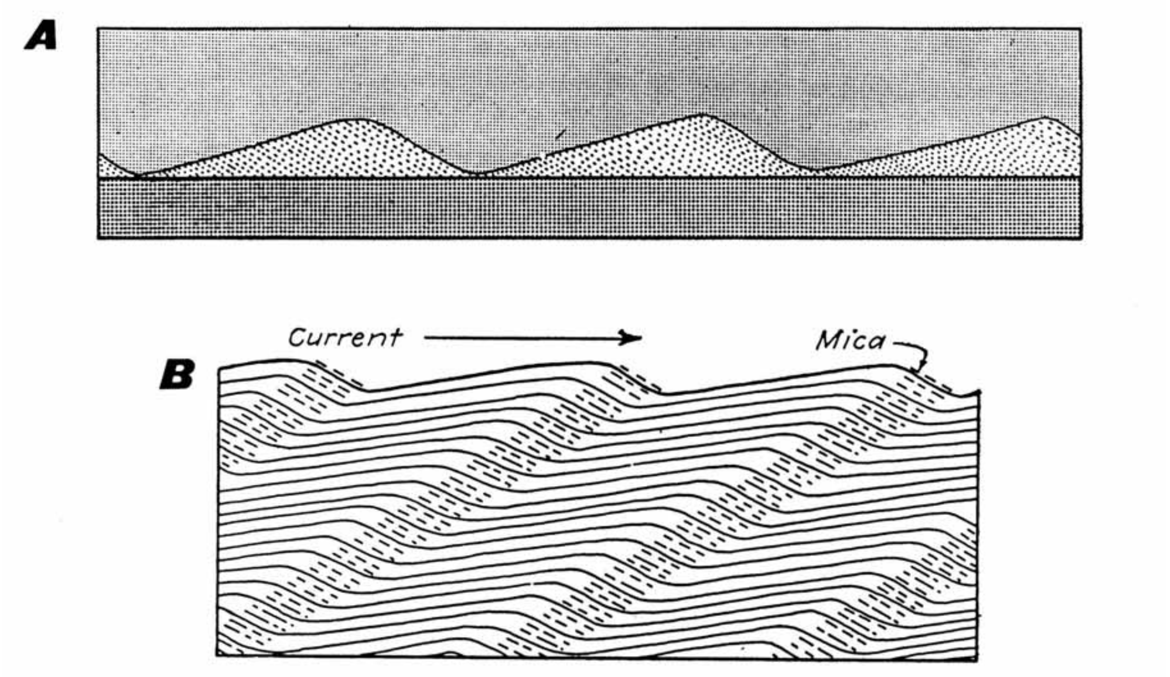


Figure 11. Sketches of ripple cross laminae formed under varying conditions of sediment supply.
A. Cross laminae formed by migration of ripples from left to right when no new sediment is added from the current. (R. R. Shrock, 1948, fig. 57, p. 103.)
B. Climbing-ripple laminae formed when sediment falls 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.)

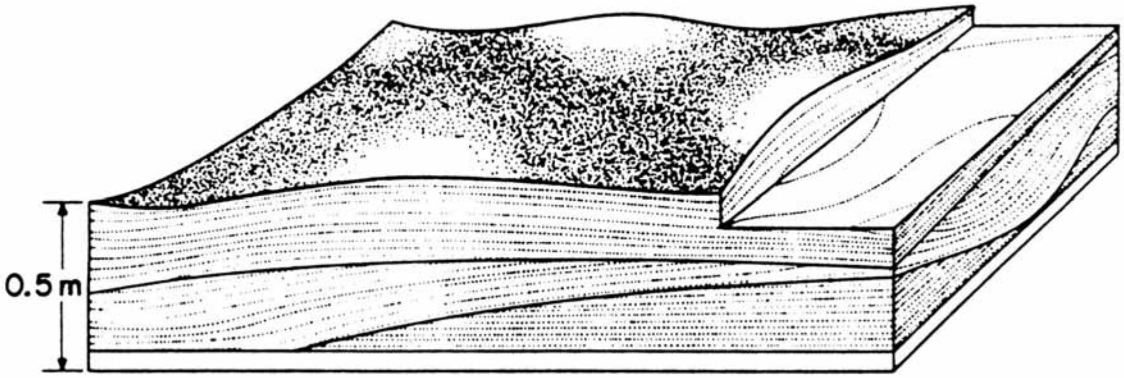


Figure 12. Sketch of hummocky strata. (R. H. Dott, Jr. and Joanne Bourgeois, 1982, fig. 1, p. 663.)

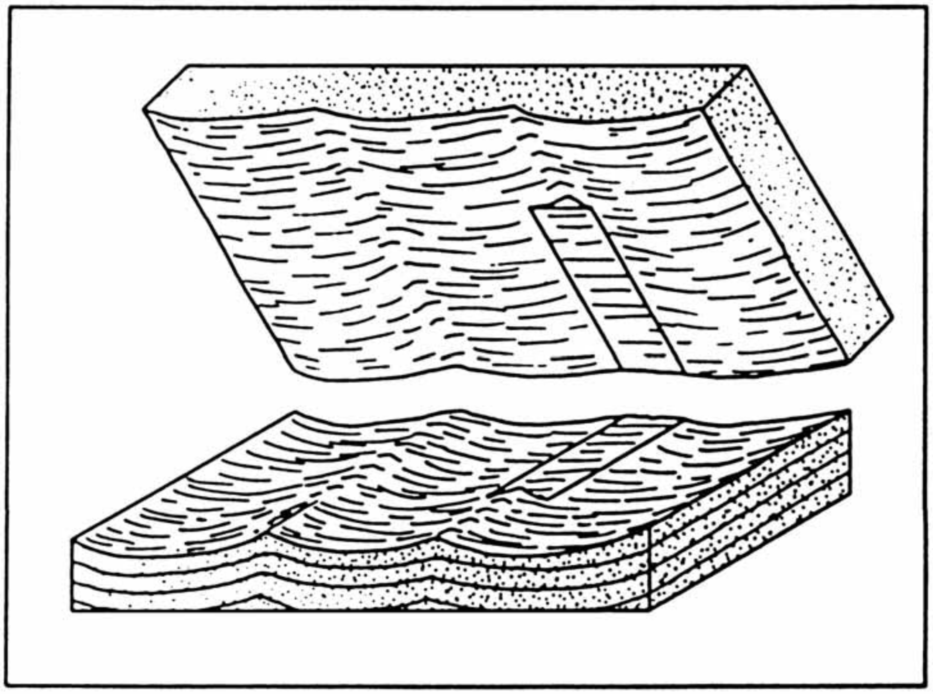


Figure 13. Sketch of symmetrical ripples.

A current carrying sand in suspension that crosses a substrate composed of cohesive fine sediment (as contrasted with the coarser, cohesionless sediment discussed previously) may interact with the bottom to form scour marks or tool marks. These features, sculpted in the basal 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 flow of the former current (Figure 14).

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, typically shallow-water or even nonmarine sediments, and include mud (or desiccation) cracks, rain-drop impressions, and animal footprints. Figure 15 is a composite diagram illustrating common sedimentary structures.

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

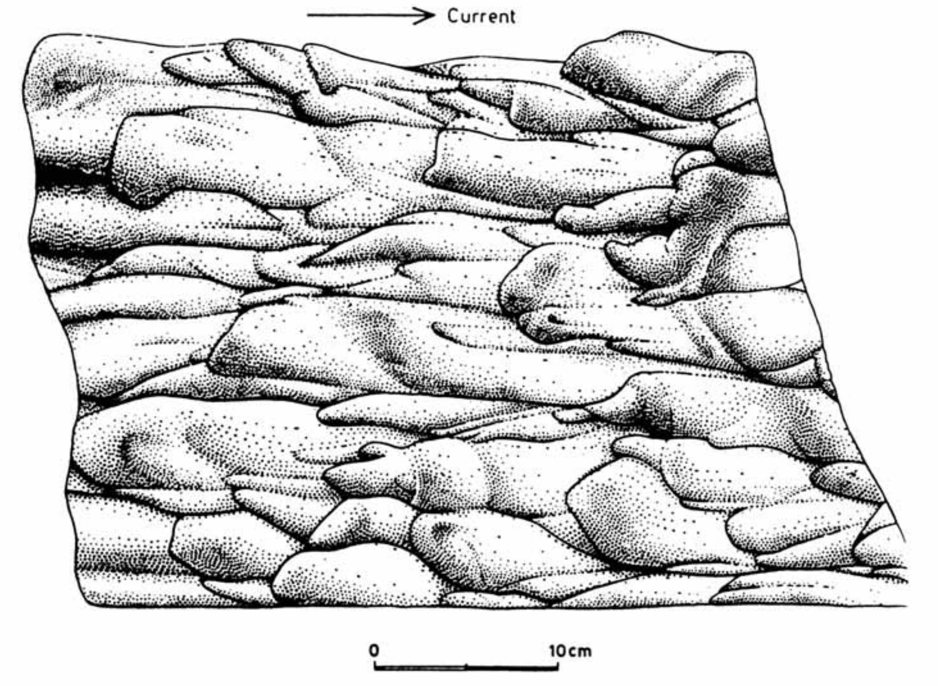


Figure 14. Sketch of counterparts of flutes, sole marks on base of Miocene sandstone bed, Apennines, Italy. (P. E. Potter and F. J. Pettijohn, 1977, fig. 5-2, p. 160, from E. ten Haaf, 1959, fig. 12.)

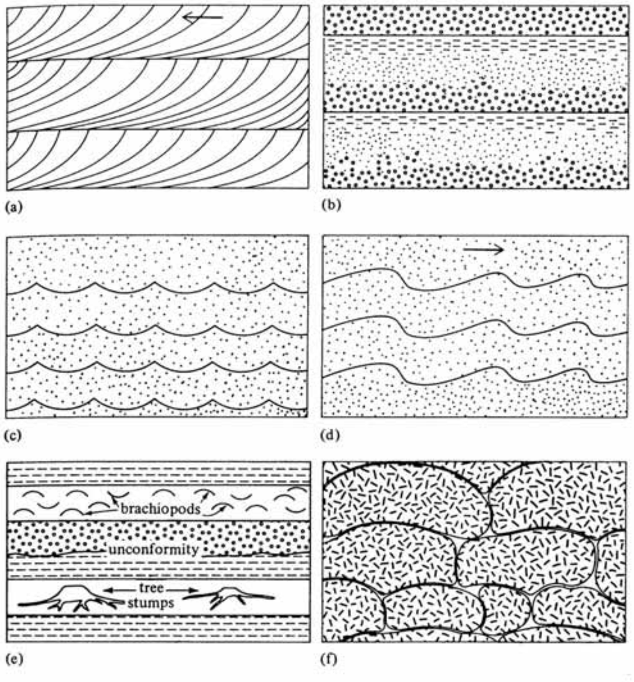


Figure 15. Diagrammatic sketches of primary sedimentary structures (a through e) and cross sections of pillows (f) used in determining topping (younging) directions in layered rocks.

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

Mechanical Aspects of Deformation

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

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

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

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

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

When subjected to differential forces, under high confining pressures and elevated temperatures, rocks (like humans) begin to behave foolishly, squirming in many directions and upsetting the original orientation of primary- or secondary planar- and linear features within them. Geologists try to sort out the effects of deformation by working out the order in which these surfaces or linear features formed using a relative nomenclature based on five letters of the alphabet: D, F, S, L, and M. Episodes of deformation are abbreviated by (Dn), of folding by (Fn), of the origin of surfaces (such as bedding or foliation) by (Sn), of the formation of linear features (such as mineral streaking or intersection lineations produced by intersections of S1 and S0) by Ln, and of metamorphism by (Mn), where n is a whole number starting with 1 (or in some cases, with zero). Bedding, for example, is typically designated as 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 16, note the geometric relationship of anticlines and synclines. Axial surfaces physically divide folds roughly in half. Note that in Figure 16, 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.

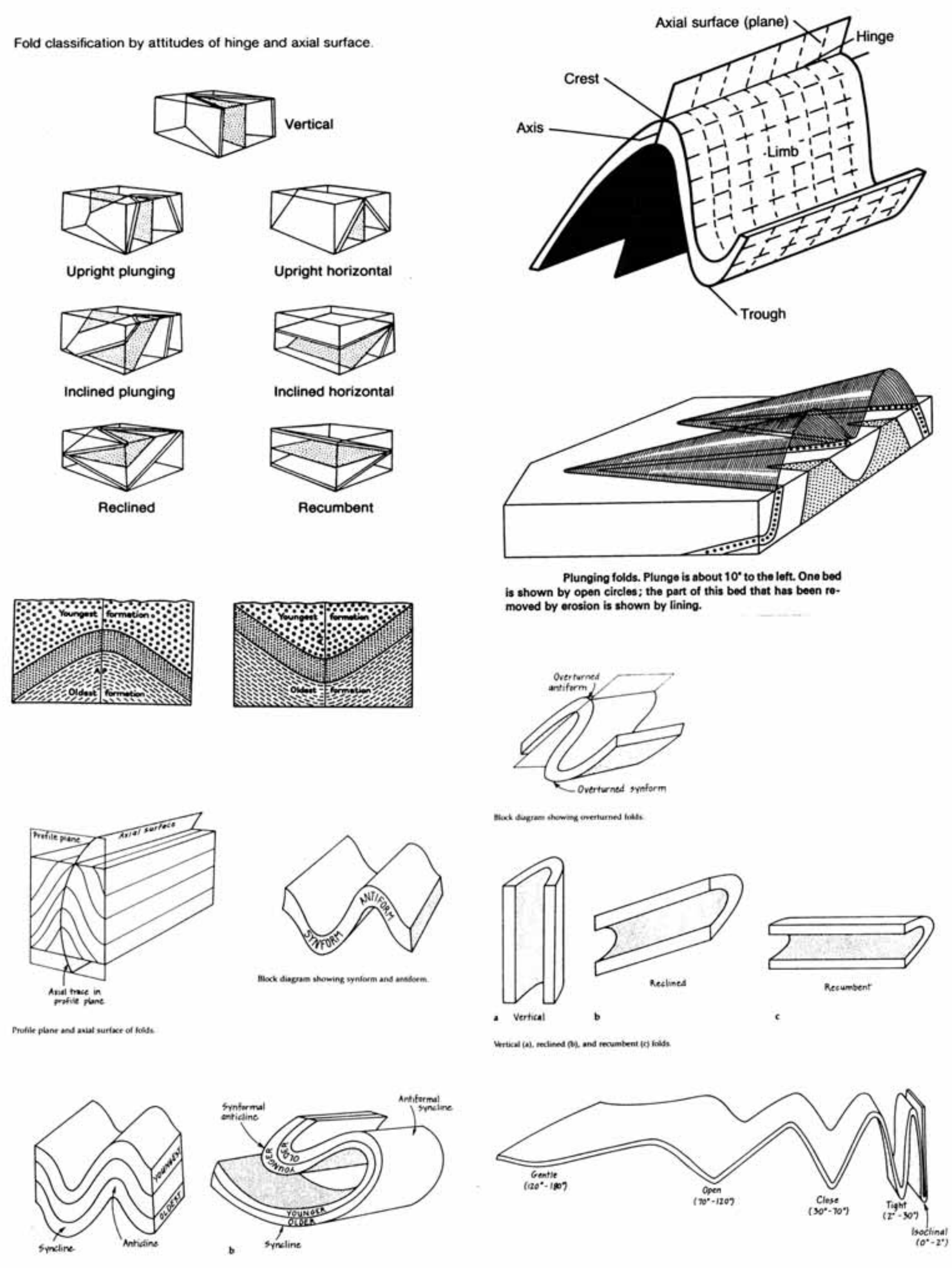
In eroded anticlines, strata forming the limbs of the fold dip away from the central hinge area or core (axis) of the structure. In synclines, the layers forming the limbs dip toward the hinge area. Given these arrangements, we expect that in the arches of eroded anticlines, older stratigraphic layers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

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 [1769-1839] 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, Henry

Darwin [1808-1866], and William Barton [1804-1882], 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.



Fold classification by attitudes of hinge and axial surface.

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

Block diagram showing overturned folds.

Profile plane and axial surface of folds.

Block diagram showing synform and antiform.

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

Figure 16. Composite diagram from introductory texts showing various fold styles and nopersonsclature (non-sexist, 90s, politically correct terminology) as discussed in the text.

Realize that in the upright folds shown in Figure 16, 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. 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 16.) 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 17, inset). The block situated below the fault plane is called the footwall block and the block situated above the fault plane, the hanging-wall block.

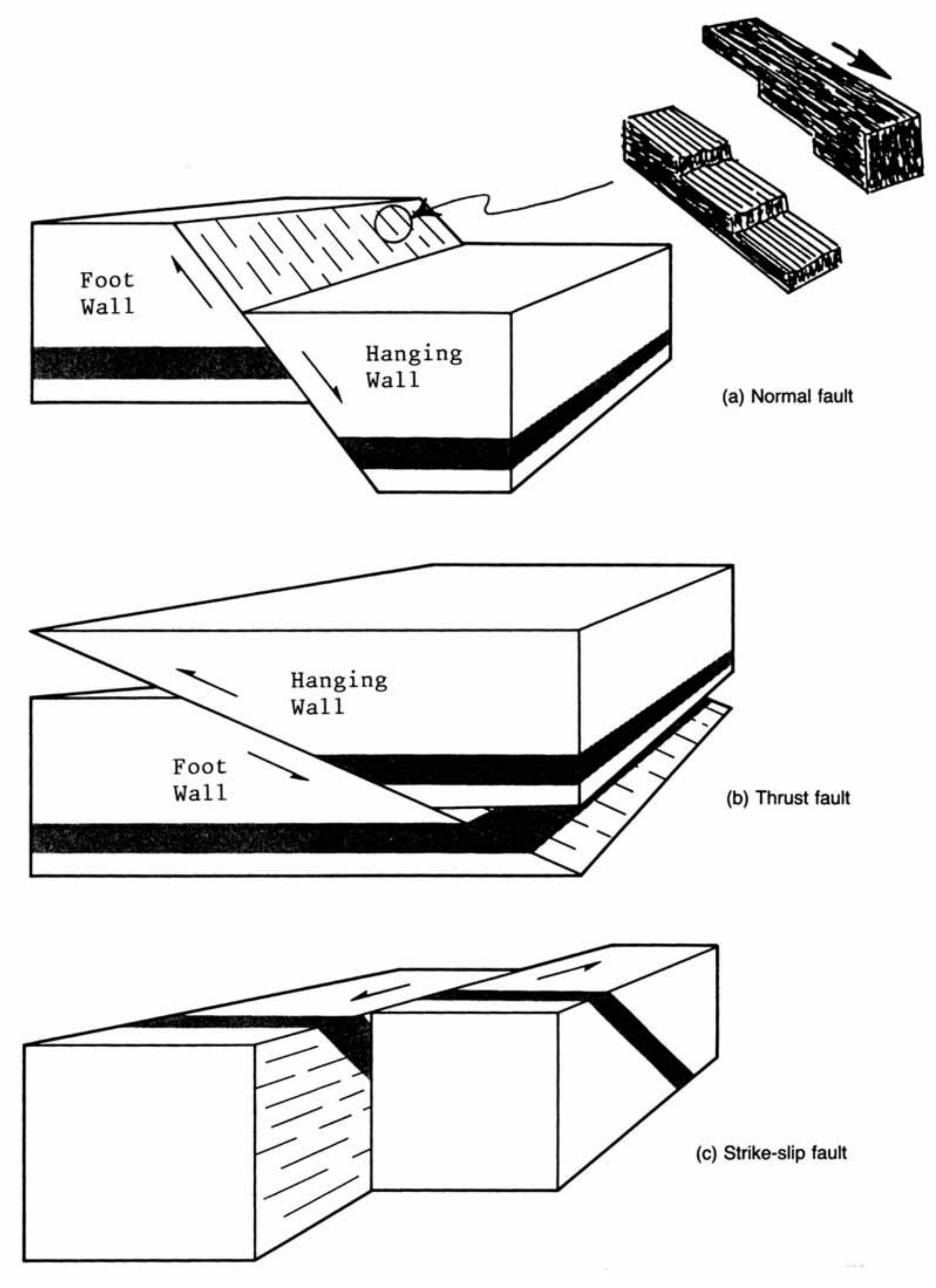


Figure 17. The three main types of faults shown in schematic blocks. Along a normal fault (a) the hanging-wall block has moved relatively downward. On a thrust fault (or reverse fault) (b) the hanging-wall block has moved relatively upward. Along a strike-slip fault (c), the vertical reference layer (black) has been offset by horizontal movement (left-lateral offset shown here). Inset (d) shows segments of two blocks along a slickensided surface show how the jagged "risers" of the stairsteps (formed as pull-apart tension fractures) can be used to infer sense of relative motion. [(a), (b), (c), Composite diagram from introductory texts; (d), J. E. Sanders, 1981, fig. 16.11 (b), p. 397.]

Normal- and reverse faults. Imagine extending (stretching) or compressing a block-like portion of the Earth's crust. Extensional force may causes the crust to rupture along a fracture that is not vertical. In this case, the block above the dipping fracture, known as the hanging-wall block, will slide down the fracture surface producing a normal fault. [See Figure 17 (a).] Compressive forces drive the hanging-wall block up the fracture surface to make a reverse fault. A reverse fault with a low angle (<30°) is called a thrust fault. [See Figure 17 (b).] In all of these cases, the slickensides on the fault will be oriented more or less down the dip of the fault plane and the relationship between the tiny "risers" that are perpendicular to the striae make it possible to determine the relative sense of motion along the fault. Experimental- and field evidence indicate that the asymmetry of slickensides is not always an ironclad indicator of relative fault motion. As such, displaced geological marker beds or veins are necessary to verify relative offset. Fault motion up- or down the dip (as in normal faults, reverse faults, or thrusts faults) is named dip-slip motion.

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

The large-scale repetition of strata on low-angle thrusts was first shown in the Scottish Highlands. Soon thereafter, spectacular examples were found in the Alps and, indeed, in nearly all mountain chains. Studies in the Appalachians made possible new understanding between thrusts and folds. Examples were found illustrating all gradations from small breaks across the axes of overturned folds (Figure 18) 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 19).

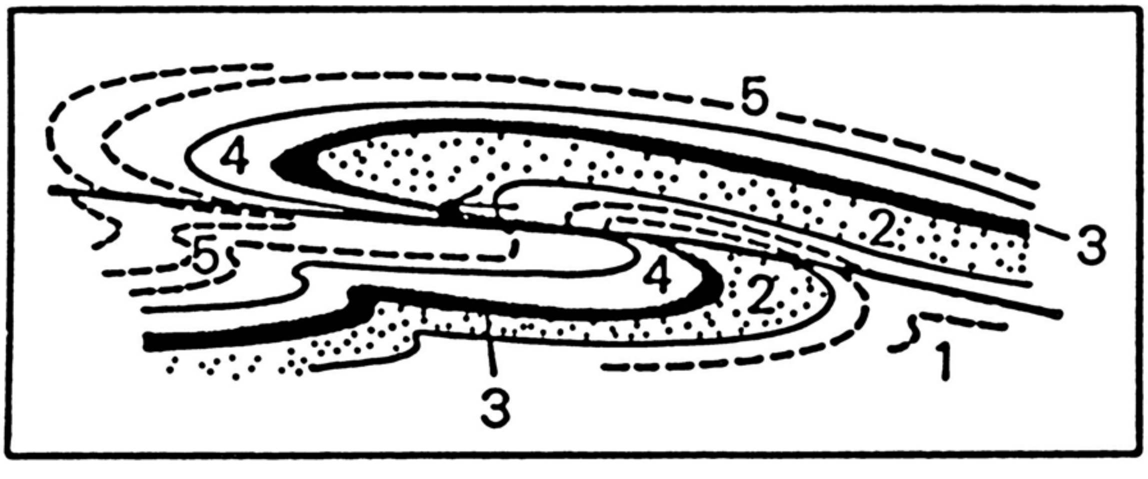
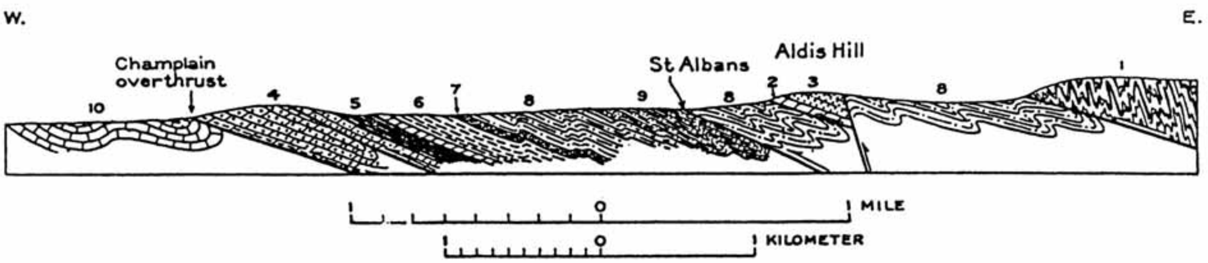


Figure 18. Overturned fold broken by a low-angle thrust fault, schematic profile section. Units are numbered in order of decreasing age, from 1 (oldest) to 5 (youngest). (J. E. Sanders, 1981, fig. 16.14, p. 398.)



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 19. 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.)

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.

Studies in the Appalachians led John L. Rich [1884-1956] to propose the concept of "bedding thrusts" (Rich, 1934). 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 20). (These segments that cut bedding at steep angles have subsequently been named ramps.) What was totally different about Rich's analysis is the relationship between thrusts and folds. Because of the geometric arrangement of the ramps and the beds, any forward displacement causes the strata of the upper block to be folded. As the strata are pushed against the ramp, they become parallel to it, forming one limb of a ramp-related anticline. Where the strata that have been displaced past the ramp return to the next bedding-parallel segment of the thrust surface, they dip downward toward this surface, thus forming the second limb of the ramp-related anticline. Where later deformation has not obscured the relationships, Rich's mechanism creates flat-topped anticlines whose widths are direct functions of the amount of displacement on the thrust and intervening flat-bottom synclines whose widths are determined by the spacing between adjacent ramps.

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.

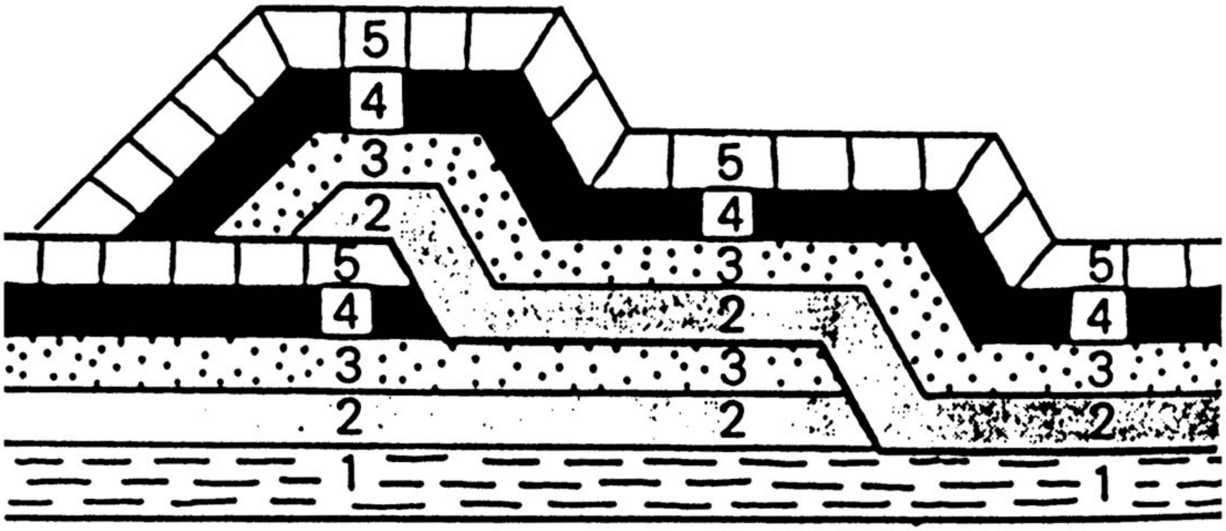


Figure 20. Folds formed by movement on a bedding-plane thrust according to the mechanism proposed by J. L. Rich; schematic profile section with units numbered in order of decreasing age from 1 (oldest) to 5 (youngest). (J. E. Sanders, 1981, fig. 16.1e, p. 390.)

Interesting geometric patterns result from the erosion of overthrust sheets of strata that have been folded after they were overthrust. Where a "hole" has been eroded through the upper plate (allochthon), it is possible to peer downward through the allochthon and see the autochthon exposed in a window (synonyms: inlier, or, in the German tongue, fenster) surrounded by the trace of the thrust fault that was responsible for the dislocation (Figure 21). By contrast, if most of the upper plate has been eroded, only a remnant outlier or klippe may remain. (See Figure 21.) 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).

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

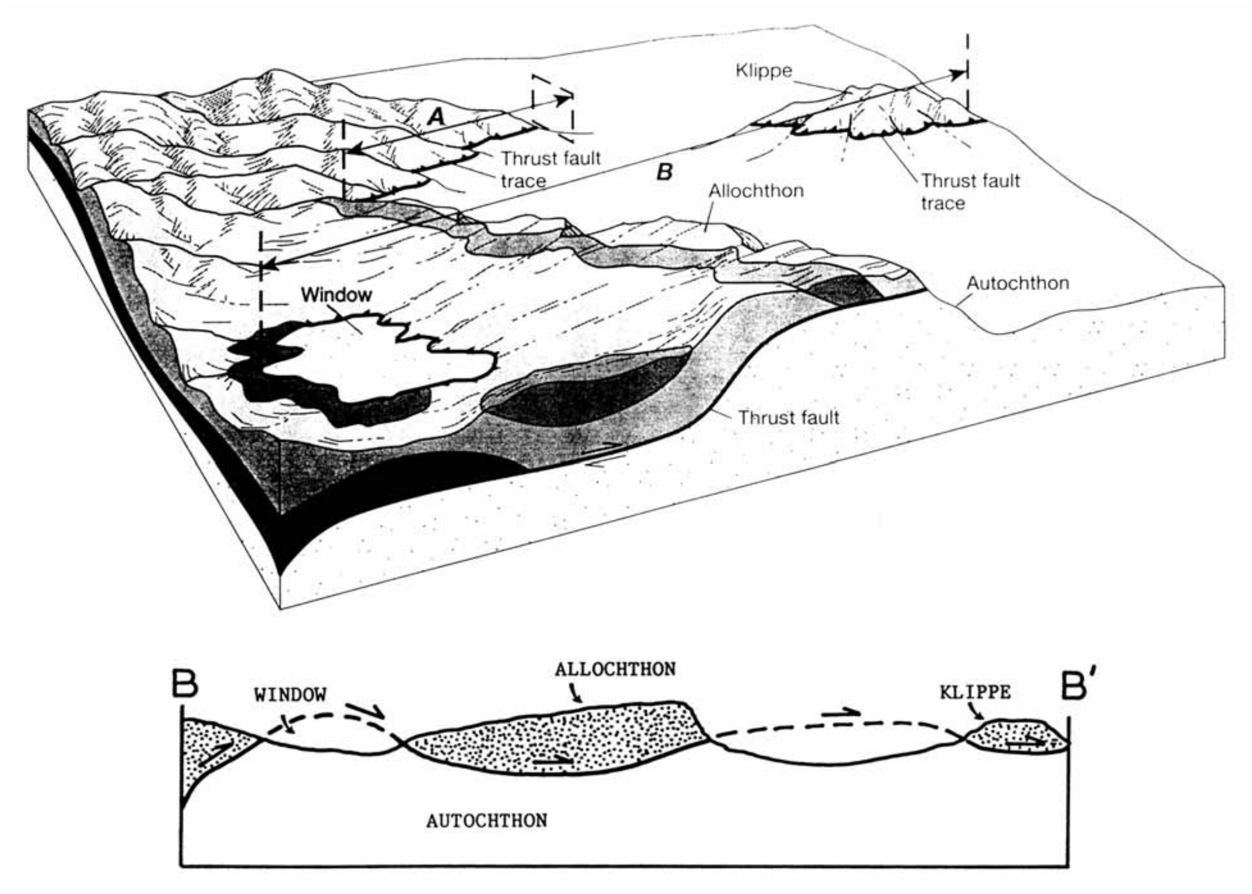


Figure 21. Block diagrams illustrating the relationships among major components of low-angle thrust sheets, including allochthons, autochthons, klippen, and windows. (R. J. Twiss and E. M. Moores, 1992, Fig. 6.4, p. 99; section B-B' drawn by CM.)

Strike-slip faults. Rather than simply extending or compressing a block of rock, imagine that the block 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 17 (c).] On a strike-slip-fault plane, slickensides are oriented subhorizontally and again may provide information as to which direction the blocks adjoining the fault surface moved.

Two basic kinds of shearing couples and/or strike-slip motion are possible: left lateral and right lateral. These are defined as follows. Imagine yourself standing on one of the fault blocks and looking across the fault plane to the other block. If the block across the fault from you appears to have moved to the left, the fault is left lateral [illustrated in Figure 17 (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 22 lists brittle- and ductile fault terminology as adapted from Sibson (1977) and Hull et al. (1986). Begining at roughly 10 to 15 km and continuing downward, rocks under stress behave aseismically and relieve strain by recrystallization during ductile flow. These unique metamorphic conditions prompt the development of highly strained (ribboned- and polygonized) quartz, feldspar porphyroclasts (augen), and frayed micas, among other changes, and results in highly laminated rocks called mylonites. (See Figure 22.)

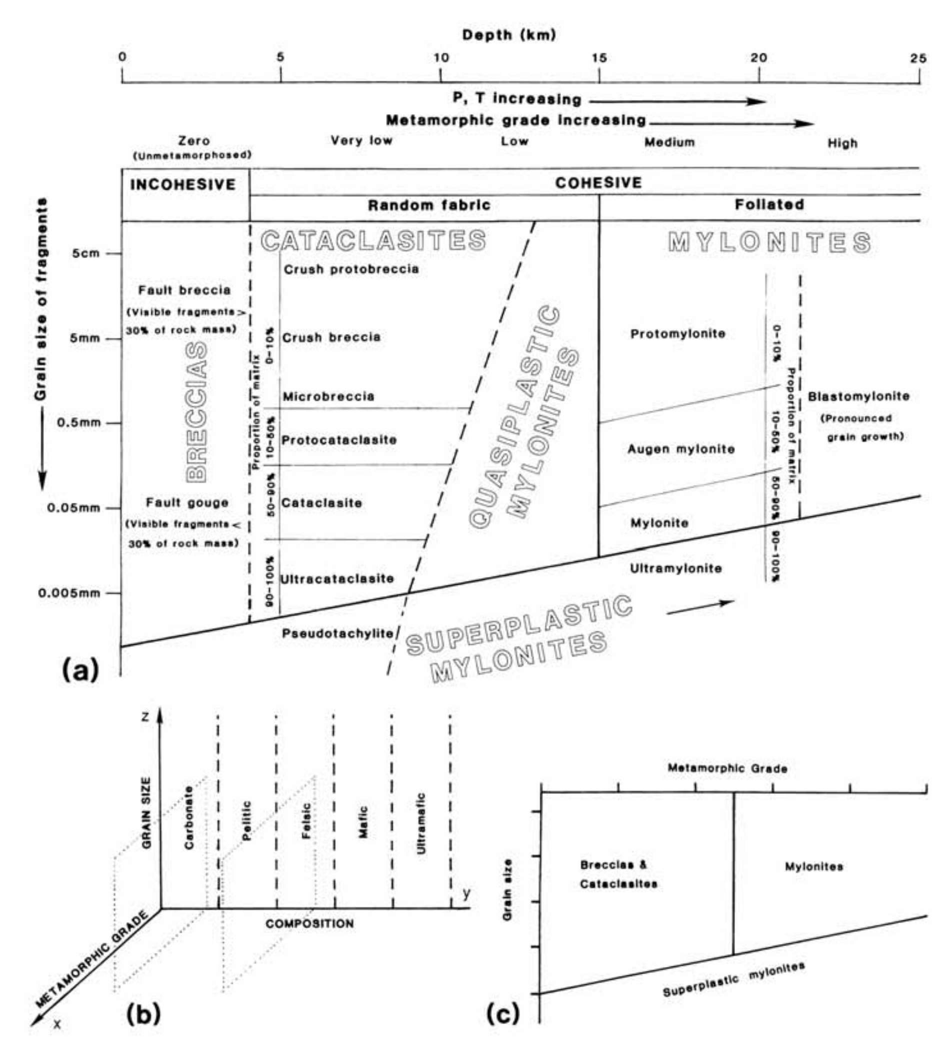


Figure 22. Fault-rock terminology. (a) Classification of fault rocks that have been derived from quartzo-feldspathic lithologies (e. g. granite). (Adapted from R. Sibson, 1977.) (b) The particle size - metamorphic grade - lithologic composition grid used for classifying fault rocks. (After J. Hull, R. Koto, and R. Bizub, 1986.) (c) Fault-rock diagram for marl showing expanded mylonite (sic) and superplastic mylonite fields as compared to those shown on the diagram for granite in (a) (Gautam Mitra and R. Stephen Marshak, 1988, fig. 11-23, p. 227.)

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 23).

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, this 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 23.)

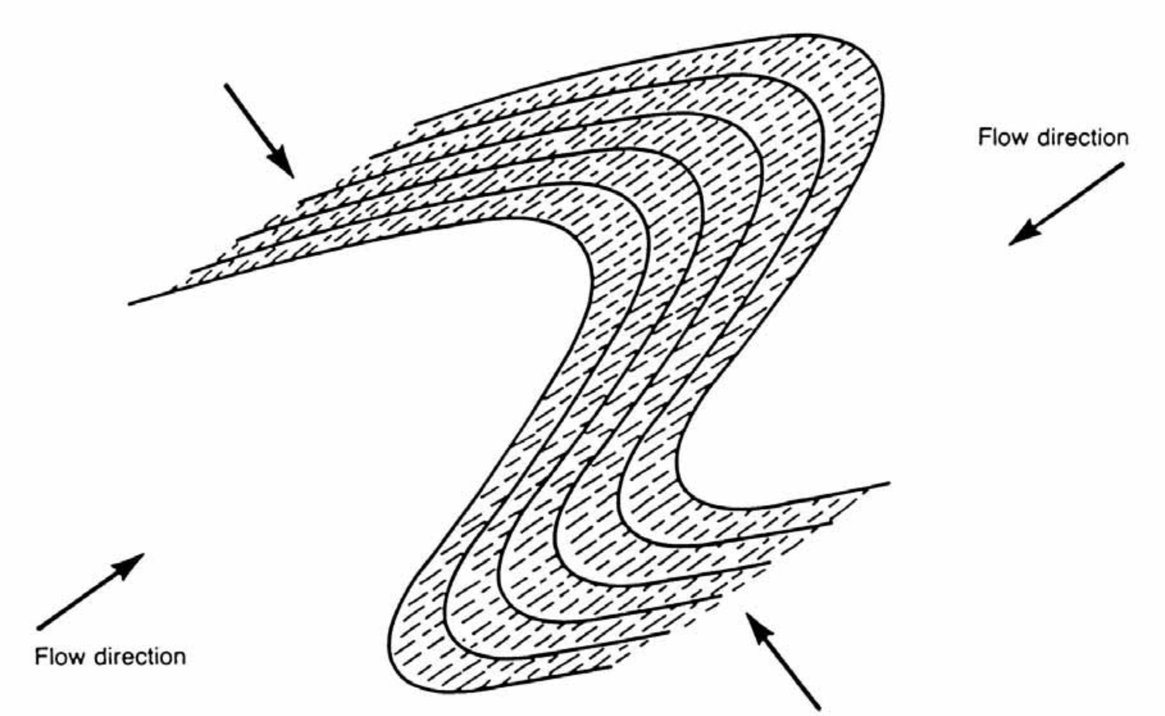


Figure 23. Sketch of slaty cleavage oriented parallel to axial surface of folds. (R. D. Hatcher, Jr., 1990, fig. 15-22, p. 335.)

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 relative 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 (discussed in a following section), 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).

Geologic Dating of Episodes of Deformation

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

Surfaces of unconformity. Surfaces of unconformity mark temporal gaps in the geologic record and commonly result from periods of uplift and erosion. Such uplift and erosion is commonly caused during the terminal phase of regional mountain-building episodes. As correctly interpreted by James Hutton at the now-famous surface of unconformity exposed in the cliff face of the River Jed (Figure 24), 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.

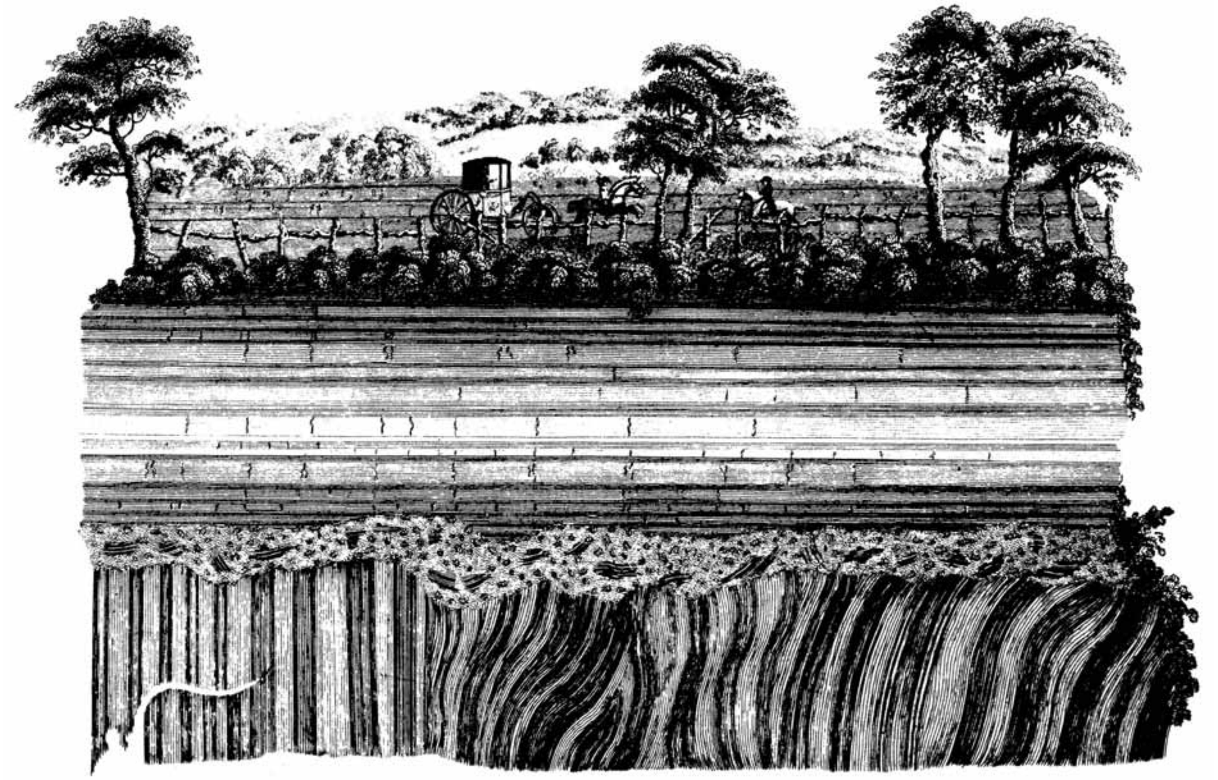


Figure 24. Surface of unconformity with basal conglomerate in overlying strata exposed along the River Jed, south of Edinburgh, Scotland. [James Hutton, "Theory (sic) of the Earth", 1795.]

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

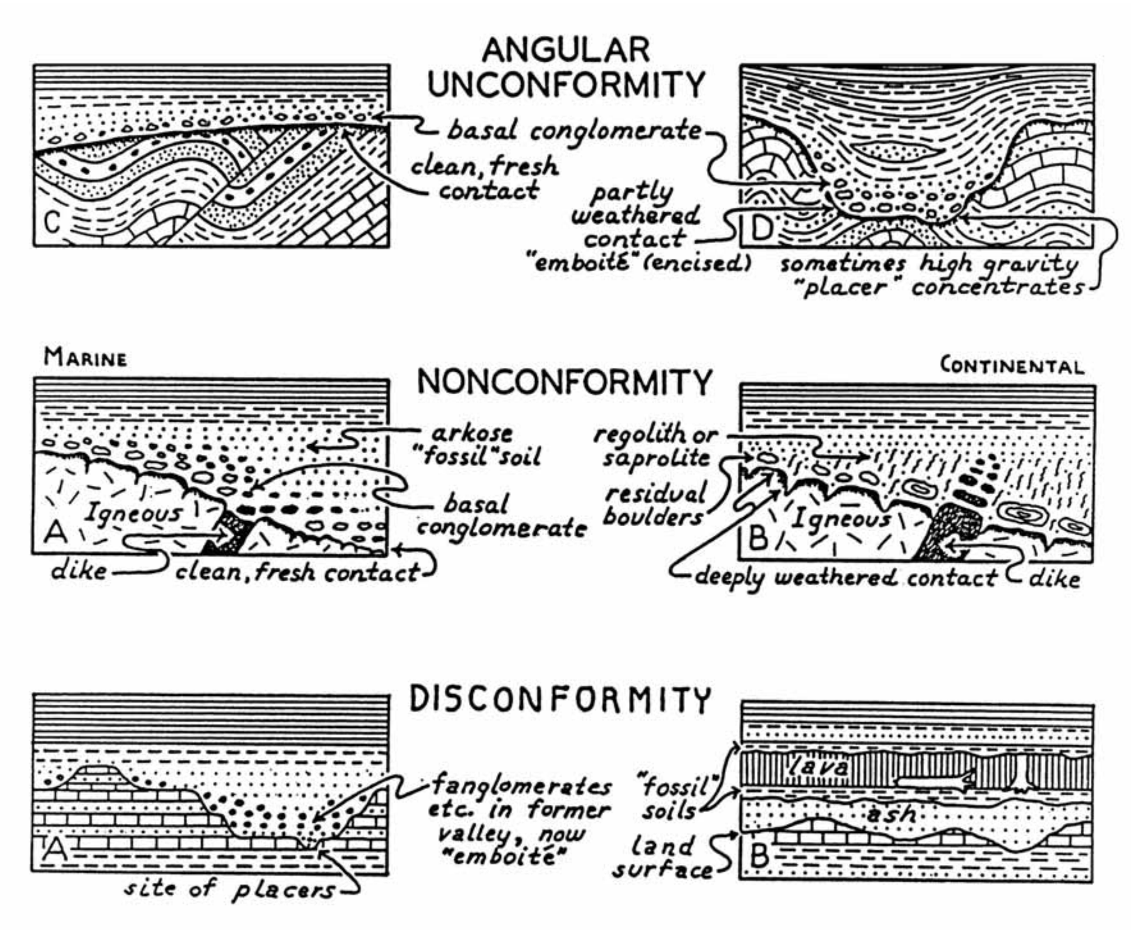


Figure 25. Varieties of geologic relationships along surfaces of unconformity, which mark gaps in the geologic record. (Drawings by Rhodes W. Fairbridge.)

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

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

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

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

Bedrock-forming Machinery: Geotectonic Cycles

Major components of the bedrock result from the operation of lithosphere plates in geotectonic cycles. Two contrasting plate-tectonic settings where geotectonic cycles operate are continental margins and intraplate nonmarine basins.

Continental Margin

A geotectonic cycle at a continental margin typically begins when two plates split apart and a new ocean starts to form. The trailing edges of the moving plates cool and subside. Sediments are deposited in what is known as a passive-margin phase (Figure 26). Eventually the deposited sediments are subjected to a convergent-margin phase in which they are deformed by being folded and duplicated on low-angle thrusts (Figure 27) and in many cases, metamorphosed and some of the rocks partly melted as part of mountain-building processes collectively designated as orogeny. Such cycles accompany the opening- and closing of an ocean basin. Commonly such orogenic cycles are punctuated by periods of uplift and extensive erosion.

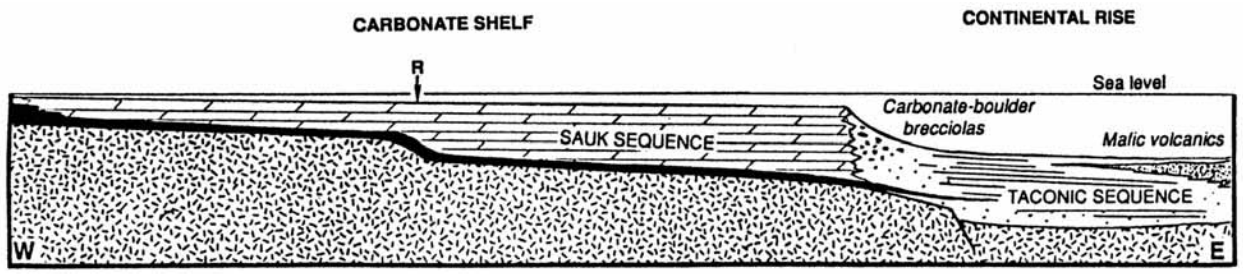


Figure 26. Schematic reconstructed geologic profile-section across Early Paleozoic passive continental margin in what is now eastern New York State. R = Rickard's Line, west of which the thin Sauk Sequence that has not been involved in low-angle overthrusts begins with the Upper Cambrian Potsdam Sandstone and east of which the thicker Sauk Sequence has been duplicated along low-angle thrusts and begins with the Lower Cambrian Poughquag Quartzite. The nature of the change of level at Rickard's Line is not known. Short line segments in random pattern, Proterozoic "basement" rocks not differentiated; black, basal quartzose unit; dolostone pattern for Sauk Sequence includes limestones (now calcite marbles) on seaward part of the former carbonate shelf (modern east, but Early Paleozoic south). (J. E. Sanders, 1995, fig. 1, p. 24, based on Baiying Guo, 1994 ms.)

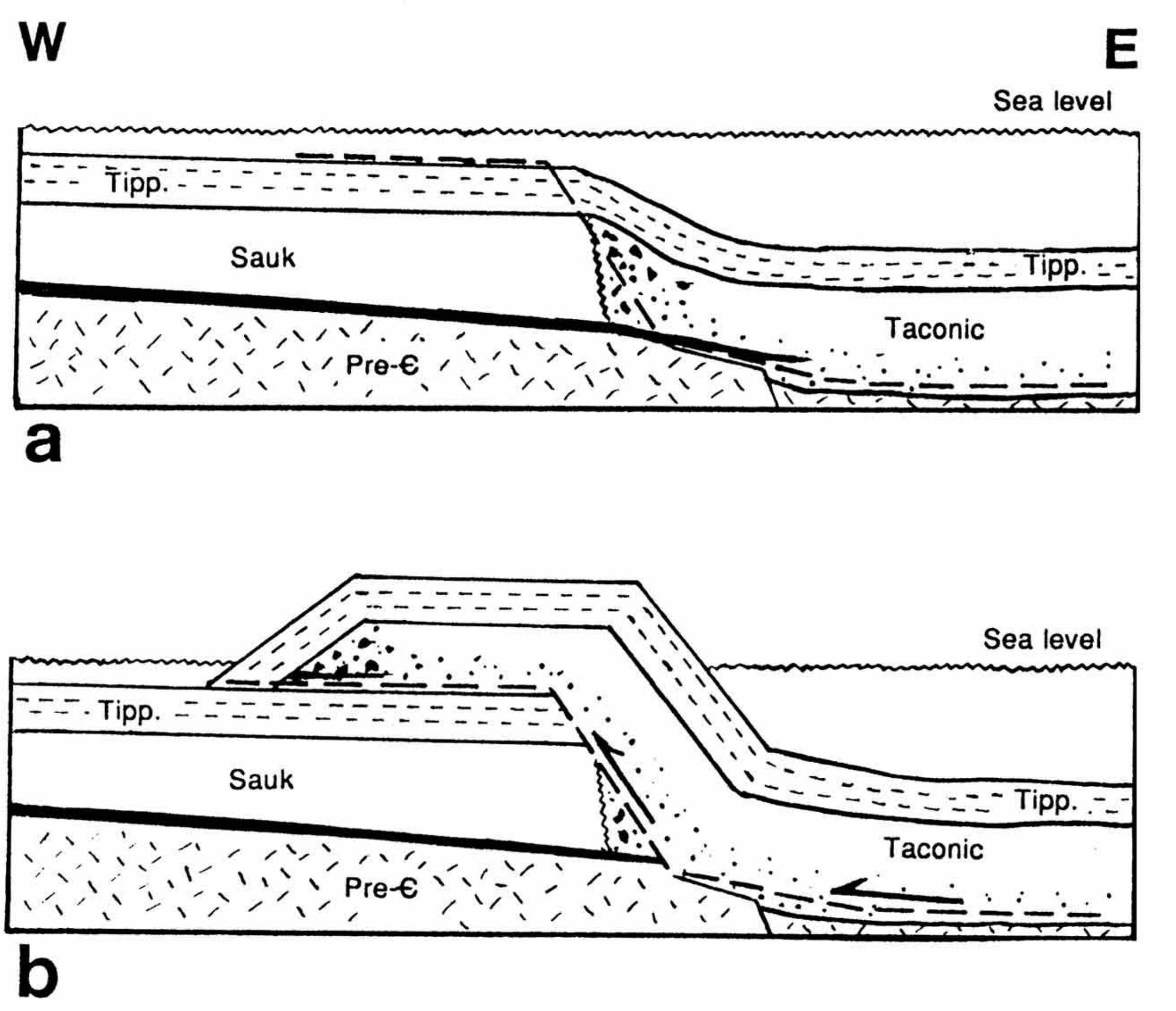


Figure 27. Bedding-type thrust forms after former passive margin becomes a convergent margin, schematic profile-sections. (J. E. anders, 1995, fig. 8, p. 37.)
a. Before thrusting; dashed line shows course of future thrust.
b. Early stage of duplication of strata along bedding-type thrust; effects of erosion not shown.

Intraplate Nonmarine Basin

A geotectonic cycle in an intraplate nonmarine basin begins when large parts of a continental lithosphere plate are elevated, some more than others. Deep vertical fractures form. The more-elevated blocks furnish sediments that accumulated on the lagging-behind blocks that become the adjacent lowlands into which the sediments derived from the elevated blocks are deposited.

Three Major Units of New York City's Bedrock

Viewed broadly, New York City's bedrock record can be divided into three major units that are products of three continental-margin geotectonic cycles (two completed, one still in progress, perhaps at its half-way mark) and one completed intraplate nonmarine-basin geotectonic cycle (Table 1). The Pleistocene glacial features (listed in Table 1 as Unit 1, are discussed in a later section. We have numbered these units in order of increasing ages, from top down, but shall discuss them in the reverse order, from the bottom up. The three bedrock units are: (2) the coastal plain (65 to 15 million years old); (3) the Newark basin-filling strata and Palisades sheet of igneous rock (220 to 170 million years old); and (4) a "basement complex" consisting of the "stumps" of the central part of the much-eroded Appalachian Mountains (1350 to 450 million years old).

Unit (4): "Basement complex" of Proterozoic- and Paleozoic Age

The basement complex includes metamorphic rocks that were deformed and even recrystallized several times during plate convergence at a former continental margin. Unit (4) bedrock of the "basement complex" is exposed in Manhattan and The Bronx and is known to underlie all other units (3) through (1).

The rocks composing the "basement complex" resulted from the operation of two long-completed continental-margin cycles, the older Grenville and younger Appalachian. The Grenville cycle spanned roughly 700 million years (Ma) and ended with the Grenville Orogeny dated at 1100 Ma. The Appalachian cycle began about 570 ma and before it ended at 260 Ma included three convergent orogenic episodes (Taconian at 450 Ma; Acadian, at 365 Ma; and terminal Appalachian, ~260 Ma).

Rocks of the Grenville cycle. The rocks of the Grenville cycle are the oldest recognized strata in southeastern New York (Layer I of Table 2). They include the Fordham Gneiss in the Manhattan Prong of Westchester County and the New York City area and the Hudson Highlands gneisses (Figure 28). The Highlands gneisses are composed of complexly deformed layered feldspathic gneiss, schist, amphibolite, calc-silicate rocks, and massive granitoid gneiss. They constitute a complex whose internal stratigraphic relationships are poorly understood. Taken as a whole, however the ancient Grenville-cycle sequence nonconformably underlies the younger Appalachian-cycle rocks described in the following section.

In the Pound Ridge area (PR in Figure 29), the Fordham gneisses have yielded 1100 Ma 207Pb/206Pb zircon ages (Grauert and Hall, 1973) that fall well within the range of the Grenville orogeny. Rb/Sr data of Mose (1982) suggest that metasedimentary- and metavolcanic protoliths of the Fordham date back to 1350 Ma. Farther south in Westchester County, subunits in the Fordham have been cut by the Pound Ridge Gneiss and correlative Yonkers Gneiss [post-Grenville granitic gneisses]. Using Rb-Sr, Mose and Hayes (1975), have dated the Pound Ridge Gneiss as latest Proterozoic (579ñ21 Ma). This gneiss body shows an intrusive-, or possibly an nonconformable relationship (Patrick Brock, personal communication) with the Grenvillian basement sequence. The Yonkers Granitic Gneiss has yielded ages of 563+30 Ma (Long, 1969b) and 530+43 Ma (Mose, 1981). The Pound Ridge along with the Yonkers Gneiss, are thought to be the products of latest Proterozoic alkali-calcic plutonism (Yonkers) and/or -volcanism (Pound Ridge?) in response to rifting of the ancient Gondwanan supercontinent.

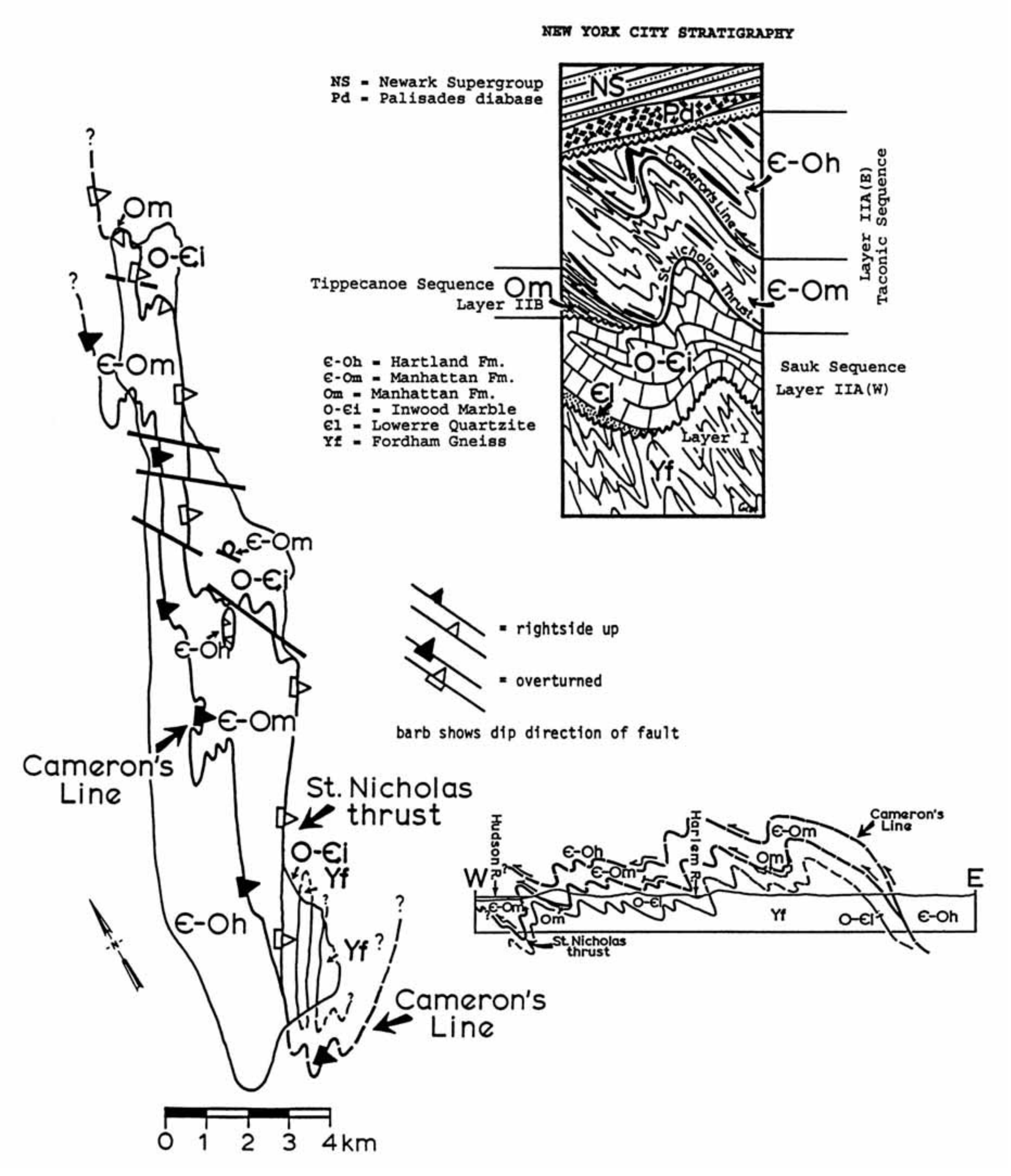


Figure 28. Geologic map of Manhattan Island showing a new interpretation of the stratigraphy- and structure of the rocks formerly included together as a single unit, the "Manhattan Schist. Geologic section (inset) shows folded Taconian ductile thrusts (the St. Nicholas thrust and Cameron's Line) mapped on Manhattan Island and in The Bronx. (Drawn and mapped by C. Merguerian.)

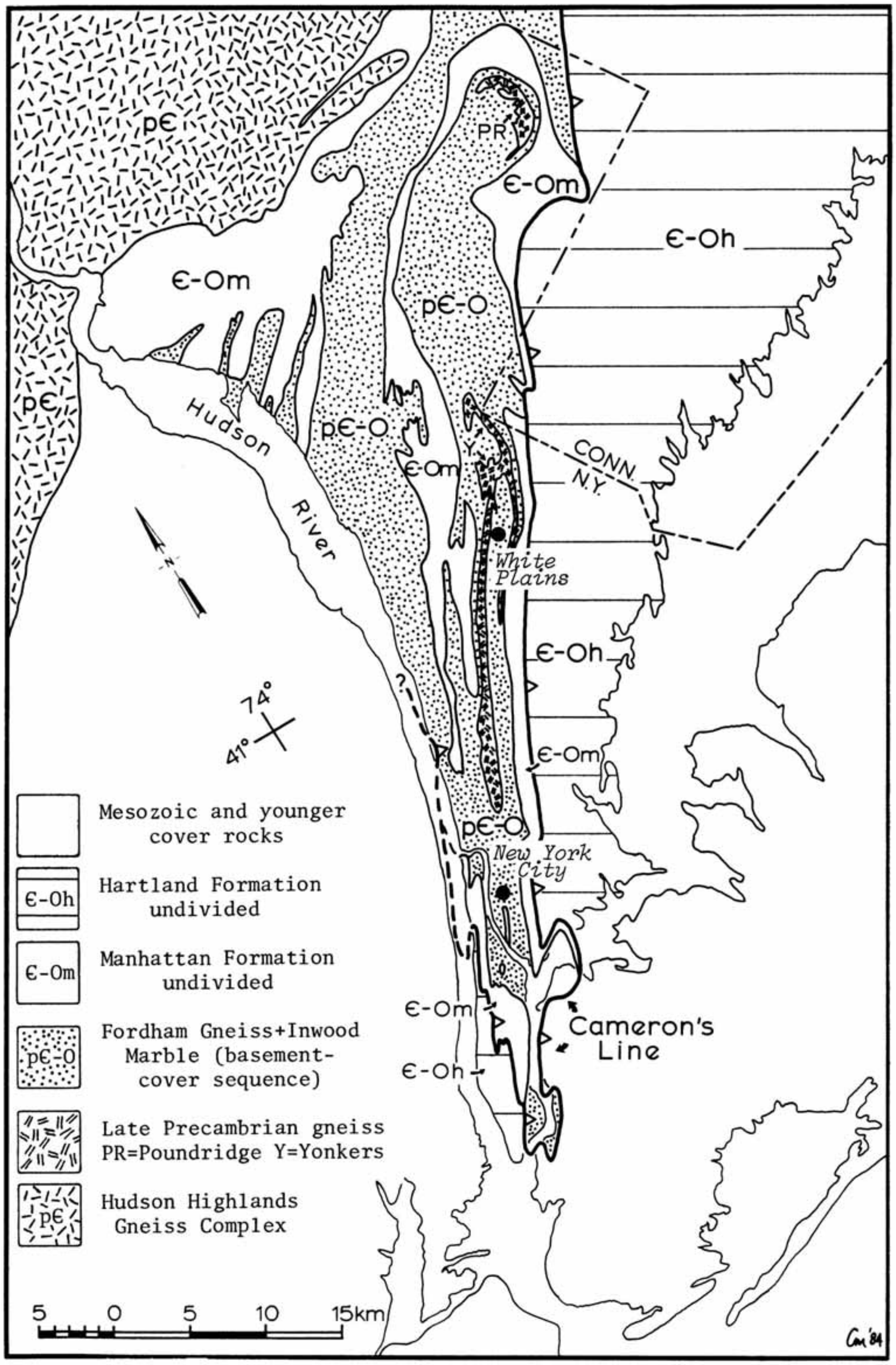


Figure 29. Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks from Grenville cycle (Layer I; rocks of Proterozoic Y age) and early phases of Appalachian cycle (Layer II; rocks of Early Paleozoic age). Most faults and intrusive rocks have been omitted. (Douglas G. Mose and Charles Merguerian, 1985, fig. 1, p. 21.)

Recent work by Pamela Brock (1989, 1993 ms., and personal communication) in the vicinity of the Peach Lake quadrangle, New York and Connecticut, shows the presence of a vast rift sequence (now metamorphosed) of potash feldspar-rich felsic gneiss, calc-silicate rock, volcaniclastic rock, amphibolite gneiss, and minor quartzite (Ned Mountain Formation) that rest nonconformably on the Fordham basement rocks. As such, Brock may have identified a metamorphosed, easterly volcaniclastic facies of Proterozoic Z intrusive igneous rocks whose probable feeder area is now marked by the Yonkers and Pound Ridge gneisses.

Southeast of the Hudson Highlands, the Grenville rocks consist of the Fordham Gneiss, which has been intricately folded with the Paleozoic-age rocks of the Appalachian cycle that form the bulk of the Manhattan Prong.

Many of the Grenville-cycle units are unconformably overlain by the Lower Cambrian Lowerre quartzite (Hall, 1976; Brock, 1989), the basal unit of the Appalachian-cycle rocks. The Grenville-cycle sequence represents the ancient continental crust of proto-North America that became a trailing edge, passive continental margin early in the Paleozoic Era.

Rocks of the Appalachian cycle. Nonconformably overlying Layer I of the Grenville cycle in western Connecticut and New York City are the Cambro-Ordovician formations that are products of the early (Taconian) part of the Appalachian cycle (Layer II of Table 2). These sedimentary- and igneous rock units have been highly metamorphosed, folded, and faulted. (See Figure 29.) They began their geologic lives roughly 550-450 million years ago as thick accumulations of both shallow- and deep-water sediments adjacent to the Early Paleozoic shores of proto-North America (Figure 30). For ease of discussion, Layer II can be divided into two sub-layers, IIA and IIB.

The older of these, IIA, represents strata deposited along the ancient passive-margin of North America. (See Figure 26.) The passive-margin deposits of Layer IIA can be subdivided into two facies [IIA(W) and IIA(E)] that differ in their original geographic positions with respect to the shoreline and shelf edge. A nearshore facies [Layer IIA(W)], deposited in shallow water, is collectively designated as the Sauk Sequence. This sequence includes former basal sandy sediment and overlying thick Cambro-Ordovician carbonate sediments, which were predominantly dolomitic in nearshore areas. During the time when the Sauk Sequence was being deposited, what is now New York is thought to have been situated in the tropical parts of the Southern Hemisphere in such a position that what is now east was formerly south and what is now west, formerly north (Figure 31). The Sauk clastics and -carbonates in New York City are the Lowerre Quartzite and Inwood Marble. In western Connecticut and Massachusetts, the basal-Sauk sandy unit is the Cheshire Quartzite and the carbonate rocks, here containing more limestone than in localities closer to the ancient shoreline, are named the Woodville- and Stockbridge Marble. Thus, the Sauk strata began life as sandy- and limey sediments in an environment not significantly different from the present-day Bahama Banks (minus the margaritas!).

Farther offshore, fine-textured terrigenous time-stratigraphic equivalents of the shallow-water Sauk strata (shelf sequence) were deposited in deep water on oceanic crust [Layer IIA(E)]. This deep-water sequence is also of Cambrian- to Ordovician age. In upstate New York, it is known as the Taconic Sequence. Locally, it is represented by units Ꞓ-Ot and Ꞓ-Oh of the Manhattan Schist(s). (See Figure 28.) In western Connecticut, these are the Waramaug and Hartland formations, respectively (Merguerian, 1983a, 1985).

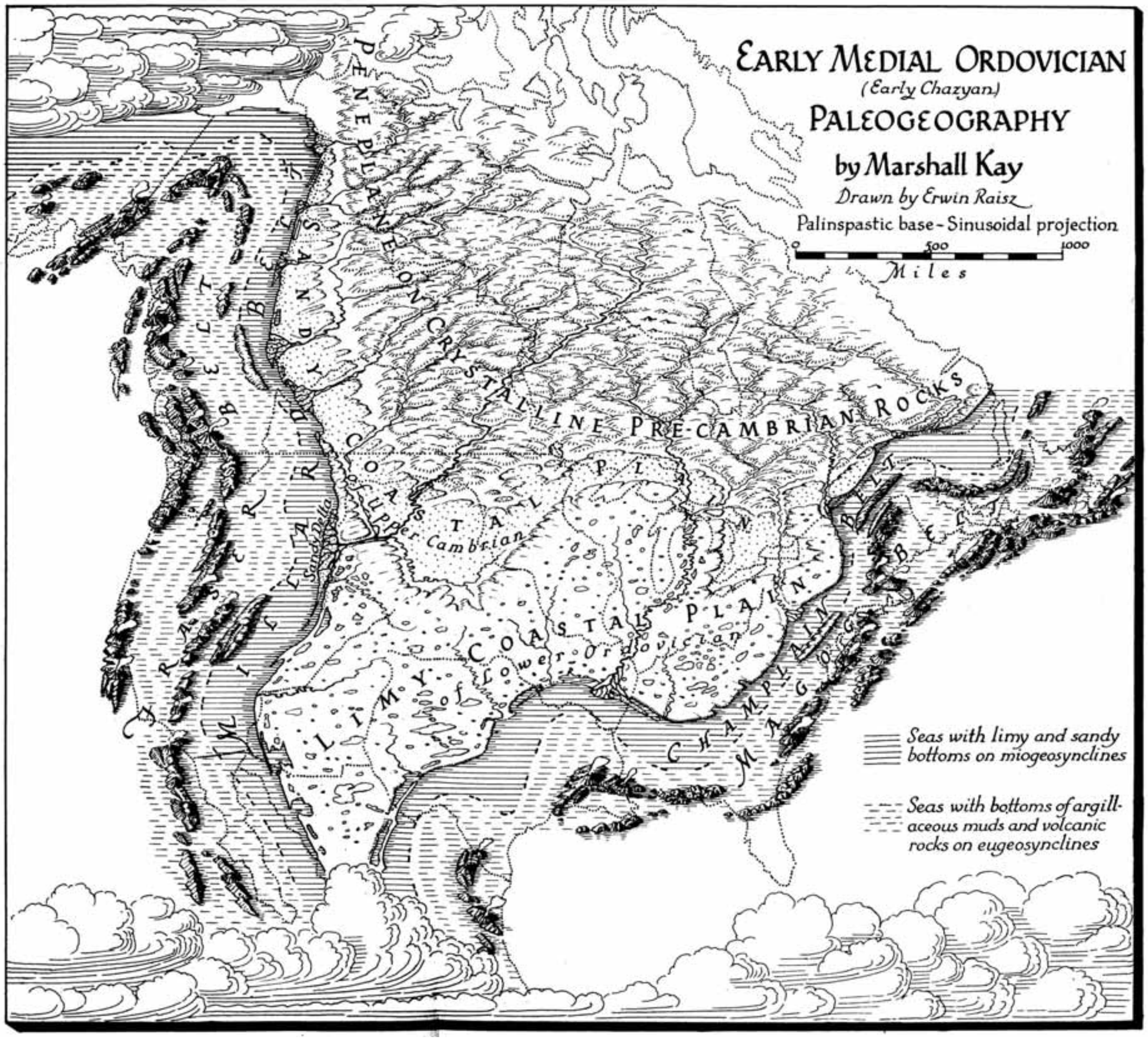


Figure 30. Paleogeographic reconstruction of North America as it is inferred to have existed during the Cambrian Period. Not shown are paleolatitudes and position of the Early Paleozoic Equator, which extended across what is now North America passing through Oklahoma, Kansas, and the Dakotas such that what is now east in the Early Paleozoic was south. (G. M. Kay, 1951, plate 1, facing p. 1.)

Layer IIB consists of younger strata designated collectively as the Tippecanoe Sequence. The Tippecanoe strata overlie the Sauk Sequence [Layer IIA(W)] above a surface of unconformity of regional extent. The change from passive margin to convergent margin took place while the Tippecanoe Sequence was accumulating. The basal unit of the Tippecanoe Sequence is a limestone (the "Balmville") deposited at the end of the passive-margin phase.

Overlying this limestone is a thick body of dark-colored terrigenous strata composed of clay- and sand-sized sediment), the filling of a foreland basin that formed during the earliest part of the convergent-margin regime that supplanted the passive-margine regime in mid-Ordovician time.

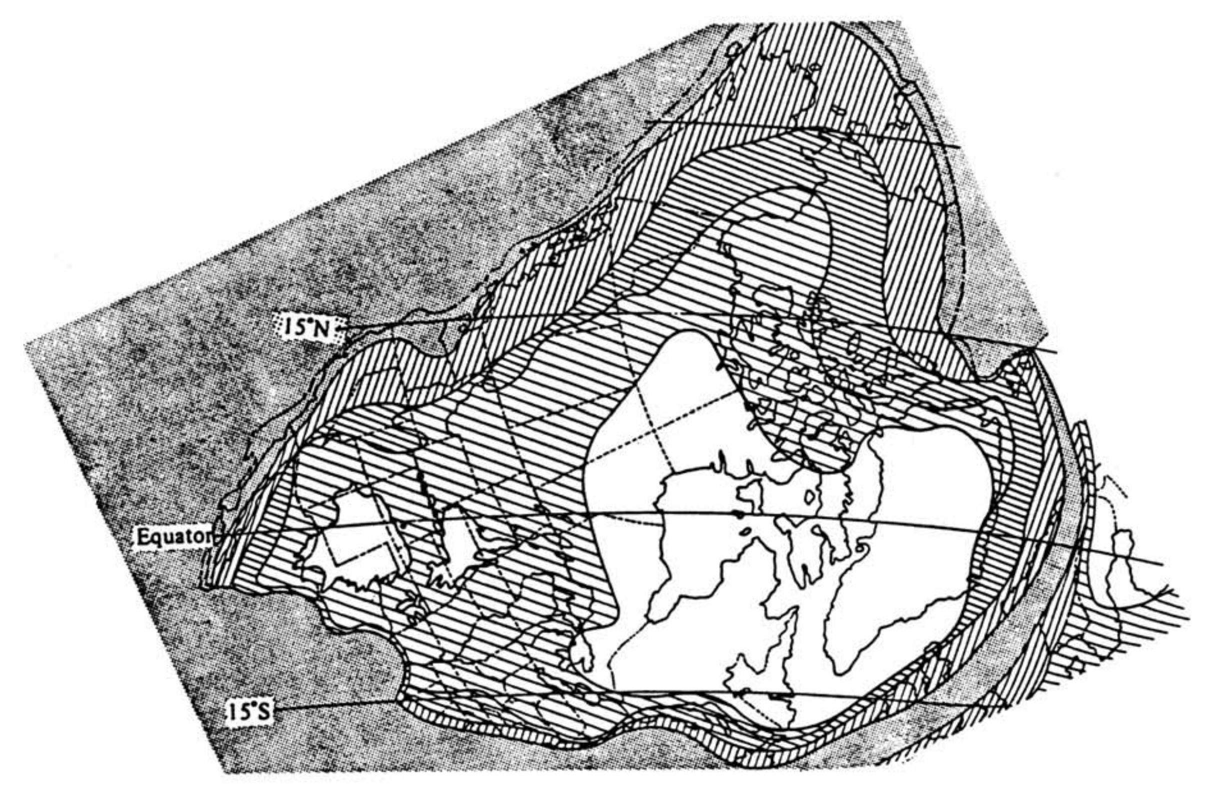


Figure 31. Paleogeographic map showing North America in its Early Paleozoic position astride the Earth's Equator. (Charles Merguerian and J. E. Sanders, 1996, fig. 2, p.118; after C. K. Seyfert and L. A. Sirkin, 1979.)

Unit (3): Newark Basin-filling Strata and the Palisades Igneous Sheet

Bedrock unit (3) consists of strata that filled the Newark basin (Layer V of Table 2). The Newark strata overlie the "basement complex" along an ancient erosion surface (Figure 32; Sharp, 1929a). The Newark episode began at about 220 Ma and lasted until 170 Ma. On the basin blocks, nonmarine sedimentary strata, possibly as thick as 10 km, collected; interlayered with the sedimentary strata are widespread flood basalts, products of former lava lakes fed from the deep-seated fractures, and extensive sheets of intrusive igneous rock that formed where the molten igneous material cooled underground. The tilted edges of these sheets of igneous rock are prominent parts of our local landscape: the Palisades along the W bank of the Hudson River (Figure 33) from Haverstraw, NY to Hoboken, NJ (tilted edge of an intrusive sheet) and the Watchung ranges in north-central New Jersey, which are formed by the tilted edges of three flood-basalt complexes that resist erosion more than the shales and sandstones with which they are interstratified (Figure 34). (See also Figure 1, on cover.)

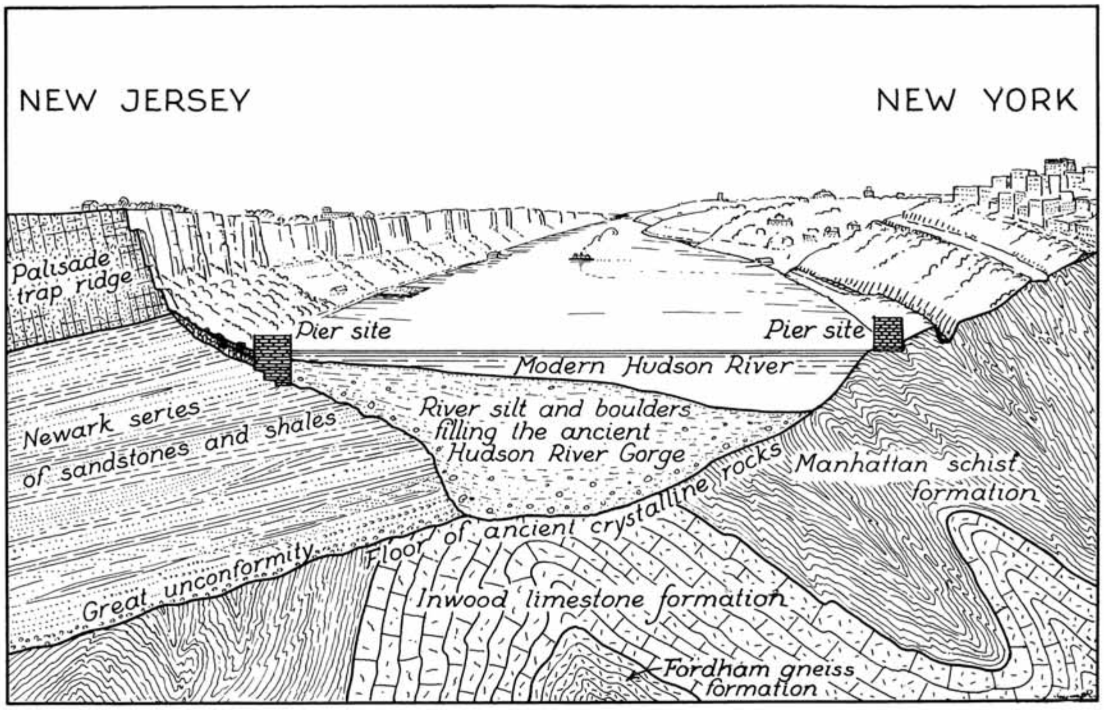


Figure 32. Block diagram of view up the Hudson River with front face showing geologic relationships interpreted from the borings made for construction of the George Washington Bridge. (C. P. Berkey, 1948, fig. 7, p. 62.)

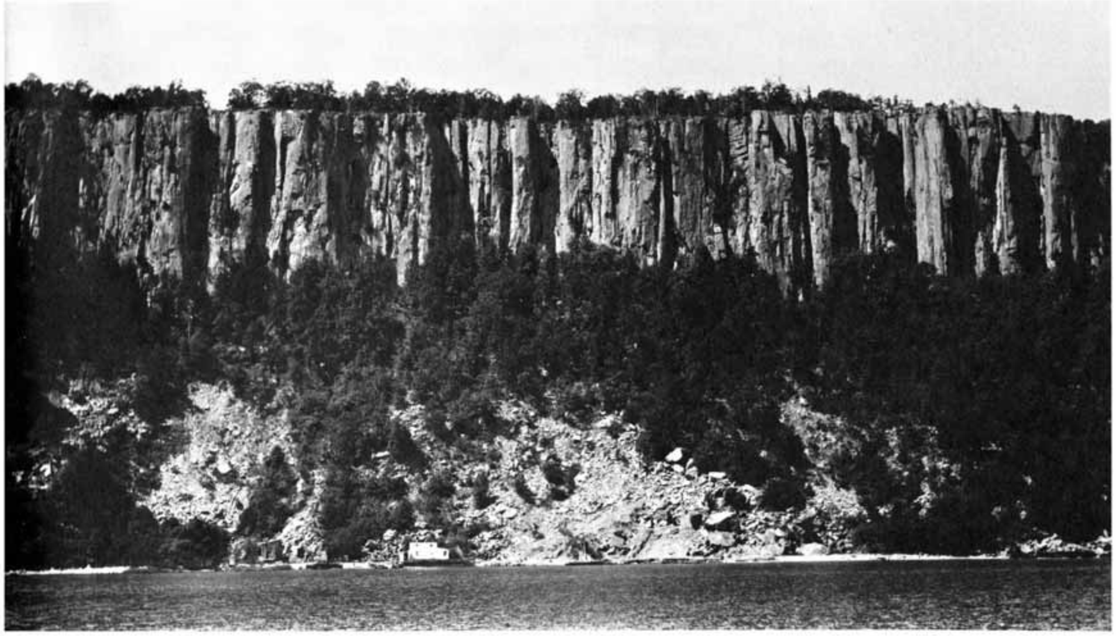


Figure 33. View of Palisades from above the Hudson River looking west. The nearly vertical columns of rock are bounded by steep joints that formed during contraction when the magma solidified to form the mafic igneous rock. (J. E. Sanders, 1981, fig. 6-26a, p. 165.)

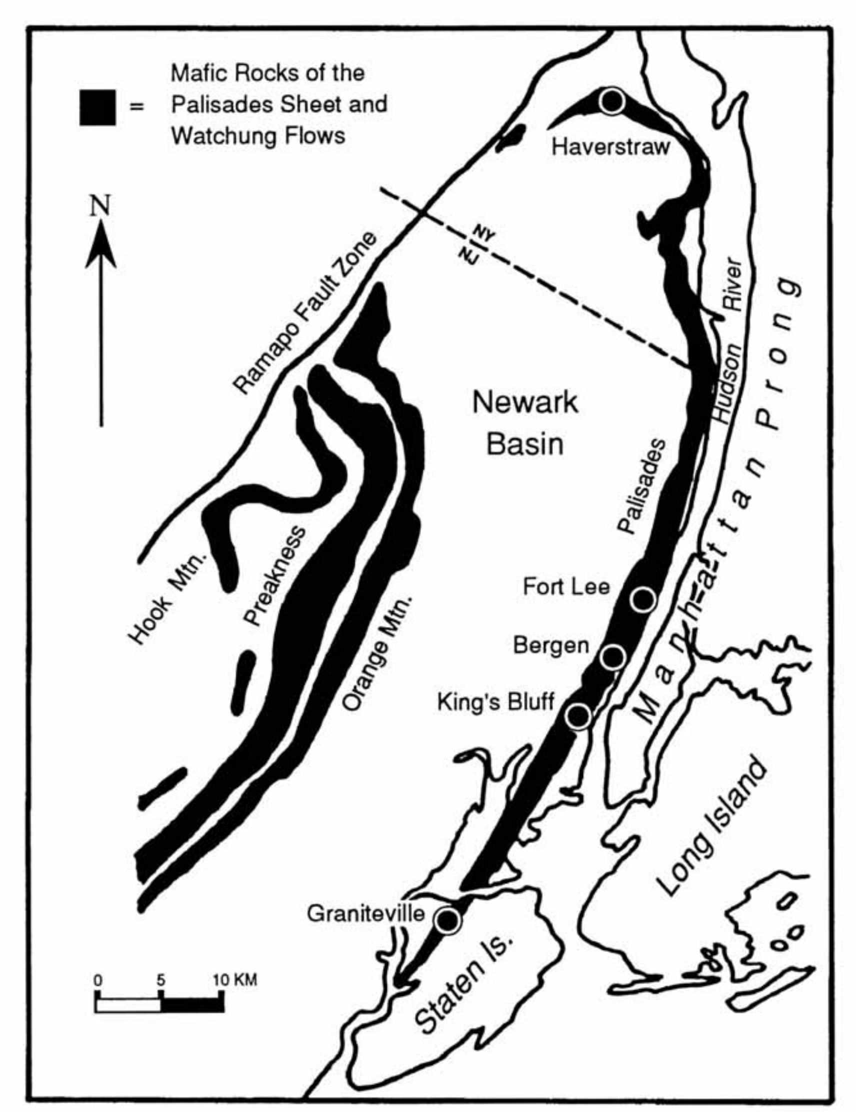


Figure 34. Index map showing the northern half of the Newark-Delaware Basin, the Palisades intrusive sheet, Watchung basalts, and place-names mentioned in the text. (After K. R. Walker, 1969, fig. 1, p. 6.)

The Newark strata of Unit (3) nonconformably overlie the older metamorphic terrane of the Manhattan Prong of Unit (4) and are themselves overlain in angular unconformity by the virtually horizontal Upper Cretaceous sediments of the Atlantic Coastal-Plain succession of Unit (2), the basal unit in the wedge of sediments that has been accumulating along the passive eastern margin of the North American continent for the last 170 million years or so. The area underlain by the Newark strata is shown on the geologic map of the Newark quadrangle (Lyttle and Epstein, 1987).

The name Newark, from Newark, New Jersey, is a venerable one in American stratigraphy; it was proposed by W. C. Redfield in 1856. Today, the term Newark has been accorded the status of a Supergroup (Cornet, 1977 ms.; Olsen, 1980c, Froelich and Olsen, 1985; Luttrell, 1989). The age range geologists have assigned to the Newark Supergroup has oscillated back and forth like a geological pendulum. During the 19th century, based on studies of their fossil fish, Redfield (1856, 1857), assigned them to the Jurassic. By contrast, the dinosaurs suggested Late Triassic. Given this situation, the Newark strata were referred to as the Jura-Trias (for instance, Darton, 1902 in the New York City Folio 83 of the U. S. Geological Survey).

Many geologists, however, took the Newark strata to be synonymous with Triassic. By contrast, Kümmel (1897) initially used only "Newark." When he became associated with the U. S. Geological Survey Folio projects, however, he used "Triassic" (Kümmel , 1914).

But geologists who were inclined toward tidiness in classification were uncomfortable with the notion that a well-behaved formation should span the boundary between two geologic periods. Accordingly, when Pirsson and Schuchert (in their Textbook of Geology published in 1915) proposed the name "Palisades Disturbance" for the episode of crustal unrest that was supposed to mark the end of the Triassic Period, they decided that all the Newark strata were of Late Triassic age. Thus, they started a line of thought that persisted for 60 years. In addition, they also started a tradition that might be expressed by the title of a modern book: "We learned it all in kindergarten." In our analogy, "we" is all geologists trained in the United States, "kindergarten" is the first-year course in geology, and "learned it all" refers to knowledge about the Newark strata. Based on the Pirsson-Schuchert scheme of things, Widmer (1964, p. 85) wrote: "There are no known Jurassic sediments in eastern North America."

Modern students (starting with Cornet and Traverse, 1975) have re-established what the real old-timers knew all along: the age range of the Newark strata is Late Triassic and Early Jurassic. (For a general summary of the geologic literature on the Newark Group up to 1984, see Margolis, Robinson, and Schafer, 1986.)

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

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

Where the three well-known sheets of extrusive basalt (First-, Second-, and Third Watchung basalts, the Orange Mountain Basalt, Preakness Basalt, and Hook Mountain Basalt, respectively) and/or the distinctive black argillites of the Lockatong Formation are present, the Newark sedimentary strata are easy to subdivide. But where one is faced with an isolated exposure of a Newark-type reddish-brown sandstone, -siltstone, or -shale, or even a coarse conglomerate with reddish-brown sandstone matrix, the problem of assigning the correct formation verges on hopeless. Ultimately, some mineral- or lithologic criteria may prove to be helpful for stratigraphic assignment. As such, an important attribute of the Newark strata is the red-brown color of most of them. This color, in fact, has left its imprint on most of the Pleistocene sediments.

On Staten Island, only the basal formation, the Stockton Arkose, and its overlying Lockatong Formation are present. The parts of the Stockton that are not red are light gray. They can be distinguished from the overlying gray Cretaceous sands by the large content (25 to 33% or more) of feldspar. The Lockatong is typically a dark gray, tough rock named argillite. Toward the SW, the thickness of these two formations is much greater than in the Watchung syncline. In the Delaware Valley, for example, the thickness of the Stockton is 1650 m and that of the Lockatong, 1200 m (McLaughlin, 1959, p. 85). The Lockatong Formation is the unit into which the tabular, generally concordant Palisades sheet has been intruded.

Paul Olsen (1986) has given the name Van Houten cycles to lake deposits made during a change from deep water to shallow water (or even no water) and back to deep water again. Such changes characterize lakes in closed drainage basins. The water-level fluctuations are controlled entirely by climatic changes.

Studies of the cyclicity by Van Houten (1962, 1964) and Olsen (1984, 1986, and continuing from the Newark-basin cored borings) have indicated cycles having periods coinciding with the climatic cycles computed by Milankovitch based on variations in the Earth's orbital elements. The finding of such Milankovitch-type cycles in rocks as old as Late Triassic-Early Jurassic demonstrates that the computer-modelling gurus who claimed that the Milankovitch periodicities break down within a few million years have got their mathematics all wrong.

Much new information about the Newark strata is coming from the detailed studies of the cores from recently drilled "just-for-science" holes (Olsen and Kent, 1995; Olsen, Kent, Cornet, Witte, and Schlische, 1996).

Intrusives vs. extrusives. Associated with the Newark sedimentary strata are sheets of mafic igneous rocks including both intrusives (the Palisades sheet) and extrusives (the three "Watchung" basalt sheets in the Watchung syncline and several scattered areas along the Ramapo fault and elsewhere). A recurrent subject of interest among petrologists specializing in the study of igneous rocks has been whether the Palisades intrusive activity accompanied any, or all, or only some of the three Watchung extrusives. [Geologists apply the mighty word consanguinity to igneous rocks that resulted from crystallization from a single magma.] Several methods are available for assessing consanguinity. One is chemical analysis of the rocks; another, dates of crystallization.

According to petrographic studies and modal calculations of Sichko (1970 ms.) and geochemical studies of Puffer (1988) and Husch (1990), a likely correlation is between the high-Ti magma that solidified to form the Palisades and the various lavas that cooled to form the multiple flows of the Orange Mountain Formation (First Watchung Basalt). Husch (1990) also correlated a low-Ti magma component of the Palisades with the upper low-Ti flow unit of the Preakness Formation (Second Watchung Basalt).

Initially, the Palisades sheet was viewed as a product of a single charge of magma. More recently, however, evidence has been found that this sheet is composite and formed as a result of several discrete injections of magma. Based on their interpretation of the duration of deposition under the influence of climate cycles in the associated sedimentary strata, Olsen and Fedosh (1988) calculated that approximately 2.5 Ma elapsed between the time of extrusion of the Orange Mountain Formation and that of the Preakness Formation. This means that if igneous activity within the Palisades sheet took place at the same time as that of the extrusion of these two ancient lava flows, then more than 2.5 Ma were available for the composite Palisades intrusive sheet to cool. The general absence of chilled zones within the main mass of the Palisades intrusive implies that all pulses of magmatic activity took place in a short time interval, before the mafic intrusive had cooled.

The synchroneity of intrusion of the Palisades with one or more of the Watchung flows also settles a further point, the depth of intrusion. Depth of intrusion then is the stratigraphic thickness of Newark strata between the base of the oldest Watchung flow and the base of the Palisades sheet. Using an outcrop-belt map distance of 18 km between the base of the Palisades and the base of the Orange Mountain Basalt and an average dip of 12.5°, the stratigraphic thickness would equate to [Sine 12.5° (0.2164) X 18 km = 3.89 km]. A 10°-dip assumption would decrease the estimate to 3.12 km. A 15°-dip assumption would increase the estimate to 4.65 km. We discuss this point further in our description of the features to be seen at Stop 1.

The Palisades mafic sheet was intruded into the base of the Newark Supergroup during the Sinemurian age of the Early Jurassic (roughly 201±1 Ma) according to recent U/Pb data on Palisades zircon and baddeleyite by Dunning and Hodych (1990). These data conform with Sutter's (1988) 40Ar/39Ar dating, which has yielded a 202.2±1.3 Ma age for a fused xenolith of Stockton arkose within the Palisades.

Tectonic History of the Newark Basin

Nearly all currently fashionable interpretations about the Newark strata begin with the phrase "rift basin." Such basins are diagnostic features of extensional tectonics. With respect to the Newark basin, the concept of rift tectonics has been refined slightly by including the notion of "reactivation tectonics." And, now we are beginning to hear words like "inversion tectonics." And, praise be! "compression" and "folding." In the following sections, we try to explain these modern tectonic concepts. After that, we evaluate them as applied to the Newark basin.

Extensional tectonics; rift basins. Bird and Dewey (1970) suggested that the Newark troughs formed after plate spreading and "extensional necking." Subsequently, this concept has been elaborated by many others; the diagnostic products of such lithosphere stretching are rift basins.

The distinguishing hallmarks of extensional tectonics are listric normal faults. Such faults are steep at the Earth's surface, but they curve around to a horizontal orientation at a depth of 15 km or so, where the rheological properties of the lithosphere change from brittle to ductile (Figure 35). The normal faults in the extensional network do not extend laterally along the Earth's surface for great distances; they die out. Beyond where one fault ends, another may appear. In between is a relay ramp (Figure 36).

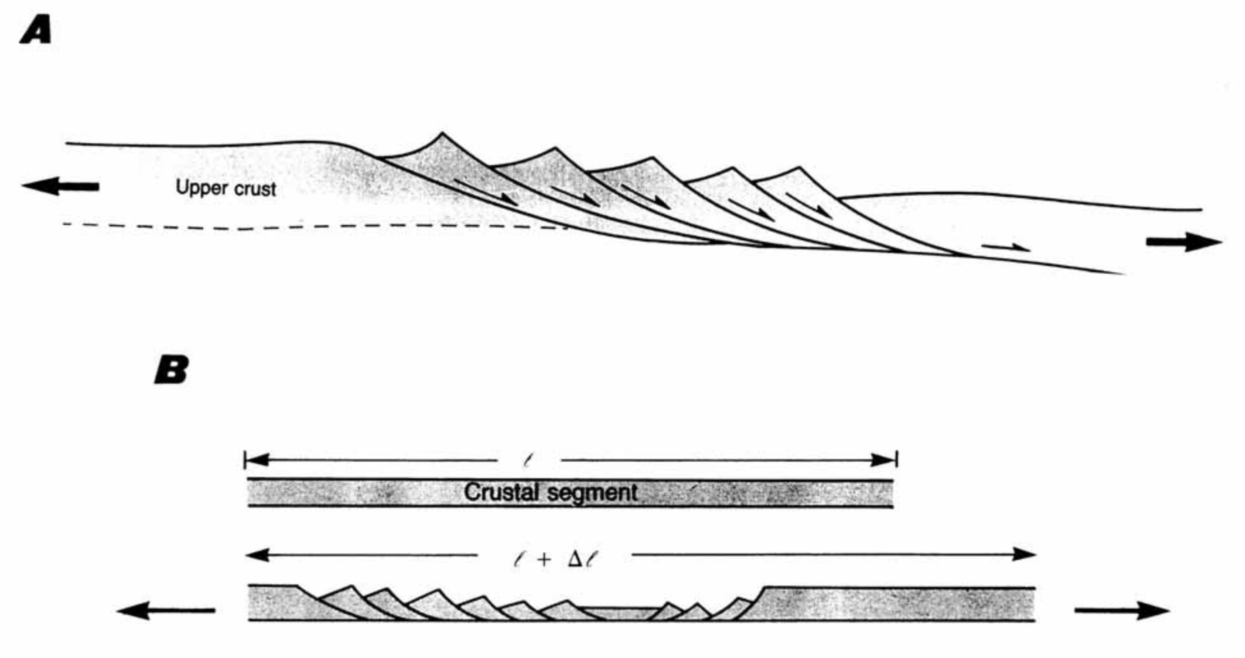


Figure 35. Profile section; steep brittle faults propagating downard, curving, and becoming horizontal at depth in the brittle-ductile transition zone. (R. D. Hatcher, Jr., 1990, A, fig. 10-15 (c), p. 190; and B fig.13-8 (c), p. 261.)
A. All faults curve in the same sense.
B. Before- and after sketch of a crustal segment in a pre-extended condition (above) and after extension and thinning. Notice that two sets of curving normal faults are present.

Displacement on the curved surfaces of listric normal faults causes the formerly horizontal surface of the Earth moving downward along the fault to dip toward the fault (Figure 37). Because the angle between the fault and the land surface is fixed by the relationships at the Earth's surface, as further displacement on the curved fault takes place, the formerly horizontal top of the downshifted block becomes tilted to ever-steeper angles.

The mechanism shown in Figure 37 could cause a basin to form and to fill with sediment. Moreover, cessation of the movement on the fault would stop all the activity. When movement on the fault stopped, many strata, which were initially deposited in a horizontal orientation, would dip toward the fault. The amount of this dip is greatest in the oldest strata and progressively diminishes to zero in the youngest beds.

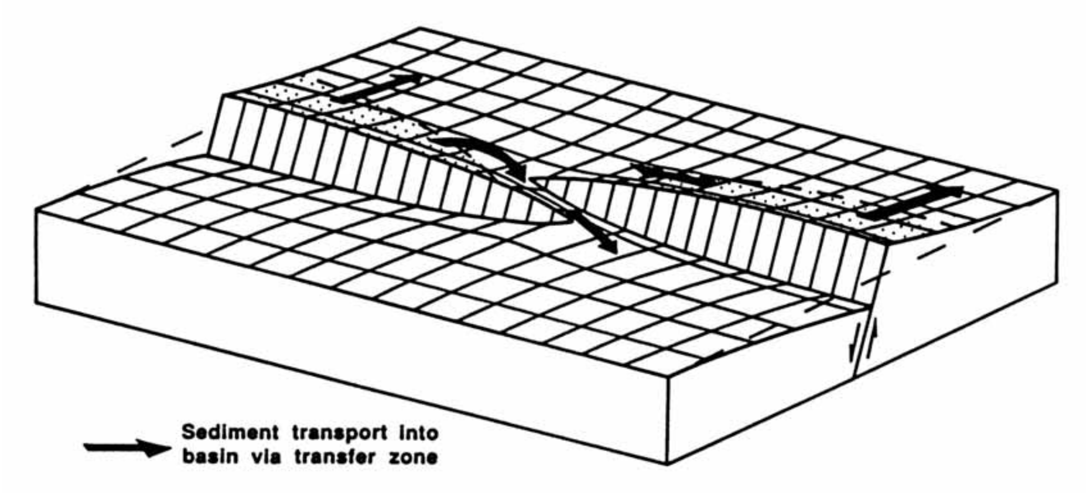


Figure 36. Schematic block diagram viewed diagonally from above showing two normal faults that are offset en ‚chelon and separated by a relay ramp (=transfer zone). Black arrows on top of diagram indicate major transport directions of sediment on upthrown block. On the downthrown block, coarser synrift sediments accumulate near the ramp. (A. Roberts and G. Yielding, 1994, fig. 11.19, p. 242.)

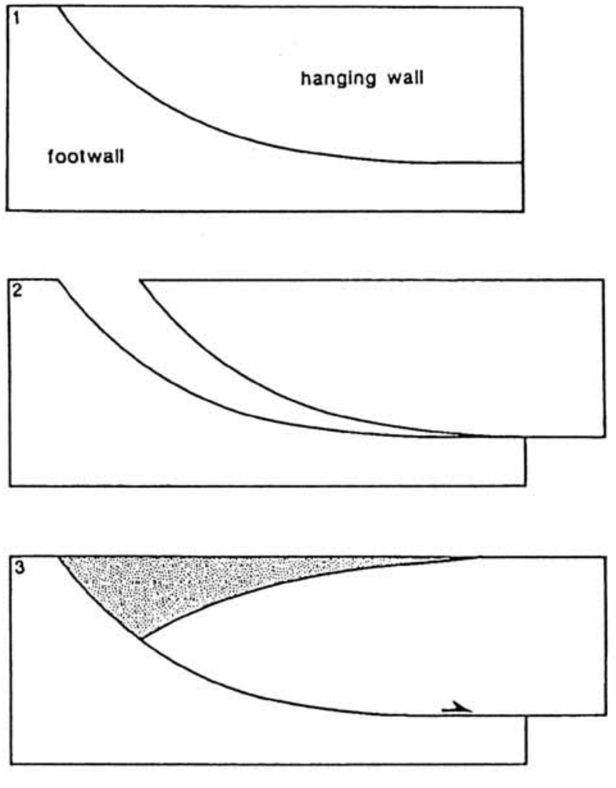


Figure 37. Wedge-shaped basin (stippled) formed by movement of a crustal block along a listric normal fault. Progressive movement causes the initially horizontal land surface to be bent downward to maintain the constant angle between the fault and the land surface (where the fault is steep) as the surface moves along the curved fault surface. (J. M. Crespi, 1988, fig. 1, p. 221.)

We consider that application of this concept to the Newark basin is nothing more than a modern-day variation of H. D. Rogers' depositional scheme whereby the tilted strata are initial dips; no postdepositional tilting is required. (Many of the ideas such as this have been proposed by workers who have seen the deep seismic-reflection profiles which may show in the subsurface of the Newark basin features such as those shown in Figure 38. JES has not seen any continuous seismic-reflection profiles from the Newark basin, so his thinking is based on outcrop data only.)

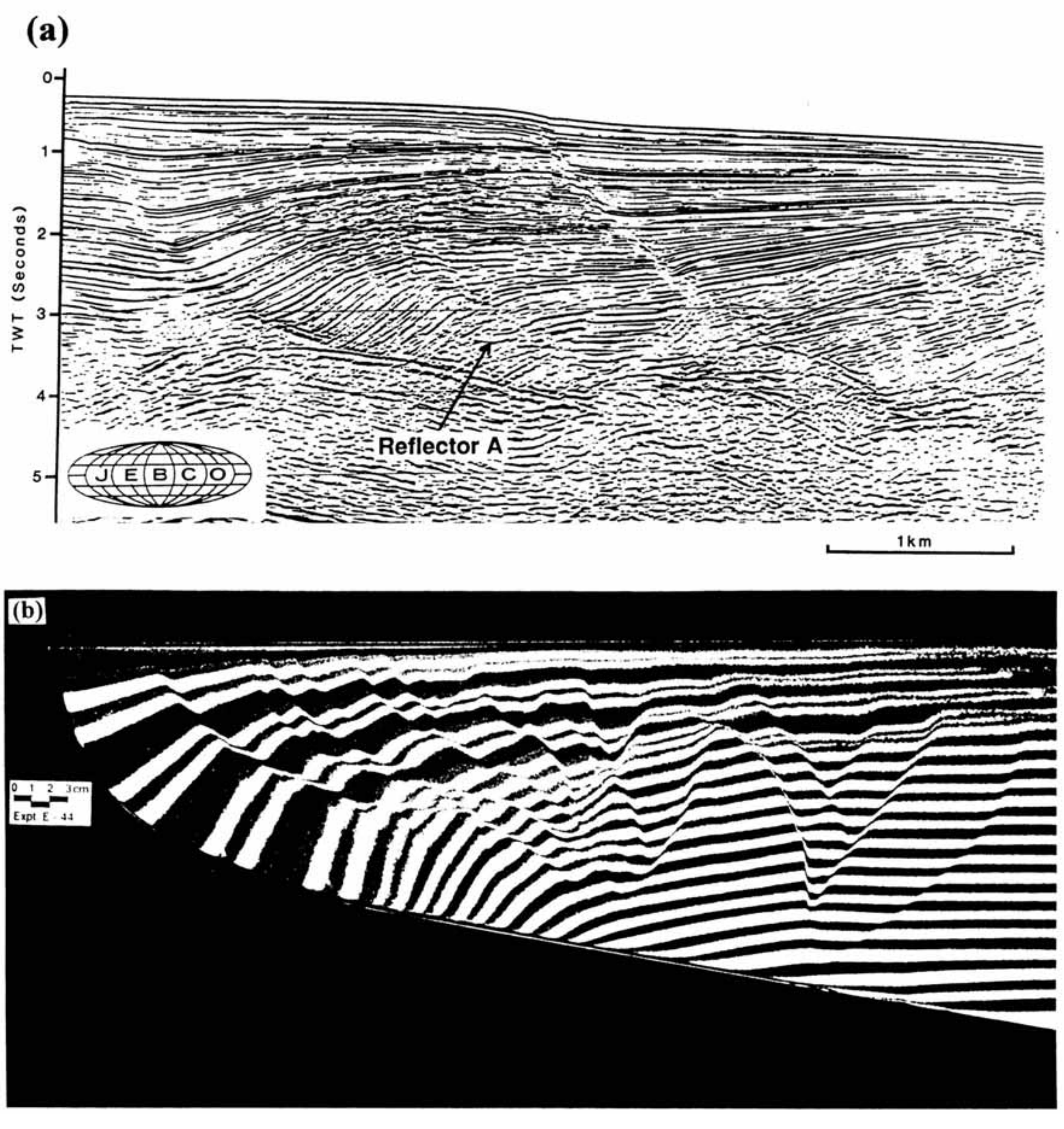


Figure 38. Effects on strata of upper block as a result of displacement along a curving normal fault. The angle between fault and strata remains constant. As the strata move downward and the fault curves, they dip toward the fault.
(a) Continuous seismic-reflection profile in Gulf of Mexico.
(b) View of sand-box model with rigid footwall block. (A. Roberts and G. Yielding, 1994, fig. 11.20, p. 243.)

Two other characteristic features of networks of normal faults, resulting from horizontal extension, that are associated with rift basins are: (1) reversal of polarity (change of direction of the strata dipping toward the active faults), a feature typically found where one normal fault dies out at a relay ramp and another fault extends beyond such a ramp; and (2) the concave-up shapes of basin floors facing concave fault surfaces. The polarity-reversal configuration results from simple extension. It does not mean that the strata, originally all horizontal, were postdepositionally arched.

The concave-up basin floor facing a concave sector of the normal fault is a configuration that results from the dying out of the displacement along a fault at both ends of the fault. The thicknesses of sediments deposited in such a basin are greatest at the point of maximum fault displacement and diminish to zero along the fault in both directions away from the point of maximum thickness.

Many of these attributes of rift basins have been displayed dramatically on the continuous-seismic-reflection profiles that Bruce Rosendahl and his associates have collected from the large lakes in the East African rift valley (Rosendahl, 1987; Rosendahl and Livingstone, 1983; Rosendahl, Reynolds, Lonben, Burgess, McGill, Scott, Lambiase, and Derksen, 1986). These concepts have been applied by many geologists to the so-called tilted-fault-block or "half-graben" variety of sedimentary basins (Leeder and Gawthorpe, 1987; Lindholm, R. C., 1978a; Manspeizer, 1988a, b; Manspeizer and Cousminer, 1976; Manspeizer, Cousminer and Puffer, 1978; Kinsman, 1975; Klitgord and Behrendt, 1979; Klitgord and Hutchinson, 1985; Klitgord, Hutchinson, and Schouten, 1988).

Reactivation tectonics. The concept of reactivation tectonics is based on the proposition that younger faults follow older faults; in the younger tectonic episode, older faults are reactivated. In the case of the Newark basin-marginal fault, deep continuous seismic-reflection profiles show that at depth, the reflector trace of this fault is the same as that from an Early Paleozoic thrust (Ratcliffe and Burton, 1985; Ratcliffe, Burton, D'Angelo, and Costain, 1986).

A not-so-subtle "hidden agenda" lurking behind this emphasis on the coincidence between Newark-age faults and pre-Newark faults can be expressed as follows: the Newark faults followed pre-existing zones of weakness, therefore, no post-Newark structural complexity needs be inferred, and thus let the long-standing "Ho-hum" attitude about the Newark continue to prevail. (See, for example, Lindholm, 1978b; Petersen and others, 1984.) Ratcliffe and Burton (1985; 1988) and Ratcliffe, Burton, D'Angelo, and Costain (1986) have emphasized the results from continuous seismic-reflection profiles that show the Newark basin-marginal faults following ancient (Paleozoic) mylonite zones that formed along regional thrusts.

Inversion tectonics. By inversion tectonics is meant the activities that cause the strata in a rift basin to be deformed by postdepositional compression. The basic concept has grown out of continuous-seismic-reflection profiles that show a change from sediment accumulation in a basin to sediment deformation as a result of later activities. (For example, see Cooper and Williams, 1989; Hayward and Graham, 1989; Manspeizer, 1994; Manspeizer and Gates, 1995; McClay and Buchanan, 1992; and Schlische, 1995a.) What are the products of inversion to some are just plain old-fashioned folds and thrusts--the results of compression to others.

Strike-slip tectonics: pull-apart basins. The concepts of strike-slip tectonics have developed mainly from studies along the San Andreas fault system in California. Within a complex zone where strike-slip motion is taking place are three zones: (1) a zone of extension (which could produce "normal" faults, small basins formed by such local extension known as pull-apart basins, and dikes); (2) a zone of compression at right angles to the zone of extension (within the zone of compression folds can be formed); and (3) a zone of strike-slip faulting that is diagonal to the directions of maximum tensional- and compressional stresses (Figure 39). Within the territory affected by a single strike-slip couple, one gets only those consequences listed; nothing else takes place. If anything else has been done, some other mechanism needs to be sought.

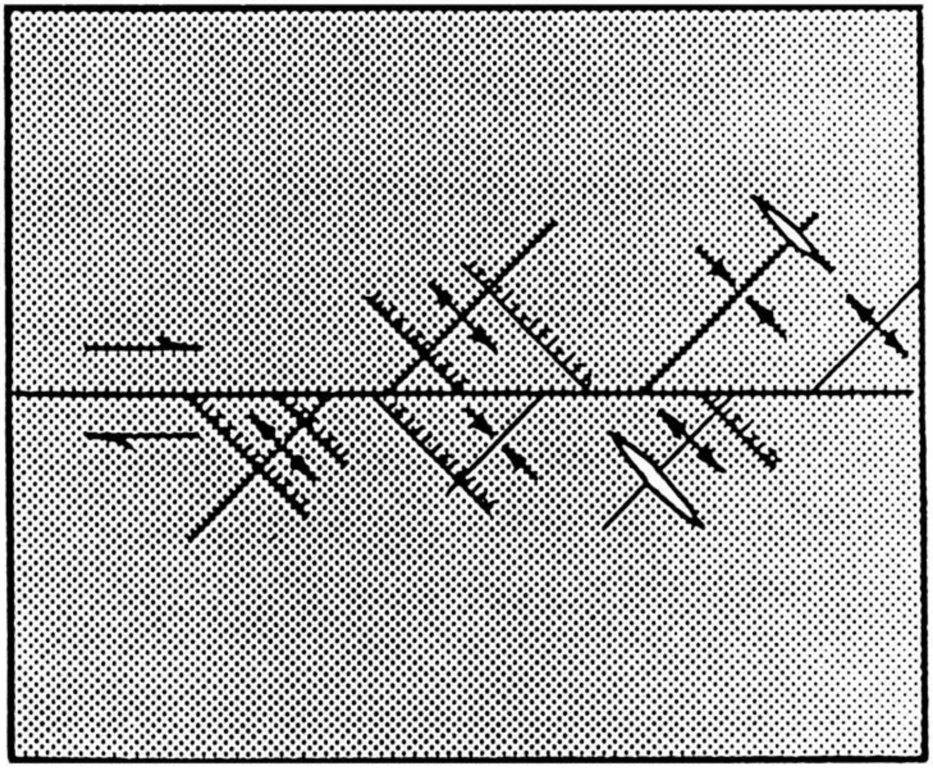


Figure 39. Schematic sketch map of relationships where a right-lateral strike-slip couple has been applied. Vertical right-lateral strike-slip fault crusses center of sketch. Fold axes trend NE-SW; at right angless to the folds are normal faults and open fractures (white areas) trending NW-SE. (J. E. Sanders in G. M. Friedman, J. E. Sanders, and D. C. Kopaska-Merkel, 1992, Box 17.1 fig. 4 (c), p. 633.)

The features of pull-apart basins (Figure 40) have been discussed by Burchfiel and Stewart (1966), Crowell (1974), Wernike (1985), and Wernike and Burchfiel (1982). Only Manspeizer (1980) has suggested that part of the Newark basin may be a pull-apart feature.

As a prelude to our evaluation of the validity of applying these modern tectonic ideas to the Newark basin, we list and comment on what we regard as some self-evident conclusions about the Newark strata.

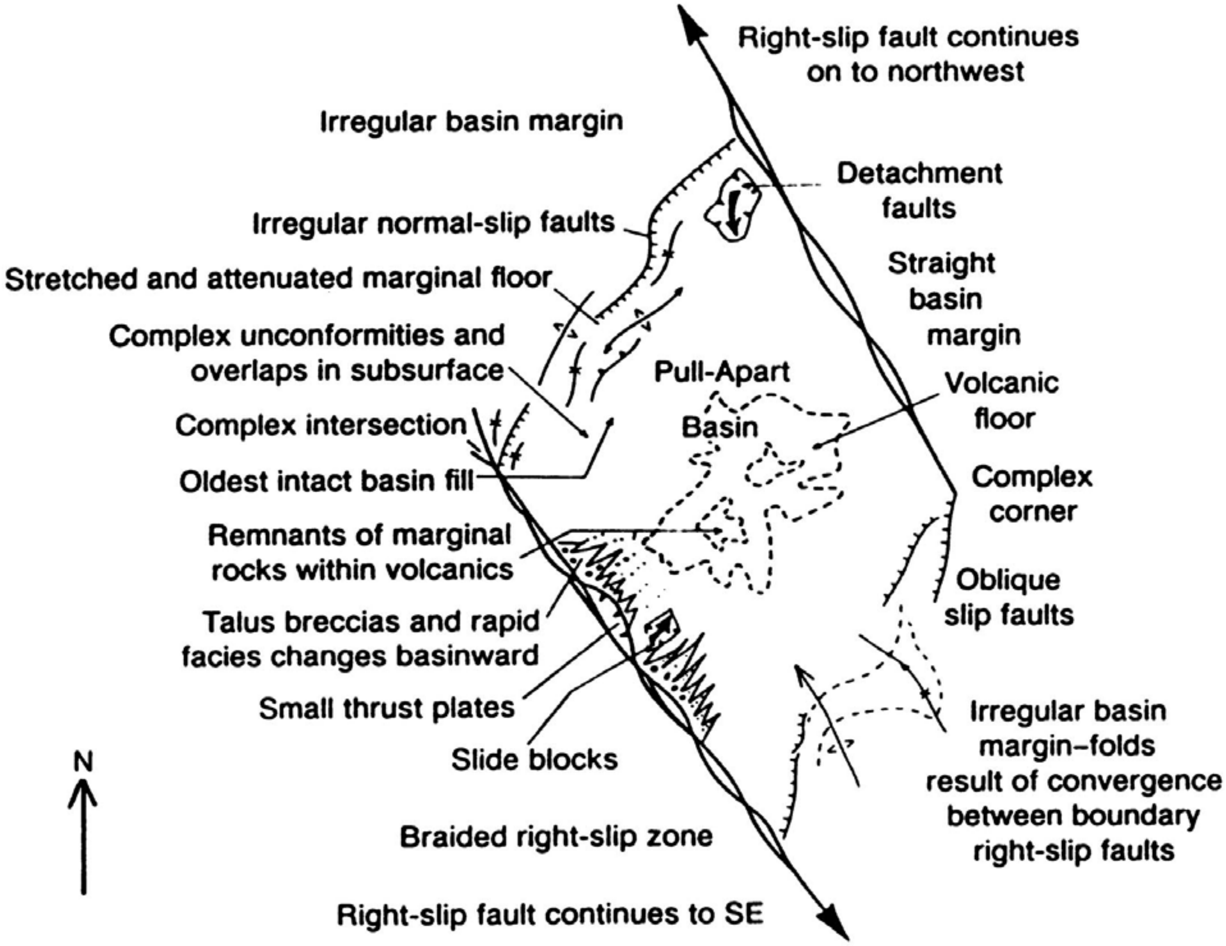


Figure 40. Pull-apart basin seen on schematic tectonic map. (J. C. Crowell, 1974.)

Some Important, Self-evident Conclusions (with comments) About the Newark Strata

In this section, we present a numbered list as follows:

1. The Newark strata were deposited on the subsiding block of a basin bounded on the northwest by the Ramapo Fault. The basin-forming movement began late in the Triassic Period roughly 200 Ma. This fault movement established a new geologic setting, where previously the Appalachian Mountain chain, which had undergone its climactic deformation early in the Permian Period (about 270 Ma), had been experiencing uplift and erosion, with the sediments being exported to unknown destinations.

    a. The basin-marginal fault(s) coincide with pre-existing zones of weakness, some of which had been active since Proterozoic time (Ratcliffe, 1971).

b. During deposition, this fault was active repeatedly. This repeated activity is indicated by the vertical distribution of basin-marginal rudites throughout all sedimentary formations.

2. Within the Newark basin, drainage was internal. That is, rivers flowed into the lowland and the water either soaked into the sediments or formed lakes. The level of these lake fluctuated in response to climate cycles having periods ranging from 20,000 to 400,000 years (van Houten, 1962, 1964; Olsen, 1980c, 1984, 1986).

3. The setting in which the Newark strata accumulated persisted for perhaps 30 Ma. At the beginning of the Jurassic Period, a new factor appeared--mafic magma (derived from either the basaltic layer in the continental crust or from the upper mantle). During at least three episodes, this deep mafic magma came to the Earth's surface and was spread out in great lava lakes. The following conclusions are valid with respect to this deep source of magma.

a. Presumably, the magma was tapped by deep fractures. How deep? This is not known, but it can be hedged in by the following considerations. The continental crust in a newly elevated mountain chain is thick (that is why the chain was elevated). After long-continued erosion, the chain loses its relief--the thickened crust loses thickness by being eroded at the top (Manspeizer, Cousminer, and Puffer, 1978, Figure 7, p. 914, Episode I). After the erosion, the typical thickness might prevail, say between 35 and 40 km.

b. A problem exists between reconciling this indication of fractures capable of tapping a deep magma source and the modern notions about basins forming by lithosphere stretching (as mentioned by Dewey and Bird, 1970, and presumed by many others later on who accept the concept of "rift basins"). As mentioned above, the rift-valley scheme depends on extension of the lithosphere, which causes brittle fracture in the upper part of the upper part of the crust, and the faults curve around to become horizontal in the lower, ductile zone. Thus, such faults by definition would never reach as deep as the Earth's mantle. (See Figure 35.) According to Manspeizer (1980, p. 338-341), the magma did not come up via the basin-marginal faults. In eastern Pennsylvania, however, in the Cornwall iron district, large mafic plutons are present along the basin-marginal fault.

c. The numerous dikes present in- and near the Newark-type basins may not have been related to the conduits that supplied the lava flows and Palisades intrusive sheet. According to JES, in central CT, many dikes occupy faults that offset the folded sheets of extrusive igneous rock (Sanders, 1963). Sutter and Smith (1979) also emphasized that the basin-central dikes were intruded after the strata had been tilted. They inferred that other conduits, locations not known, fed the lava flows which are interbedded with the sedimentary strata.

4. The entire stratigraphic column, including the interbedded volcanic sheets, accumulated with but minor deviations from horizontality (an example of an exception is the variation in thickness of the sedimentary strata interbedded with the Preakness Formation, discussed by J. V. Lewis, 1907a, 1908a). At some point, deposition stopped, and all the strata were deformed. JES finds no field evidence to support the concept that the strata became progressively tilted during deposition, as characterizes rift basins. (See Figure 37.) This means that the basin-marginal

faults must have been vertical all the way from the Earth's surface to the level in the Earth's mantle where they tapped the mafic magma.

Is the Newark Basin a Rift Basin?

By virtue of numerous repetitions, the Newark basin has become almost synonymous with rift basin and as a shining example of the products of rift tectonics. The "hidden agenda" behind this usage is that when one has incanted the magic phrase "rift basin," then all other things fall into place and our brains can go back into peaceful relaxation. Until very recently, partisans of "rift-tectonics-says-it-all" school have presumed that the machinery, which commenced operating when the Newark basin initially formed, simply kept on running, and one day, just stopped. And, when the tectonic "music" stopped being played, everything was in place. All players in the game had found seats.

Our fundamental reasons for doubting that the Newark basin is a rift basin is the field evidence in support of the view that during the episode of sedimentation, subsidence took place in such a way that the strata were deposited horizontally. In particular, the parallel relationships among the extrusive sheets does not support the concept that significant differential tilting toward the basin-marginal fault took place while strata accumulated.

However, we readily admit that one's explanation of post-Newark folds and -faults basically depends on how one interprets the orientation of the Newark strata. At one end of the ideological spectrum are those who insist that the Newark strata assumed their present attitudes as a result of the operations of the same geologic machinery that caused the Newark basins to form, to subside, and to accumulate sediments. At the other end of this spectrum are those few (including the two of us) who have applied the tried-but-true Stenoan principle "that the strata were essentially horizontal when deposited" and that the modern-day lack of horizontality requires a postdepositional tectonic explanation.

The ultimate in horizontal reference planes is the top of an ancient lava flow; it serves as a kind of gigantic level bubble. Three complexes of ancient lava flows and interstratifed sedimentary strata are present in the Newark basin of northern New Jersey (the tilted, eroded edges of which now form the three Watchung Mountains). As described above, field relationships adequately demonstrate the parallelism of these three sheets of extrusive igneous rocks. The attitudes of these extrusive sheets and their associated sedimentary strata define at least two sets of folds. The vertical axial surfaces of some of these folds are parallel to the basin-marginal faults (=longitudinal folds) and those of others are normal to the basin-marginal faults (=transverse folds). These folds have been offset by several sets of faults (whose existence has been universally acknowledged since the pioneering 19th-century work on them by W. M. Davis [1888a, 1898] in central Connecticut). Lateral offsets of the vertical axial surfaces of some of the transverse folds demonstrate that, along some of the faults that are demonstrably younger than the transverse folds, substantial components of strike-slip offset exist (Sanders, 1962a).

Our efforts in convincing the geological world of Sanders' (minority of one) contentions that the Newark strata have been folded have been gaining favor very slowly (after all, now it's a minority of two - a massive 100% increase!). As expressed above, we argue that four primary surfaces in the Newark basin have been folded and faulted after sedimentation of the basin ceased. These primary, originally horizontal features include bedding, the tops of the Watchung basalt sheets, the surface of nonconformity at the base of the Newark Supergroup, and the central part of the Palisades sheet. In the post Bird and Dewey (1970) era, most tectonic models attempt to explain Newarkian folds and faults in the context of sea-floor-spreading extensional tectonics. Both longitudinal- and transverse folds have been explained this way in the past except for Sanders' early 1960's publications which stressed the importance of strike-slip faults and related folds. Instead, elaborate manipulations have been proposed to avoid the dreaded "C" word, compression.

A major implication of our interpretation is that the marginal faults were steep, so that they relatively downthrown block could move without significantly rotating. If that is true, then all the modern dips have resulted from post-depositional tectonic activity that differed notably from the tectonic activity which caused the basin to form and its floor to subside relative to the marginal elevated block.

An Alternative Plate-tectonic View of the Newark Basin

Our alternative view of the plate-tectonic history of the Newark basin is that it formed not by massive regional extension, as characterizes rift basins, but rather by differential vertical movement. We visualize the Newark basin as being a small part of a true graben having steep marginal faults. In such an arrangement, the basin itself would be analogous to the dropped keystone block of an arch, known as a crestal-collapse graben.

Crestal-collapse-graben basin? We have obviously not worked through all of the ramifications of our suggestion that the Newark basin resulted from relative regional elevation rather than lithosphere stretching. The plate-tectonic setting of a crestal-collapse-graben basin would be one of epeirogenic uplift, presumably related to phase changes and the thermal situation "down below." The whole point is that such a basin is not in any way directly connected to a new ocean.

Another point, which we reiterate again, is that we infer that the tectonic setting that ended the life span of the Newark basin differed significantly from that which caused the basin to form and to fill with sediments. We think that the postdepositional history is related to rapid, short-lived plate motions. We first review the possibilities for deformation by application of plate-related strike-slip couples, and then take up the Jurassic continental history of North America.

Structures formed by application of large strike-slip couple. One of the fundamental tectonic premises of plate tectonics holds that horizontal plate motion is accompanied by deformation resulting from the application of strike-slip couples. In a previous section, we explained what this means in terms of three coexisting zones of: (1) compression, (2) tension, and (3) strike-slip displacement. We interpret the postdepositional deformation of the Newark in terms of the short-lived- and successive application of three such couples (Sanders, 1971, 1974b). The largest of these is inferred to have been a right-lateral couple with the main slip zone concentrated along 40° north latitude, and to have caused the regional change of strike of the entire Appalachians in southeastern Pennsylvania. This is what S. W. Carey (1953) termed an orocline. The Newark strata have been deformed just as much as the Appalachian. In short, the Newark structures follow the Appalachian structures; they did so before this oroclinal bending and maintain this coincidence after the bending. Therefore, the statement that the Newark faults followed pre-existing Appalachian faults is interesting, but is irrelevant with respect to the subject of the age- and extent of the postdepositional deformation of the Newark.

Mid-Jurassic plate re-arrangement. In order to provide a mechanism for the switchover in tectonic style that resulted in the compresssional deformation of the Newark Basin, we need to look westward toward our Cordilleran neighbors. In the Cordilleran belt of the western United States, studies indicate that between Late Triassic and Late-Jurassic time, significant Mesozoic tectonic pulsations took place (Figure 41). These interactions started with a Late Triassic strike-slip faulting "truncation" event, evolved into a mid-Jurassic arc-arc subduction event (the Nevadan Orogeny), and were followed by post-Nevadan Andean subduction that ultimately resulted in the emplacement of the Sierra Nevada Batholith (Schweickert and Cowen, 1975; Schweickert, 1981; Schweickert and Snyder, 1981; Schweickert, Bogen, Girty, Hanson, and Merguerian, 1984; and Schweickert, Merguerian, and Bogen, 1988).

Determination of apparent polar-wander (APW) paths for plates is the result of careful paleomagnetic analysis of temporally constrained iron-bearing sediments and mafic igneous rocks from a given region. Researchers ("paleomagicians" to some) are able to plot as points on an x-y graph (with x and y representing, respectively, paleolatitude and paleolongitude) the time-sequence distribution of paleomagnetic poles. Such poles correspond to the location of the Earth's spin axis as observed from the lithospheric plate under examination. As such, the connection of dated poles of rotation results in (1) gently curved segments (tracks) which indicate linear plate motions, linked by (2) sharply curved segments (cusps) that signify abrupt changes in lithospheric plate motion (translation as well as rotation).

According to Irving and Irving (1982) and Gordon, Cox, and O'Hare (1984), Jurassic North American plate motion was constant but rapid at roughly 7 cm/yr. Mid- to Late Triassic motion was even faster. More importantly, apparent-polar-wander paths calculated for the Mesozoic (Figure 42) show two major cusps at 170 Ma and 200 Ma, respectively (mid- to late-Jurassic). These indicate a marked change in plate motions. We suspect these cusps are signals produced by dramatic Mesozoic Cordilleran lithospheric plate interactions. Clearly, the post-Sonoman pre-Late Triassic strike-slip truncation event, Nevadan arc-arc collisional orogeny, and post-Nevadan "Andean" subduction resulted in major Cordilleran plate reconfigurations and mantle-flow reorganization. The age of the 170 Ma cusp is important as it would correspond to a period of time after the Newark basin-filling strata had been deposited. We therefore reach deep into our bag of tricks here to suggest that what was happening "way out west" affected what we see preserved here on the east! Thus, we have suggested (Merguerian and Sanders, 1994b) that deformation of the Newark Basin resulted from the combined effects of east-coast mid-Atlantic ridge-push variations (prompted by changes in Atlantic sea-floor spreading rates?) and compressional lithosperic strain transmissions from out west which together resulted in changeovers to compressional tectonics by around 170 Ma, between the terminal-stage

Appalachian compression and the spreading that following the mid-Jurassic tilting and -erosion of the Newark strata. The abrupt polar-wander-path changes (cusps) would support these major shifts in plate reorganization. Deformation during activation of the Newark basin margins by strike-slip couples could have forced the deformation of the Newark strata. Undoubtedly, this changeover stage is governed by factors far deeper than the two of us (mantle-flow perturbations and readjustments?) can fathom but we keep our minds churning and arms waving just the same.

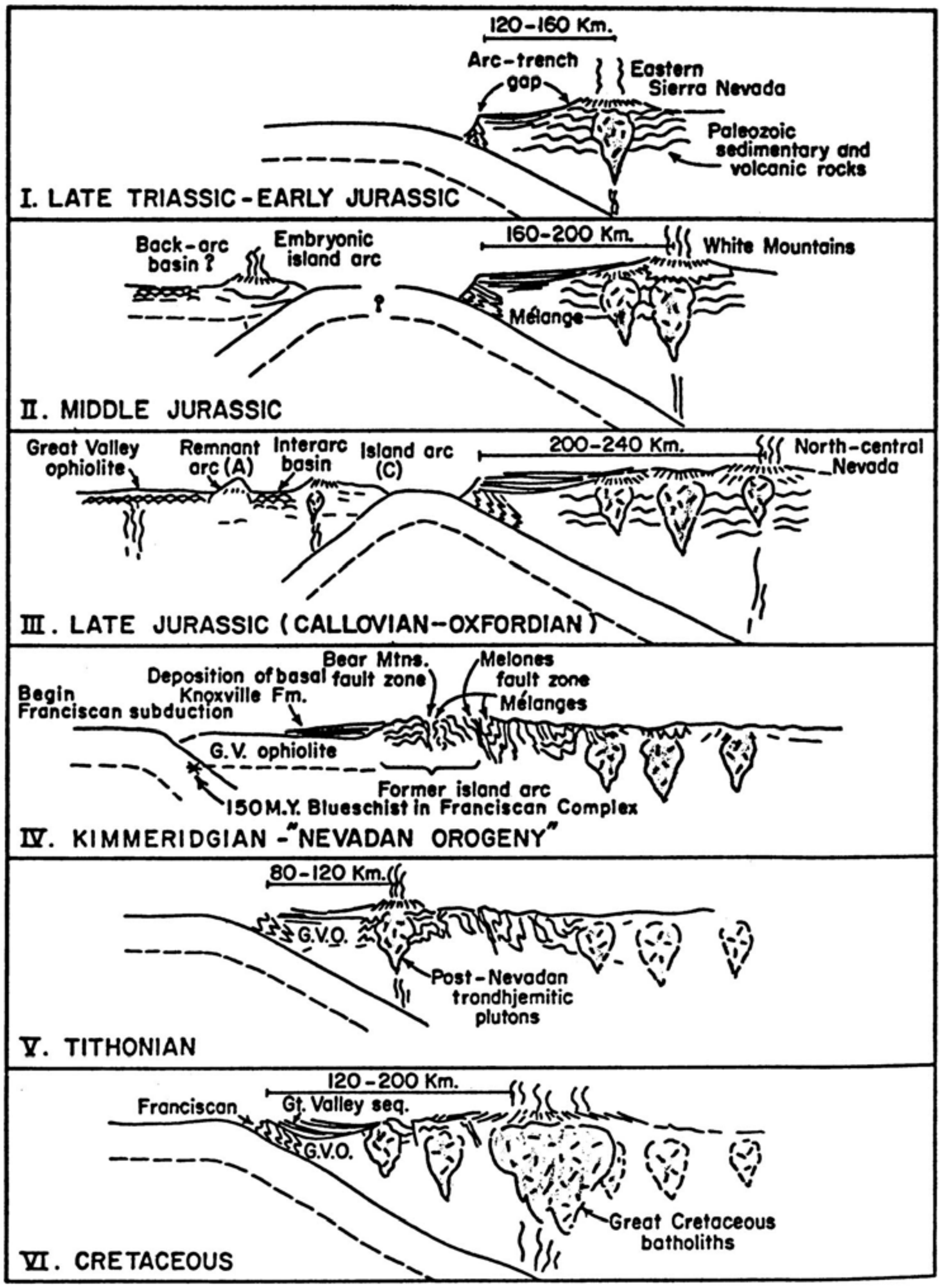


Figure 41. Hypothetical schematic sections showing the postulated tectonic evolution of the Sierra Nevada range during Mesozoic time. (R. A. Schweickert and D. Cowen, 1975, fig. 3, p. 1334.)

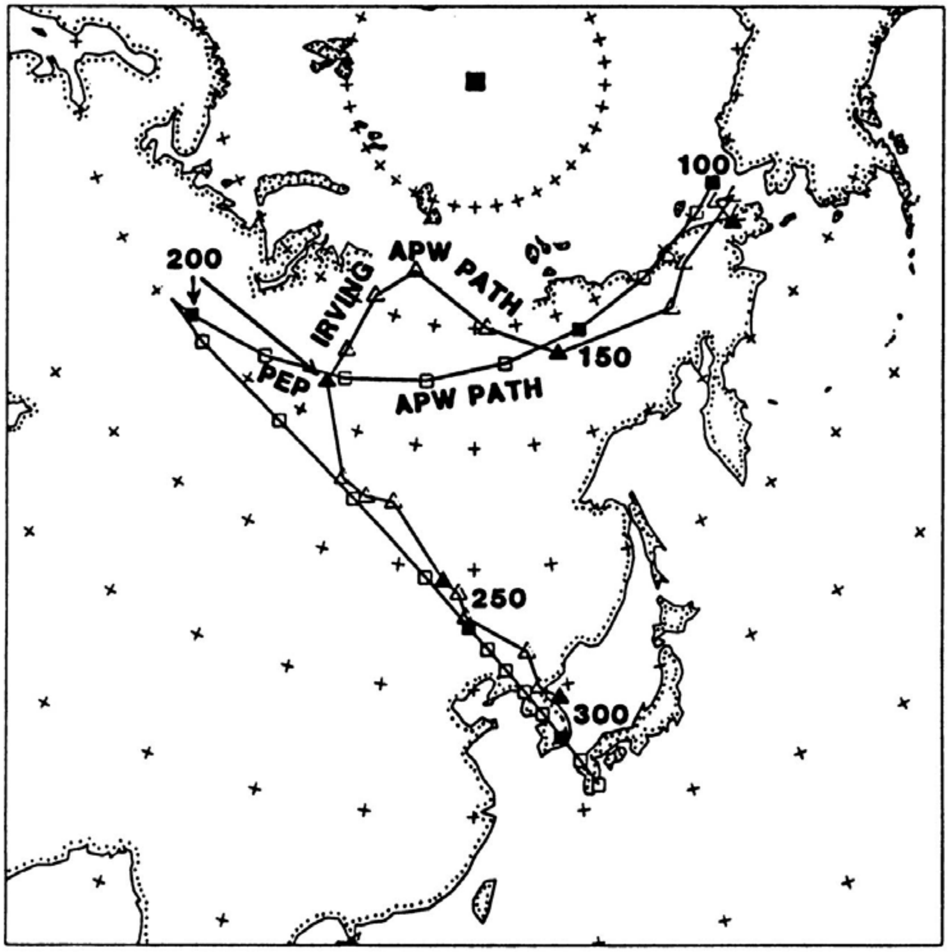


Figure 42. Two conflicting apparent-polar-wander (APW) paths for North America shown at 10 Ma intervals based 1) on the data of Irving and Irving (1982) which shows a cusp at 170 Ma (open triangles) and 2) the data of Gordon, Cox, and O' Hare (1984) which indicates a best-fit Jurassic cusp at 200 Ma (open squares). Stereographic projection. (R. G. Gordon; A. Cox; and S. O' Hare, 1984, fig. 15, p. 524.)

The Atlantic cycle begins. After all these strike-slip couples had done their things and had become inactive, perhaps by the end of the Jurassic Period [dated only by "guessing"; but Schlische (1995a) mentions an angular unconformity within the Jurassic in subsurface of Canada offshore] then the new tectonic regime that characterizes a passive continental margin became established.

We regard the Newark episode as being a product of the great plate-tectonic switchover from the setting that culminated in the Appalachian deformation to the setting that has characterized the opening- and spreading of the Atlantic Ocean. In our view, the Newark belongs to neither the Appalachian nor the Atlantic cycles, but is a distinctive product of a short-lived plate-tectonic changeover regime that intervened between these two longer-lived tectonic cycles.

No matter. It is clear that whatever happened to the Newark strata of Unit (3) took place prior to Late Cretaceous time, when the Upper Cretaceous coastal-plain strata of Unit (2) started to be deposited. At Sand Hill, NJ, in an outlier, Upper Cretaceous strata rest on the exposed edge of the Rocky Hill-Palisades sill, a relationship that gives a vague limit for the date of deformation of the Newark rocks (Widmer, 1964).

In the middle of the Jurassic Period, because of tectonic deformation that included folding and faulting (but not large-scale low-angle thrusting nor regional-scale metamorphism), strata ceased accumulating in the Newark basin. This Newark-basin-ending tectonic activity formed no mountain chain; thus, it has not been accorded the status of an "orogeny."

Thus, in summary, we think the geotectonic cycle that formed the Newark strata does not belong in the continental-margin category. We classify the Newark episode as being a kind of switchover setting between the preceding completed Appalachian continental-margin episode and the following Atlantic continental-margin episode, still in progress (Sanders, Friedman, and Sternbach, 1981; Merguerian and Sanders, 1994b).

After all the post-Newark elevation and great erosion, an erosion surface having low relief (= a peneplain) formed. The surface that formed early in the Cretaceous Period is the Fall Zone surface (Sharp, 1929b). Evidence from borings indicates that this surface, formerly horizontal, now dips SE about 80 feet per mile (Figure 43). Since Fuller's time, many water wells deep enough to reach the basement rocks have been drilled (DeLaguna and Brashears, 1948; Suter, DeLaguna, and Perlmutter, 1949) and many geophysical shot points established (Oliver and Drake, 1951). In general, the newer maps show that relief on this surface is small. A possible exception is a deep valley that extends SW from New Haven Harbor, Connecticut. The age of this valley has not been determined definitively; JES thinks that the most-likely possibility is pre-Cretaceous (Sanders, 1965, 1989 ms., 1994a). Flint (1963b) described upland remnants of the Fall Zone surface in Connecticut.

Unit (2): Atlantic Coastal-plain Strata

Unit (2) includes the coastal-plain strata that underlie Long Island, parts of Staten Island, and eastern New Jersey. In these localities can be seen the eroded edges of a vast body of sediment that thickens toward the ocean (Figure 44). This body of sedimentary strata is analogous to the one that accumulated during the passive-margin phase of the Appalachian geotectonic cycle of the Early Paleozoic. (See Figure 26.)

The coastal-plain strata are products of the Atlantic continental-margin geotectonic cycle that began at about 150 Ma. We are still in the passive-margin, sediment-accumulation stage of this cycle; thus we seem to be at about the half-way point.

Along the northern margin of the New York Bight, the Atlantic Ocean has overstepped the elevated- and truncated edge of the coastal-plain strata (Figure 45). Although the Upper Cretaceous strata are exposed in a few places on Long Island, for the most part, from New York Harbor to the E and NE, the top of the depositional terrace is submerged. This arrangement implies two tectonic events: (1) an earlier elevation of New England; and (2) a later subsidence, in some places greater in amount than the earlier elevation. During the first event, the elevation of New England changed the strike of the coastal-plain strata from N45°E (in eastern New Jersey) to about N75°E (on Long Island), and thus formed the framework of the New York Bight. During the second event, the formerly elevated area subsided to enable the sea to overstep the eroded edges of the Upper Cretaceous strata. This subsidence is still going on. Our coasts are being submerged not because the sky is falling, but because the ground is sinking. This sinking is in the opposite sense and is overriding any isostatic rebound associated with the melting of the last Pleistocene glacier.

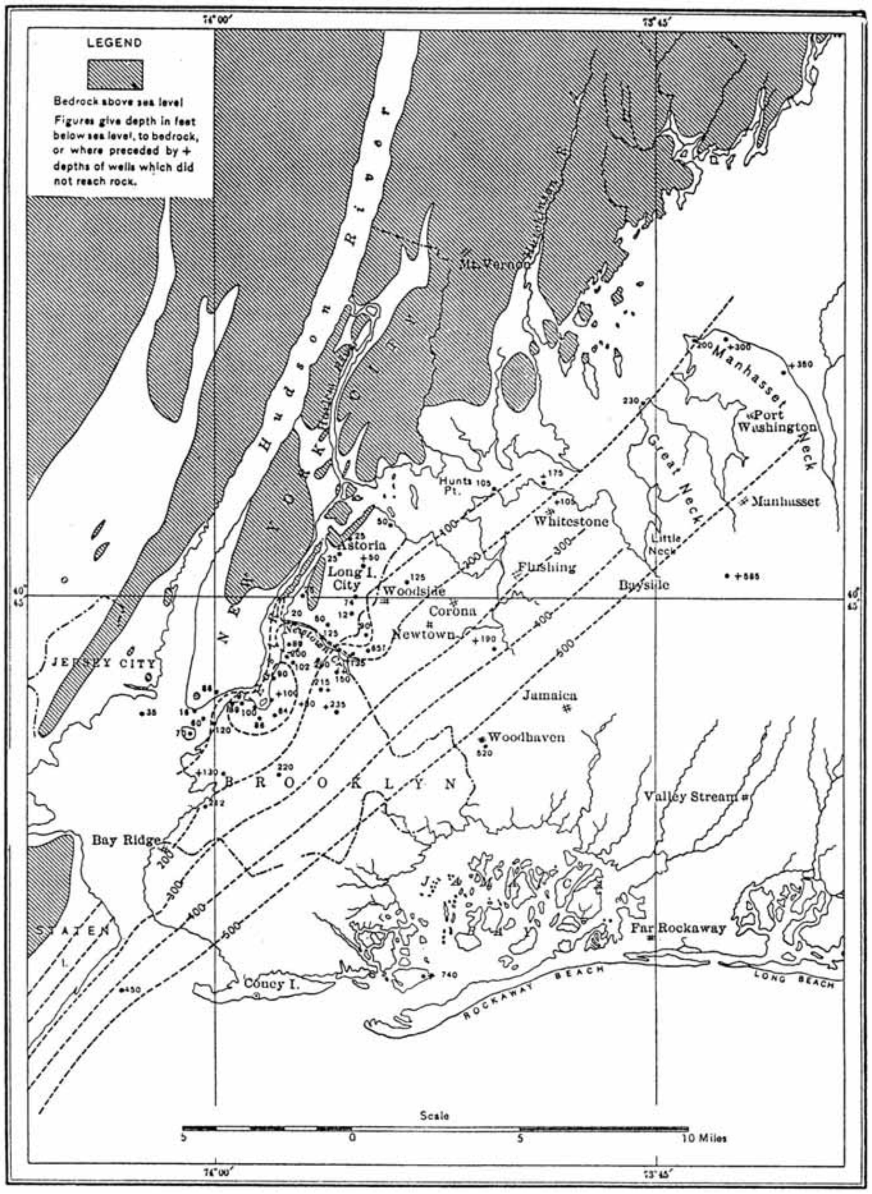


Figure 43. Map of NW Long Island showing contours on top of basement surface sloping 80 feet per mile to the SE. (A. C. Veatch, Pl. XV in M. L. Fuller, 1914, between p. 66 and 67.)

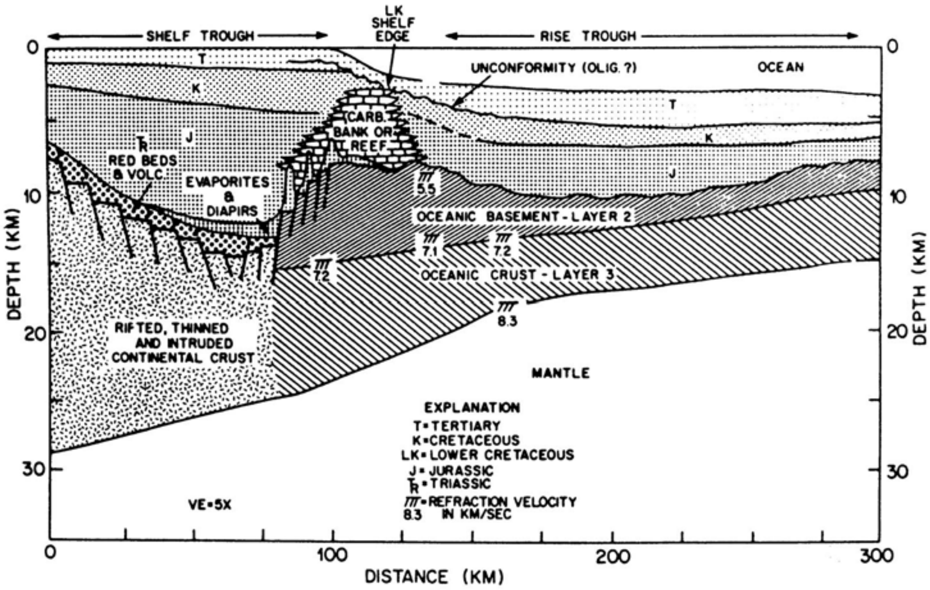


Figure 44. Diagrammatic profile-section across continental terrace off Cape May, New Jersey, based on U. S. Geological Survey miltichannel-seismic Line 06. (Robert E. Sheridan, 1981, fig. 5, p. 44.)

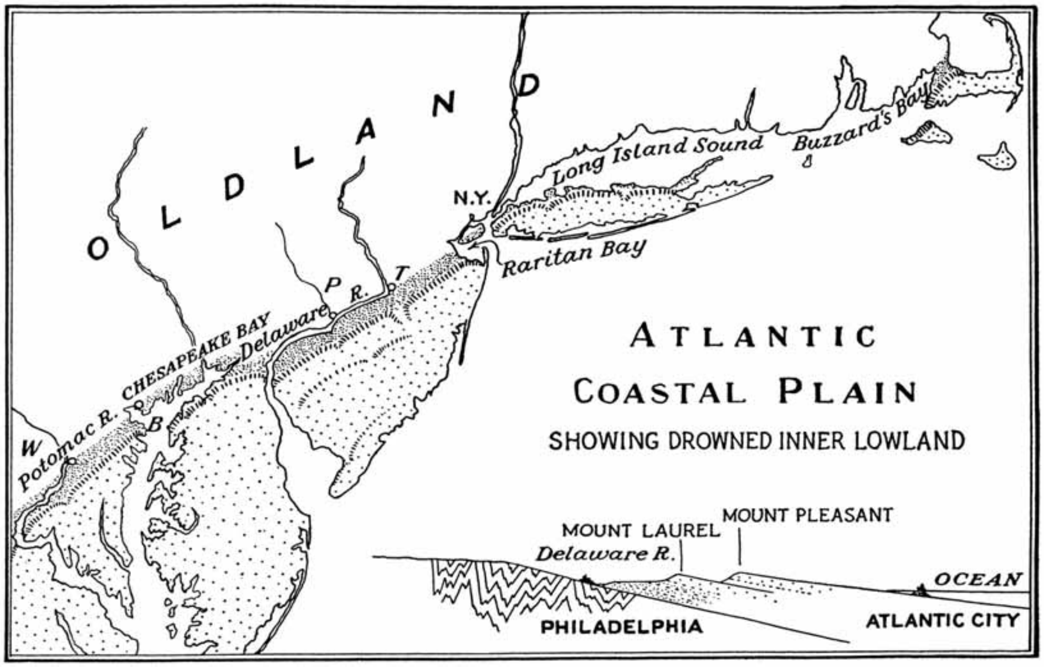


Figure 45. Diagrammatic map of part of Atlantic Coastal Plain (open stipple) from Washington, D. C. (W at lower L) to Cape Cod, Massachusetts showing how the inner lowland (close stipple) at the preserved edge of the coastal-plain strata has been submerged northeast of New York City (N.Y.). Inset schematic profile-section (large vertical exaggeration) extends SE from Philadelphia, PA (P) to Atlantic Ocean off Atlantic City, NJ (not shown on map). (A. K. Lobeck, 1939, p. 456.)

The coastal-plain strata consist of sands that have been cemented only locally (the hematite-cemented sandstones and -conglomerates, or "ironstones"), and the interbedded clays have not become fissile. Hereabouts, the exposures show only the Upper Cretaceous part of the sequence. Elsewhere, however, younger units are present. The youngest widespread marine unit in the coastal-plain succession is of Miocene age.

A characteristic of the coastal-plain sands is their great mineralogic maturity. They generally lack feldspar and contain only quartz, some fine-grained detrital muscovite, and resistant varieties of heavy minerals, such as zircons. Notably absent are any particles derived from the Newark Supergroup. The absence of Newark debris supports the conclusion that the coastal-plain strata formerly extended far enough inland to fully bury the Newark outcrop areas. Some of the distinctive heavy minerals show that the crystalline central core of the Appalachians was not covered, but was providing debris. Simiarly, sand composed of serpentinite particles indicates that the Staten Island Serpentinite was exposed.

The coastal-plain strata belong to the large category of basin-margin sediment fillings whose interpretations have been revolutionized as a result of new concepts of seismic stratigraphy. These new concepts have grown out of detailed analyses of the new generation of continuous seismic-reflection- profile records collected from moving research ships. Instead of confining the analysis of the seismic records to evidence of buried geologic structures, the chief goal of seismic surveys and the only point of interest by most geophysicists, a group of geologists at the Exxon Research Laboratories in Houston, TX, under the leadership of Peter Vail, have shown how these new seismic records contain evidence of the profound influence exerted by changes of sea level on the sedimentary strata that accumulate at the margins of the oceanic basins. Analysis of data from passive continental margins collected worldwide has enabled Vail and his co-workers to compile a sea-level curve.

The notion that the stratigraphic record exposed on the continents records numerous changes of sea level had been proposed early in the 20th century, by the American geologist A. W. Grabau among others and various European geologists such as the Termier's and Umbgrove. Subsequently, the pendulum of geologic fashion in interpreting strata swung in the opposite direction and the effects of sea-level changes were not much emphasized. But, now it's back to Grabau and then some, but with one difference: the new "young Turks" think that they invented (not re-invented) the great wheel. They do not mention Grabau (1936a, b; 1940), T. C. Chamberlin (1909), Charles Schuchert (1916), E. O. Ulrich (1911, 1913, 1916), or Stuart Weller, to name a few of the notable early American proponents of the interpretation that the continental stratigraphic record had accumulated in response to numerous, extensive changes of sea level. To be sure, the main emphasis of many of these early American studies was to use the gaps in the stratigraphic record as boundaries between systems, for example. In contrast, armed with the new regional look made possible by the seismic-profile records, the seismic stratigraphers are able to show how sea-level changes are expressed--not only in the areas where formerly the breaks resulting from an episode of emergence were emphasized but also in the basins, where deposition was continuous. The seismic expression of strata deposited at a high stand of the sea differs from that of strata deposited at a low stand. Therein lies the secret of success of the new interpretations.

Given such a powerful stimulus, nearly all stratigraphers are now reevaluating their data in terms of sea-level changes. An example is R. K. Olsson's (1988) use of benthic Foraminifera from the Upper Cretaceous in the coastal plain of New Jersey for making estimates of paleodepths of the Cretaceous sea. Combining the information from all sources, Olsson has prepared the stratigraphic chart of the formations of the New Jersey coastal plain (Figure 46).

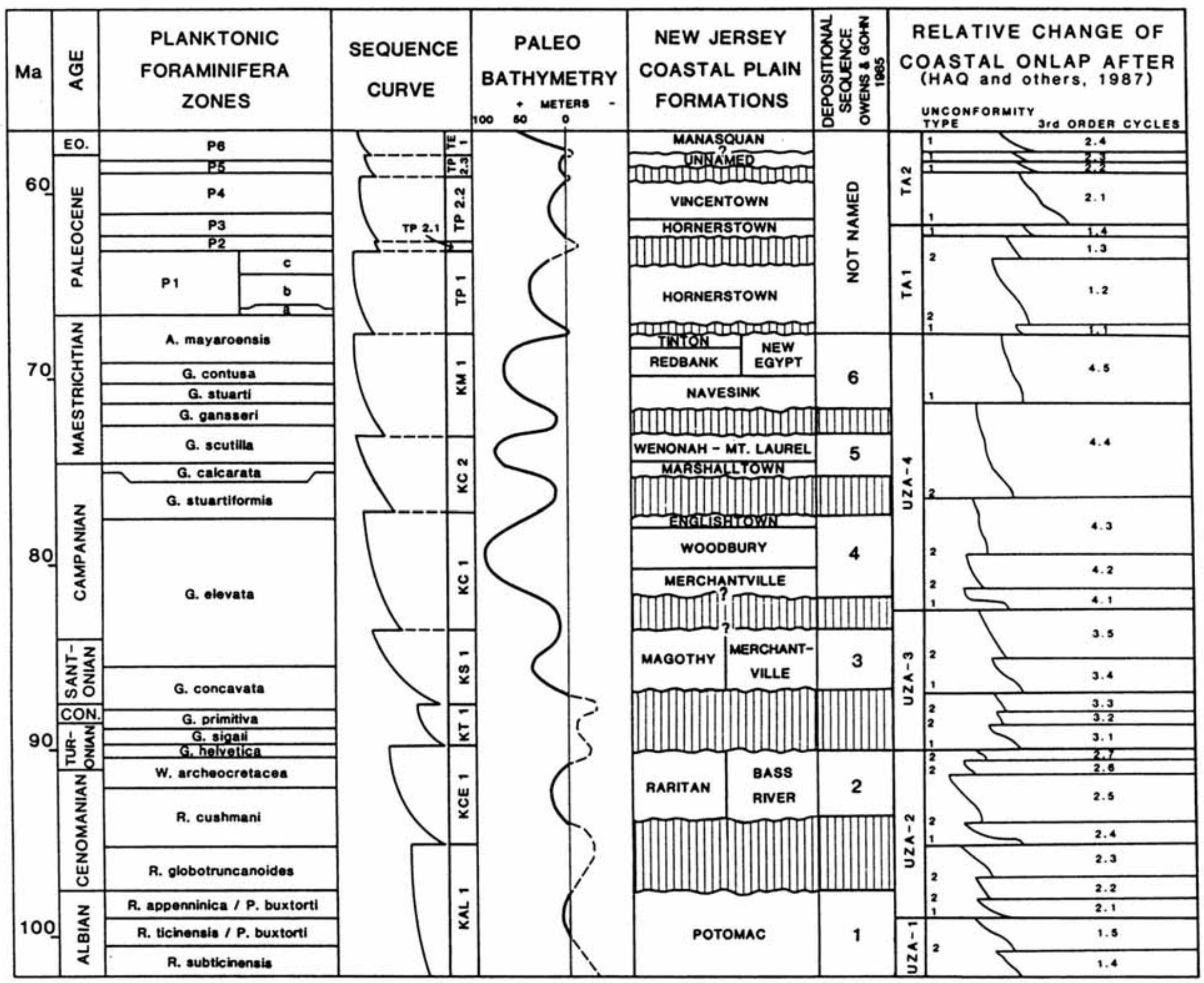


Figure 46. Chart of Upper Cretaceous formations of New Jersey Coastal Plain (column to right of center) showing inferred ages, zones based on planktonic foraminifera, newly recognized sequences (and sequence curve), paleobathymetry curve, and inferred sea-level curve based on coastal onlap inferred from continuous seismic-reflection profiles (right-hand column). (R. K. Olsson, 1988, fig. 7, p. 293.)

The episode of coastal-plain sediment accumulation that began late in the Cretaceous Period (~95 Ma) continued until the Miocene Epoch (~25 Ma). From the record in New Jersey, we can infer that a series of fans built southeastward from the rising Appalachians. These fans pushed the shoreline southeastward and ended the episode of accumulation of marine sediments in what is now New Jersey. (However, marine sediments continued to accumulate in areas now submerged.) In the Pliocene Epoch (starting about 6 Ma), regional uplift, possibly combined with the first of many episodes of eustatic lowering of sea level, enabled deep valleys to be eroded. One such valley, named a strike valley because it is parallel to the strike of the gently tilted coastal-plain strata, formed along the eroded updip edge of the preserved Cretaceous strata. (This feature has also been named the inner-cuesta lowland.) The depression that has been filled with sea water and forms Long Island Sound (Figure 47) began its career as such a stream-eroded strike-valley lowland.

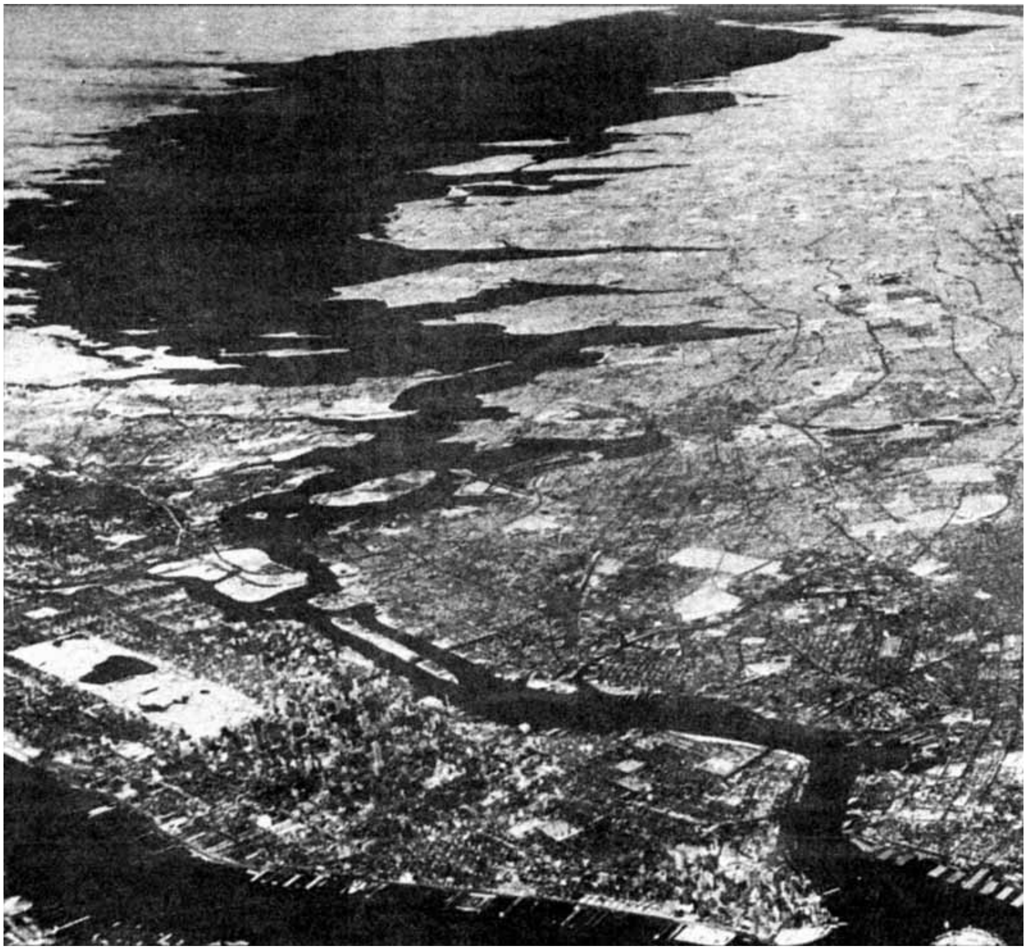


Figure 47. Oblique photograph looking northeastward along the axis of the Long Island Sound. The Sound in a natural boundary (unconformity) between crystalline rocks of the New England Appalachians (to the left; north) and southward dipping sediments of the Coastal Plain and overlying glacial sediments (to the right, south).

Other deep valleys that trend across the strike of the gently dipping coastal-plain strata have been incised into the top of the Cretaceous. Some of these have been completely filled with sediments so that they lack topographic expression on the modern land surface.

Late in the Miocene Epoch, the coastal-plain sands and clays were elevated and truncated by erosion to form a surface upon which the Quaternary glaciers acted.

REGOLITH: UNIT (1): THE GLACIAL SEDIMENTS

Overlying all the foregoing units is a discontinous blanket of materials that is collectively designated as "regolith." (Regolith is something one can dig with a shovel as contrasted with pounding on the bedrock with a hammer). Regolith is an "umbrella" term that covers many contrasting kinds of materials; most engineers apply the term "soil" as a synonym of the geologists' term regolith. Some regolith, such as some soils (in the agricultural sense) are residual deposits that formed by extensive chemical alteration of the underlying bedrock. Much regolith has been transported and may or may not have been derived from the underlying bedrock. Hereabouts, most of the regolith rests on a fresh bedrock surface that has been smoothed, rounded, polished, and in some cases, scored with remarkable sets of linear, parallel grooves and striae (Figure 48).

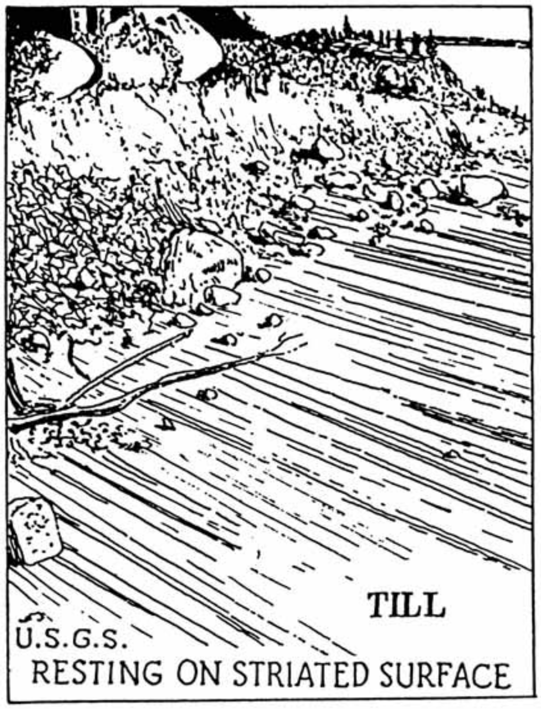


Figure 48. Sketch of a glaciated bedrock surface exposed by wave action; boulders resting on the linear striae have been eroded out of the bluff of till in the background. This sketch (locality not given) depicts what can be seen along the shore of Long Island Sound at South Twin Island, Pelham Bay Park, New York City. (A. K. Lobeck, 1939, upper right-hand sketch on p. 301, from U. S. Geological Survey.)

Although at least 1,500 miles separates New York City from the nearest modern glacier, in many parts of the city, the telltale signs left behind by former glaciers are present. Studies of modern glaciers and the effects of glaciers flowing over a particular region began in Switzerland. In the decade 1786-1796, Horace-Benedict de Saussure [1740-1799] published detailed accounts about the geologic work of alpine glaciers in Switzerland that presented geologists who had never seen a glacier with an clear understanding of what glaciers can do to a bedrock surface over which they flow, of their great long-distance block/boulder-transporting power, and of the distinctive ridges of bouldery morainal debris heaped up at the glacier's terminus. The lessons of de Saussure were appreciated by many readers of his books. Among these were the aforementioned James Hutton and his friend the mathematician-astronomer, John Playfair [1748-1819], in Scotland (Playfair, 1802, section 349) and Sir Charles Lyell [1797-1875] (who adopted a glacial origin for the landforms known as moraines in Scotland, but held to the concept of a marine origin for the "drift" deposits elsewhere in the British Isles) (Flint, 1947, p. 4).

Based on these classic studies, geologists are able to use characteristic glacial features to speak confidently of past glaciers and to reconstruct the directions of flow and former extents of long-gone glaciers. We present the evidence geologists use to infer the former presence of a continental glacier where no such glacier exists today; we emphasize the features that can be used to reconstruct the flow direction. Later, we discuss some of the implications of our studies of the direction of flow of the long-vanished Pleistocene continental glaciers that visited the New York metropolitan area.

Kinds of Features Glaciers Erode on Bedrock That Can Be Used For Inferring Ice-flow Direction(s)

Features that a glacier erodes on the bedrock that can be used to infer ice-flow direction include striae and grooves, crescentic marks, long axes of roche moutonnées and "roche-moutonnée structures" and long axes of rock drumlins. We describe each of these briefly and show their value in reconstructing ancient ice-flow directions.

Striae and Grooves

Glaciers are one of the few geologic agents known to create extensive sets of parallel scratches and even large parallel grooves on solid bedrock. (See Figure 48.) The ice flowed along the trend of the linear elongate features.

Crescentic Marks

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 49).

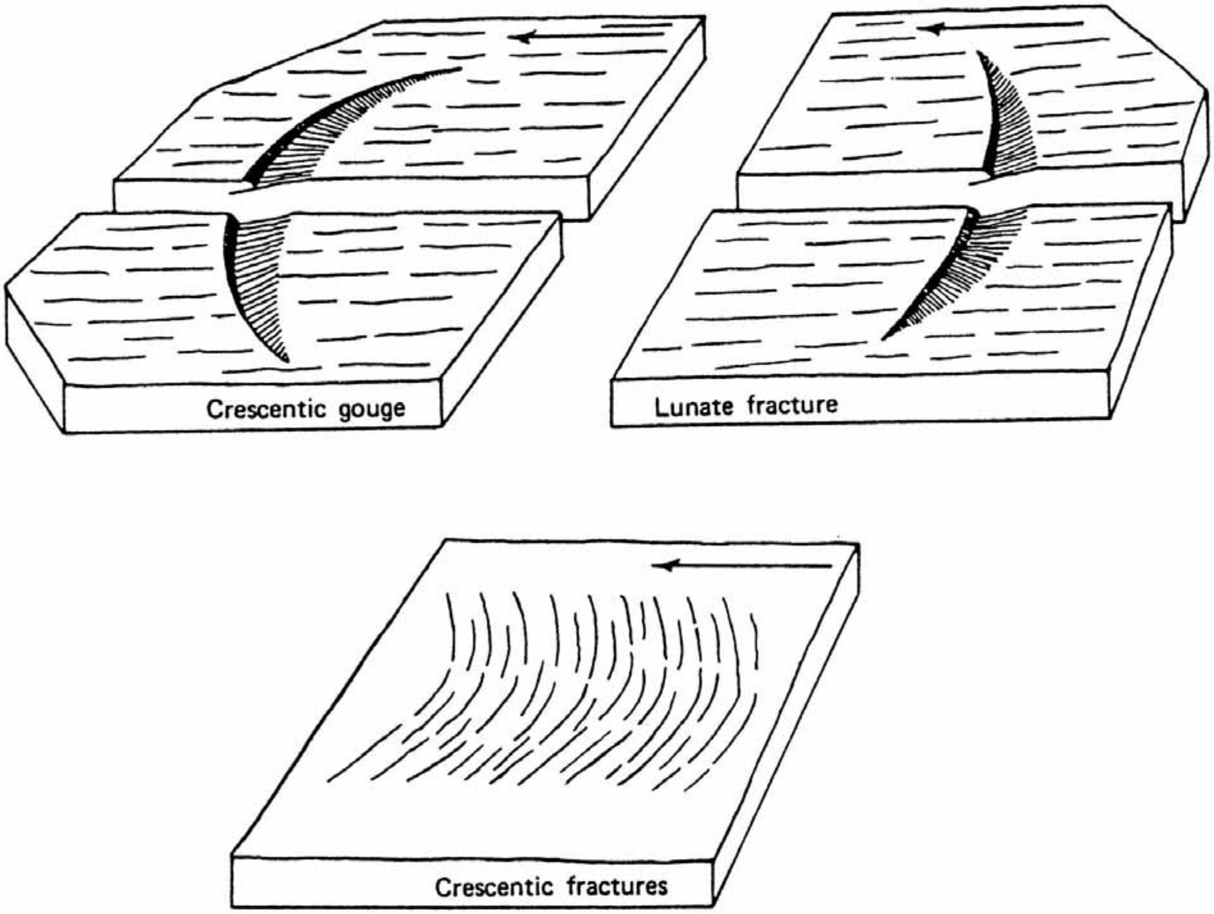


Figure 49. Three kinds of crescentic marks formed on bedrock by a glacier. Arrows show direction of ice flow. (R. F. Flint, 1971, fig. 5-5, p. 95.)

Orientations of Long Axes of Roche Moutonnées and "Roche-moutonnée" Structures

The distinctly asymmetric relief features sculpted by a glacier in the bedrock are known as roche moutonnées (Figure 50). These are smooth, broadly rounded and gently dipping on the side from which the ice flowed (a result of the glacier's grinding on an obstruction to flow); but jagged, irregular, and steep on the side toward which the ice flowed (a result of quarrying and plucking along joints where the ice pulled away from the crest of the obstruction).

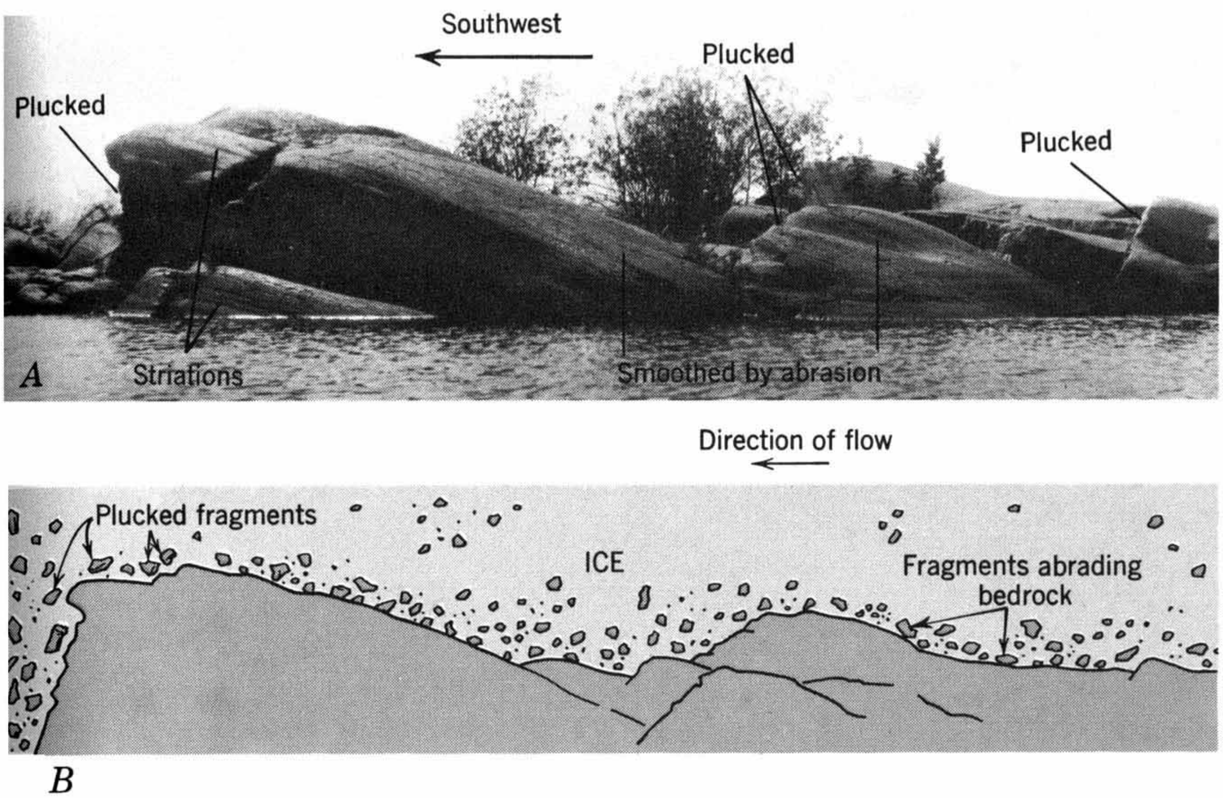


Figure 50. Roche moutonnées in longitudinal profile. (C. R. Longwell, R. F. Flint, and J. E. Sanders, 1969, fig. 12-7, p. 165.)
A. View of roche moutonnées sculpted in Proterozoic granitic rock along shores of Lake Athabaska, Saskatchewan, Canada, by glacier that flowed from NE (at R) to SW (at L).
B. Schematic sketch of the Lake Athabaska roche moutonnées beneath a glacier.

The asymmetry described above is based on the effects of a single direction of ice flow. In the New York City region, we have found many features displaying only part of the morphologic expression of a classic roche moutonnée. The rounded, gently dipping part is present, but the jagged, steep side is not present. Evidently a "classical" roche moutonnée made by one glacier has been modified by flow across and over it of a glacier flowing from a direction that differs by about 45° from the direction of the first glacier.

In our studies of ice-flow directions we have made use of the orientation of the median axis of the elongate, rounded up-ice side of a classic roche moutonnée (Figure 51). We have been using the informal term "roche-moutonnée structure" for these.

Figure 51. Sketch showing roche-moutonnée structure (above) and three-dimensional views of roche moutonnées (below). Arrow indicates direction of ice movement. (A. K. Lobeck, 1939, part of figure on p. 298.)

Orientations of Long Axes of Rock Drumlins

Drumlins are elongate streamlined hills shaped by the flow of a glacier; the long axis of a drumlin is parallel to the flow direction of the ice and the steeper side is toward the direction from which the ice came. Drumlins consist of till, of bedrock, or of some combination of till and bedrock. The term used by itself implies a feature composed of till. A rock-cored drumlin is one that consistis of both till and of bedrock. Rock drumlins consist only of bedrock. Because most drumlins consist of till, we discuss them in a following section devoted to glacial sediments. In this section, we include only rock drumlins. (We do not know why a glacier forms a rock drumlin instead of a roche moutonnée, or vice versa.) Fort Tryon Park is built on a prominent rock drumlin that was formed by a glacier flowing from NNE to SSW but was later modified by ice flowing from NW to SE (Figure 52).

Flow-directional Aspects of Glacial Sediments

Glacial sediments contain several flow-directional aspects such as composition (including erratic boulders) and asymmetric flow features such as drumlins and ice-push structures.

Composition

The composition of glacial sediments is determined by the kind of bedrock over which the ice flowed. This aspect of glacial sediments is generally known as provenance; it includes everything from erratic boulders to the color of the till.

Glacial erratics and indicator stones. Erratic boulders, that is, any boulder consisting of a kind of rock that differs from the bedrock on beneath it, were one of the first attributes noticed. They provide convincing evidence of glacial action. If the parent bedrock source of an erratic is known, then it becomes an indicator stone.

Color of the till. Because of the pattern of distribution of the preserved remnants of reddish-brown sediments that filled the Newark and Hartford basins (Figure 53), color of till and outwash can be a useful indicator of ice-flow direction. For example, in New York City, ice that flowed in a direction that is down the Hudson Valley (from NNE to SSW) did not encounter any Newark basin-filling strata. Accordingly, the color of till deposited by these glaciers is gray or yellowish brown. By contrast, ice that flowed in a direction that is across the Hudson Valley (from NNW to SSE) did encounter Newark basin-filling strata and thus acquired a distinctive reddish-brown color.

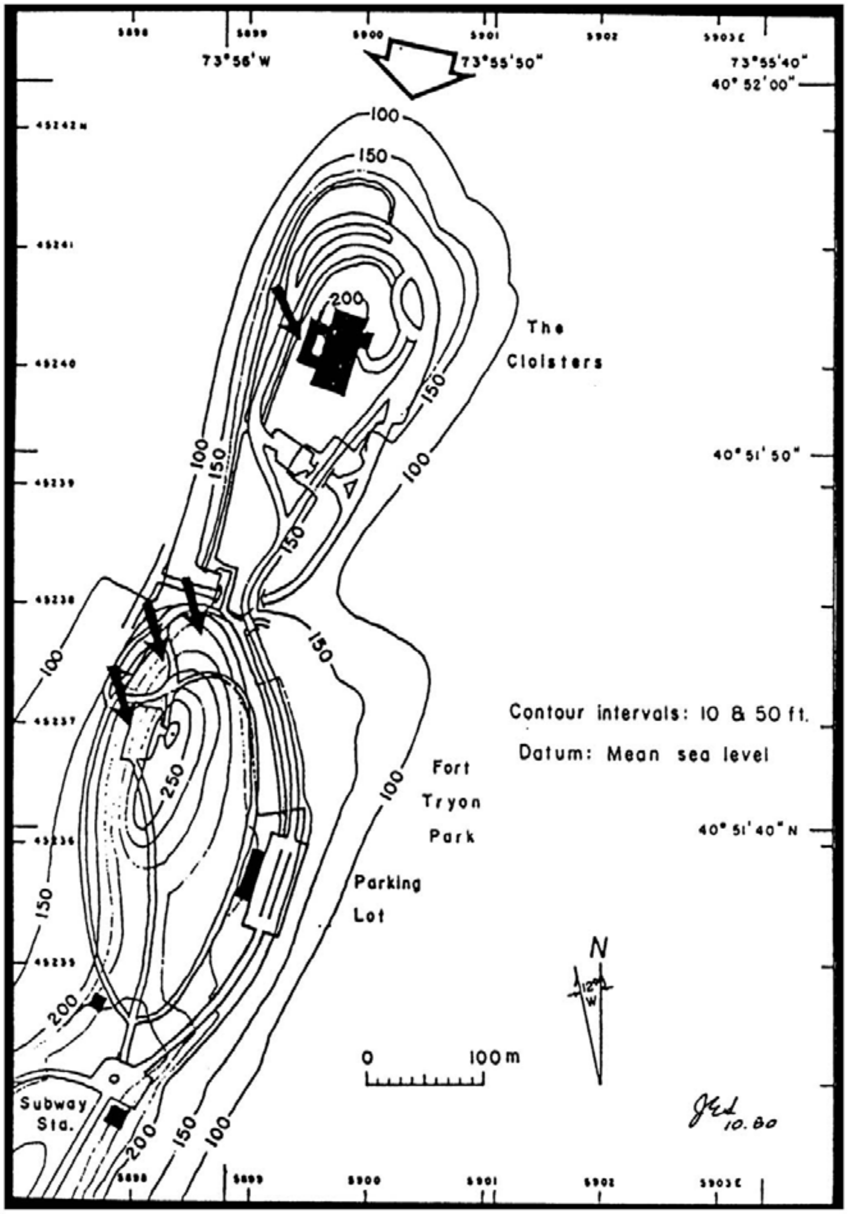


Figure 52. Enlarged topographic map of the Cloister area, Fort Tryon Park showing the two rock drumlins oriented NNE-SSW. (Enlarged and redrafted by J. E. Sanders from U. S. Geological Survey Central Park 7.5-minute quadrangle.)

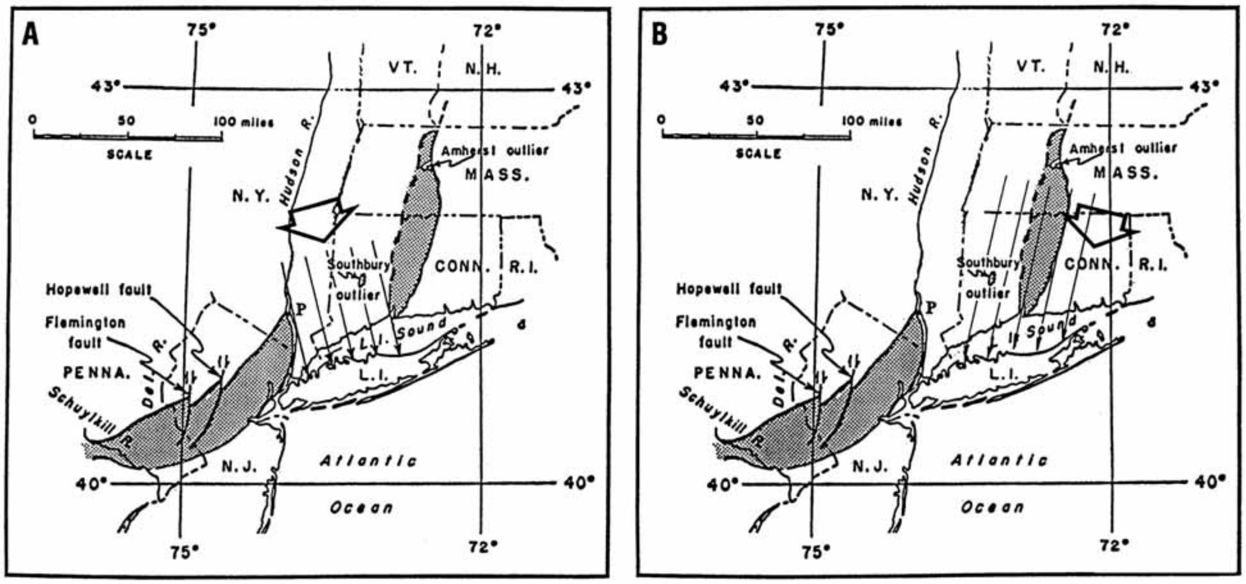


Figure 53. Regional map of part of northeastern United States showing locations of preserved filling strata of Newark Basin (NJ and PA) and of Hartford Basin (CT and MA) (light gray tone). Parallel line segments show how glacial ice flowing from each of the observed dominant directions distributes diagnostic erratics. (Base map from J. E. Sanders, 1963, fig. 7, p. 513.)

A. Flow from NNW to SSE, across the "crystalline corridor" between the fillings of these two basins, deposits reddish-brown erratics in extreme W and extreme E Long Island, but throughout a substantial stretch along the N shore of Long Island, did not deposit any reddish-brown Newark-type erratics. The distribution of erratics in the Harbor Hill Moraine and in the Ronkonkoma Moraine matches that associated with glacial flow from NNW to SSE.

B. Flow from NNE to SSW, as in the Woodfordian glacier, distributes reddish-brown erratics from the Hartford basin in CT and MA to the WSW. The absence of such erratics in the Woodfordian glacier's SSW downflow path along the N shore of Long Island suggests that the Woodfordian glacier did not reach much of Long Island and therefore did not deposit Long Island's two famous terminal-moraine ridges.

Asymmetric Flow Features

Drumlins. The long axes of the elongate, streamlined, asymmetric hills composed of till that are drumlins are parallel to the direction of flow of the glacier and the steeper side faces the direction from which the ice came (Figure 54). In this respect, the asymmetry of a drumlin is just the opposite of that displayed by a roche moutonnée, or a roche-moutonnée structure.

Ice-push structures. Includes recumbent folds and other glaciotectonic features such as thrust ramps. Tectonic analysis of the structural features usually enables a general sense of ice flow to be inferred. In some cases, one might also find soft-sediment "slickensides". Many examples are known from Long Island and Gardiners Island (Fuller, 1914). Glacial "thrusts" are well exposed in the former sand pits at Port Washington (Mills and Wells, 1974). We have described an example from Staten Island (Sanders, Merguerian, and Okulewicz, 1995a, b).

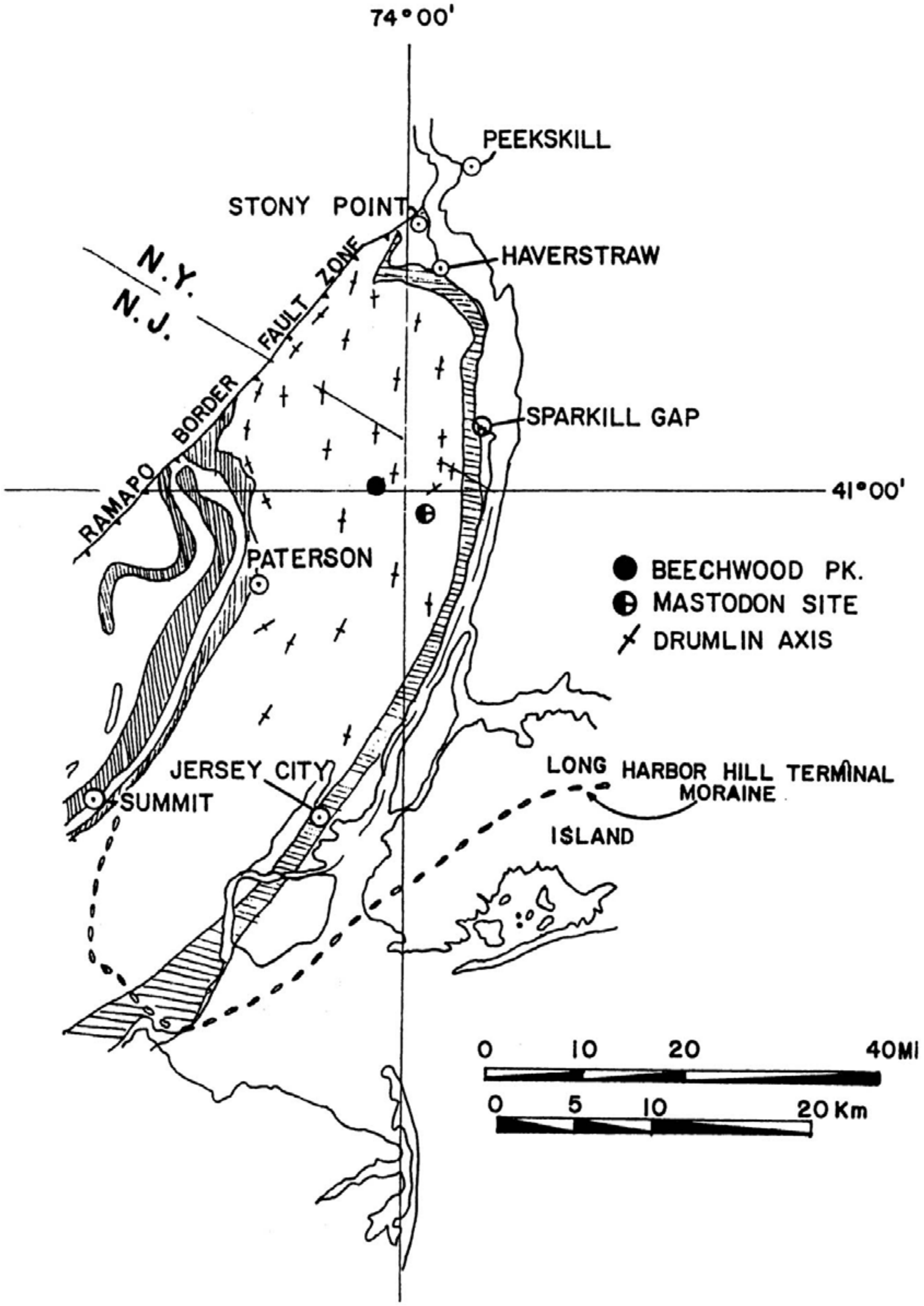


Figure 54. Sketch map of northeastern end of Newark basin and vicinity showing orientations of long axes of drumlins deposited by the "Woodfordian" glacier. (S. P. Averill, R. R. Pardi, W. S. Newman, and R. J. Dineen, 1980, fig. 1, p. 161.)

How Many Pleistocene Glaciations Have Affected New York City and Vicinity?

Although all geologists agree that New York City and vicinity have been glaciated, they do not agree on the interpretation of the local Pleistocene record with regard to number of glaciations represented. Previously published interpretations about the number of the Pleistocene continental glaciers that visited the New York City region have vacillated between one and four; we think the correct number should be five (Table 3).

The first geologists who considered this question could not agree, some saying more than one, but they were pushed into the background by the loudest- and most-prestigious one-glacier voice, that of Professor T. C. Chamberlin [1843-1928] from the University of Chicago.

The next phase of investigations of the local Pleistocene deposits included detailed mapping. The two chief local mappers both demonstrated that the deposits of more than one glaciation are present on Long Island. Based on his monographic study of the geology of Long Island, published in 1914 by the U. S. Geological Survey, Myron L. Fuller made a case for a four-glacier interpretation.

Starting in the mid-1930's revisionist-minded "Friends of the Pleistocene," who evidently never read Woodworth's (1901) New York State Museum Bulletin and cavalierly cast aside Fuller's four-glacier classification, adopted that "old-time religion," namely a belief that nearly all of our glacial features had been made during the latest glacial episode, the "Wisconsinan."

Until recently, nearly all contemporary specialists in Pleistocene geology have followed this revisionist viewpoint that one glacier--the "Wisconsinan"--did it all. However, curiously enough, starting in the 1960's, R. F. Flint (1961), probably the single most-influential individual behind the revisionistic return to the one-glacier viewpoint, found evidence that south-central Connecticut had been affected by two glaciers moving from contrasting directions. Thus began what became known as "the two-till problem" (Pessl and Schafer, 1968). The late C. A. Kaye (1964b,c,d; 1982) presented evidence for a multi-glacial interpretation of southeastern Massachusetts, emphasizing the importance of the Illinoian glaciation and the evidence that glaciers had flowed from two discrete directions, NNE to SSW and NW to SE. Subsequently, stratigraphic evidence from coastal-cliff sections cut in the drumlins in Boston Harbor (W. A. Newman, Berg, Rosen and Glass, 1987; W. A. Newman and Mickelson, 1994) and at Sankaty Head, Nantucket (Oldale, 1982; Oldale and others, 1982; Oldale and Eskenasy, 1983; Oldale and Colman, 1992), has substantiated the importance of the Illinoian glaciation.

We have found evidence supporting a multi-glacial view, and conclude that the most-appropriate classification is based on a resurrection and modification of Fuller's scheme. We raise Fuller's ante by one and, as mentioned, contend that the correct number of Pleistocene glaciations was five (Sanders and Merguerian, 1997). On today's trip, we shall examine evidence about directions of glacial flow in several scattered localities.

MORPHOLOGY OF EARTH'S SURFACE; TALE OF OUR TWO STRIKE VALLEYS

The three major bedrock units just mentioned all come together on Staten Island. Elsewhere, their relationships to one another can be expressed as a tale not of two cities but rather a "Tale of Two Strike Valleys." As mentioned, a strike valley is an elongate lowland that forms after initially horizontal strata of varying resistance to erosion have been tilted and eroded. The lowland forms where weak rocks are worn down between adjacent more-resistant rocks. Two of our prominent water bodies, the Hudson River and Long Island Sound, follow special kinds of strike valleys that we shall call basal strike valleys because they form along the geologic boundary where the base of one unit rests on older rocks.

Basal-Newark Strike Valley: Hudson River (Haverstraw-Hoboken)

From Hoboken, NJ to Haverstraw, NY, the Hudson River flows along the boundary between the Newark basin-filling strata and Palisades sheet of igneous rock of bedrock Unit (3) on the WNW and the "basement complex" of bedrock Unit (4) that underlies Manhattan, The Bronx, and Westchester County on the ESE. (See Figure 32.) Opposite Hoboken, the river makes a sharp bend to its L (viewed looking downstream) and flows out of the basal-Newark strike valley (in a N-S-trending reach that leads to The Narrows). Borings indicate that this basal-Newark strike valley continues to the SW but has been completely filled with sediments. On Staten Island, this valley extends beneath the Upper Cretaceous coastal-plain strata (Figure 55).

Basal-Coastal-Plain Strike Valley: Long Island Sound

Similarly, but with less topographic relief and lacking the striking Palisades sheet of igneous rock, Long Island Sound (See Figure 47.) follows the boundary where the coastal-plain strata of bedrock Unit (2) overlap the rocks of the "basement complex" of bedrock Unit (4).

DRAINAGE HISTORY

Two points of interest arise in connection with drainage history: (1) the possibility that the Hudson River (or some other larger river that meandered) flowed through the notches in the Watchung ridges, and (2) Lake Passaic, the proglacial lake that occupied the lowland in the axis of the Watchung syncline in the territory enclosed between the Preakness Formation and the Ramapo Range. The first involves the coastal-plain strata; the second, the retreat of the latest "Wisconsinan" glacier.

Possible Flow of Hudson River Through Notches in Watchung Ridges

The idea that the Hudson River formerly flowed through the notches in the Watchung ridges was proposed by Douglas Johnson in 1931 (Figure 56). The concept of superposition of a major meandering Hudson River from the coastal-plain strata was part of Johnson's view that the coastal-plain strata formerly extended inland to bury major parts of the Appalachians. Johnson's superposition scheme involved elevation of the coastal-plain strata and establishment of a fluvial drainage network that would then cut downward and be superposed on the pre-Cretaceous bedrock below. Johnson inferred that this superposition took place from the Cretaceous strata. As was explained by Sanders (1974a), Johnson's concept of superposition might be valid, but if it happened at all, it probably took place during the Pliocene episode of great regional uplift and would have been from the Miocene strata. If the condition shown in Figure 56 existed, it would have been possible only for a brief interval during the Pliocene Epoch.

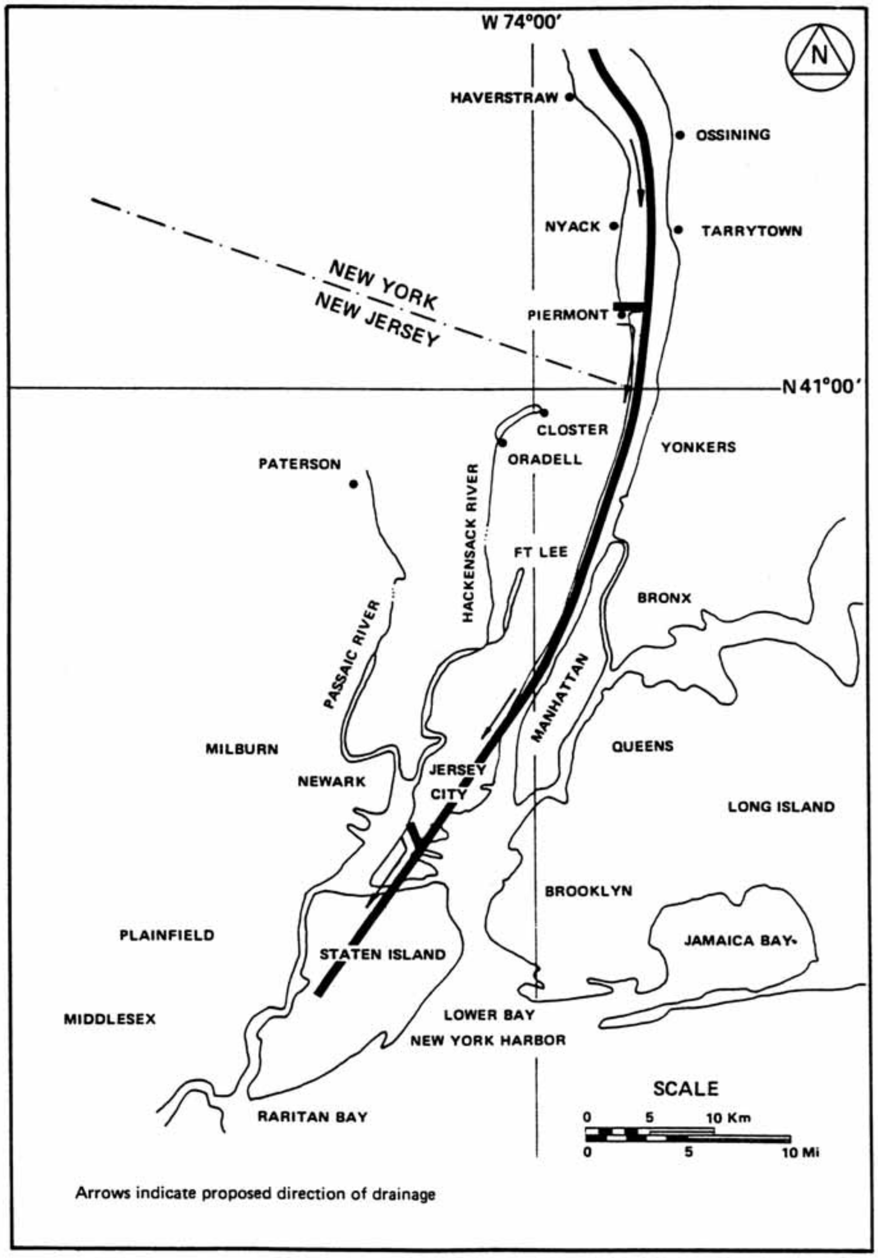


Figure 55. Strike valley at base of Newark Supergroup as inferred during the late Cretaceous, after tilting and erosion of Newark strata but prior to submergence and deposition of coastal-plain strata. (J. R. Lovegreen, 1974 ms., fig. 19, p. 148.)

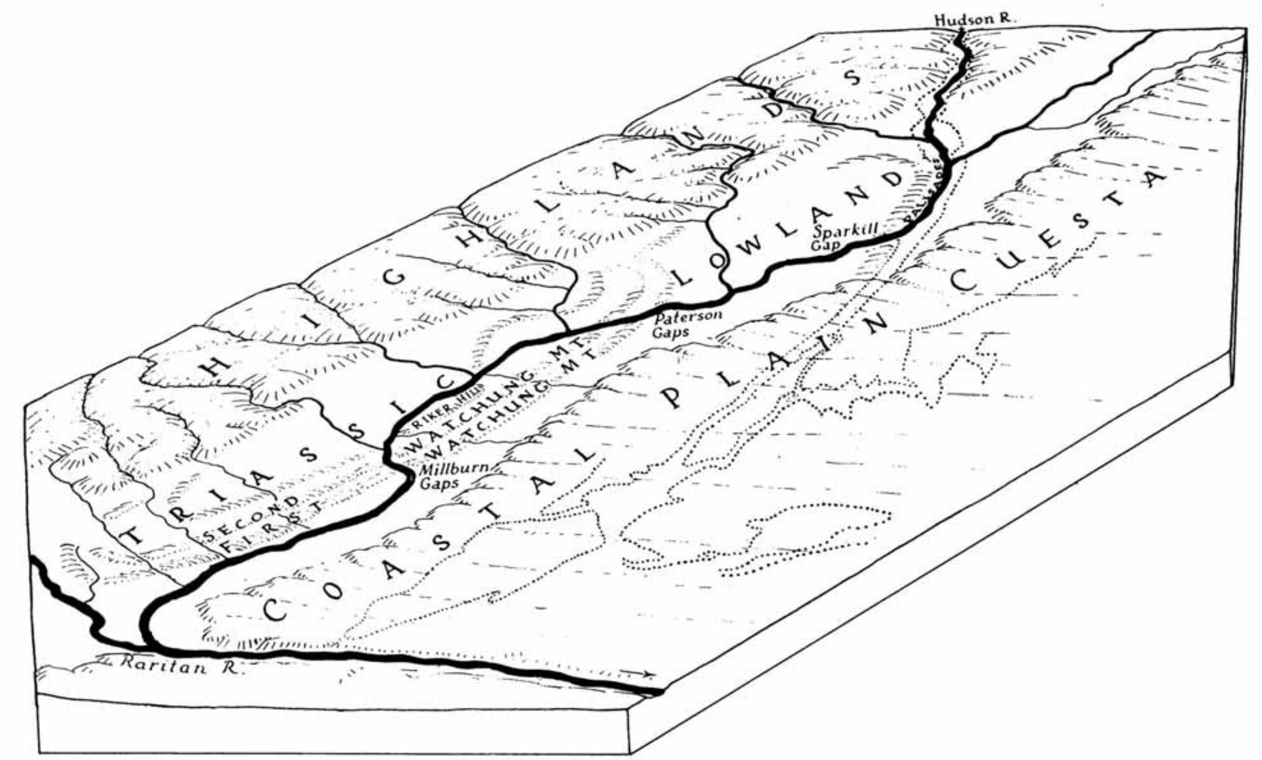


Figure 56. Block diagram showing how ancestral Hudson River, blocked by the inner coastal-plain cuesta, is inferred to have flowed southwestward through the Sparkill Gap, across the Watchung Ranges via the Paterson gaps and back again through the Millburn Gaps, to join the Raritan River near Somerville, New Jersey. Further explanation in text. (Drawn by E. Raisz for D. W. Johnson, 1931.)

Three other points should be mentioned. (1) Geomorphic evidence in the upper Hudson River in upstate New York near Hudson Falls suggests that prior to the latest "Wisconsinan" glacier, the upper Hudson River drained to the NE into the Champlain Valley lowland. This implies that the course of the Hudson south of the Hudson Highlands is too young to have been as shown in Johnson's reconstruction. (2) The presence of a major meandering river as visualized by Johnson requires a wide valley, trending NE-SW with a gentle downvalley slope to the SW. The directions of regional uplift implied by the contours on the base of the Upper Cretaceous (See Figure 43.) suggest that downvalley slopes would not have been to to SW. Such a river contrasts almost totally with all modern rivers in the New York metropolitan area, in which large-scale meanders are virtually absent. (3) Superposition of a river, not an ancestral Hudson River, from one or more of the several pre-"Wisconsinan" glaciers that flowed regionally from the NW to the SE is a possibility not considered by Johnson. The same valley-orientation requirement mentioned in (2) applies equally to any large meandering river flowing on the top of a glacier.

Lake Passaic: Proglacial Lake in Watchung Syncline Lowland

The retreat of the latest "Wisconsinan" glacier in a north-eastward direction from its terminal moraine generated a large quantity of water. In the lowland enclosed by the Preakness Formation on the south and east, by the Ramapo Range on the west, and by the glacier itself on the north (Figure 57), Lake Passaic formed.

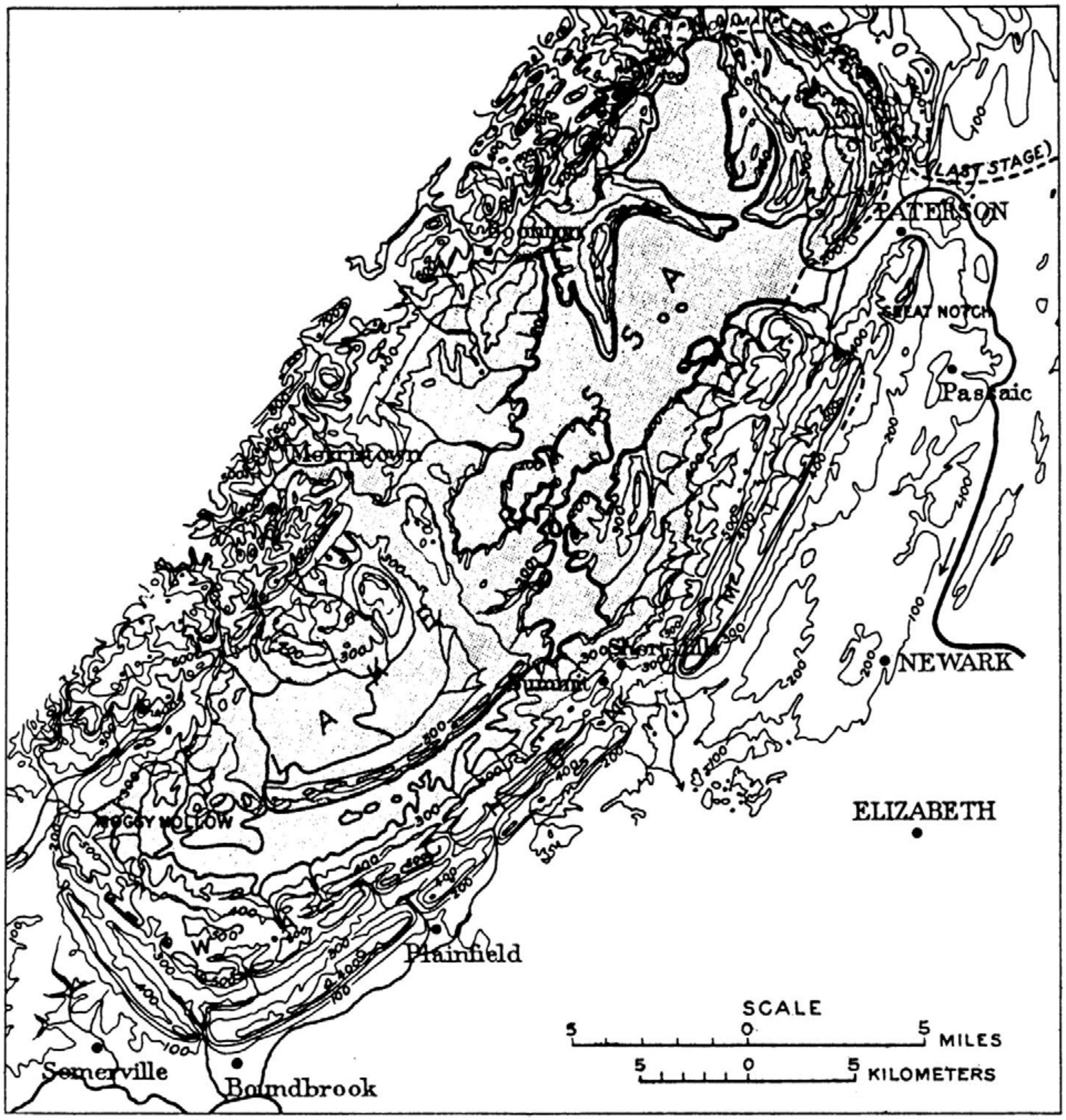


Figure 57. Glacial Lake Passaic (shaded area). (H. B. Kümmel , 1933, fig. 16, p. 71.)

So much for the geologic background. Onward to the specifics of what we will se on our field-trip stops.

LIST OF LOCALITIES TO BE VISITED

(Stops 1 through 7, in the Newark Basin are shown on the road map, Figure 58).

Figure 58. Road map showing locations of trip stops (numbered). Base from Mobil Travel Map of Greater New York. Scale given by grid squares that are approximately 3.6 miles on a side. True North is at the top of the map.

Stop 1 - Palisades Intrusive Sheet, Olivine Zone, and Lockatong Formation, Palisades Interstate Park.
Stop 2 - Pillowed basalt of Orange Mountain Formation ("First Watchung basalt").
Stop 3 - LUNCH; Lower contact of the Orange Mountain Formation ("First Watchung Basalt") and underlying sedimentary strata of the Passaic Formation (lower part of the Brunswick Formation of pre-Olsen terminology).
Stop 4 - The Great Falls of Paterson (Passaic Falls on the Passaic River); Orange Mountain and Passaic formations; evidence for faults.
Stop 5 - Upper, glaciated contact of the Orange Mountain Formation ("First Watchung basalt") at Garrett Mountain Preserve; Garrett Mountain fault block.
Stop 6 - Upper- and lower contacts of the Hook Mountain Formation ("Third Watchung basalt"); basin-marginal rudites of underlying Towaco Formation.
Stop 7 - Basin-marginal rudites of the Feltville Formation, sedimentary strata underlying the Preakness Formation ("Second Watchung basalt").

DESCRIPTIONS OF INDIVIDUAL LOCALITIES ("STOPS")

STOP 1 - Palisades intrusive sheet, Olivine Zone, and Lockatong Formation at Fort Lee in Palisades Interstate Park, New Jersey branch. [UTM Coordinates: 587.58E / 4522.67N, Central Park quadrangle].

The world-renowned mafic Palisades intrusive sheet (Figure 59) is continuously exposed along the SE margin of the Newark Basin from west of Haverstraw, New York southwestward to Staten Island, New York City where it passes beneath an intertidal salt marsh. (See Figure 34.) The sheet continues southward, although with limited exposure, into New Jersey and Pennsylvania within the Delaware subbasin. We discuss this sheet by first debating the use of the term sill for it. Then we take up its mode of intrusion and our new data on conditions in the contact zone. These include contact relationships, chilled-margin facies and discordant contacts. Then we move on to the inferred paleoflow direction of the magma from a possible feeder on Staten Island. Next come the clastic dikes and their implications about the state of lithification of the sediments at time of intrusion and provide another way of estimating the depth of intrusion. We close this part with our revised cooling-depth model.

"To be or not to be (a sill)" - only your local geologists know for sure. Prior use of the word "sill" to describe the Palisades intrusive sheet implies that the contacts of this sheet are everywhere concordant with the bedding of the country rock. In many places such concordance prevails. But on an individual-outcrop basis and near its ends, discordance has been demonstrated (Merguerian and Sanders, 1995a, b).

We think that all the alongstrike diagrams that have been drawn which show the Palisades sheet climbing from low in the Newark toward the top of the Newark, starting at Nyack, New York, do nothing more than display the prevailing ignorance of the effects on the Newark strata (including the Palisades sheet) of the transverse Danbury anticline (Sanders, 1960; Merguerian and Sanders, 1994a, b). JES (both privately and at cocktail parties) has always contended that the curvature of the Palisades sheet from Nyack to a point west of Haverstraw (near the Palisades Interstate Parkway) is not (repeat NOT) only the result of a change from a concordant- to a discordant sheet (in that it climbs in the stratigraphic succession from near the bottom to up near the top), but also merely reflects the effects of the transverse Danbury anticline. The Newark strata have been folded, folks. And by not one but by two anticlines whose axes are disposed at right angles. Thus, the attitudes of the sedimentary strata swing around from a NNE strike and WNW dip (a result of being on the NW limb of the regional anticline whose axis trends NNE-SSW) to a NW strike and a SW dip (a result of being on the SW limb of the regional Danbury anticline whose axis trends NW-SE). Only locally near its NW termination does the sheet become discordant; the amount of this discordance is not more than a few hundred meters. How this profoundly important point of regional structural geology can continue to elude otherwise-rational individuals is a complete mystery to us. Look on a regional map. Does the curvature of the outcrop belt of Palisades sheet differ significantly from those of the Watchung extrusives?

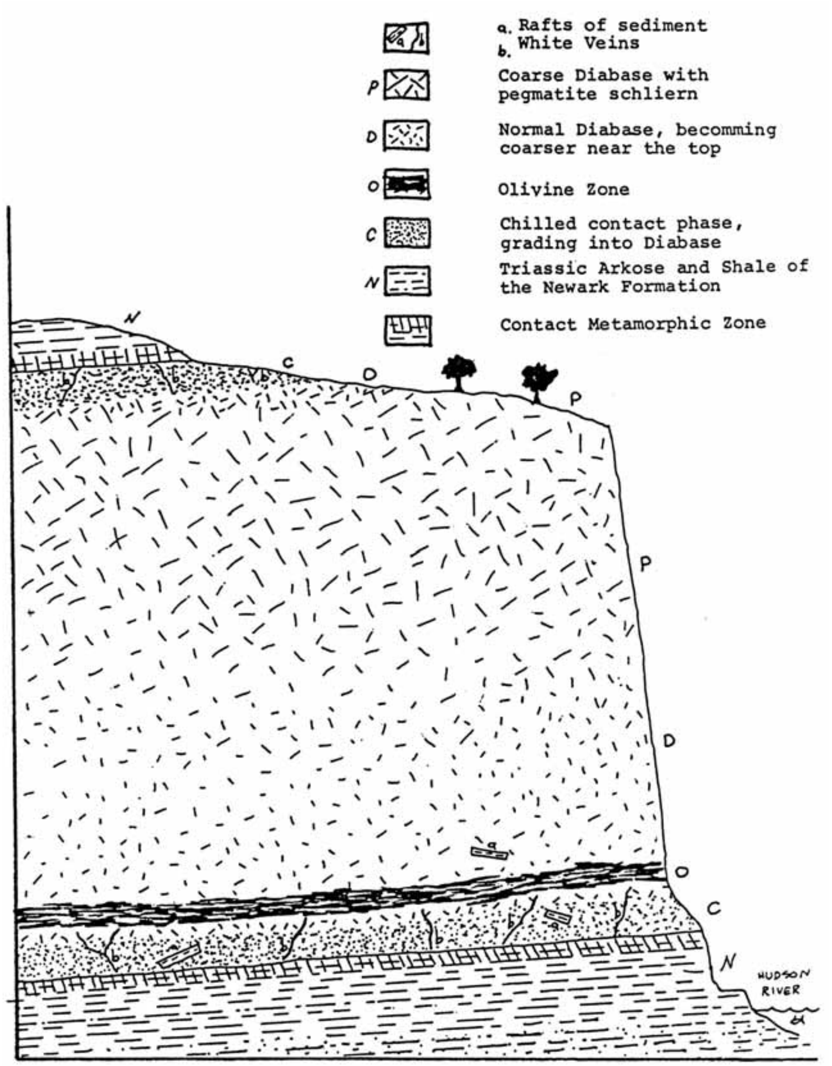


Figure 59. Schematic profile-section through Palisades intrusive sheet, New Jersey. (M. J. Sichko.)

Because this sheet of mafic igneous rocks is not concordant along its strike length (Figure 60), we have abandoned the formerly used term Palisades "sill." Rather, from Staten Island northward to Haverstraw, the sheet climbs discordantly upward through the strata from the Lockatong formation (New York City area) to the Passaic Formation (Haverstraw area). Extensions of the Palisades to the SW, (the Lambertville Sill and Rocky Hill intrusive of the Delaware Subbasin) mirror the climbing stratigraphic discordance displayed in the Newark Basin. (See Figure 60.) As such, the longitudinal profile of the Palisades indicates a lopolithic intrusive [following the definition of Grout (1918)]. However, at the NE end, post-intrusive deformation along the transverse Danbury anticline has created much of the hook-like map pattern (Merguerian and Sanders, 1994c, d; See Figure 34.)

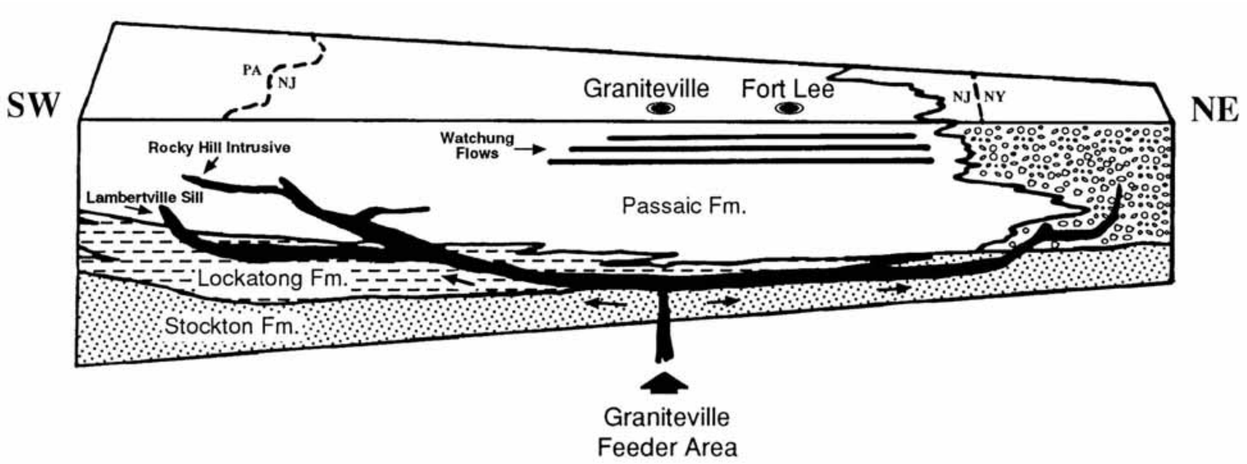


Figure 60. Block diagram showing SW- to NE-trending longitudinal profile (not to scale) of the Palisades intrusive sheet of the Newark Basin and its extension southward into the Delaware Subbasin showing, with arrows, our interpreted paleoflow patterns. Note the overall lopolithic form to the intrusive sheet as viewed in this orientation and the low stratigraphic position of the central part of the sheet including our conjectured feeder area at Graniteville, Staten Island. The positions of Fort Lee, NJ and Graniteville, NY are shown on the top (map view) of the block diagram. (After F. B. Van Houten, 1969, fig. 1, p. 315).

Concordant sheets of igneous rocks, usually mafic such as the Palisades, intercalated with sedimentary strata can be either intrusive, as is the Palisades, or extrusive, as are the Watchung sheets that we shall visit later. Figure 61 illustrates some of the contrasts between a sill and a buried former lava flow. The key relationships are found at the upper contact. A sill heats the sedimentary strata at its upper contact, but a lava flow does not. Moreover, some ancient lavas flowed into lakes or seas and thus acquired pillows, such as we shall examine at Stop 3. The top of a lava flow may display vesicles and the overlying strata may contain pieces eroded from the top of the flow.

Mode of intrusion. Historically, the Palisades has been viewed as a concordant sill-like body, the product of a single charge of magma that differentiated in situ by gravity settling [Darton (1889, 1890), Kummel (1899a, b), Lewis (1908a, b), Walker (1940), Hess (1956), Lowe (1959), and Thompson (1959)]. More recently, however, evidence has mounted that the

Palisades sheet is composite. It is inferred to have formed as a result of several injections of already differentiated magma [Walker (1969), Puffer, Geiger, and Camanno (1982), Shirley (1987), Puffer (1987, 1988), Husch (1990), Puffer, Husch, and Benimoff (1992)]. Today, the major unanswered questions center on the consanguinity of the intrusive pulses of the Palisades magma charges and their possible synchroneity with extrusion of one or more of the "Watchung" (Orange Mountain, Preakness, and Hook Mountain) basalt flows.

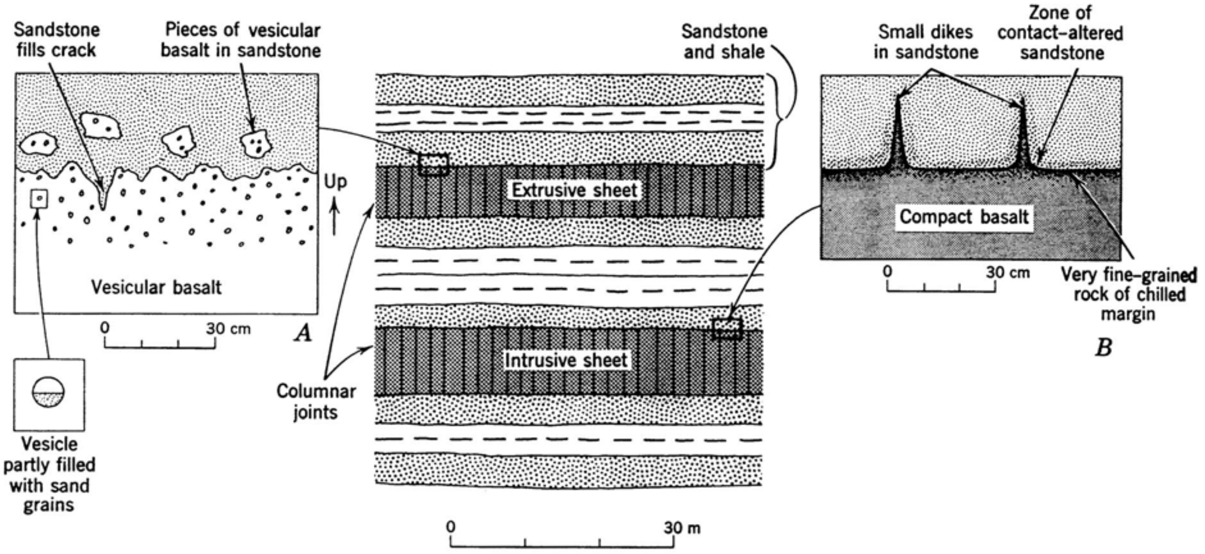


Figure 61. Comparison between intrusive- and extrusive sheets of igneous rock intercalated within sedimentary strata, schematic sections. Enlarges panels of A (extrusive) and B (intrusive) compare critical evidence at the upper contacts. (C. R. Longwell, R. F. Flint, and J. E. Sanders, fig. 20-6, p. 494.)

Our efforts have sidestepped this continuing inquiry into the possibilities of comagmatic ancestry. In search of a better understanding of the environmental conditions that prevailed during injection of the Palisades magma(s), we have focused on the basal contact relationships (Merguerian and Sanders, 1992, 1995b, 1995c). Thus far, these studies have placed constraints on the paleoflow direction of the magma and on the state of lithification of the bounding sediments, and have enabled us to estimate that the depth of intrusion of the Palisades magma(s) lay in the range of ~3 to 4 km.

Contact relationships. The lower contact of the Palisades intrusive sheet with presumably in-situ sedimentary rocks of the Lockatong Formation is spectacularly exposed on the Palisades Interstate Park access road beneath the George Washington Bridge. The rocks at this locality have been studied by many geologists, including Van Houten (1969), Olsen (1980b), and Puffer (1987). The fact that the olivine zone lurks above the roadbed allows us to infer that most of the Lockatong here has not been detached although some Lockatong screens and xenoliths are present. Within the larger xenoliths, it is possible to see the cyclic successions of strata (Van Houten cycles) that are inferred to have been deposited as the ancient lake level fluctuated (Olsen, 1980a).

These sedimentary strata have been contact metamorphosed; the contact with the Palisades intrusive locally is discordant. Present also are folds as well as numerous nondeformed clastic "dikes", which crosscut the primary igneous-sedimentary contact. Contact-zone breccias include those with angular pieces of basalt in a "matrix" of light-colored feldspathic sand.

The columnar-jointed basal part of the Palisades intrusive in New Jersey is interrupted at the level where olivine has been concentrated. The olivine zone lies above a chilled zone of aphanitic- to glassy basalt. (See Figure 59.) The sizes of the crystals in the igneous rock here change profoundly with distance above the contact. At the contact, the texture is aphanitic to glassy. With increasing distance from the contact, the texture becomes gradually coarser. As a result, many gradations and discrete mixtures can be found, from microvesiculated- to hypocrystalline basalt to aphanitic basalt (near the contact), to dolerite (a few meters above the contact), to gabbro (a few tens of meters above the contact). Local microvesicles and a pipe amygdale in the base of the Palisades sheet, together imply that the mafic magma was chilled extremely rapidly.

The contact zone displays excellent products of contact metamorphism and disrupted Lockatong bedding. As noted previously by Van Houten (1969), the layers of original argillite have been converted into a black hornfels consisting of biotite and albite with minor analcime, diopside, and calcite, or to green hornfels consisting of diopside, grossularite, chlorite, and calcite, with subordinate biotite, feldspar, amphibole, and prehnite. Miller and Puffer (1972) and Puffer (1987) have noted pinite after cordierite and tourmaline as porphyroblasts in the hornfels. Our studies indicate that although contact metamorphism has changed them to a lesser degree than the argillites, near the contact, the sandy Lockatong interlayers, are chaotic. As described below, they have been "intruded" upward into the chilled zone where they form irregular "sedimentary apophyses" more than 20 cm long.

Palisades chilled-margin facies; aphanitic basaltic sills and -dikes. Two kinds of products that formed by rapid chilling in the contact zone are present; (1) the chilled border of the main sheet, and (2) aphanitic basalt as small dikes and sills that cut various units in the contact zone.

As mentioned, close above the basal chilled-margin contact of the Palisades intrusive in Fort Lee, olivine has been concentrated. The basal igneous rocks display gradations and mixtures among micro-vesiculated to hypocrystalline basalt to aphanitic basalt (near the contact) to dolerite (a few meters above the contact). The microvesicles and a 15-cm-long pipe amygdale extending upward from the Lockatong into glassy basalt imply that the mafic magma was chilled extremely rapidly and that Newarkian pore water, formerly present in the sediment, was transformed into a vapor phase, thus enabling the sediments to become fluidized.

Locally, the main sheet has been invaded from below by clastic dikes (discussed in a following section). In some places, clastic dikes have intruded across a minor offset (~1 cm) of a basalt-Lockatong contact but in this instance, the basalt is a 0.5-m sill found intruding the Lockatong. Although a rare feature, commingled within the zone of clastic dikes, a 40-cm-thick basaltic offshoot has been found to intrude a xenolith of partly fused Lockatong. We are not sure whether this offshoot, which can be traced back into the chilled zone, is a primary Palisades chilled-margin phase or the result of a younger Palisades intrusive phase. Thus, in the contact zone, late-stage basaltic dikes have crosscut some clastic dikes; therefore some igneous activity postdates the clastic dikes which themselves were mobilized by magmatic heat.

Discordant contacts and deformation. When one focuses on the contact patterns of the igneous- and sedimentary rocks (Figure 62), one cannot help being struck by the discordance exhibited by the top-to-the-north ramp-like contact. In almost every case [including exposures near Bergen [Central Park quadrangle; UTM Coordinates: 584.78E - 4516.75N] and at King's Bluff [Weehauken quadrangle; UTM Coordinates: 582.65E - 4513.00N], the basal contact of the Palisades ramps upsection toward the NE. (See Figure 34.) The Palisades contact typically migrates gently upsection toward the N; it truncates the bedding in the bounding sedimentary rocks at low angles for distances of a few meters to tens of meters. At the northern end of a ramp, the igneous contact drops abruptly. It truncates the bedding at a high angle, thus creating a broad, saw-tooth contact pattern. Locally, at the leading edges of the Palisades northward-directed ramps, the Lockatong shows broad E-W-trending folds (Merguerian and Sanders, 1995a).

Figure 62. Outcrop view of the megascopic saw-tooth pattern produced by north-directed low-angle ramping of the basal contact of the Palisades intrusive sheet along its contact with sedimentary rocks of the Lockatong Formation in Fort Lee, New Jersey. Hammer handle is 40 cm in length and rests immediately below chilled Palisades basalt. (CM photograph).

The megascopic discordance of the ramp-like contact is obvious, as are localized folds in the bounding sedimentary strata. In one case, about 200 m north of the GWB, a chevron fold with a wavelength of 30 cm, lies immediately below a northward-ramped contact between the base of the Palisades and the Lockatong. The chevron fold plunges ~10° into N75°W with an axial surface oriented N75°W, 90°. After the regional-dip component of the Newark Supergroup has been removed, this structure reorients into a subhorizontally plunging fold. Argillites below the intrusive contact exhibit asymmetric intrafolial Z-folds plunging gently toward the west and with axial surfaces parallel to the intrusive contact, thus indicating top-to-the-right, NE-vergent shear. Elsewhere, folded NE-vergent xenoliths exhibit subhorizontal plunges and steep SW-dipping axial surfaces. The pronounced northward-ramping effect of the basal Palisades contact and the structural evidence together suggest that within the contact zone, top-to-the-northeast shearing prevailed. We can best explain the orientations- and vergences of folds and the discordant northward ramping of the basal Palisades contact by a ductile boundary response to subhorizontal intrusion of a cooling, perhaps gelatinous, high-density mafic magma whose paleoflow pattern was from the SW toward the NE.

Paleoflow direction of the Palisades magma. For the Newark Basin segment, many investigators have suggested that the Palisades magma flowed outward from buried fractures paralleling the NE-SW-trending Ramapo fault zone. To reach Fort Lee, New Jersey and vicinity, magma from such fractures would have to have flowed from NW to SE. In Fort Lee, beneath the George Washington Bridge, xenoliths, screens, and in-situ laminated lacustrine Lockatong sedimentary strata (black argillite and interlayered buff-colored feldspathic sandstone) have been contact metamorphosed and deformed. Here, the basal contact of the Palisades sheet cuts across the bedding in a ramp-like fashion toward the north. Similar contact relationships for the Palisades are exposed near Bergen and at King's Bluff, both farther south in New Jersey. (See Figure 34.) Folded xenoliths and folds of Lockatong sedimentary strata at the igneous contacts are products of subhorizontal shear. Their steep- to overturned axial surfaces trend E-W and are vertical or dip southward. Together, these marginal relationships suggest the general paleoflow of the magma was from SW to NE.

A possible feeder area, Graniteville Quarry, Staten Island, New York. Examination of the orientations- and marginal relationships of xenoliths in the Palisades of New York and New Jersey has helped us identify a possible feeder area for the intrusive sheet. At Graniteville, Staten Island [Elizabeth quadrangle boundary; UTM coordinates: 571.60E / 4497.72N], a curved, partially fused, Lockatong xenolith is vertical and largely surrounded by concentrically oriented annular joints. Studies here by Benimoff and Sclar (1984, 1988), offer proof that a xenolith of the Lockatong Formation (formerly considered to be a small dike intruding the dolerite) was not only internally altered by the heat from the surrounding mafic magma, but that some of the Lockatong actually melted in situ to produce a trondhjemitic magma. We have suggested (Merguerian and Sanders, 1992, 1994b, 1995a, 1995b) that such intense melting may have been caused by a continuous heat source, perhaps emanating from an area of active magmatic flow. Furthermore, we have suggested that the annular joint pattern surrounding the xenolith may mimic paleoisothermal cooling surfaces.

By contrast, most xenoliths reported from the New York City area dip gently and are oriented parallel to the contacts of the Palisades intrusive sheet. At Graniteville, a fused vertical xenolith and the annular cooling(?) joints imply that the magma here flowed upward and thus is close to a steeply inclined feeder channel. Geological relationships described above from Fort Lee, Bergen, and King's Bluff, New Jersey suggest that internal flow of the magma in those areas (See Figure 34.) was directed northeastward, perhaps away from Graniteville. If this is correct, then from Staten Island to Fort Lee, the lateral paleoflow pattern would have been from SW to NE. In support of this model we note that the Palisades intrusive is thickest and at its lowest stratigraphic position in the vicinity of New York City and that the body progressively thins as it migrates up section to the northeast (toward Haverstraw) and to the southwest (into the Delaware subbasin). (See Figure 60.) Thus, our proposal for magmatic paleoflow toward the NE is consistent with evidence from the quarry at Graniteville, Staten Island.

"Sedimentary apophyses" and syn-intrusive clastic dikes. In Fort Lee, the Lockatong contains many sandy interbeds of light-colored feldspathic sandstones of typical "Stockton"-type lithology. Although the sandy layers have been less obviously affected by contact metamorphism than have the argillites, near the contact the sands are chaotic. They contain small, angular xenoliths of thermally altered argillite and have been locally "intruded" upward to crosscut baked Lockatong as wispy irregular "sedimentary apophyses" up to 20 cm long. Elsewhere, an irregular "stock-like" mass of feldspathic sediment more than 0.5 m thick, which encloses angular-, brecciated chunks of chilled basalt, exhibits several elongated drusy cavities that resemble miarolitic cavities of igneous rocks.

More commonly, thin light-colored clastic dikes with sharp contacts project upward from a sandy source bed into the Palisades chilled zone. We have found more than a dozen examples of the thin, continuous light-colored "dikes" of clastic sandy sedimentary material crosscutting the chilled contact rocks. In marked contrast to their parent sedimentary sources, they are totally nondeformed. Their thicknesses vary from 0.5 cm to a few cms, and their lengths, vary from a few cm to more than a meter. Bifurcating dikes have been observed. These field relationships suggest that the clastic dikes, consisting of formerly fluidized bodies of sand, were intruded upward after the marginal magma had experienced an initial phase of chilling during diminished magmatic flow. The drusy cavities, together with the basalt microvesicles and pipe amygdales noted earlier, support the view that the clastic-dike materials included a vapor phase. We surmise that the bounding sediments still contained pore water before the cooling Palisades magma heated them. Thus, we envision that the sandy injections and dikes represent tongues of hot, fluidized cohesionless sand that were driven by pore waters in the Lockatong and its sandy interlayers that had been vaporized by magmatic heat. In the following, we outline the field- and petrographic data on which our inference that the Palisades sheet was intruded at a shallow depth of burial is based.

Petrography of the clastic dikes. Microscopic study of thin sections of representative samples indicates that the light-colored dikes are composed of thermally altered detrital sediments consisting predominantly of subangular feldspathic sand-size particles. Use of the microscope discloses [Sample PAL-5] altered, contact-metamorphosed remnant clastic textures within the "clastic dikes" with subrounded K-feldspar, plagioclase, and quartz exhibiting pronounced monomineralic overgrowths. The feldspars are clouded and show dominantly granoblastic boundaries, which together with the overall felsic mineral components, may have convinced Walker (1969) to suggest that the light-colored dikes ["rheomorphic veins" of his usage] were of igneous origin. Microscopically, the feldspar particles are clastic; some contain subrounded cores and others preserve rounded boundary edges. As such, we suggest that the granoblastic textures are the result of contact-metamorphic- induced recrystallization. Additional detrital components in the clastic dikes include basalt fragments and other lithic fragments including argillite and chert(?).

Another thin section of a clastic dike [Sample PAL-2] shows that near the contact with basalt, sizes of detrital particles increase and also that elongate quartz, K-feldspar, plagioclase, and lithic fragments have been aligned parallel to the margin. In the interior of the dike, many well-rounded quartz- and relatively fresh feldpar particles are present. We interpret that the aligned fabric of elongate particles parallel to the dike margins resulted from a dynamic flow orientation similar to that found in clastic dikes in the sedimentary realm. At the dike contact, the basalt displays a bleached zone. We interpret the coarser texture at the dike contact with basalt as being the result of localized recrystallization and metasomatism; the chilled basalt margin may have still been hot.

Lithification state of the bounding sediments at time of intrusion. Our efforts, which have focused on the basal contact relationships of the Palisades intrusive, place constraints not only on the paleoflow direction of the magma but also upon the state of lithification of the bounding sediments when the magma appeard. Using evidence about the latter, we have made a new estimate (discussion below) on the depth of intrusion of the Palisades magma(s). In the following we focus on the field evidence that at the time of intrusion, the Newarkian sediments had not yet become lithified. We describe late syn-tectonic clastic dikes, and suggest an approximate depth of intrusion.

Cooling-depth model. The presence of clastic dikes and vesiculated features in the base of the Palisades suggests that, in the vicinity of New York City, Palisades magma was intruded into Lockatong sediments that had not been buried deep enough so that they had become totally dewatering and lithified. Rather, we suspect that upon being heated by the magma in the chilled margin of the Palisades sheet, the water-bearing sediments became vapor-charged-, fluidized bodies of cohesionless sand. The fact that columnar joints penetrate the Palisades intrusive, the clastic dikes, and Lockatong xenoliths, indicates that the clastic dikes were injected quite early in the solidification history of the Palisades igneous rock.

Walton and O'Sullivan (1950) describe a comparable example of Newark sedimentary materials invading mafic igneous rock from a quarry in the West Rock sill in New Haven, CT, in the Hartford Basin. There, a layer of conglomeratic arkose produced a branching, irregular clastic dike exhibiting sharp contacts which was injected upward more than 10 m into the dolerite sill. The clastic dike consists of detrital material derived from the underlying conglomerate including several large pebbles, one of which was transported 0.6 m above the base of the sill. According to Walton and O'Sullivan, the clastic dikes were intruded at a temperature of roughly 400°C and a pressure of 0.4 Kb. We suggest similar conditions for our observed features and would argue, based on a simple stratigraphic calculation (below), that the depth of intrusion for the Palisades was in the range of 3 to 4 km.

The olivine-rich zone. About 15 m above the base of the Palisades sheet is a zone containing abundant olivine crystals. (See Figure 59.) Because the olivine-rich rock crumbles much more readily than the rock above- and below it, this rock coincides with a recessed area in the cliff face. The name "rotten rock" or "rotten zone" has been applied to the olivine-rich layer. As all former CCNY- and Barnard College undergraduate students who took introductory geology courses prior to 1975 know, an excellent exposure of the olivine zone is present at Edgewater, New Jersey, in the cut for the old trolley that took the customers (those wanting to be amused) from the former 125th Street-Edgewater ferry terminal up the cliff to the former Palisades Amusement Park.

For many years, as a result of petrologic research by investigators named Walker (Frederick Walker, 1940; K. R. Walker, 1969), the olivine zone has been interpreted as being a product of crystal settling from the mafic magma that solidified to form the Palisades, but before this magma had cooled. According to this version of the crystal-settling concept, the olivine crystals grew in the mafic magma and, being denser than the magma, sank downward in the Palisades magma chamber as far as they could go. Ultimately, they reached a level about 15 m above the basal contact where they could sink no lower because the chilled marginal parts of the igneous body had solidified to the point where the dense olivine crystals could not penetrate.

Recently, Husch (1990) has challenged this version of the crystal-settling concept. Husch's proposed alternative explanation is based on chemical considerations and comparisons with the cooling behavior of other mafic sheet-like plutons that were emplaced into the Triassic-Jurassic basin-filling strata of the Newark basins in eastern North America. Chemically, the bulk of these mafic rocks falls within the category known as high-titanium (high-Ti) rocks. In plutons composed of high-Ti magmas, the typical pattern during cooling is that the first mineral to crystallize is pyroxene (not olivine) and thus pyroxene crystals tend to be concentrated in the basal parts (as the olivine in the Walker interpretation). According to Husch (1990, p. 702):

> "The olivine zone may represent the late intrusion of an olivine-normative eastern North America (sic) magma that underwent olivine accumulation prior to its emplacement within the Palisades."

Husch evidently does not reject the concept that the olivine crystals settled out of some magma or other; he just thinks that the settling of the olivine crystals took place someplace else and that they reached their present positions not by settling vertically from above but rather via a later injection of material whose composition differed from the magma from which most of the Palisades crystallized.

We think that Husch has raised an interesting point that bears further investigation. His paper scarcely qualifies as being the last word on this subject; it is full of mays's, appears's, possibly's, might be's, it seems more likely's, and similar "weasel words."

Glacial geology of the Palisades Ridge. As mentioned, we have challenged the prevailing one-glacier-did-it-all view of our local Pleistocene record. One of the fundamental bases for our challenge consists of results from studying features that enable ice-flow direction(s) to be inferred. We can illustrate the contrasting interpretations by summarizing why R. D.

Salisbury and his associates made such elaborate studies of the glacial striae on the Palisades Ridge and how they tried to fit this into the Hudson Valley "flow-lobe" concept proposed earlier by T. C. Chamberlin.

A favorite pastime among these early specialists in glacial geology was inferring the flow lines within the glacier. Figure 63 shows what was essentially T. C. Chamberlin's version of the flow lines in what he thought was the "last" (and only) continental glacier to invade eastern North America. Two points about this map merit discussion: (1) the linear zones of presumed divergent flow (as in the Hudson Valley) and (2) its regional extent southward to Long Island's two famous "twin" terminal moraines. We consider only the first point here.

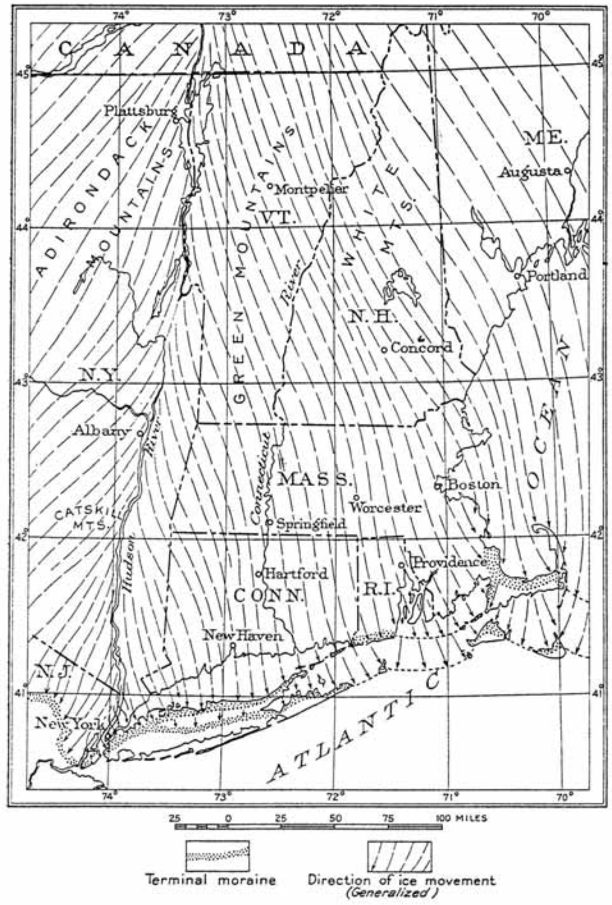


Figure 63. Map representing what was thought to have been the "last" Pleistocene continental glacier in New England showing inferred flow lines according to T. C. Chamberlin's version of accelerated flow down the Hudson Valley with corresponding flow divergence away from this valley on both sides (but incorporating Salisbury's modification of the shift of the locus of accelerated flow into the Hackensack Valley to account for the data on striae orientation on top of the Palisades Ridge) and also Chamberlin's concept that this last glacier deposited both of Long Island's terminal moraines. According to Sanders and Merguerian, this map combines the effects of at least three different glacial advances, the two older than the "last" glacier being responsible for depositing Long Island's terminal moraines. (Compiled by W. C. Alden; Laurence LaForge, 1931, fig. 4, p. 53.)

If the Hudson-Valley flow divergence advocated by Chamberlin extended all the way to the mouth of the Hudson in New York Harbor, then flow lines would have diverged to both sides of the Hudson: to the SW on the NNW side and to the SE on the SSE side. Accordingly, the orientation of striae atop the Palisades Ridge should be NNE-SSW and the erratics should be derived from localities to the NE. Similarly, striae on Manhattan would be oriented NNW-SSE (as, indeed, most of them are). Chamberlin's junior colleage at the University of Chicago, Rollin T. Salisbury [1858-1922] spent many summers mapping the glacial deposits in New Jersey and paid particular attention to the Palisades (Salisbury and Peet, 1894; Salisbury and others 1902). They showed that orientations of virtually all the striae on the Palisades Ridge are NW-SE. Thus, they concluded that the axis of fastest flow in the latest glacier, and thus of flow divergence, could not have been in the Hudson Valley, as Chamberlin had postulated, but rather must have been west of the Palisades, in the Hackensack Lowland. Thus was born the oft-repeated flow-lobe map (Figure 64). Without bothering with all our supporting arguments, we think that the Chamblerin-Alden-Salisbury flow-lobe scheme confuses the effects of two different glaciers (Figures 65 and 66).

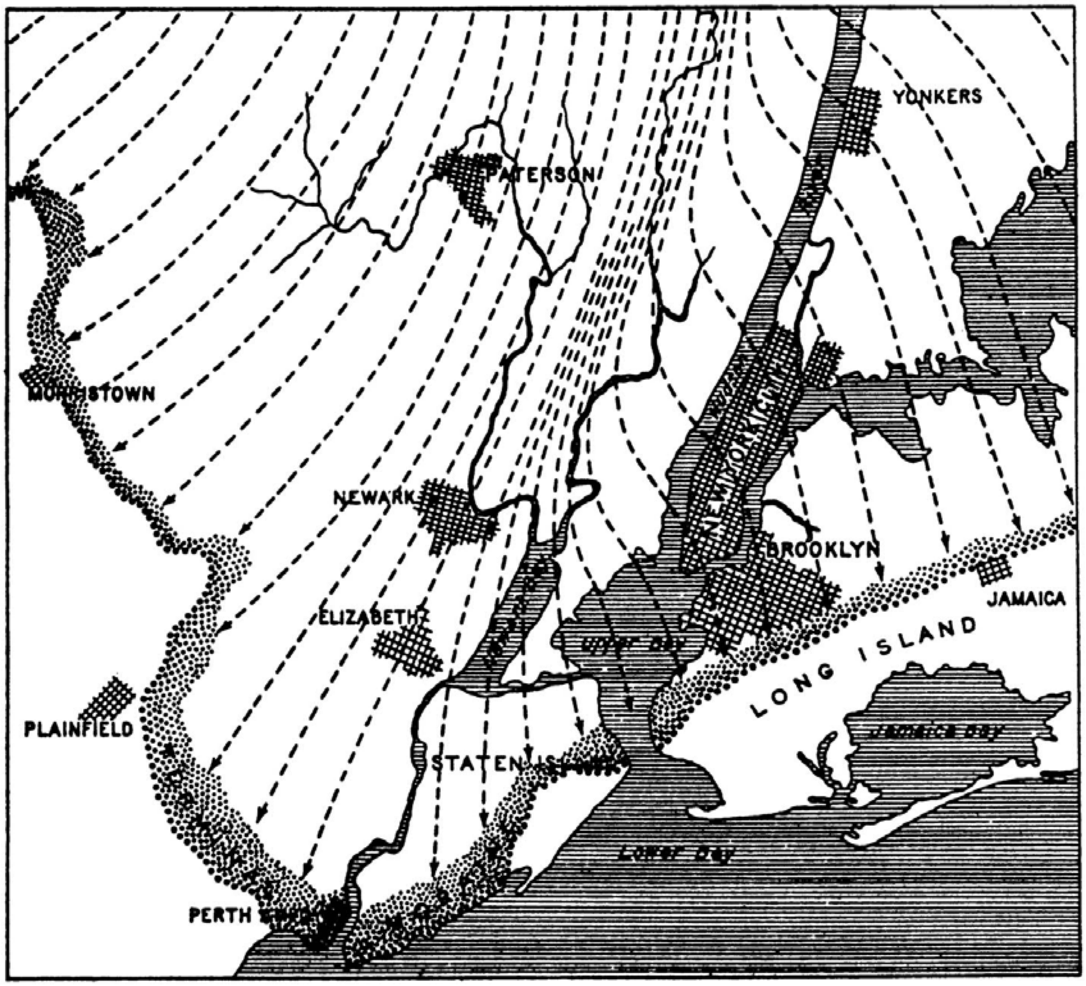


Figure 64. Map of northeastern New Jersey and southeastern New York showing inferred flow lines in the latest Pleistocene glacier. Further explanation in text. (R. D. Salisbury, 1908, fig. 11.)

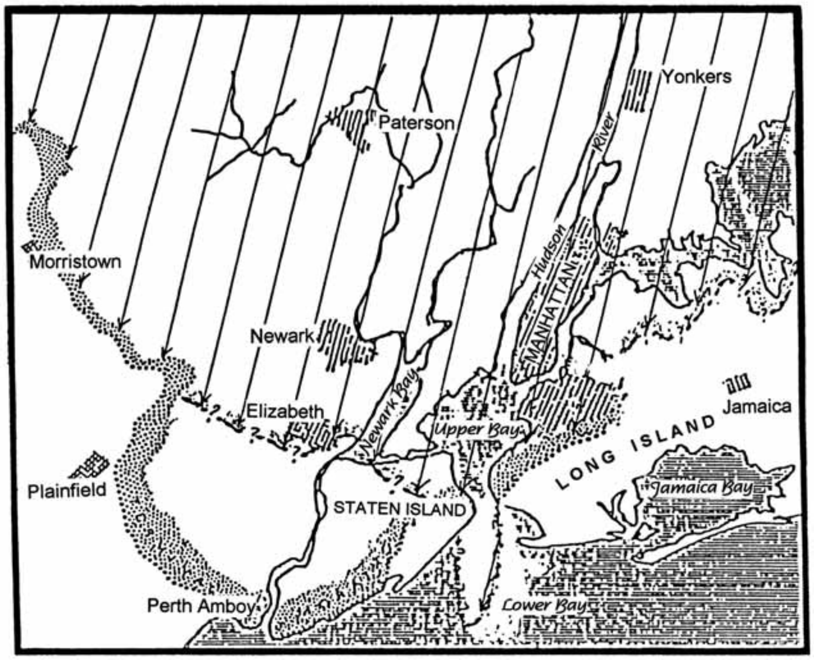


Figure 65. Inferred flow pattern of latest Wisconsinan glacier, down the Hudson and Hackensack lowlands from NNE to SSW. This glacier affected only westernmost parts of Long Island; elsewhere, its terminal moraine was along the south coast of Connecticut. (J. E. Sanders).

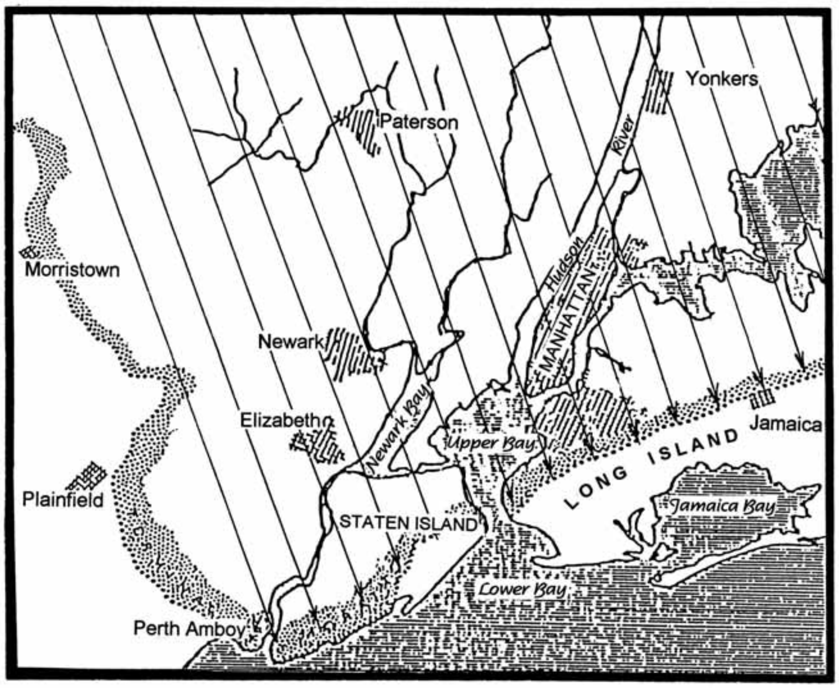


Figure 66. Rectilinear flow from NW to SE of glacier older than the latest Wisconsinan. This glacier flowed across the Hudson Valley and deposited red-brown till and -outwash on the east side of the Hudson River. We infer that the Illinoian-age glaciers flowed as shown here. (J. E. Sanders).

So much for hypothesizing. We can't help but remind the reader of Mark Twain's comment about science, namely that commonly one is able to achieve "a wholesale return in speculation from a trifling investment in fact." Let us now turn our attention to some things we can see at Stop 1.

Features to look for: Exposures along the Palisades Interstate Park access road beneath the George Washington Bridge display the lower contact of the Palisades intrusive sheet above sedimentary rocks of the Lockatong Formation, former lake deposits in the lower part of the Newark Supergroup [Van Houten (1969), Olsen (1980a), and Puffer (1987)].

Just at the park entrance, the road crosses the 150-foot contour line. A little farther along, on the inside of the curve in the road, one can see two special features of the Palisades igneous rock: (1) the zone containing abundant olivine crystals, whose base lies at about 160 feet; and (2) the patterned columnar joints.

The olivine zone wastes away by granular disintegration. As a result, a recessed zone forms in the cliff face and overlying columns are undermined and thus collapse in response to gravity. Remember ---> "It's the law ... and it's a good one!"

One of the characteristics of columnar joints is that they are oriented perpendicular to the surface against which the igneous rock cooled. From features in the sedimentary strata, we are confident that the strata started out horizontal and were afterward tilted to the NW at their present angle of about 12°. As far as the columnar joints go, their existing attitudes could have resulted from cooling against a horizontal surface and later tilting or from intrusion after the strata had acquired their existing dip.

The cooling joints do not continue through the olivine zone. One possible explanation for this relationship is based on the fact that the accumulated solid olivine crystals would not lose any significant volume. By contrast, the continued cooling of the magma would involve loss of volume by thermal contraction and this loss promotes the formation of the columnar joints.

The fact that the olivine zone, which lies about 15 m above the basal contact of the sheet, is visible above the roadbed makes us suspect that the base of the Palisades is exposed at the level of the access road and that the most of the exposed Lockatong is essentially in place, although a few xenoliths and screens are present locally. The Lockatong strata have been contact metamorphosed and although the basal contact of the intrusive sheet is generally concordant, this contact locally is discordant. The strata also display evidence that they have been ductilely folded, the probable result of mechanical contrasts between the higher-density magmatic fluid and the contact-heated sediments.

In order to appreciate the fine points of what is upcoming, it is necessary for everyone to be able to distinguish the igneous rock of the intrusive sheet from the sedimentary rocks of the large xenoliths, which the magma broke off from the Lockatong Formation. Where both are dark-colored rocks having aphanitic texture (crystals so small that individuals cannot be seen without a microscope), special care is required. Fresh igneous rock lacks any bedding and typically displays a bluish-gray color; joint faces tend to weather yellowish brown. [JES ascribes this to the oxidation of a paper-thin film of pyrite and not to weathering of the silicate minerals forming the igneous rock. The basis for this conclusion is that in cores of fresh rock drilled in quarries, a typical feature of the joint faces is a paper-thin layer of pyrite rosettes.] By contrast, the aphanitic sedimentary rock is black and displays bedding ranging from thin laminae to interbeds composed of light gray particles in the size range of silt or very fine sand.

Although many small xenoliths can be found along the contact area of the Palisades intrusive sheet in Fort Lee, the bulk of the sedimentary rock here is in situ (in place) and probably not part of a large xenolith that has been detached from its pre-intrusion position. Within the in-situ strata and the larger xenoliths, it is possible to see the cyclic successions (named Van Houten cycles) that are inferred to have been deposited as the ancient lake level fluctuated from no water to deep water and back again to no water (Olsen, 1980b, p. 352):

"...each can be split into three lithologically identified divisions (from the bottom up): 1, a thin (ca 0.5 m) platy to massive gray siltstone representing a fluvial (sic) and mudflat (sic) to lacustrine (transgressive) facies; 2, a microlaminated (sic) to coarsely laminated black to green-gray fine, often calcareous siltstone (0.1 - 1.0 m) formed during maximum lake transgression; and 3, a generally thickly bedded or massive gray (sic) or gray-red siltstone or sandstone (sic) (0.5 - 4.0 m) usually showing a disrupted fabric and current bedding and sometimes bearing reptile footprints and root horizons (regressive facies)...The mean thickness of these detrital cycles varies from 5.2 m in exposures in the Delaware River valley, central New Jersey, to 1.5 m near Fort Lee." (Figure 67).

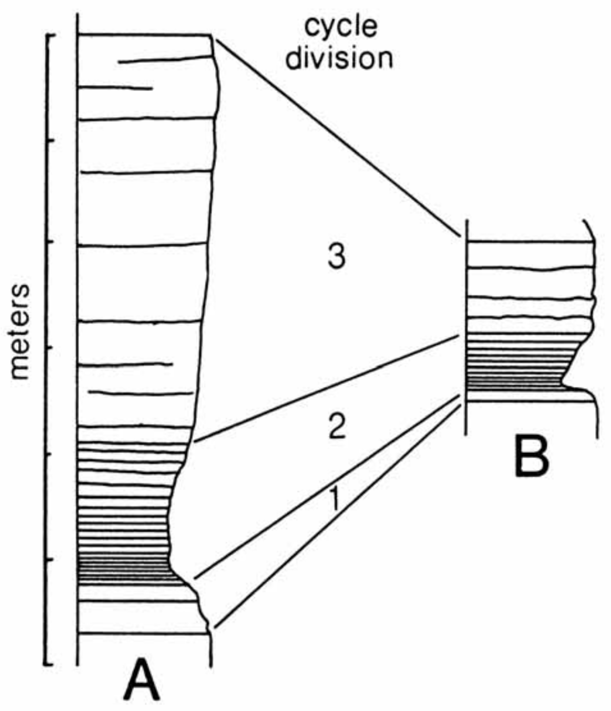


Figure 67. Diagram of generalized Lockatong detrital cycles: A, cycle from center of Newark Basin; B, cycle from northeastern Newark Basin. Cycle division numbers explained in text. (P. E. Olsen 1980c, fig. 1, p. 353.)

"The microlaminated sediments of division 2 are made up of couplets of laminae, one of which is more calcareous than the other (in their unmetamorphosed state) (Fig. 3). Similar sediments are produced in a variety of modern lakes; in most of the studied cases the couplets are the result of seasonal variation in sedimentation and are thus varves."

By counting these as varves, Olsen arrived at figures of 20,000 yr per cycle in central New Jersey in contrast with shorter durations (5,000 to 10,000 yr) for the cycles at Weehawken.

Olsen supports the interpretation that these cycles were the depositional response to large-scale changes in lake level that were caused by big swings in the Earth's climate. The quantity of water is inferred to have fluctuated between two extremes: (1) plentiful water, resulting in large- and deep lakes, and (2) scanty water, yielding small lakes, possibly even no lakes. Large lakes clearly mean a climate in which rainfall was abundant; small lakes or no lakes imply just the opposite. In terms of the getting-to-be-fashionable language for describing cyclic sediments (proposed by Beerbower, 1964), such changes of level in a lake are assigned to the category of allocyclic (a result of major changes in environment) as contrasted with cyclic deposits that are products of a shifting shoreline or a shifting stream channel and that do not involve major change(s) in the environment (which are named autocyclic).

Immediately north of the George Washington Bridge is a spectacular exposure of the Palisade basal contact. As originally diagrammed by Olson (1980c), and reexamined by your heroes, JES and CM, the Palisades is in discordant contact relationship with a deformed slab of the Lockatong Formation (Figure 68). Above the Lockatong, at the south end of the xenolith, note the chilled aphanitic (very fine) texture in the Palisades at the contact with the metamorphosed sedimentary rock. Microscopic vesicles occur in the chilled-contact basalt suggesting the presence of pore water in the sediments prior to intrusion. What is more, the sandy sediments are chaotic near the contact and have "intruded" upward into the Palisades as "sedimentary apopyses" and clastic dikes.

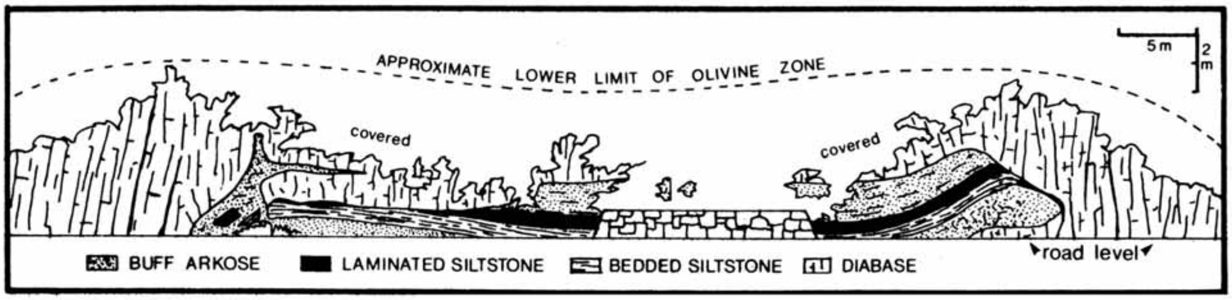


Figure 68. Sketch of exposures on River Road, Palisades Interstate Park south of the traffic circle. Basal contact of the intrusive sheet here is discordant and a large slab of the Lockatong Formation has been bent upward by the force of the Palisades magma. (P. E. Olsen, 1980c, fig. 39, p. 387.)

In the same area, a basaltic offshoot, 40 cm thick, intrudes the Lockatong beneath the primary igneous contact. We have found more than a dozen examples of thin (a few cm thick), continuous "dikes" of light-colored, clastic sandy sedimentary material, exhibiting sharp margins, that crosscut the chilled contact rocks and extend upward for more than a meter. Microscopic study of thin sections indicates that these light-colored dikelets [termed "rheomorphic veins" by Walker (1969) and interpreted by him and others as products of partial melting] are, in fact, composed of thermally altered detrital sediments. The microscope discloses altered, contact-metamorphosed remnant clastic textures within these "clastic dikes". Present are diagnostic subrounded feldspars, quartz particles displaying pronounced overgrowths, and other lithic fragments. In the same area within the igneous contact zone, a basaltic offshoot, 40 cm thick, has been found to intrude a xenolith of partly fused Lockatong; chilled basalt has been fractured and intruded by a "clastic dike" 0.5 m thick composed of feldspathic- and quartzose sand. Such relationships may have been produced during cooling of the chilled margin as hot tongues of vapor-charged fluidized, formerly cohesionless sand in the contact zone were "intruded" across the igneous/sediment interface (Merguerian and Sanders 1992, 1994a, 1995a, b).

In addition to the clastic dikes, vesicles, pipe amygdales, and brecciated chilled-margin facies of the Palisades suggest that the mafic magma was intruded at relatively shallow depths (we suspect ~3 to 4 km) where the overburden to which the Lockatong sediments were being subjected had not yet become great enough to cause them to be dewatered and totally lithified. As such, we envision that during intrusion of the mafic magma, at the base of the Palisades intrusive sheet, "wet- and wild" conditions prevailed.

As discussed in detail in a previous paragraph, in the Fort Lee area, we have noticed that the intrusive cuts across the bedding at a high angle in a sawtooth-like pattern. (See Figure 63.) In addition to the ramp-like configuration toward the north of the basal contact, immediately beneath the basal contact of the intrusive sheet, the sedimentary strata are broadly arched; disposed in tight, chevron folds with vertical, east-west-trending axial surfaces; and we have noted asymmetric intrafolial z-folds in the bounding argillites. We have argued that the folds could have only formed by differential flow in a SW-NE direction and that, given the discordant ramp-like relationships noted earlier, that here the paleoflow dirction of the Palisades magma must have been from SW to NE. Remembering that a xenolith at the Graniteville quarry of Staten Island was oriented vertically, we wonder whether the feeder for the Palisades intrusive sheet is not centered near Staten Island and that from there, the magma flowed northeastward to Fort Lee. Other investigators have postulated that the magma flowed outward from fractures that trended NE-SW, parallel to the Ramapo fault. If so, in order to reach Fort Lee, the paleoflow direction of the magma would have been from NW to SE. Perhaps the clue to unravelling this issue will be found in the part of the Palisades intrusive sheet southwest of Staten Island, where, if we are correct, paleo-flow indicators should indicate the magma moved from NE to SW.

STOP 2 - Pillowed basalt of Orange Mountain Formation ("First Watchung Basalt"). E side of McBride Avenue 0.7 mi NE of intersection of Glover Avenue and McBride Avenue. [UTM Coordinates: 568.1E / 4528.9N, Paterson quadrangle].

Pillows are ellipsoidal bodies of extrusive igneous rock that cooled rapidly under water. The chilled margins of most pillows are glassy; the texture of the igneous rock within the pillow becomes progressively coarser with distance inward from the margins. In addition to their indications of extrusion under water, pillows can usually be used to determine original top direction with considerable confidence. This results from the fact that where several layers of pillows have accumulated, the bottoms of the upper pillows accommodate themselves to the shapes of the tops of pillows next below. If a single pillow happens to cool more or less in the middle of the gap between two pillows below, then the bottom of the upper pillow will form a kind of protruding part that points downward (Figure 69).

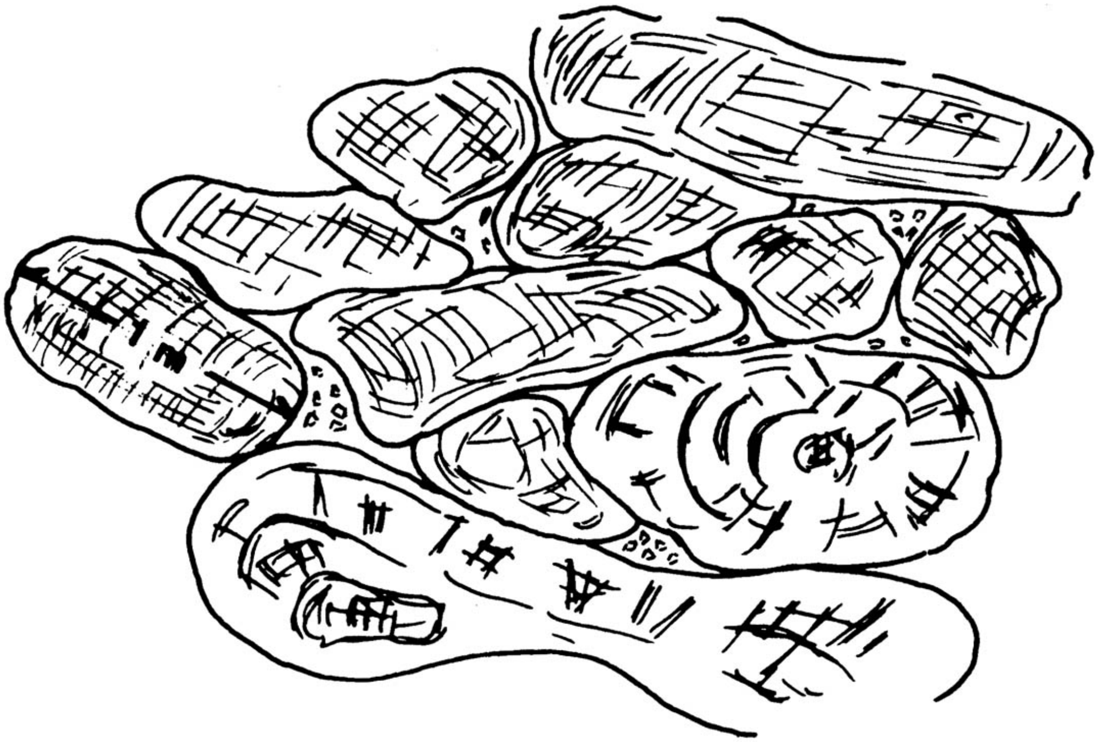


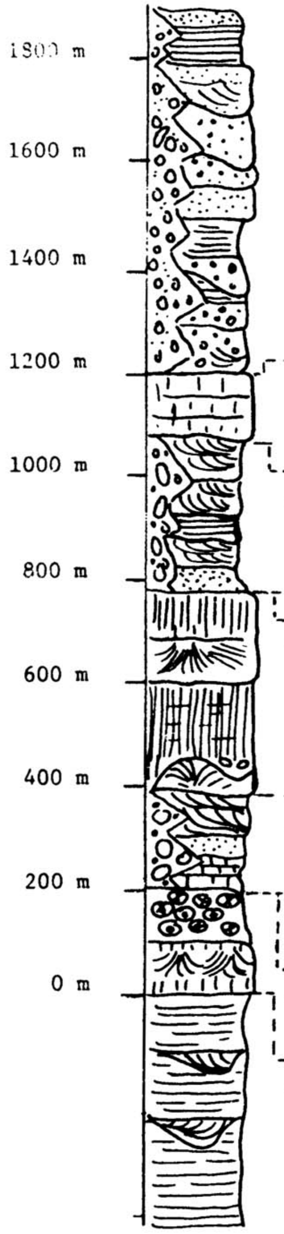
Figure 69. Pillows from Orange Mountain Formation upper New Street Quarry, Paterson, NJ. (Warren Manspeizer, 1980, fig. 14, p. 323).

Geologists exploring the sea floor in research submarines been photographed modern pillows forming where lava oozing out of a fissure reacts with the water in such a way that individual pillows are squeezed out, expand, and then separate. The pillowed part of the Orange Mountain Formation is inferred to have resulted from the extrusion of lava on the bottom of a large lake.

The McBride Avenue exposures are about in the middle of the outcrop belt of the Orange Mountain Formation here. Farther south, however, the pillows are reported from exposures that look to be near the base of the formation (J. V. Lewis, 1908a, 1915b). JES is not familiar with the local stratigraphic details within the Orange Mountian Formation here in Paterson, but sees indications that the Orange Mountain Formation of New Jersey closely resembles the expanded Talcott Formation that JES mapped in southern Connecticut (Sanders, 1962b, 1970; Sanders, Guidotti, and Wilde, 1963). If the Orange Mountain and Talcott are indeed closely similar, then the possibility exists that the Orange Mountain Formation is thicker than many believe and that its pillowed part will be about in the middle.

STOP 3 - Lower contact of the Orange Mountain Formation ("First Watchung Basalt") and underlying sedimentary strata of the Passaic Formation. [UTM Coordinates: 569.0E / 4529.45N, Paterson quadrangle].

We will eat lunch at the Great Falls Hydroelectric Plant. After lunch, we shall walk to the Municipal Parking Lot to study the low cuts along the W side of the lot. Consult Figure 70 for a general columnar section of the strata of the Newark Supergroup from the top of the Passaic Formation to the Boonton Formation. Figure 71 is a sketch of the exposure in the Municipal Parking Lot.



BOONTON FORMATION: alternating sequences of red-brown conglomerate with cyclical sheets of fining-upward structures and poorly sorted graded beds, and black-to-gray thnly-laminated dolomitic siltstones with fish fossils.

HOOK MOUNTAIN BASALT: fine-to-moderately coarse-grained, abundantly vesicular and amygdaloidal basalt in 3 distinct flow units with poorly developed columnar structures.

TOWACO FORMATION: interbeds of laterally persistent finely-laminated gray calcareous siltstone and black-to-olive green shale, and cross-bedded gray sandstone and conglomerate in fining-upward sequences.

PREAKNESS BASALT: moderately coarse-grained with little glass; closely spaced, non-curvi-columnar joints of the entablature; and tumuli, pillow lava, palagonite forset bedding; 3 clearly-defined flow units.

FELTVILLE FORMATION: buff-to-gray feldspathic sandstone with thin stringers of coal; underlain by gray-to-black limestone (biopelsparite and intrasparite) with plant fragments and fish fossils; interfingers westward with massively-bedded dark-gray border conglomerate.

ORANGE MOUNTAIN BASALT: fine-grained with typical Tomkeieff structures; pillow lava, flow lobes and fissure eruptions.

PASSAIC FORMATION: red-brown sandstones in fining-upward sequences with cut-and-fill channels, calcrete, worm burrows, and dinosaur footprints; sequence becomes coarser-grained to the northeast.

Figure 70. Columnar section of Newark Supergroup from upper part of Passaic Formation to Boonton Formation. (Warren Manspeizer, 1980, fig. 5, p. 319.)

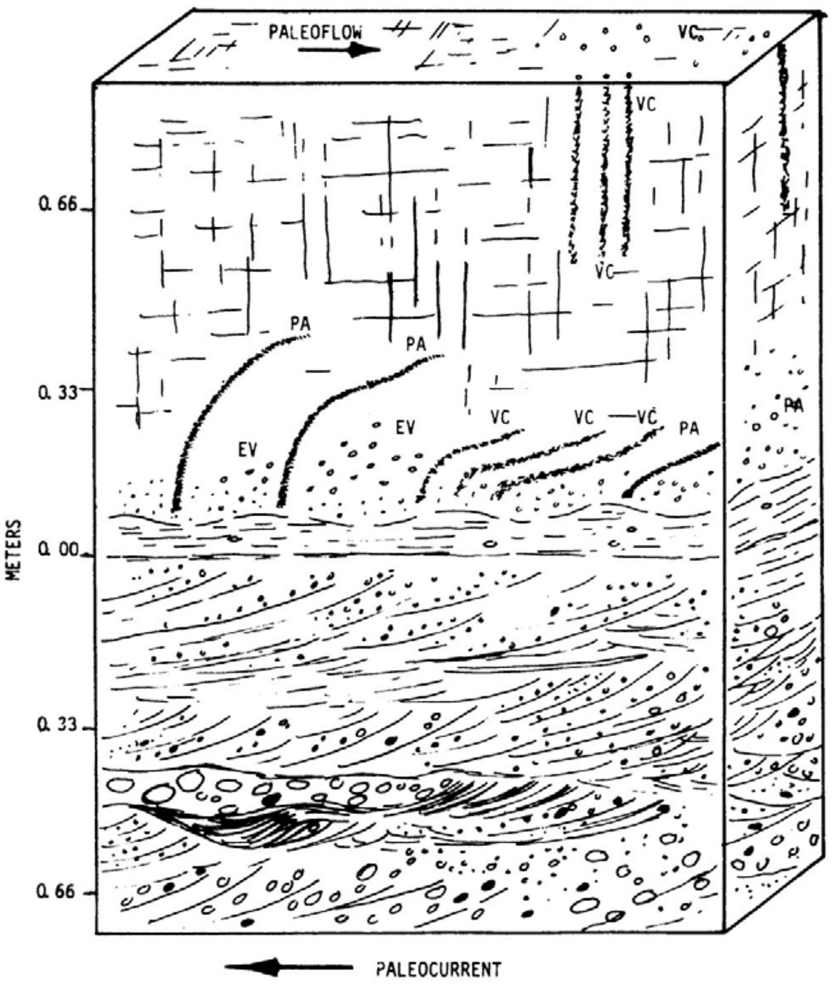


Figure 71. Block diagram of contact between extrusive igneous rock and sandstone, Municipal Parking Lot, Paterson, New Jersey, Stop 3. (Warren Manspeizer, 1980, fig. 6, p. 319.)

In the low cuts one can see the contact between an overlying mafic extrusive igneous rock (Orange Mountain Formation) and a sedimentary rock (top of Passaic Formation). The contact is not a plane surface but displays considerable irregularity. Two possibilities could explain this arrangement: (1) The contact was originally a plane surface (i. e., a bedding-surface) and it was afterward displaced by faults; or (2) shallow stream channels could have been eroded into the top of the Passaic Formation and these channels subsequently filled with lava that solidified to form the Orange Mountain Basalt.

To go about trying to demonstrate which of these possibilities is the correct explanation, one would first try to show the lateral relationships along the contact. If the contact is a faulted bedding surface, then the relationships would be as sketched in Figure 72-A. Evidence of faulting (slickensides, gouge) might be present along the steeply dipping segments of the basalt/sandstone contact. Proof of faulting would consist of finding that these steeply dipping surfaces continue downward as fractures and along them the sedimentary layers below have been displaced.

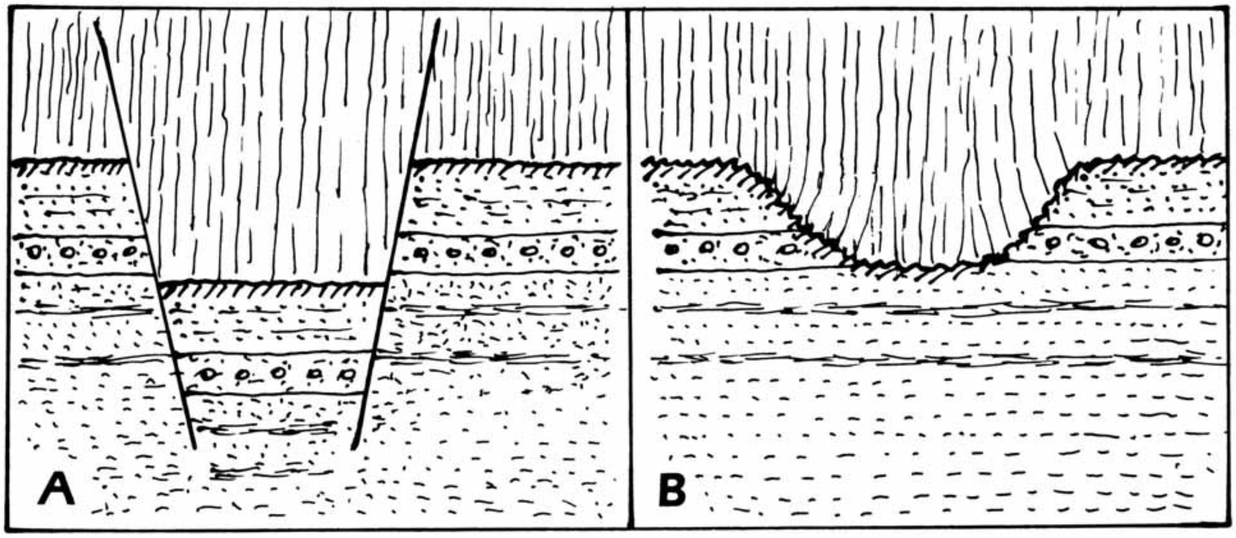


Figure 72. Sketch of irregular contact at base of a lava flow (vertical lines) overlying sandstone (stippled); zone of contact metamorphism at base of lava flow indicated by short closely spaced slanted lines. (JES diagram.)

A - strata offset by fault.
B - lava fills shallow stream valley; strata not offset.

By contrast, if the irregular contact has resulted from lava flowing over the dissected top of the Passaic Formation, then the steep segments of the basalt/sandstone contact would display no evidence of faulting and they would not continue as fractures downward into the sedimentary strata; thus, sedimentary layers below would not be offset (Figure 72-B). A bit of digging and blasting might be required to determine which of these two possibilities is correct.

The direction of in which a sheet of ancient lava flowed can be determined from cylindrical (="pipe") vesicles and -amygdales. Typically these are bent over in the direction toward which the lave flowed. According to Manspeizer (1980, fig. 6, p. 319), pipe amgydales here are bent over toward the NE. (See Figure 67.) This is the opposite to the direction inferred for the paleoslope of the land surface (based on directions of flow of streams that deposited the cross strata). As a result, the lava onlaps the regional paleoslope.

Passaic Formation. Start by examining the particles and then expand the scale to study the kinds of layers and their relationships (if any) to the particle sizes. The first thing that strikes one is the red color, a function of finely divided hematite that serves as a pigment and, in part, as a cement. The sandstone is coarse and pebbly. Notice the angularity and composition in of the clasts: limestone + quartzite + reworked shale pebbles and cobbles. Weathering out of limestone clasts has left a kind of pitted surface, a kind of "holy stone" (not to be confused with Blarney Stone!), and the 30-cm clast of sandstone within the pebbly sandstone.

From the regional geologic relationships it is known that the Newark basin was filled by nonmarine strata. Accordingly, a strong probability exists that coarse layers would have been deposited by streams. To carry that line of thought one step further, let us compare and contrast the conditions in various kinds of streams. According to Manspeizer (1980, p. 343; description of Stop 2, and A), the regional paleoslope was toward the SW.

Geologic structure. In terms of the three-dimensional arrangements here, see where you would project the contact in a westward direction. Does its projection intersect the river? As you can see by looking across toward the falls, igneous rock of the Orange Mountain Formation forms the narrow gorge and extends all the way to the water level.

STOP 4 - The Great Falls of Paterson; Orange Mountain and Passaic formations. (On the Paterson quadrangle, the falls are labeled as the Passaic Falls.) [UTM Coordinates: 568.9E / 4529.5N, hillside exposures E and N of stadium: 569.05E / 4529.75N for contact and 569.15E / 4529.85N for cliff face near dog pound, glacial erratic at 568.95E / 4529.65N.]

The waterfall here drops about 75 feet (from the 120-ft contour at the lip to about 45 ft below). The Passaic River, flowing northeastward (more or less parallel to the strike of the tilted strata), pours into a fracture that trends N-S. The water tumbles over the lip on the rock forming the W side of the fracture, and then flows southward along the fracture, then makes a U-turn and continues flowing NE. No gorge has formed downstream, as has been eroded, for example, by the upstream retreat of the lip of Niagara Falls. In its flow along a fracture and absence of a gorge, Great Falls are a miniature version of the mighty Victoria Falls on the Zambesi River in southeastern Africa (Zambia/Zimbabwe). (See Figure 2.)

The quantity of water flowing over Great Falls has been lower than normal lately because of the withdrawals allowed to various upriver communities. They drink this stuff--after treatment, of course.

The view downstream from the footbridge shows that igneous rock extends all the way to the water's edge on the lower level (altitude about 45 ft). Exposed on the wall of the steep gorge is nearly the full thickness of the lower of the two flow units of the Orange Mountain Basalt shown in Figure 73. Keep this fact in mind as we move northward past the stadium.

Walk back toward the parking lot and proceed down the path toward the river. Stop at the first exposure (on S side of a small knoll beneath the d of the label Stadium; enclosed by the 170-ft contour line). Find the contact at the base of the Orange Mountain Formation (or of one of the extrusive sheets within this formation if not the base) and the underlying pebbly sandstone (top of Passaic Formation or a sedimentary member within the Orange Mountain Formation).

Notice the relationship between the landscape and the contact: a small bench at the top of the sandstone; trees growing where they can send roots into the cliff. The altitude of the contact here is about 100 feet, which is about 50 feet higher than the base of the basalt downstream from the falls. [About 15 years ago, during a class field trip, JES noticed this relationship, but he has not seen it mentioned in other guidebooks and has not examined the geologic map in the US Geological Survey Passaic Folio, No. 157 (Darton, Bayley, Salisbury, and Kummel, 1908). We interpret this offset as being the effect of a fault, but the details remain to be determined. In any event, displacement of at least 70 feet is suggested.] We think that the northward- and upward shift of the basal contact of the extrusive rock is evidence for two other small faults.

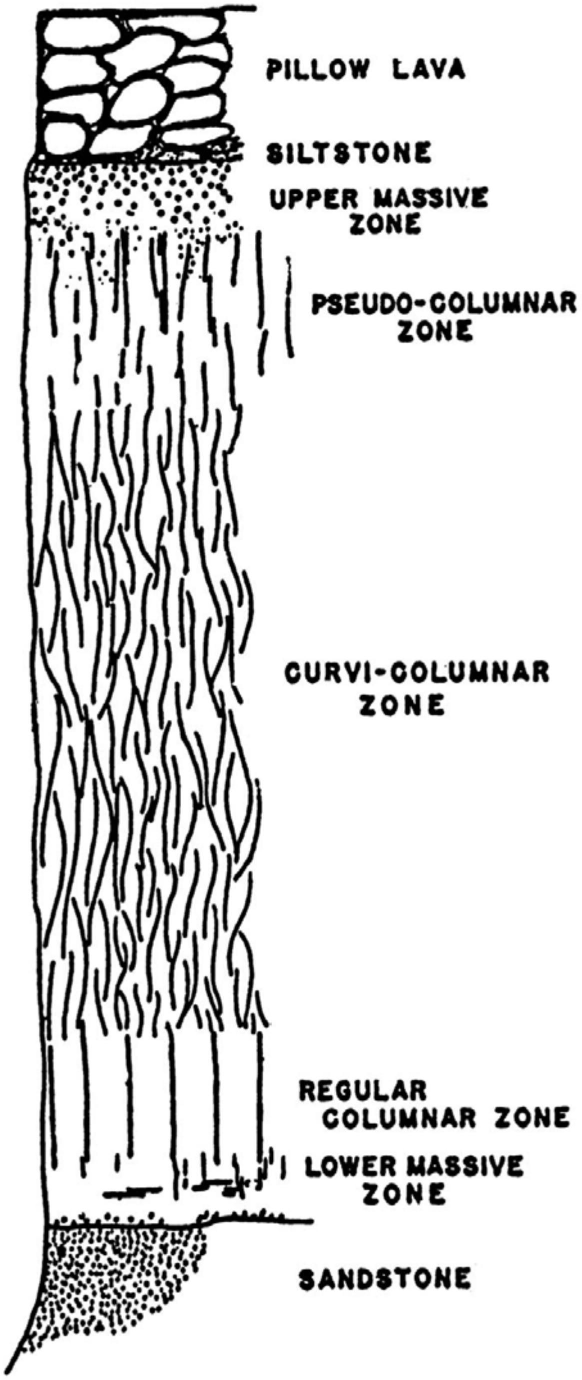


Figure 73. Columnar section of Orange Mountain Basalt near Great Falls, Paterson, New Jersey showing pillows in a discrete flow unit above a non-pillowed sheet. (W. H. Bucher and P. F. Kerr, 1948, fig. 1, p. 112.)

Notice the sequence of columnar joints in the extrusive rock and the chilled margin at the base. Right at the base, the joints parallel the basal contast. These give way upward to a zone about 5 m thick that is characterized by large polygonal columns (Bucher and Kerr's "regular columnar zone" of Figure 73). These two features are not exposed in the gorge downstream of the waterfall. The top of the flow unit is not exposed here, but if it were, what features might be present to enable you to distinguish the sheet as an extrusive as contrasted with an intrusive? (For a review of hints, see Figure 61.)

Note the features of the Passaic Formation (if that is what these strata are, and not sedimentary members of the Orange Mountain Formation). Compare with the features seen at Stop 3. In your comparison, include bedding characteristics, sizes of channels, composition of pebbles, and coarseness of particles. Note that the average trend of the channels is S85°W and that the inferred paleoflow of the water in them is from the east! [This is quite in contrast to the accepted view that the Newark Basin filled in with sediment derived from the uplifted highlands (Ramapo Mountains) to the west.]

Note the numbers marked by various methods on the cliff face near the dog pound, an attempt by an unknown geologist(s) to break out individual units. Three channels are especially obvious. The lowest one occurs below unit 5, a second between units 9 and 10, and the third between units 14 and 15. The channels are indicated by sharp contrasts in particle size and by the presence of pebbles in their basal parts. The pebbles are largely (>50%) carbonate with lesser amounts of quartz and recycled red sandstone.

We suggest that the dominantly structureless-, uniform-, locally laminated sands and interspersed rudites here are the result of flash floods which produced debris flows on the outer fringes of a subaerial fan as contrasted with the upward-fining cross-stratified point-bar successions formed by the migration of meandering streams; in this regard, the absence of shales is especially significant. Thus, we suggest that the sediment blankets are time-stratigraphic deposits similar to their interlayered volcanic conterparts.

On the walk back up the trail, notice the large boulder of Proterozoic gneiss. It is an erratic weathered out of Pleistocene till and must have come from the west, northwest, or north.

STOP 5 - Upper, glaciated contact of the Orange Mountain Formation ("First Watchung basalt") at Garrett Mountain Reservation. [UTM Coordinates of old house: 569.50E / 4577.75 N, Paterson quadrangle, altitude: 500 feet].

From parking lot, follow trail uphill to the building, and then take the trail along the crest of the ridge. Part way up the hill is a large erratic of hornblende-bearing granitic rock from the Proterozoic sequence of the Hudson Highlands. Does the hornblende mean that it came from west of Hudson?

From the crest of the ridge enjoy the splendid view eastward toward Manhattan (atmospheric conditions permitting). Notice the two clusters of skyscrapers: at the Battery and in midtown Manhattan. This is a function of the depth of bedrock. Where the tall buildings have been built, solid bedrock is close to the surface. In between, where no tall buildings have been built, the depth to bedrock becomes several hundred feet.

Along the trail, look for vesicles in the basalt (we are near the top of a flow unit where vesicles are to be expected) and the glacial features. Present here are glacial grooves trending N10°E-S10°W, about parallel to the trend of Garrett Mountain, and a miniature roche-moutonnée structure.

The recent floods have been another catastrophe to those living near the junction of the Pompton and Passaic rivers but probably have strengthened the arguments for the US Army Corps of Engineers and sundry politicians who have been advocating the constuction of the flood-diversion tunnel, the proposed route of which is shown by the dots marking core sites in Figure 74. During 1990-91, other cores have been collected at points selected to extend the stratigraphic coverage from the strata penetrated by the line of cores along the proposed route of the flood-diversion tunnel so as to yield cores through the full thickness of the strata filling the Newark basin. These are housed at Lamont-Doherty Earth Observatory of Columbia University and are being studied by Paul Olsen and associates.

The Garrett Mountain block lies east of a fault that is downthrown on the east. JES suspects that another fault, possibly the one extending northward from the label Orange Mountain Basalt in the lower center of Figure 74, may be upthrown on the east, thus bringing up the Passaic Formation against higher-than-normal parts of the Orange Mountain Formation. JES suspects that this up-on-the east fault extends NE-SW along the eastern side of the First Watchung Mountain. If so, then this fault defines a horst block with the Garret Mountain block. Under this fault hypothesis, the only places where the full thickness of the Orange Mountain Formation would be exposed are located at the northeast- and southwest ends of the Watchung ridges, where the curvature of the strata on the limbs of the transverse Watchung syncline causes the outcrop belts to curve around to the northwest away from this possible fault.

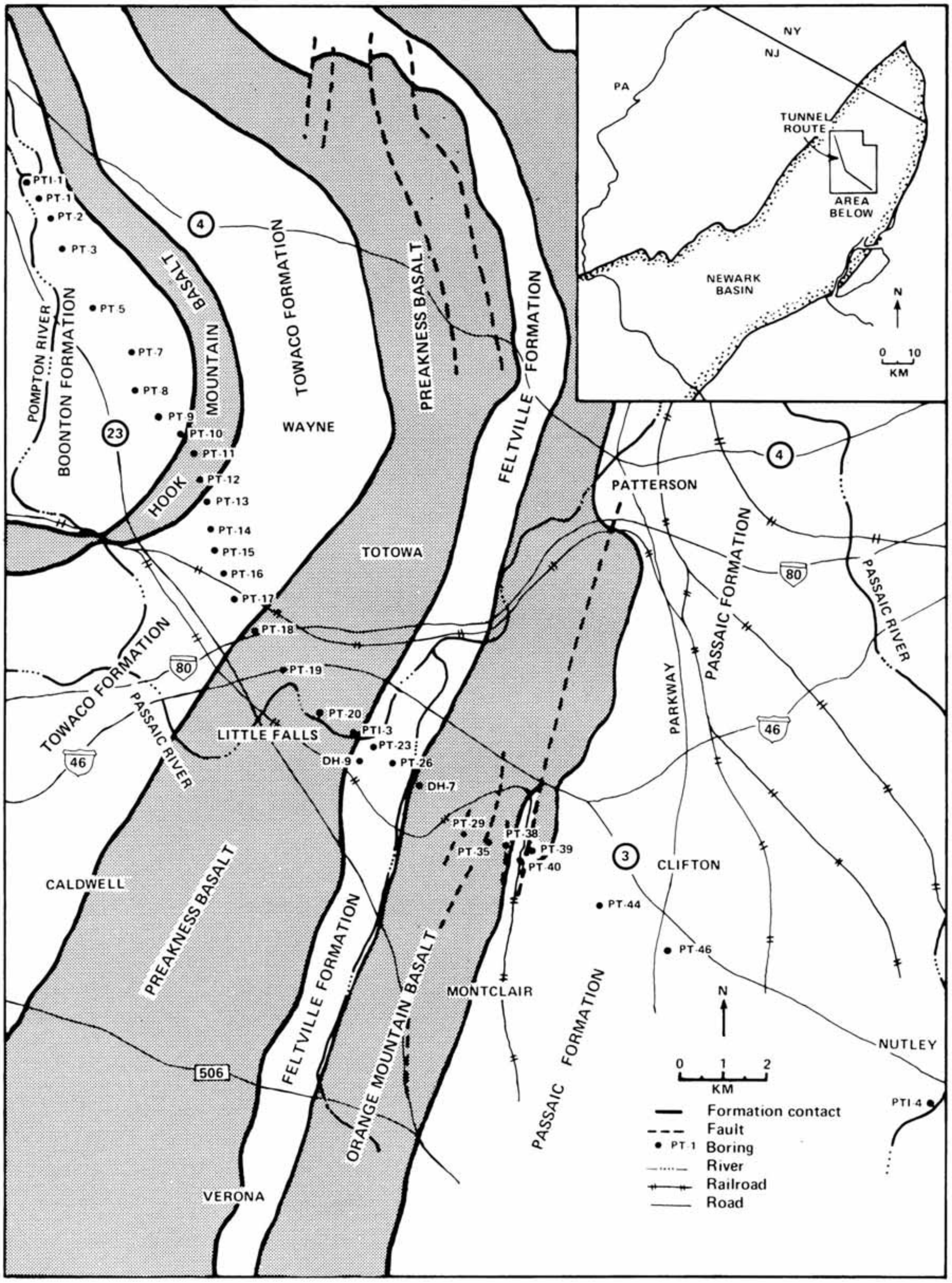


Figure 74. Geologic map in vicinity of proposed flood-diversion tunnel. Dots mark sites of core borings made in 1985 and 1986. (M. S. Fedosh and J. P. Smoot, 1988, fig. 1, p. 20.)

STOP 6 - Upper- and lower contacts of the Hook Mountain Formation ("Third Watchung Basalt"). Near parking lot for shopping center at junction of Paterson-Hamburg Turnpike and Oakland Road, Pompton, in gap cut through Packanack Mountain by Ramapo River where US Route 202 makes a 90-degree corner at the S end of Pompton Lake. [UTM Coordinates: 560.7E / 4537.8N, Pompton Plains quadrangle.]

The strata here strike NW and dip SW (a result of being on the SW limb of a transverse anticline whose axis strikes NW-SE). The highland about one mile due W of us is underlain by Proterozoic rocks of the Ramapo block; the Ramapo fault, the basin-marginal fault at the NW edge of the Newark basin, lies along the foot of the steep slope. The Ramapo River flows southwestward along the trace of the Ramapo fault.

The top of the Hook Mountain Formation is not visible at Stop 6, but on the basis of the amygdaloidal-vesicular structure of the igneous rock exposed at the edge of the parking lot one can infer that the top is not far away. Refer to Tables 3 for the results of chemical analyses of samples of intrusive igneous rock collected from various parts of the Palisades sheet, and to Table 4, chemical analyses from specimens collected from the extrusive sheets (Orange Mountain and Hook Mountain formations.

The waterfall is made by the Ramapo River flowing over the Hook Mountain Basalt, which as mentioned here strikes NW-SE and dips SW, at a right angle to the Ramapo Fault, which trends NE-SW. Because of this structural arrangement, our traverse from Stop 6 to Stop 7, going parallel to the Ramapo Fault, will be downsection.

The contact at the base of the Hook Mountain Formation is exposed in the cuts along the east side of US Route 202 (if we go there, be careful of the traffic). Notice the sequence of the columnar joints in the basalt and the coarse particles in the basin-marginal rudites of the underlying Towaco Formation.

STOP 7 - Basin-marginal rudites of Feltville Formation [sedimentary strata underlying the Preakness Formation ("Second Watchung basalt")]. Behind Oakland Diner. [UTM Coordinates: 562.2E / 4540.5N, Wanaque quadrangle.]

REST/PIT/REFRESHMENT STOP. After you have rested, pitted, and been refreshed, we will assemble outside to look at the cuts at the edge of the parking lot.

This locality is situated close to the Ramapo fault (buried beneath sediments of Ramapo River at foot of escarpment) near the NW end of Preakness Mountain, the type locality of the Preakness Formation ("Second Watchung Basalt"). The strike of the strata is NW-SE and the dip is to the SW. The sedimentary strata are from near the top of the Feltville Formation. JES uses the general term "basin-marginal rudites" to avoid becoming entangled in the debate about whether these coarse materials were deposited on subaerial fans, sublacustrine fans, or even on lacustrine beaches. The critical information for deciding about the environment of deposition is not exposed here. What can be seen here, however, is an abundance of boulders of Cambro-Ordovician carbonates (mostly dolostones, not metamorphosed, and some limestones), vesicular basalt (presumably derived by eroding the Orange Mountain Formation), and Green Pond Conglomerate (basal unit of Layer IIIE of Table 2); and medium-rare boulders of Proterozoic gneiss (hold the steak sauce, please!). The predominance of pieces from the Paleozoic sedimentary formations indicates that the main body of the Proterozoic rocks forming the Ramapo block in today's landscape had not yet been exposed during the early part of the Jurassic Period when the Feltville Formation was being deposited.

At Oakland, we have ended a traverse downsection that began at the top of the Hook Mountain Basalt. We have cut through the entire Towaco Formation and the Preakness Formation and are in the topmost part of the Feltville Formation. Despite this change in stratigraphic position, the kind of rock (rudite) has remained about the same. Put another way this means that in localities within about a mile or so of the Ramapo fault, nearly all sedimentary formations consist of basin-marginal rudites. The total stratigraphic range of such rudites has not been determined, but it might come close to equalling the entire thickness of the Newark basin-filling strata.

Why do you suppose that all the boulders are cut by fractures? (Are they really what they are cracked up to be?)

ACKNOWLEDGEMENTS

We are grateful to the staff of the 92nd Street Y, especially Ms. Batia Plotch, who decided to "take a chance" on conducting this program. We thank Ms. Jennifer March, of the Palisades Park Commission for granting our request to visit the exposures on the access road to Ross' Dock in Palisades Interstate Park at Fort Lee. These trips would not be possible without the support and use of facilities at Hofstra University, Duke Geological Laboratory, and Busy Horse, Inc.

TABLES

Table 01 - GEOLOGIC TIME CHART

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

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

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

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

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

LAYER VII - QUATERNARY SEDIMENTS

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

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IIA[W] - SAUK SEQUENCE

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

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

LAYER IIA[E] - TACONIC SEQUENCE

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

Stockbridge
or Inwood Marbles

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

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

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

LAYER I - PROTEROZOIC BASEMENT ROCKS

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

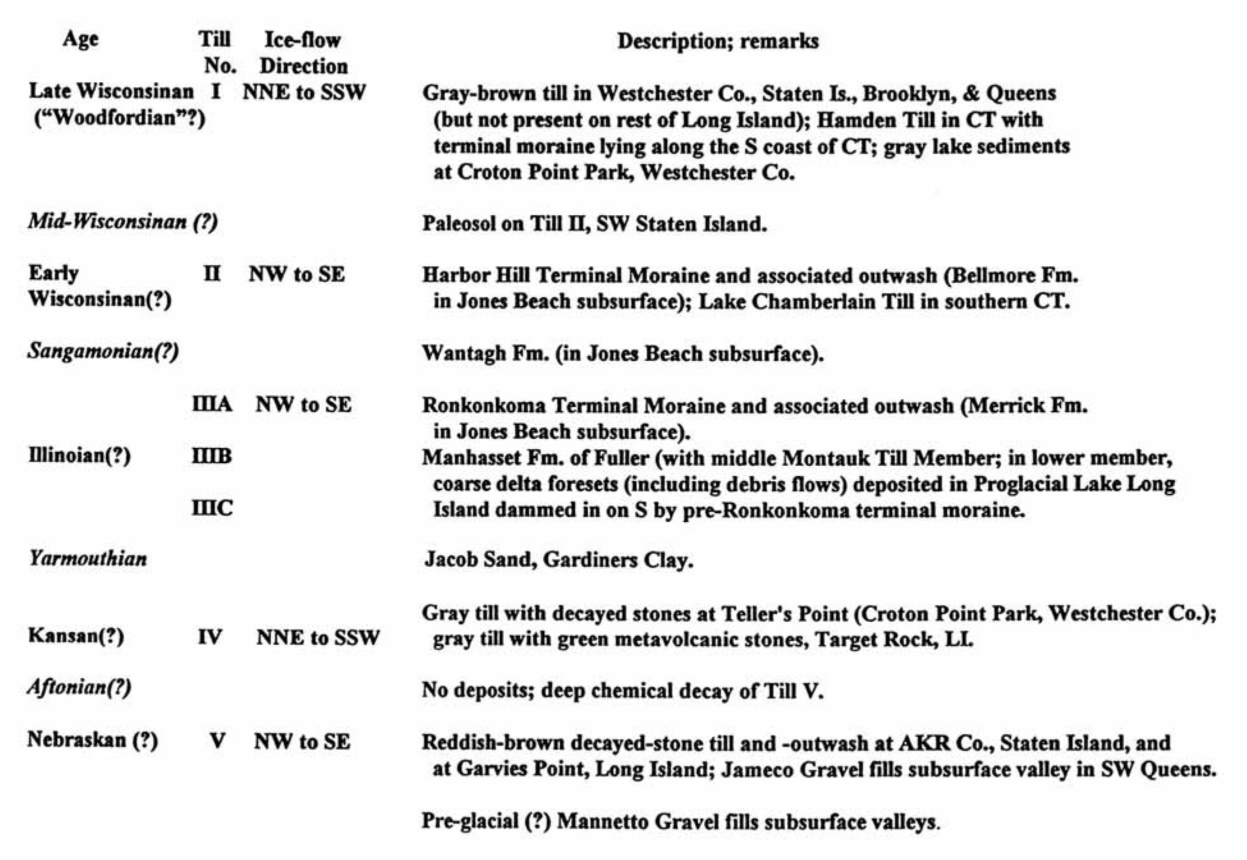
~~~~~~~~~~~~~~~~~~~~**Surface of unconformity**~~~~~~~~~~~~~~~~~~~~

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

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

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

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



Age	Till No.	Ice-flow Direction	Description; remarks
Late Wisconsinan ("Woodfordian"?)	**I**	**NNE to SSW**	**Gray-brown till in Westchester Co., Staten Is., Brooklyn, & Queens (but not present on rest of Long Island); Hamden Till in CT with terminal moraine lying along the S coast of CT; gray lake sediments at Croton Point Park, Westchester Co.**
Mid-Wisconsinan (?)			**Paleosol on Till II, SW Staten Island.**
Early Wisconsinan(?)	**II**	**NW to SE**	**Harbor Hill Terminal Moraine and associated outwash (Bellmore Fm. in Jones Beach subsurface); Lake Chamberlain Till in southern CT.**
Sangamonian(?)			**Wantagh Fm. (in Jones Beach subsurface).**
Illinoian(?)	**IIIA**	**NW to SE**	**Ronkonkoma Terminal Moraine and associated outwash (Merrick Fm. in Jones Beach subsurface).**
	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.

REFERENCES CITED

Averill, S. P., Pardi, R. R., Newman, W. S., and Dineen, R. J., 1980, Late Wisconsin-Holocene history of the lower Hudson region: new evidence from the Hackensack and Hudson River valleys, p. 160-186 in Manspeizer, Warren, ed., Field studies of New Jersey geology and guide to field trips: New York State Geological Association Annual Meeting, 52nd, Newark, New Jersey, 10-12 October 1980: Newark, NJ, Rutgers University Newark College of Arts and Sciences Geology Department, 398 p.

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

Benimoff, A. I., and Sclar, C. B., 1988, The Graniteville quarry, Staten island, NY: An outstanding location for illustrating igneous phenomena: Northeastern Geology, v. 10, p.. 1-10.

Berkey, C. P., 1948, Engineering geology in New York City, Excursion No. 4, p. 51-66 in Creagh, Agnes, ed., Guidebook of Excursions: Geological Society of America Annual Meeting, 61st, New York City, 135 p.

Bird, J. M., and Dewey, J. R., 1970, Lithosphere-continental margin (sic) tectonics and the evolution of the Appalachian orogen: Geological Society of America Bulletin, v. 81, p. 1031-1059.

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

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

Bucher, W. H., and Kerr, P. F., 1948, Excursion to the First Watchung basalt at Paterson, New Jersey, Excursion No. 11, p. 109-116 in Creagh, Agnes, ed., Guidebook of Excursions: Geological Society of America Annual Meeting, 61st, New York City, 135 p.

Burchfiel, B. C., and Stewart, J. H., 1966, "Pull-apart" origin of the central segment of Death Valley, California: Geological Society of America Bulletin, v. 77, p. 439-442.

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

Carlston, C. W., 1946, Appalachian drainage and the highland border sediments of the Newark series: Geological Society of America Bulletin, v. 57, p. 997-1031.

Chamberlin, T. C., 1909,

Cooper, M. A., and Williams, G. D., eds., 1989, Inversion tectonics: Papers presented at a meeting on Inversion Tectonics held 03-04 March 1987 at the Royal Society of London: Geological Society of London Special Publication No. 44, 375 p. Oxford-London-Edinburgh-Boston-Melbourne, Blackwell Scientific Publications for the Geological Society.

Cornet, Bruce, 1977 ms., The palynostratigraphy and age of the Newark Supergroup: University Park, PA, Pennsylvania State University Department of Geology Ph. D. dissertation, 506 p.

Cornet, Bruce; and Traverse, Alfred, 1975, Palynological contributions to the chronology (sic) and stratigraphy of the Hartford Basin in Connecticut and Massachusetts, p. 1-33 in Geoscience and Man: American Association of Stratigraphic Palynologists Annual Meeting, 6th, Proceedings, v. 11,

Cornet, Bruce; Traverse, Alfred; and MacDonald, N. G., 1973, Fossil spores, pollen and fishes from Connecticut indicate early Jurassic age for part of the Newark Group: Science, v. 182, p. 1243-1247.

Cousminer, H. L.; and Manspeizer, Warren, 1976, Triassic pollen date Moroccan High Atlas and the incipient rifting of Pangaea as Middle Carnian: Science, v. 191, p. 943-944.

Coward, M. P.; Dewey, J. F.; and Hancock, P. L., eds., 1987, Continental extensional tectonics: London, UK, Geological Society of London Special Publication No. 28, 637 p.

Crespi, J. M., 1988, Using balanced cross sections to understand Early Mesozoic extensional faulting, p. 220-229 in Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Crowell, J. C., 1974, Origin of the late Cenozoic basins in southern California, p. 190-204 in Dickinson, W. R., ed., Tectonics and sedimentation: Tulsa, OK, Society of Economic Paleontologists and Mineralogists Special Publication No. 22, 204 p.

Dallmeyer, R. D., 1975, The Palisades sill: a Jurassic intrusion (sic)? Evidence from 40Ar/39Ar incremental release (sic) ages: Geology, v. 3, p. 243-245.

Darton, N. H., 1889, On the great lava flows and intrusive trap sheets of the Newark system in New Jersey: American Journal of Science, 3rd series, v. 38, p. 134-139.

Darton, N. H., 1890, The relations (sic) of the traps of the Newark system in the New Jersey region: U. S. Geological Survey Bulletin 67, 82 p.

Darton, N. H., 1902, Juratrias rocks, p. 6-10 in Merrill, F. J. H., and others, Description of the New York City district [N. Y.- N. J]: U. S. Geological Survey Geologic Atlas of the United States, New York City Folio 83, 19 p. (maps).

Darton, N. H., 1909, Newark group, p. 7-8 in Bascom, Florence; and others, 1909, Decription of the Philadelphia district: U. S. Geological Survey Geologic Atlas of the United States, Philadelphia Folio No. 162.

Darton, N. H., Bayley, W. S., Salisbury, R. D., and Kümmel , H. B., 1908, Description of the Passaic quadrangle, New Jersey-New York: United States Geological Survey Geologic Atlas of the United States, Passaic Folio, No. 157, 27 p., 4 maps.

Darton, N. H., and Kümmel , H. B., 1908, Newark system, p. 7-13 in Darton, N. H., Bayley, W. S., Salisbury, R. D., and Kümmel , H. B., 1908, Decription of the Passaic quadrangle: U. S. Geological Survey Geologic Atlas of the United States Passaic Folio No. 157, 27 p., 4 maps.

Davis, W. M., 1882a, Brief notice of observations on the Triassic trap rocks of Massachusetts, Connecticut and New Jersey: American Journal of Science, 3rd series, v. 24, p. 345-349.

Davis, W. M., 1882b, The structural value of the trap ridges of the Connecticut Valley: Boston Society of Natural History Proceedings, v. 22, p. 116-124.

Davis, W. M., 1883, On the relations (sic) of the Triassic traps and sandstones of the eastern United States: Harvard College Museum of Comparative Zoology Bulletin, v. 7 (1880-1884), p. 249-309.

Davis, W. M., 1886, The structure of the Triassic formation of the Connecticut valley: American Journal of Science, 3rd series, v. 32, p. 342-353.

Davis, W. M., 1888a, The structure of the Triassic formation of the Connecticut Valley, p. 455-490 in United States Geological Survey Annual Report, 7th (1885-1886), xxx p.

Davis, W. M., 1888b, Remarks on the mechanical origin of the Triassic monoclinal in the Connecticut valley: Boston Society of Natural History Proceedings, v. 23, p. 339-341.

Davis, W. M., 1889a, The faults in the Triassic formation near Meriden, Conn. A week's work in the Harvard summer school of geology: Cambridge, MA, Harvard College Museum of Comparative Zoology Bulletin, v. 16, p. 61-87.

Davis, W. M., 1896, The quarries in the lava (sic) beds at Meriden, Connecticut: American Journal of Science, 4th series, v. 1, p. 1-13 (map).

Davis, W. M., 1898, The Triassic formation of Connecticut: U. S. Geological Survey Annual Report, 18th, Part 2, p. 1-192. (Agglomerates on p. 62-67).

Davis, W. M., and Whittle, C. L., 1889, The intrusive (sic) and extrusive trap sheets in the Connecticut Valley: Harvard College Museum of Comparative Zoology Bulletin, v. 16, no. 6, p. 99-138 (Geology series, v. 2). (The co-author's name is Whittle, not Whipple, as in Emerson and J. V. Lewis citations.)

deLaguna, Wallace; and Brashears, M. L., Jr., 1948, The configuration of the rock floor in western Long Island, New York: New York State Department of Conservation Water Power and Control Commission Bulletin GW-13, 32 p.

Dennis, J. G., 1987, Structural geology. An introduction: Dubuque, IA, Wm. C. Brown Publishers, 448 p.

Dewey, J. F., and Bird, J. M., 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, no. 14, p. 2625-2647.

Dunning, G. R., and Hodych, J. P., 1990, U/Pb zircon and baddelyite ages for the Palisades and Gettysburg sills of the northeastern United States: implications for the age of the Triassic/Jurassic boundary: Geology, v. 18, p. 795-798.

Du Toit, A. L., 1907, Pipe amygdaloids: Geological Magazine, decade 5, v. 14, p. 13-17.

Faust, G. T., 1975, A review and interpretation of the geologic setting of the Watchung basalt flows, New Jersey: U. S. Geological Survey Professional Paper 864-A, 42 p.

Faust, G. T., 1978, Joint systems in the Watchung basalt flows, New Jersey. Studies on the Watchung basalt flows of New Jersey: U. S. Geological Survey Professional Paper 864-B, 46 p.

Fedosh, M. S., and Smoot, J. P., 1988, A cored stratigraphic section through the northern Newark basin, New Jersey, p. 19-24 in Froelich, A. J.; and Robinson, G. R., Jr., eds., 1988, Studies of the early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Fenner, C. N., 1908, Factors indicative of physiographic conditions prevailing at the time of the trap extrusions in New Jersey: Journal of Geology, v. 16, p. 299-327.

Fenner, C. N., 1910, The Watchung basalt and the paragenesis of its zeolites and other secondary minerals: New York Academy of Sciences Annals, v. 20, p. 93-187.

Flint, R. F., 1935, How many glacial stages are recorded in New England?: Journal of Geology, v. 43, p. 771-777.

Flint, R. F., 1945, Glacial map of North America: Geological Society of America Special Papers No. 60, 37 p.

Flint, R. F., 1947, Glacial geology and the Pleistocene Epoch: New York, John Wiley and Sons, Inc., 589 p.

Flint, R. F., 1951, Highland centers of former glacial outflow in northeastern North America: Geological Society of America Bulletin, v. 62, no. 1, p. 21-37.

Flint, R. F., 1961, Two tills in southern Connecticut: Geological Society of America Bulletin, v. 72, no. 11, p. 1687-1691.

Flint, R. F., 1963a, Status of the Pleistocene Wisconsin stage in central North America: Science, v. 139, p. 402-404.

Flint, R. F., 1963b, Altitude, lithology, and the Fall Zone in Connecticut: Journal of Geology, v. 71, no. 6, p. 683-697.

Flint, R. F., 1965, Introduction; historical perspectives, p. 3-11 in Wright, H. E., and Frey, D. G., eds., The Quaternary of the United States: Princeton, NJ, Princeton University Press, 922 p.

Flint, R. F., 1971, Glacial (sic) and Quaternary geology: New York-London-Sydney-Toronto, John Wiley and Sons, Inc., 892 p.

Flint, R. F., and Gebert, J. A., 1974, End moraines on and off the Connecticut shore (abstract): Geological Society of America Abstracts with Programs, v. 6, no. 7, p. 738-739.

Flint, R. F., and Gebert, J. A., 1976, Latest Laurentide ice sheet: new evidence from southern New England: Geological Society of America Bulletin, v. 87, no. 2, p. 182-188.

Folger, D. W., Dillon, W. P., Grow, J. W., Klitgord, K. D., and Schlee, J. S., 1979, Evolution of the Atlantic continental margin of the United States, p. 87-108 in Talwani, Manik; Hay, W. W.; and Ryan, W. B. F., eds., Deep drilling (sic) results in the Atlantic Ocean; continental margins and paleoenvironment: Maurice Ewing Symposium, 2nd, 19-25 March 1978, Harriman, NY, Proceedings: Washington, D. C., American Geophysical Union Maurice Ewing Series No. 3, 437 p.

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

Froelich, A. J., and Olsen, P. E., 1985, 1. Newark Supergroup, a revision of the Newark Group in eastern North America, p. 1-3 in Robinson, G. R., and Froelich, A. J., eds., U. S. Geological Survey workshop on the Early Mesozoic basins of the eastern United States, Second, Proceedings: U. S. Geological Survey Circular 946, 147 p.

Froelich, A. J.; and Gottfried, David, 1985, Early (sic) Jurassic diabase sheets of the eastern United States--a preliminary overview. Section 15, p. 79-86 in Robinson, G. R., and Froelich, A. J., eds., U. S. Geological Survey workshop on the Early Mesozoic basins of the eastern United States, Second, Proceedings: U. S. Geological Survey Circular 946, 147 p.

Fuller, M. L., 1914, The geology of Long Island, New York: U. S. Geological Survey, Professional Paper 82, 231 p.

Gilbert, G. K., 1906, Crescentic gouges on glaciated surfaces: Geological Society of America Bulletin, v. 17, p. 303-306.

Gordon, R. G., Cox, A., and O' Hare, S., 1984, Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous: Tectonics, v. 3, p. 499-537.

Grabau, A. W., 1936a, Oscillation or pulsation: International Geological Congress, 16th, Washington, D. C., 1933, Reports, v. 1, p. 539-553.

Grabau, A. W., 1936b, Classification of Paleozoics on pulsation theory (sic): Pan-American Geologist, v. 66, no. 1, p. 19-38.

Grabau, A. W., 1940, The rhythm of the ages: Peking, China, Henri Vetch Pub., 561 p.

Grauert, B., and Hall, L. M., 1973, Age (sic) and origin of zircons from metamorphic rocks in the Manhattan Prong, White Plains area, southeastern New York: Washington, D. C., Carnegie Institution of Washington Yearbook, v. 72, p. 293-297.

Groshong, R. H., 1989, Half-graben structures: Balanced models of extensional fault-bend folds: Geological Society of America Bulletin, v. 101, p. 96-105.

Hall, L. M., 1968a, Geology in the Glenville area, southwesternmost Connecticut and southeastern New York, Trip D-C, p. 1-12 in Orville, P. M., ed., Guidebook for field trips in Connecticut: New England Intercollegiate Geological Conference, Annual Meeting, 60th, New Haven, Connecticut.

Hall, L. M., 1968b, Times of origin and deformation of bedrock in the Manhattan Prong, p. 117-127 in Zen, Ean; White, W. S.; Hadley, J. B.; and Thompson, J. B., Jr., eds., Studies of Appalachian geology, northern and maritime: New York, Wiley-Interscience Publishers, 475 p.

Hall, L. M., 1976, Preliminary correlation of rocks in southwestern Connecticut, p. 337-349 in Page, L. R., ed., Contributions to the stratigraphy of New England: Boulder, CO, Geological Society of America Memoir 148, 445 p.

Harris, S. E., 1943, Friction cracks and the direction of glacial movement: Journal of Geology, v. 51, p. 244-258.

Hatcher, R. D., Jr., 1990, Structural geology. Principles, concepts, and problems: Columbus-Toronto-London-Melbourne, Merrill Publishing Co., 531 p.

Hayward, A. B., and Graham, R. H., 1989, Some geometrical characteristics of inversion, p. 17-39 in Cooper, M. A., and Williams, G. D., eds., Inversion tectonics: Papers presented at a meeting on Inversion Tectonics held 03-04 March 1987 at the Royal Society of London: Geological Society of London Special Publication No. 44, 375 p. Oxford-London-Edinburgh-Boston-Melbourne, Blackwell Scientific Publications for the Geological Society.

Hull, J.; Koto, R.; and Bizub, R., 1986, Deformation zones in the Highlands of New Jersey: Geological Association of New Jersey Guidebook 3, p. 19-66.

Husch, J. M., 1988, Significance of major- and trace-element variation trends in Mesozoic diabase, west-central New Jersey and eastern Pennsylvania, p. 141-150 in Froelich, A. J.; and Robinson, G. R., Jr., eds., 1988, Studies of the early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Husch, J. M., 1990, Palisades sill: Origin of the olivine zone by separate magmatic injection rather than gravity settling: Geology, v. 18, p. 699-702.

Husch, J. M., Sturgis, D. S., and Bambrick, T. C., 1984, Mesozoic diabases from west-central New Jersey; major (sic) and trace element (sic) geochemistry of whole rock (sic) samples: Northeastern Geology, v. 6, no. 1, p. 51-63.

Hutchinson, D. R., and Klitgord, K. D., 1988a, Deep structure of rift basins from the continental margin around New England, p. 211-219 in Froelich, A. J.; and Robinson, G. R., Jr., eds., Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey, Bulletin 1776, 423 p.

Hutchinson, D. R., and Klitgord, K. D., 1988b, Evolution of rift basins on the continental margin off southern New England, Chapter 4 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

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

Iddings, J. P., 1886, The columnar structure in the igneous rocks on Orange Mountain New Jersey: American Journal of Science, 3rd series, v. 35, p. 321-330.

Irving, E., and Irving, G. A., 1982, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana: Geophysical Surveys, v. 5, p. 141-188.

Johnson, D. W., 1931, Stream sculpture on the Atlantic slope, a sutdy in the evolution of Appalachian Rivers: New York, NY, Columbia University Press, 142 p.

Justus, P. S., and Weigand, P. W., 1971, Distribution of dolerite magma types and variations of dike-swarm pattern: clues to tectonic history of Appalachians in Early Mesozoic: Pennsylvania Academy of Science Proceedings, v. 45, p. 202-203.

Kaye, C. A., 1964a, Boulder train of silicified Paleozoic wood, southeastern Massachusetts: Geological Society of America Bulletin, v. 75, no. 3, p. 233-236.

Kaye, C. A., 1964b, Outline of Pleistocene geology of Martha's Vineyard, Massachusetts: United States Geological Survey Professional Paper 501-C, p. C134-C139.

Kaye, C. A., 1964c, Illinoisan (sic) and early Wisconsin moraines of Martha's Vineyard, Massachusetts: United States Geological Survey Professional Paper 501-C, p. C140-C143.

Kaye, C. A., 1964d, The Pleistocene geology of Martha's Vineyard, Massachusetts: Itinerary for the Friends of the Pleistocene Annual Reunion, 27th: U. S. Geological Survey Open-File Report.

Kaye, C. A., 1982, Bedrock (sic) and Quaternary geology of the Boston area, Massachusetts, p. 25-40 in Legget, R. F., ed., Geology under cities: Boulder, CO, The Geological Society of America Reviews in Engineering Geology, v. 5, 131 p.

Kinsman, D. J. J., 1975, Rift valley (sic) basins and sedimentary history of trailing continental margins, p. 83-126 in Fischer, A. G.; and Judson, Sheldon, eds., Petroleum and global tectonics: Princeton, NJ, Princeton University Press, 322 p.

Klitgord, K. S., and Behrendt, J. D., 1979, Basin structure of the U. S. continental margin, p. 85-112 in Watkins, J. S.; Montadert, L.; and Dickerson, P. W., eds., Geological (sic) and geophysical investigations of the continental margins: Tulsa, OK, American Association of Petroleum Geologists Memoir 29, 801 p.

Klitgord, K. S., and Hutchinson, D. R., 1985, Distribution and geophysical signatures of early Mesozoic rift basins beneath the U. S. Atlantic continental margin, Chapter 9, p. 45-53 in Robinson, G. R., Jr.; and Froelich, A. J., eds., U. S. Geological Survey workshop on the Early Mesozoic basins of the eastern United States, Second, Proceedings: U. S. Geological Survey Circular 946, 147 p.

Klitgord, K. D.; Hutchinson, D. R.; and Schouten, H., 1988, U. S. Atlantic continental margin; stuructral (sic) and tectonic framework, p. 19-56 in Sheridan, R. E., and Grow, J. A., eds., The Atlantic continental margin, U. S.: Boulder, CO, Geological Society of America, The Geology of North America, V. I-2, 610 p.

Kümmel , H. B., 1897, The Newark System, report of progress: New Jersey Geological Survey State Geologist Annual Report for 1896, p. 25-88.

Kümmel , H. B., 1898, The Newark System, or Red Sandstone belt: New Jersey Geological Survey State Geologist Annual Report for 1897, p. 23-159.

Kümmel , H. B., 1899a, The Newark rocks of New Jersey and New York: Journal of Geology, v. 7, p. 23-52.

Kümmel , H. B., 1899b, The extension of the Newark system of rocks: New Jersey Geological Survey State Geologist Annual Report for 1901, p. 43-57.

Kümmel , H. B., 1914, Triassic rocks, p. 13-16, 20 in Bayley, W. S., Salisbury, R. D., and Kümmel , H. B., Description of the Raritan quadrangle, New Jersey: United States Geological Survey Geologic Atlas of the United States Raritan Folio, No. 191, 32 p. (maps)

Kümmel , H. B., 1933, Glacial history of the Passaic Valley and related glacial features, p. 64-77 in Berkey, C.P., ed., New York City and vicinity: International Geological Congress, 16th, United States, Guidebook 9, New York excursions: Washington, D. C., U. S. Government Printing Office, 151 p.

Kümmel , H. B., 1940, The geology of New Jersey: Trenton, NJ, New Jersey Department of Conservation and Development, Geological Series, Bulletin 50, 203 p.

LaForge, Laurence, 1932, Geology of the Boston area, Massachusetts: U. S. Geological Survey Bulletin 839, 105 p.

Leeder, M. R., and Gawthorpe, R. L., 1987, Sedimentary models for extensional tilt-block/half-graben basins, p. 139-152 in Coward, M. P.; Dewey, J. F.; and Hancock, P. L., eds., Continental extensional tectonics: London, UK, Geological Society of London Special Publication No. 28, 637 p.

Lewis, J. V., 1907a, The double crest of Second Watchung Mountain: Journal of Geology, v. 15, p. 39-45.

Lewis, J. V., 1907b, The origin and relations (sic) of the Newark Rocks, Part III, p. 99-129 in Geological Survey of New Jersey Annual Report of the State Geologist for the year 1906: Trenton, NJ, MacCrellish & Quigley, State Printers, 192 p.

Lewis, J. V., 1907c, Properties of trap rocks for road construction, Part III, p. 165-172 in Geological Survey of New Jersey Annual Report of the State Geologist for the year 1906: Trenton, NJ, MacCrellish & Quigley, State Printers, 192 p.

Lewis, J. V., 1908a, Petrography of the Newark igneous rocks of New Jersey. Part IV, p. 97-167 in Geological Survey of New Jersey Annual Report of the State Geologist for the year 1907: Trenton, NJ, The John L. Murphy Publishing Company, Printers, 192 p.

Lewis, J. V., 1908b, The Palisades diabase of New Jersey: American Journal of Science, v. 176, p. 155-162.

Lewis, J. V., 1914, Origin of pillow lavas (sic): Geological Society of America Bulletin, v. 25, p. 591-654 (Massachusetts and Connecticut, p. 621-622).

Lewis, J. V., 1915a, Origin of the secondary minerals of the Triassic trap rocks: New Jersey Geological Survey Bulletin 16, p. 45-49.

Lewis, J. V., 1915b, The pillow lavas (sic) of the Watchung Mountains: New Jersey Geological Survey Bulletin 16, p. 51-56.

Lindholm, R. C., 1978a, Tectonic control of sedimentation in Triassic-Jurassic Culpeper basin, Virginia (abstract): American Association of Petroleum Geologists Bulletin, v. 62, p. 537 (only).

Lindholm, R. C., 1978b, Triassic-Jurassic faulting in eastern North America--a model based on pre-Triassic structures: Geology, v. 6, no. 6, p. 365-368.

Lobeck, A. K., 1918, The superb position of New York City as a center for physiographic study: New York Academy of Sciences Annals, v. 28, p. 1-50.

Lobeck, A. K.,

Lobeck, A. K., 1952, Panoramic view of the New York region as seen from the Palisades: New York, NY, Columbia University, Scenic Folder No. 1 (folded sheet).

Lobeck, A. K., and Raisz, E. J., 1930, The physiography of the New York region: New York, New York, Columbia University, The Geographical Press, 8 p. (with sketches by R. L. Dickinson).

Longwell, C. R., 1922, Notes on the structure of the Triassic rocks in southern Connecticut: American Journal of Science, 5th series, v. 4, p. 233-236.

Longwell, C. R., 1928, The Triassic of Connecticut: American Journal of Science, 5th series, v. 16, p. 259-263.

Longwell, C. R., 1933, The Triassic belt of Massachusetts and Connecticut, p. 93-118 in Longwell, C. R. ed., Eastern New York and western New England: International Geological Congress, 16th, United States 1933, Guidebook 1, Excursion A-1: Washington, D. C., U. S. Government Printing Office, 118 p.

Longwell, C. R., 1943, Geologic interpretation of gravity anomalies in the southern New England-Hudson Valley region: Geological Society of America Bulletin, v. 54, p. 555-590.

Longwell, C.R., 1937, Sedimentation in relation to faulting: Geological Society of America Bulletin, v. 48, p. 433-442.

Longwell, C. R., Flint, R. F., and Sanders, J. E., 1969, Physical geology: New York, NY, John Wiley and Sons, 685 p.

Lovegreen, J. R., 1974 ms., Paleodrainage history of the Hudson Estuary: New York, NY, Columbia University Department of Geological Sciences Master's Thesis, 151 p., 8 pl.

Lowe, K. E., 1959, Structure of the Palisades intrusion (sic) at Haverstraw and West Nyack, New York, p. 1127-1139 in Lowe, K. E., Chm. and Consulting Ed., Modern aspects of the geology of New York City and environs: New York Academy of Sciences Annals, v. 80, art 4, p. 1047-1170.

Lucas, M., and others, 1988, A foreland-type fold and related structures in the Newark rift basin, Chapter 12 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Luttrell, G. L., 1989, Stratigraphic nomenclature of the Newark Supergroup of eastern North America: U. S. Geological Survey Bulletin 1572, 136 p.

Lyttle, P. T., and Epstein, J. B., 1987, Geologic map of the Newark 1° by 2° quadrangle, New Jersey, Pennsylvania, and New York: United States Geological Survey Miscellaneous Investigations Series Maps, Map I-1715 (2 sheets; scale 1:250,000).

MacClintock, Paul, 1953, Crescentic crack, crescentic gouge, friction crack, and glacier movement: Journal of Geology, v. 61, p. 186.

Mandl, G.; and Crans, W., 1981, Gravitational gliding in deltas, p. 41-54 in McClay, K. R., and Price, N. J., eds., Thrust (sic) and nappe tectonics: Geological Society of London Special Publication No. 9, 539 p. (Published for the Geological Society of London by Blackwell Scientific Publications, Oxford-London-Edinburgh-Boston-Melbourne.)

Mann, P.; Hempton, M. R.; Bradley, D. C.; and Burke, K., 1983, Development of pull-apart basins: Journal of Geology, v. 91, p. 529-554.

Manspeizer, Warren, 1980, Rift tectonics inferred from volcanic (sic) and clastic structures, p. 314-350 in Manspeizer, Warren, ed., Field studies in New Jersey geology and guide to field trips: New York State Geological Association, 52nd, October 1980, Newark, New Jersey, Guidebook: Newark, New Jersey, Rutgers University, Newark College of Arts and Sciences, 398 p.

Manspeizer, Warren, ed., 1988a, Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Manspeizer, Warren, 1988b, Triassic-Jurassic rifting and opening of the Atlantic: an overview, Chapter 3, in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Manspeizer, Warren, 1994, Multiple tectonic inversions of east coast (sic) Mesozoic rift basins: case study from the Durham Basin, N. C. (abstract): Geological Society of America Abstracts with Programs, v. 26, no. 3, p. 58 (only).

Manspeizer, Warren; and Cousminer, H. L., 1976, Crustal thinning: A precursor to the break-up (sic) of Pangaea and the opening of the Atlantic Ocean (abstract): Geological Society of America Abstracts With Programs, v. 8, p. 995-996.

Manspeizer, Warren; Cousminer, H. L.; and Puffer, J. L., 1978, Separation of Morocco and eastern North America: a Triassic-Liassic stratigraphic record: Geological Society of America Bulletin, v. 89, p. 910-920.

Manspeizer, Warren; and Gates, A. E., 1995, Episodic rifting and basin inversion: Permo-Triassic events (abstract): Geological Society of America Abstracts with Programs, v. 27, no. 1, p. 66-67.

Margolis, Jacob; Robinson, G. R., Jr.; and Schafer, C. M., 1986, Annotated bibliography of studies of the geology (sic), geochemistry (sic) mineral resources (sic), and geophysical character (sic) of the Early Mesozoic basins of the eastern United States, 1880-1984: U. S. Geological Survey Bulletin 1688, 492 p.

Mason, B. H., 1960, Trap rock minerals of New Jersey: New Jersey Geological Survey Bulletin 64, 51 p.

May, P. R., 1971, Pattern of Triassic-Jurassic diabase dikes around the North Atlantic in the context of predrift position of the continents: Geological Society of America Bulletin, v. 82, p. 1285-1292.

McHone, J. G., 1996a, Broad-terrane Jurassic flood basalts across northeastern North America (abstract): Geological Society of America Abstracts with Programs, v. 28, no. 3, p. 79 (only)

McHone, J. G., 1996b, Broad-terrane Jurassic flood basalts across northeastern North America: Geology, v. 24, no. 4, p. 319-322.

McHone, J. G., and Philpotts, A. R., 1995, Trip C. The Holyoke basalt in southern Connecticut, p. C-1 to C-7 in McHone, N. W., ed., Guidebook for fieldtrips in eastern Connecticut and the Hartford basin: Geological Society of America Northeast Section, Annual Meeting, 30th, Cromwell, CT, 19-22 March 1995: Connecticut Geological and Natural History Survey Guidebook No. 7, not consecutively paginated.

McClay, K. R., and Buchanan, P. G., 1992, Thrust faults in inverted extensional basins, p. 93-104 in McClay, K. R., ed., Thrust tectonics: Meeting 04-07 April 1990, Engham, UK: London, Chapman & Hall, 447 p.

McLaughlin, D. B., 1959, Ch. 4, Mesozoic rocks, p. 53-114 in Willard, Bradford; Freedman, J.; McLaughlin, D. B.; and others, Geology (sic) and mineral resources of Bucks County, Pennsylvania: Pennsylvania Geological Survey, 4th series, Bulletin C9, 243 p.

Merguerian, Charles, 1983a, Tectonic significance of Cameron's Line in the vicinity of the Hodges Complex--an imbricate thrust (sic) model for western Connecticut: American Journal of Science, v. 283, p. 341-368.

Merguerian, Charles, 1983b, The structural geology of Manhattan Island, New York City (NYC), New York (abstract): Geological Society of America Abstracts With Programs, v. 15, no. 3, p. 169 (only).

Merguerian, Charles, 1985, Geology in the vicinity of the Hodges Complex and the Tyler Lake granite, West Torrington, Connecticut, p. 411-442 in R. J. Tracy, ed., New England Intercollegiate Geological Conference, 77th, New Haven, Connecticut: Connecticut Geological and Natural History Survey Guidebook No. 6, 590 p.

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

Merguerian, Charles; and Baskerville, C. A., 1987, The geology of Manhattan Island and the Bronx, New York City, New York, p. 137-140 in Northeastern Section of the Geological Society of America, Centennial Fieldguide, v. 5, 481 p.

Merguerian, Charles; and Sanders, J. E., 1992a, Xenoliths as indicators of paleoflow and paleoenvironmental conditions in the Palisades sheet, New York and New Jersey (abstract): Geological Society of America, Abstracts with Programs, v. 24, no. 3, p. 62-63.

Merguerian, Charles; and Sanders, J. E., 1994a, Danbury anticline of Sanders (1960) revisited: Postdepositional structural explanation for northeast end of Newark Basin, Rockland County, NY (abstract): Geological Society of America Abstracts with Programs, v. 26, no. 3, p. 62 (only).

Merguerian, Charles; and Sanders, J. E., 1994b, Post-Newark folds and -faults: implications for the geologic history of the Newark Basin (extended abstract), p. 57-64 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994: Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Merguerian, Charles; and Sanders, J. E., 1994c, Trip 33, Staten Island and vicinity, 16 October 1994: New York Academy of Sciences 1994 Trips on the Rocks Guidebook, 151 p.

Merguerian, Charles; and Sanders, J. E., 1995a, NE-, not SE-, (sic) directed paleoflow of the Palisades magma: new evidence from xenoliths and contact relationships (extended abstract): p. 64-77 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 22 April 1995: Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 135 p.

Merguerian, Charles; and Sanders, J. E., 1995b, Late syn-intrusive clastic dikes at the base of the Palisades intrusive sheet, Fort Lee, NJ, imply a shallow (~3 to 4 km) depth of intrusion (extended abstract): p. 54-63 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 22 April 1995: Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 135 p.

Merguerian, Charles; and Sanders, J. E., 1995c, Trip 34: Palisades and the Newark basin, 29 April 1995 (revision of Trip 20, 26 October 1991): New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 120 p.

Miller, B. B. and Puffer, J. H., 1972, The cordierite zone of hornfels near the base of the Palisades Sill at Weehauken, New Jersey (abs.): New Jersey Academy of Sciences Bulletin, v. 17, p. 46.

Mills, H. C., and Wells, P. D., 1974, Ice-shove deformation and glacial stratigraphy of Port Washington, Long Island, New York: Geological Society of America Bulletin, v. 85, no. 3, p. 357-364.

Mose, D. G., 1981, Avalonian igneous rocks with high initial 87Sr/86Sr ratios: Northeastern Geology, v. 3, p. 129-133.

Mose, D. G., 1982, 1,300-million-year-old rocks in the Appalachians: Geological Society of America Bulletin, v. 93, p. 391-399.

Mose, D. G.; and Hayes, John, 1975, Avalonian igneous activity in the Manhattan Prong, southeastern New York: Geological Society of America Bulletin, v. 86, no. 7, p. 929-932.

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

Newman, W. A., Berg, R. C., Rosen, P. S., and Glass, H. D., 1987, Pleistocene stratigraphy of Boston Harbor drumlins: Quarternary Research, v. 34, p. 148-159.

Newman, W. A., and Mickelson, D. M., 1994, Genesis of Boston Harbor drumlins, Massachusetts, p. 333-343 in Dardis, G. F., and McCabe, A. M., eds., Subglacial processes, sediments (sic) and landforms (sic): Symposium, University of Ulster, July 1992: Sedimentary Geology, v. 91, nos. 1-4 (special volume), 382 p.

Oldale, R. N., 1982, Pleistocene stratigraphy of Nantucket, Martha's Vineyard, the Elizabeth Islands, and Cape Cod, Massachusetts, p. 1-34 in Larson, G. L., and Stone, B. D., eds., Late Wisconsinan glaciation of New England. A symposium: Dubuque, IA, Kendall/Hunt Publishing Company, 242 p. (Symposium held at Northeastern section, Geological Society of America, 13 March 1980, Philadelphia, Pennsylvania.)

Oldale, R. N., and Colman, S. M., 1992, On the age of the penultimate full glaciation of New England, p. 163-170 in Clark, P. U., and Lea, P. D., eds., The last Interglacial-Glacial transition in North America: Boulder, CO, Geological Society of America Special Paper 270, 317 p.

Oldale, R. N., and Eskenasy, D. M., 1983, Regional significance of pre-Wisconsin till from Nantucket Island, Massachusetts: Quaternary Research, v. 19, p. 302-311.

Oldale, R. N., Valentine, P. C., Cronin, T. M., Spiker, E. C., Blackwelder, B. W., Belknap, D. F., Wehmiller, J. R., and Szabo, B. J., 1982, Stratigraphy (sic), structure (sic), absolute age (sic), and paleontology of the upper Pleistocene deposits at Sankaty Head, Nantucket Island, Massachusetts: Geology, v. 10, no. 5, p. 246-252.

Oliver, J. E., and Drake, C. L., 1951, Geophysical investigations in the emerged (sic) and submerged Atlantic Coastal Plain. Part VI, the Long Island area: Geological Society of America Bulletin, v. 62, p. 1287-1296.

Olsen, P. E., 1978, On the use of the term Newark for Triassic and Early (sic) Jurassic rocks of eastern North America: Newsletters Stratigraphy, v. 7, no. 2, p. 90-95.

Olsen, P. E., 1980a, The latest (sic) Triassic and Early (sic) Jurassic formations of the Newark basin (eastern North America, Newark Supergroup): Stratigraphy, structure, and correlation: New Jersey Academy of Science Bulletin, v. 25, p. 25-51.

Olsen, P. E., 1980b, Triassic and Jurassic formations of the Newark basin, p. 2-39 in Manspeizer, Warren, ed., Field studies in New Jersey geology and guide to field trips: New York State Geological Association, 52nd, October 1980, Newark, NJ, Guidebook: Newark, New Jersey, Rutgers University, Newark College of Arts and Sciences, 398 p.

Olsen, P. E., 1980c, Fossil great lakes of the Newark Supergroup in New Jersey, p. 352-398 in Manspeizer, Warren, ed., Field studies in New Jersey geology and guide to field trips: New York State Geological Association, 52nd, October 1980, Newark, NJ, Guidebook: Newark, NJ, Rutgers University Newark College of Arts and Sciences, 398 p.

Olsen, P. E., 1984 ms., Size (sic) and shape of the original Newark Basin--historical accident sets the stage for ecosystem development, Chapter 3, p. 184-223 in Comparative paleolimnology of the Newark Supergroup--A study of ecosystem evolution: New Haven, CT, Yale University Department of Biological Sciences, Ph. D. Dissertation, 726 p.

Olsen, P. E., 1984, Periodicity of lake-level cycles in the Late Triassic Lockatong Formation of the Newark basin (Newark Supergroup, New Jersey and Pennsylvania, p. 129-146 in Berger, Andre; Imbrie, John; Hays, J.; Kukla, George; and Salzman, Barry, eds., Milankovitch and climate, NATO Symposium: Dordrecht, Holland, D.Reidel Publishing Company, part 1.

Olsen, P. E., 1986, A 40-million year (sic) lake record of orbital climatic forcing: Science, v. 234, p. 842-847.

Olsen, P. E., 1988a, Continuity of strata in the Newark and Hartford basins, p. 6-18 in Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of the early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Olsen, P. E., 1988b, Paleontology (sic) and paleoecology of the Newark Supergroup (Early Mesozoic, eastern North America), Chapter 8 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Olsen, P. E., and Kent, D. V., 1995, Milankovitch climate forcing in the tropics of Pangea during the Late Triassic: Palaeogeography, Palaeoclimatoloty, and Palaeoecology, in press.*

Olsen, P. E.; Kent, D. V.; Cornet, B.; Witte, W. K.; and Schlische, R. W., 1996, High-resolution stratigraphy of the Newark rift basin (early Mesozoic, eastern North America): Geological Society of America Bulletin, v. 108, no. 1, p. 40-77.*

Olsen, P. E., McCune, A. R., and Thomson, K. S., 1982, Correlation of the Early (sic) Mesozoic Newark Supergroup by vertebrates, principally fishes: American Journal of Science, v. 282, p. 1-44.

Olsson, R. K., 1980, The New Jersey coastal plain and its relationship with the Baltimore Canyon trough, p. 112-129 in Manspeizer, Warren, ed., Field studies in New Jersey geology and guide to field trips: New York State Geological Association, Annual Meeting, 52nd, October 1980, Newark, New Jersey, Guidebook: Newark, NJ, Rutgers University Newark College of Arts and Sciences, Department of Geology, 398 p.

Olsson, R. K., 1988, Foraminiferal modeling of sea-level change in the Late (sic) Cretaceous of New Jersey, p. 289-297 in Wilgus, C. K.; Hastings, B. S.; Kendall, C. G. St. C.; Posamentier, H. W.; Ross, C. A.; and Van Wagoner, J. C., eds., Sea-level changes--an integrated approach: Tusla, OK, Society of Economic Paleontologists and Mineralogists Special Publication No. 42, 407 p.

Opdyke, N. D., 1961, The paleomagnetism of the New Jersey Triassic; a field study of the inclination error in red sediments: Journal of Geophysical Research, v. 66, p. 1941-1949.

Oshchudlak, M. E., and Hubert, J. F., 1988, Petrology of Mesozoic sandstones in the Newark basin, central New Jersey and adjacent New York, Chapter 13 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Parker, R. A., Houghton, H. F., and McDowell, R. C., 1988, Stratigraphic framework and distribution of early (sic) Mesozoic rocks of the northern Newark basin, New Jersey and New York, p. 31-39 in Froelich, A. J.; and Robinson, G. R., Jr., eds., Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Percival, J. G., 1842, Report on the geology of the state of Connecticut: New Haven, CT, Osborn and Baldwin, 495 p.

Pessl, Fred, Jr., 1966, A two-till locality in northeastern Connecticut: U. S. Geological Survey Professional Paper 550-D, P. D89-D93.

Pessl, Fred, Jr., 1971, Till fabrics and till stratigraphy in western Connecticut, p. 92-105 in Goldthwait, R. P., ed., Till. A symposium: Columbus, OH, The Ohio State University Press, xxx p.

Pessl, Fred, Jr.; and Schafer, J. P., 1968, Two-till problem in Naugatuck-Torrington area, western Connecticut, Trip B-1. p. B1-B25 in Orville, P. M., ed., Guidebook for field trips in Connecticut: New England Intercollegiate Geological Conference Annual Meeting, 62nd, New Haven, Connecticut: Hartford, CT, Connecticut Geological and Natural History Survey Guidebook No. 2, not consecutively paginated.

Petersen, T. A.; Brown, L. A.; Cook, F. A.; Kaufman, Sidney; and Oliver, J. A., 1984, Structure of the Riddleville basin from COCORP seismic data and implications for reactivation tectonics: Journal of Geology, v. 92, no. 3, p. 261-271.

Phillips, J. D., 1988, A geophysical study of the northern Hartford basin and vicinity, Massachusetts, p. 235-247 in Froelich, A. J.; and Robinson, G. R., Jr., eds., Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Phillips, J. D., and Forsythe, D. W., 1972, Plate tectonics, paleomagnetism, and the opening of the Atlantic: Geological Society of America Bulletin, v. 83, p. 1579-1600.

Philpotts, A. R., 1985, Recent petrologic studies of Mesozoic igneous rocks in Connecticut, p. 107-110 in Robinson, G. R., Jr.; and Froelich, A. J., eds., U. S. Geological Survey workshop on the Early Mesozoic basins of the eastern United States, Second, Proceedings: U. S. Geological Survey Circular 946, 147 p.

Philpotts, A. R., and Burkett, D. H., 1985, Mesozoic diabases from west-central New Jersey: a discussion: Northeastern Geology, v. 6, p. 47-49.

Philpotts, A. R.; and Reichenbach, Ingrid, 1985, Differentiation of Mesozoic basalts of the Hartford basin, Connecticut: Geological Society of America Bulletin, v. 96, no. 9, p. 1131-1139.

Pirsson, L. V.; and Schuchert, Charles, 1915, A textbook of geology: New York, NY, John Wiley and Sons, 1051 p.

Pitman, W. C., III; and Talwani, Manik, Sea-floor spreading in the North Atlantic: Geological Society of America Bulletin, v. 83, p. 619-646.

Playfair, John, 1802, Illustrations of the Huttonian theory (sic) of the Earth: (1956 reprint edition, Urbana, IL, University of Illinois Press), 528 p.

Pratt, L. M., and Burruss, R. C., 1988, Evidence for petroleum generation (sic) and migration in the Hartford and Newark basins, p. 74-79 in Froelich, A. J.; and Robinson, G. R., Jr., eds., Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Pratt, L. M., Shaw, C. A., and Burruss, R. C., 1988, Thermal histories of the Hartford and Newark basins inferred from maturation indices of organic matter, p. 48-62 in Froelich, A. J.; and Robinson, G. R., Jr., eds, Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Puffer, J. H., 1987, The Palisades Sill and Watchung basalt flows, northern New Jersey, p. 91-96 in Roy, D. C., ed., Northeastern Section of the Geological Society of America, Centennial Fieldguide, Volume 5, 481 p.

Puffer, J. H., 1988, The Watchung Basalts revisited, p. 83-105 in Husch, J. M., and Hozik, M. J., eds., Geology of the central Newark basin, field guide and proceedings: Geological Association of New Jersey, 5th Annual Meeting: Lawrenceville, New Jersey, Rider College, xxx p.

Puffer, J. H., Geiger, F. J., and Camanno, E. J., 1982, Mesozoic igneous rocks of Rockland County, New York: Northeastern Geology, v. 4, no. 3/4, p. 121-130.

Puffer, J. H.; Hurtubise, D. O.; Geiger, F. J.; and Lechler, Paul, 1981a, Chemical composition and stratigraphic correlation of the Mesozoic basalt units of the Newark Basin, New Jersey, and the Hartford Basin, Connecticut: Summary: Geological Society of America Bulletin, v. 92, Part I, no. 4, p. 155-159.

Puffer, J. H.; Hurtubise, D. O.; Geiger, F. J.; and Lechler, Paul, 1981b, Chemical composition and stratigraphic correlation of the Mesozoic basalt units of the Newark Basin, New Jersey, and the Hartford Basin, Connecticut: Geological Society of America Bulletin, v. 92, Part II, no. 4, p. 515-553.

Puffer, J. H., Husch, J. M., and Benimoff, A. I., 1992, The Palisades Sill and Watchung basalt flows, northern New Jersey and southeastern New York: a geological summary and field guide: New Jersey Geological Survey, Open-file Report OFR 92-1, 27 p.

Puffer, J. H., and Lechler, P., 1979, The geochemistry of Cushetunk Mountain, New Jersey: New Jersey Academy of Sciences Bulletin, v. 24, p. 1-5.

Puffer, J. H., and Lechler, P., 1980, Geochemical cross sections through the Watchung Basalt of New Jersey: Geological Society of America Bulletin, Part I, v. 91, p. 7-10; Part II, p. 156-191.

Puffer, J. H., and Philpotts, A. R., 1988, Eastern North American quartz tholeites: geochemistry and petrology, Chapter 24 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Raisz, E. J., 1930, Physiographic diagram of the New York region: Maplewood, NJ, The Geographic Press, Hammond Map Co.

Rankin, D. W., 1976, Appalachian salients and recesses: Late Precambrian continental breakup and the opening of the Iapetus Ocean: Journal of Geophysical Research, v. 81, no. 32, p. 5605-5619.

Ratcliffe, N. M., 1971, The Ramapo fault system in New York and adjacent New Jersey--a case of tectonic heredity: Geological Society of America Bulletin, v. 82, p. 125-141.

Ratcliffe, N. M., 1980, Brittle faults (Ramapo Fault) and phyllonitic ductile shear zones in the basement rocks of the Ramapo seismic zones New York and New Jersey, and their relationship to current seismicity, p. 278-311 in Manspeizer, Warren, ed., Field studies in New Jersey geology and guide to field trips: New York State Geological Association, 52nd, October 1980, Newark, New Jerseu, Guidebook: Newark, NJ, Rutgers University Newark College of Arts and Sciences, 398 p.

Ratcliffe, N. M., 1988, Reinterpretation of the relationship of the western extension of the Palisade sill to the lava flows (sic) at Ladentown, New York, based on new core data, p. 113-135 in Froelich, A. J.; and Robinson, G. R., Jr., eds., 1988, Studies of the early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Ratcliffe, N. M., and Burton, W. C., 1985, Fault reactivation (sic) models for origin of the Newark basin and studies related to eastern U. S. seismicity, p. 36-45 in Robinson, G. R., and Froelich, A. J., eds., United States Geological Survey workshop on the Early Mesozoic basins of the eastern United States, Second Proceedings, United States Geological Survey Circular 946, 147 p.

Ratcliffe, N. M., and Burton, W. C., 1988, Structural analysis of the Furlong fault and the relation (sic) of mineralization (sic) to faulting and diabase intrusion, Newark basin, Pennsylvania, p. 176-193 in Froelich, A.J., and Robinson, G. R., Jr., eds., 1988, Studies of the early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Ratcliffe. N. M., Burton, W. C., D'Angelo, R. M., and Costain, J. K., 1986, Low-angle extensional faulting, reactivated mylonites, and seismic reflection (sic) geometry of the Newark basin margin in eastern Pennsylvania: Geology, v. 14, p. 766-770.

Redfield, W. C., 1843, Notice of newly discovered fish beds and a fossil foot mark in the Red Sandstone formation of New Jersey: American Journal of Science, series, v. 43, p. 134-1326.

Redfield, W. C., 1856, On the relations (sic) of the fossil fishes of the sandstone of Connecticut and other Atlantic states to the Liassic and Oolitic periods: American Journal of Science, 2nd series, v. 22, p. 357-363.

Redfield, W. C., 1857, On the relations (sic) of the fossil fishes of the sandstone of Connecticut and other Atlantic states, to the Liassic and Jurassic periods: American Association for the Advancement of Science Proceedings, v. 10, part. 2, p. 180-188.

Ressetar, R. M., 1976 ms., Major (sic) and minor element (sic) geochemistry of the Holyoke Basalt, Connecticut Triassic Basin: Columbia, SC, University of South Carolina Department of Geology Master's Thesis, 62 p.

Rich, J. L., 1934, Mechanics of low-angle overthrust faulting as illustrated by Cumberland thrust block, Virginia, Kentucky, and Tennessee: American Association of Petroleum Geologists Bulletin, v. 18, no. 12, p. 1584-1596.

Roberts, Alan; and Yielding, Graham, 1994, Continental extensional tectonics, Ch. 11, p. 223-250 in Hancock, P. L., ed., Continental deformation: Oxford-New York-Seoul-Tokyo, Pergamon Press, 421 p.

Rodgers, D. A., 1980, Analysis of pull-apart basin (sic) development produced by en ,chelon (sic) and strike-slip faults, p. 27-41 in Ballance, P. F.; and Reading, H. G., eds., Sedimentation in oblique-slip mobile zones: International Association of Sedimentologists Special Publication No. 4, xxx p.

Rogers, H. D., 1839, Middle Secondary Red Sandstone formation, p. 19-23 in Pennsylvania State Geological Survey Annual Report, 3rd: Harrisburg, 119 p.

Rogers, H. D., 1840, Description of the geology of the State of New Jersey, being a final report: Philadelphia, PA, C. Sherman and Company, 301 p.

Rogers, H. D., 1842, [Remarks on a paper by Edward Hitchcock]: American Journal of Science, series, v. 43, p. 170.

Rogers, H. D., 1854, [On the inclination and thickness of the sandstone of the Connecticut Valley, remarks on a paper by Edward Hitchcock]: Boston Society of Natural History Proceedings, v. 4, p. 379-380.

Rogers, H. D., 1858, Geology of Pennsylvania. A government survey with a general view of the geology of the United States, essays on the Coal-Formation and its fossils, and a description of the coal-fields of North America and Great Britain: Edinburgh and London, W. Blackwood and Sons; Philadelphia, PA, J. Lippincott and Company, in Two Volumes, v. 2, part 2, p. 667-1045.

Rogers, H. D., 1865, Description of the geology of the State of New Jersey, being a final report: Trenton, NJ, J. R. Freese, "State Gazette" Office, 227 p.

Rogers, W. B., 1842, [On the prevailing dip in the various areas of New Red Sandstone of the Atlantic slope, remarks on a paper by Edward Hitchcock]: American Journal of Science, 1st series, v. 43, p. 171-172.

Rogers, W. B., 1860, [On the stratigraphic relations (sic) of deposits formed in an ocean under conditions of stationary (sic), subsiding (sic), and rising position of the sea bottom]: Boston Society of Natural History Proceedings, v. 7, p. 246-249, 273-275.

Rosendahl, B. R., 1987, Architecture of continental rifts with special reference to East Africa: Annual Reviews of Earth and Planetary Sciences, v. 15, p. 445-503.

Rosendahl, B. R., and Livingstone, D. A., 1983, Rift lakes of East Africa: New seismic data and implications for future research: Episodes, v. 6, no. 1, p. 14-19.

Rosendahl, B. R.; Reynolds, D. J.; Lonben, P. M.; Burgess, C. F.; McGill, J.; Scott, D.; Lambiase, J. J.; and Derksen, S. J., 1986, Structural expressions of rifting: Lessons from Lake Tanganyika, p. 27-38 in Frostick, L. E.; Renaut, R. W.; Reid, Ian; and Tiercelin, J. T., eds., Sedimentation in the African rifts: Geological Society of London Special Publication No. 25, 381 p.

Russell, I. C., 1877, On the intrusive nature of the Triassic trap sheets of New Jersey: American Journal of Science, 3rd series, v. 15, p. 277-280.

Russell, I. C., 1878, On the physical history of the Triassic formation in New Jersey and the Connecticut valley: New York Academy of Sciences Annals, v. 1 (1879), p. 220-254.

Russell, I. C., 1880, On the former extent of the Triassic formation of the Atlantic states: American Naturalist, v. 14, p. 703-712.

Russell, I. C., 1892, Correlation papers. The Newark System: U. S. Geological Survey Bulletin 85, 344 p.

Russell, W. L., 1922, The structural and stratigraphic relations (sic) of the Great Triassic fault of southern Connecticut: American Journal of Science, 5th series, v. 4, p. 483-497.

Sanders, J. E., 1958, Stratigraphy and structure of the Triassic rocks of central Connecticut: New England Intercollegiate Geological Field Conference, Annual Meeting, 50th, Guidebook for Trip B, 13 p. (mimeographed).

Sanders, J. E., 1960, Structural history of Triassic rocks of Connecticut Valley belt and its regional implications: New York Academy of Sciences Transactions, Series II, v. 23, p. 119-132.

Sanders, J. E., 1962a, Strike-slip displacement on faults in Triassic rocks in New Jersey: Science, v. 136, p. 40-42.

Sanders, J. E., 1962b, Stratigraphy of the Talcott Formation (Upper Triassic), southern Connecticut (abstract): Geological Society of America Special Papers No. 68, p. 260 (only).

Sanders, J. E., 1962c, Relationship of folds to faults in Upper Triassic rocks northeast of the Schuylkill (Pennsylvania to Massachusetts) (abstract): Geological Society of America Special Papers No. 68, p. 260-261.

Sanders, J. E., 1963, Late Triassic tectonic history of north-eastern United States: American Journal of Science, v. 261, p. 501-524.

Sanders, J. E., 1965a, Sediment-filled deep valleys underlying New Haven Harbor, Connecticut, revealed by continuous seismic profiling using sparker and pneumatic sources (abstract): American Geophysical Union Transactions, v. 46, no. 1, p. 105 (only).

Sanders, J. E., 1968, Stratigraphy (sic) and primary sedimentary structures of fine-grained, well-bedded strata, inferred lake deposits, Upper Triassic, central and southern Connecticut, p. 265-305 in Klein, G. deV., ed., Late Paleozoic and Mesozoic continental sedimentation, northeastern North America: Geological Society of America Special Paper 106, 315 p.

Sanders, J. E., 1970, Stratigraphy (sic) and structure of the Triassic strata of the Gaillard graben, south-central Connecticut: Connecticut Geological and Natural History Survey Guidebook No. 3, 15 p.

Sanders, J. E., 1971, Triassic rocks, northeastern North America: regional tectonic significance in light of plate tectonics (extended abstract): Geological Society of America Abstracts With Programs, v. 3, no. 7, p. 781-783.

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

Sanders, J. E., 1974b, Guidebook to field trip in Rockland County, New York: New York, NY, Petroleum Exploration Society of New York, 87 p.

Sanders, J. E., 1978, Primary sedimentary structures, p. 680-682 in Fairbridge, R. W.; and Bourgeois, Joanne, eds., The encyclopedia of sedimentology: Encyclopedia of Earth Sciences, v. VI: Stroudsburg, PA, Dowden, Hutchinson, and Ross, 901 p.

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

Sanders, J. E., 1989 ms., Sediment-filled deep V-shaped, bedrock-walled valleys underlying New Haven Harbor, Connecticut, revealed by continuous seismic-reflection profiling using sparker- and compressed-air sound sources: 75 p, 16 figs.

Sanders, J. E., 1994a, Buried, anomalously deep V-shaped valley in bedrock surface, New Haven Harbor, Connecticut (extended abstract), p. 94-102 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 23 April 1994, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 165 p.

Sanders, J. E., 1994b, Newark basin-filling strata and associated mafic igneous rocks, p. 201-212 in Benimoff, A. I., ed., The geology of Staten Island, New York: Geological Association of New Jersey Annual Meeting, 11th, Somerset, NJ, 14-15 October 1994, Field guide and proceedings, 296 p.

Sanders, J. E., 1994c, Coastal-plain sands and clays of Late Cretaceous age, p. 213-216 in Benimoff, A. I., ed., The geology of Staten Island, New York: Geological Association of New Jersey Annual Meeting, 11th, Somerset, NJ, 14-15 October 1994, Field guide and proceedings, 296 p.

Sanders, J. E., 1995, Lower Paleozoic carbonate-clast diamictites: Relationship to thrust sheets that advanced across the floor of the Northern Appalachian Ordovician foreland basin: Northeastern Geology and Environmental Sciences, v. 17, no. 1, p. 23-45.

Sanders, J. E., Friedman, G. M., and Sternbach, C. A., 1981, Extinct (sic) and active continental margin (sic) deposits and their tectonic-switchover products: Appalachian orogen ("Eastern Overthrust Belt")-Catskill Plateau-Newark basin-Atlantic coastal plain, p. 104-232 in Hobbs, G. W., ed., Field guide to the geology of the Paleozoic, Mesozoic, and Tertiary rocks of New Jersey and the central Hudson valley: New York, NY, Petroleum Exploration Society of New York, 232 p.

Sanders, J. E., Guidotti, C. V., and Wilde, Pat, 1963, Foxon fault and Gaillard graben in the Triassic of southern Connecticut: Connecticut Geological and Natural History Survey Report of Investigations No. 2, 16 p.

Sanders, J. E.; and Merguerian, Charles, 1991a, Pleistocene tills in the New York City region: New evidence confirms multiple (three and possibly four) glaciations from two directions (NNE to SSE (sic) and NW to SE) (abstract): Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 123 (only).

Sanders, J. E.; and Merguerian, Charles, 1991b, Pleistocene geology of Long Island's north shore: Sands Point and Garvies Point to Target Rock: Long Island Geologists' Association Field Trip 29 June 1991 Guidebook: Hempstead, NY, Hofstra University Department of Geology, 40 p.

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

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

Sanders, J. E.; and Merguerian, Charles, 1994b, Glacial geology of the New York City region, p. 93-200 in Benimoff, A. I., ed., The geology of Staten Island, New York: Geological Association of New Jersey Annual Meeting, 11th, Somerset, NJ, 14-15 October 1994, Field guide and proceedings, 296 p.

Sanders, J. E. and Merguerian, Charles, 1995a, Evidence for pre-Woodfordian ages of Long Island's terminal moraines (extended abstract), p. 91-106 in Hanson, G. N., chm., Geology of Long Island and metropolitan New York, 22 April 1995, Stony Brook, NY: Stony Brook, NY, Long Island Geologists Program with Abstracts, 135 p.

Sanders, J. E.; and Merguerian, Charles, 1995b, New York City region: Unique testing ground for flow models of Quaternary continental glaciers (abstract): Geological Society of America Abstracts with Programs, v. 27, no. 6, p. A-168 (only).

Sanders, J. E.; and Merguerian, Charles, 1996, Trip 39: Glacial geology of Long Island, 01-02 June 1996 (revision of Trip 15, 17-18 November 1990): New York Academy of Sciences Section of Geological Sciences Trips on the Rocks Guidebook, 129 p.

Sanders, J. E.; and Merguerian, Charles, 1997, Geologic setting of a cruise from the mouth of the East River to the George Washington bridge, New York Harbor: New York, NY, American Rock Mechanics Assocation, NYRocks 97, hosted by Columbia University Field-Trip Guidebook, 147 p.

Sanders, J. E., and Rampino, M. R., 1978, Wisconsinan stratigraphy, New York metropolitan area: interpretation of newly recognized units does not support modern concepts of the "Laurentide" ice sheet (abstract): Geological Society of America Abstracts with Programs, v. 10, no. 2, p. 84 (only).

Savage, E. L., 1968, Trip C: The Triassic rocks of the northern Newark Basin, p. 49-100 in Finks, R. M., ed., New York State Geological Association Annual Meeting, 40th, Queens College, Guidebook: Flushing, NY, Queens College Department of Geology, 253 p.

Sawyer, D. S., 1985, Brittle fracture in the upper mantle during extension of continental lithosphere: Journal of Geophysical Research, v. 90, p. 3021-3025.

Schaller, W. T., 1932, The crystal cavities of the New Jersey zeolite region: U. S. Geological Survey Bulletin 832, 90 p.

Schlische, R. W., 1991, Half-graben filling models: Implications for the evolution of continental extensional basins: Basin Research, v. 3, p. 123-141.

Schlische, R. W., 1992, Structural (sic) and stratigraphic development of the Newark extensional basin, eastern North America: Implications for the growth of the basin and itws bounding structures: Geological Society of America Bulletin, v. 104, no. x, p. 1246-1263.

Schlische, R. W., 1993, Anatomy (sic) and evolution of the Triassic-Jurassic continental rift system, eastern North America: Tectonics, v. 12, p. 1026-1042.

Schlische, R. W., 1995a, Rift basin (sic) inversion around the margins of the North Atlantic Ocean: Chronology, causes, and consequences (abstract): Geological Society of America Abstracts with Programs, v. 27, no. 1, p. 80 (only).

Schlische, R. W., 1995b, Geometry (sic) and origin of fault-related folds in extensional settings: American Association of Petroleum Geologists Bulletin, v. 79, no. 11, p. 1661-1678.

Schlische, R. W., and Anders, M. H., in press, Stratigraphic effects and tectonic implications of the growth of normal faults and extensional basins, p. xxx-aaa in Beraton, K. K., ed., Reconstructing the structural history of Basin and Range extension using sedimentology and stratigraphy: Boulder, CO, Geological Society of America Special Paper 303, yyy p

Schneider, E. D., 1972, Sedimentary evolution of rifted continental margins, p. 109-118 in Shagam, R.; Hargraves, R. B.; Morgan, W. J.; van Houten, F. B.; Burk, C. A.; Holland, H. D.; and Hollister, L. C., eds., Studies in Earth and space sciences: Geological Society of America Memoir 132, 685 p.

Scholz, C. A., 1995, Deltas of the Lake Malawi rift, East Africa: Seismic expression and exploration implications: American Association of Petroleum Geologists Bulletin, v. 79, no. 11, p. 1679-1697.*

Schuberth, C. J., 1968, The geology of New York City and environs: Garden City, NY, Natural History Press, 304 p.

Schweickert, R. A., 1981, Tectonic evolution of the Sierra Nevada Range, p. 87-131 in Ernst, W.G., ed., The geotectonic evolution of California, Rubey volume I: Englewood Cliffs, NJ, Prentice-Hall Inc., 706 p.

Schweickert, R. A.; Bogen, N. L.; Girty, G. H.; Hanson, R. E.; and Merguerian, C., 1984, Timing (sic) and structural expression of the Nevadan orogeny, Sierra Nevada, California: Geological Society of America Bulletin, v. 95, p. 967-979.

Schweickert, R. A.; and Cowan, D., 1975, Early Mesozoic tectonic evolution of the western Sierra Nevada, California: Geologic Society of America Bulletin, v. 86, p. 1329-1336.

Schweickert, R. A.; Merguerian, Charles, and Bogen, N. L.; 1988, Deformational (sic) and metamorphic history of Paleozoic and Mesozoic basement terranes in the southern part of the western Sierra Nevada metamorphic belt, p. 789-822 in Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States, Rubey Volume VII: Englwood Cliffs, NJ, Prentice Hall, Inc., 1153 p.

Schweickert, R. A.; and Snyder, W. S., 1981, Paleozoic plate tectonics of the Sierra Nevada and adjacent regions, p. 182-202 in Ernst, W. G., ed., The geotectonic development of California, Rubey volume I: Englewood Cliffs, NJ, Prentice-Hall Inc., 786 p.

Sclater, J. G., and Francheteau, J., 1970, The implications of terrestrial heat flow (sic) observations on current tectonic (sic) and geochemical models of the crust (sic) and upper mantle of the Earth: Royal Astronomical Society Geophysical Journal, v. 20, p. 509-542.

Seidemann, D. E., 1989, Age of the Triassic/Jurassic boundary a view from the Hartford basin: American Journal of Science, v. 289, p. 553-562.

Seidemann, D. E., Masterson, W. D., Dowling, M. P., and Turekian, K. K., 1984, K-Ar dates and 40Ar/39Ar age spectra for Mesozoic basalt flows of the Hartford Basin, Connecticut and the Newark Basin, New Jersey: Geological Society of America Bulletin, v. 95, p. 594-598.

Sharp, H. S., 1929a, A pre-Newark peneplane and its bearing on the origin of the lower Hudson River: American Journal of Science, v. 218, p. 509-518.

Sharp, H. S., 1929b, The fall zone peneplane: Science, v. 69, p. 544-545.

Sheridan, R. E., 1976, Sedimentary basins of the Atlantic margin of North America, p. 113-132 in Bott, M. H. P., ed., Sedimentary basins of the continental margin and craton: Inter-Union Commission on Geodynamics Symposium, Durham University, England, 05-09 April 1976, Proceedings: Tectonophysics, v. 36, nos. 1-3 (special issue), 314 p.

Sheriden, R. E., 1969, Subsidence of continental margins: Tectonophysics, v. 7, p. 219.

Shirley, D. N., 1985, Differentiation of the Palisades sill (abstract): Geological Society of America Abstracts With Programs, v. 17, no. 7, p. 716 (only).

Shirley, D. N., 1987, Differentiation and compaction in the Palisades sill: Journal of Petrology, v. 28, p. 835-865.

Shirley, D. N., 1988, Effects of postcumulus fractionation in the Palisades sheet: further evidence from Weehawken, New Jersey, p. 135-141 in Froelich, A. J.; and Robinson, G. R., Jr., eds., Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Sibson, R., 1977, Fault rocks and fault mechanisms: Geological Society of London Journal, v. 133, p.191-213.

Sichko, M. J., Jr., 1970 ms., Structural (sic) and petrological study of the Second Watchung basaltic flow near Pluckemin, New Jersey: Brooklyn, NY, Brooklyn College Department of Geology Master's Thesis, 80 p.

Sleep, N. H., 1971, Thermal effects of the formation of Atlantic continental margins by continental breakup: Royal Astronomical Society Geophysical Journal, v. 24, p. 325-350.

Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, no. 2, p. 93-114.

Sloss, L. L., 1964, Tectonic cycles of the North American craton, p. 449-460 in Merriam, D. F., ed., Symposium on cyclic sedimentation: Kansas Geological Survey Bulletin 169, 2 vols. (v. 1, p. 1-380; v. 2, p. 381-636).

Sloss, L. L., 1984, Comparative anatomy of cratonic unconformities (sic), p. 1-6 in Schlee, J. S., ed., Regional unconformities (sic) and hydrocarbon accumulation: Tulsa, OK, American Association of Petroleum Geologists Memoir 36, 184 p.

Sloss, L. L., ed., 1988, Sedimentary cover--North American craton, U. S.: The Geology of North America, v. D-2: Boulder CO, Geological Society of America, xxx p.

Sloss, L. L., 1988, Forty years of sequence stratigraphy: Geological Society of America Bulletin, v. 100, no. 11, p. 1661-1665.

Sloss, L. L., 1990, The greening of stratigraphy, 1933-1983, p. 635-644 in Lederberg, Joshua, compiler, The excitement and fascination of science: reflections by eminent scientists: Palo Alto, CA, Annual Reviews Inc., v. 3, part 1, 1297 p. (+index, 23 p.) (Reprinted from Annual Reviews in Earth and Planetary Sciences 1984, v. 12, p. 1-10.)

Smith, R. C., II; and Rose, A. W., 1970, The occurrence (sic) and chemical composition of two distinct types of Triassic diabase in Pennsylvania (abstract): Geological Society of America Abstracts With Programs, v. 2, no. 7, p. 688 (only).

Smith, R. C., II; Rose, A. W.; and Lanning, R. M., 1975, Geology (sic) and geochemistry of Triassic diabase in Pennsylvania: Geological Society of America Bulletin, v. 86, p. 943-955.

Smith, T. E., 1976, Paleomagnetic study of Lower Mesozoic diabase dikes and sills of Connecticut and Maryland: Canadian Journal of Earth Sciences, v. 13, p. 597-609.

Smith, T. E., and Noltimier, H. C., 1979, Paleomagnetism of the Newark trend (sic) igneous rocks of the north central (sic) Appalachians and the opening of the central Atlantic Ocean: American Journal of Science, v. 279, p. 779-817.

Smoot, J. P., 1985, The closed-basin hypothesis and its use in facies analysis of the Newark Supergroup. Chapter 2, p. 4-10 in Robinson, G. R.; and Froelich, A. J., eds., U. S. Geological Survey workshop on the Early Mesozoic basins of the eastern United States, Second, Proceedings: U. S. Geological Survey Circular 946, 147 p.

Smoot, J. P., and Olsen, P. E., 1988, Massive mudstones in basin analysis and paleoclimate interpretation of the Newark Supergroup, Chapter 10 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Smoot, J. P., and Robinson, G. R., Jr., 1988, Sedimentology of stratabound base-metal occurrences in the Newark Supergroup, p. 356-376 in Froelich, A. J.; and Robinson, G. R., Jr., eds., Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Spiker, E. C., Kotra, R. K., Hatcher, P. G., Gottfried, R. M., Horan, M. F., and Olsen, P. E., 1988, Source of kerogen in black shales from the Hartford and Newark basins, eastern United States, p. 63-68 in Froelich, A. J.; and Robinson, G. R., Jr., eds., Studies of the Early Mesozoic basins of the eastern United States: U. S. Geological Survey Bulletin 1776, 423 p.

Spry, Alan, 1962, The origin of columnar jointing (sic), particularly in basalt flows (sic): Geological Society of Australia, v. 8, p. 191-216.

Sumner, J. R., 1978, Geophysical investigation of the structural framework of the Newark-Gettysburg Triassic basin, Pennsylvania: Geological Society of America Bulletin, v. 88, p. 935-942.

Suter, Russell; de Laguna, W.; and Perlmutter, N. M., 1949, Mapping of geologic formations and aquifers of Long Island, New York: New York State Department of Conservation Water Power and Control Commission Bulletin GW-18, 212 p.

Sutter, J. F., 1988, Innovative approaches to the dating of igneous events in the early Mesozoic basins of the eastern United States: p. 808-831 in Froelich, A. J., and Robinson, G. R., Jr., eds., Studies of the early Mesozoic basins of the eastern United States: United States Geological Survey Bulletin 1776, 423 p.

Sutter, J. F., and Smith, 1979, 40Ar/39Ar ages of diabase intrusions from Newark trend basins in Connecticut and Maryland: initiation of central Atlantic rifting: American Journal of Science, v. 279, p. 808-831.

Taylor, K. C., and 9 others, 1993, Electrical conductivity (sic) measurements from the GISP2 and GRIP Greenland ice cores: Nature, v. 366, p. 549-552.

Thomas, W. A., 1988, Early Mesozoic faults of the northern Gulf Coastal Plain in the context of opening of the Atlantic Ocean, Chapter 19 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Thompson, H. D., 1959, The Palisades Ridge in Rockland County, New York: New York Academy of Sciences Annals, v. 80, p. 1106-1126.

Tomkeieff, S. I., 1940, The basalt lavas (sic) of the Giant's Causeway District of Northern Ireland: Bulletin volcanologique, series 2, v. 6, p. 89-143.

Turner-Peterson, C. E., 1980, Sedimentology (sic) and uranium mineralization in the Triassic-Jurassic Newark basin, Pennsylvania and New Jersey, p. 149-175 in Turner-Peterson, C. E., ed., Uranium in sedimentary rocks-application of the facies concept to exploration: Society of Economic Paleotologists and Mineralogists Rocky Mountain Section Short-course Notes.

Turner-Peterson, C. E., and Smoot, J. P., 1985, New thoughts on facies relationships in the Triassic Stockton and Lockatong formations, Pennsylvania and New Jersey, Chapter 3, p. 10-17 in Robinson, G. R., Jr.; and Froelich, A. J., eds., U. S. Geological Survey workshop on the Early Mesozoic basins of the eastern United States, Second, Proceedings, U. S. Geological Survey Circular 946, 147 p.

Tyrrell, G. W., 1937, Flood basalts and fissure eruption: Bulletin Volcanologique, series 2, no. 1, p. 89-111.

Ulrich, E. O., 1911, Revision of the Paleozoic systems: Geological Society of America Bulletin, v. 22, p. 281-680.

Ulrich,E. O., 1913, Revision of the Paleozoic systems: Geological Society of America Bulletin, v. 24, p. 625-668.

Ulrich, E. O., 1916, Correlation by displacements of the strand line: Geological Society of America Bulletin, v. 27, p. 5- 8.

van der Meer, J. J. M., ed., Tills and glaciotectonics: Proc. INQQUA Meeting, Amsterdam, The genesis and lithology of glacial deposits: Rotterdam, A. A. Balkema, xxx p.

Van Houten, F. B., 1960, Composition of Upper Triassic Lockatong Argillite, west-central New Jersey: Journal of Geology, v. 68, no. 6, p. 666-669

Van Houten, F. B., 1962, Cyclic sedimentation and the origin of analcime-rich upper Triassic Lockatong Formation, west-central New Jersey and adjacent Pennsylvania: American Journal of Science, v. 260, p. 561-576.

Van Houten, F. B., 1964, Cyclic lacustrine sedimentation, Upper Triassic Lockatong Formation, central New Jersey and adjacent Pennsylvania, p. 497-531 in Merriam, D. F., ed., Symposium on cyclic sedimentation: Lawrence, KA, University of Kansas, Kansas Geological Survey Bulletin 169, 2 volumes (v. 1, p. 1-380; v. 2, p. 381-636).

Van Houten, F. B., 1965, Composition of Triassic and associated formations of Newark Group, central New Jersey and adjacent Pennsylvania: American Journal of Science, v. 263, p. 825-863.

Van Houten, F. B., 1969, Late (sic) Triassic Newark Group, north-central New Jersey and adjacent Pennsylvania and New York, p. 314-347 in Subitzky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: Geological Society of America, Annual Meeting, Atlantic City 1969: New Brunswick, NJ, Rutgers University Press, 382 p.

Van Houten, F. B., 1977, Triassic-Liassic deposits of Morocco and eastern North America: a comparison: American Association of Petroleum Geologists Bulletin, v. 61, p. 79-99.

Van Houten, F. B., 1980, Late Triassic part of Newark Supergroup, Delaware River section, west-central New Jersey, p. 264-276 in Manspeizer, Warren, ed., Field studies in New Jersey geology and guide to field trips: New York State Geological Association, 52nd, October 1980, Newark, New Jersey, Guidebook: Newark, NJ, Rutgers University Newark College of Arts and Sciences, 398 p.

Venkatakrishnan, R.; and Lutz, R., 1988, A kinematic model for the evolution of Richmond Triassic basin, Virginia, Chapter 18 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Walcott, R. I., 1972, Gravity, flexure, and the growth of sedimentary basins at a continental margin: Geological Society of America Bulletin, v. 83, p. 1845-1848.

Walker, Frederick, 1940, Differentiation of the Palisades diabase: Geological Society of America Bulletin, v. 51, p. 1059-1106.

Walker, K. R., 1969, The Palisades sill, New Jersey: a reinvestigation: Geological Society of America Special Paper 111, 178 p.

Walton, M. S., Jr., and O'Sullivan, R. B., 1950, The intrusive mechanics of a clastic dike: American Journal of Science, v. 248, p. 1-21.

Watts, A. B., 1981, The U. S. Atlantic continental margin: subsidence history, crustal structure and thermal evolution, p. 2-1 to 2-75 in Bally, A. W., ed., Geology of passive continental margins: history, structure,and sedimentologic record (with special emphasis on the Atlantic margins): Tulsa, OK, American Association of Petroleum Geologists Education Course Note Series No. 19.

Watts, A. B., and Ryan, W. B. F., 1976, Flexure of the lithosphere and continental margin (sic) basins, p. 24-44 in Bott, M. H. P., ed., Sedimentary basins of the continental margin and craton: Inter-Union Commission on Geodynamics Symposium, Durham University, England, 05-09 April 1976, Proceedings: Tectonophysics, v. 36, nos. 1-3 (special issue), 314 p.

Weigand, P. W., and Ragland, P. C., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contributions to Mineralogy and Petrology, v. 29, p. 195-214.

Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere: Candian Journal of Earth Sciences, v. 22, p. 108-125.

Wernicke, B.; and Burchfiel, B. C., 1982, Modes of extensional tectonics: Journal of Structural Geology, v. 4, p. 105-115.

Wheeler, Girard, 1938, Further evidence of broad-terrane Triassic: Journal of Geomorphology, v. 1, p. 140-142.

Wheeler, Girard, 1939, Triassic fault-line deflections and associated warping: Journal of Geology, v. 47, p. 337-370.

Whelpley, J. D., 1845, [Trap and sandstone of the Connecticut Valley; theory of their relation]: American Association of Geologists and Naturalists Proceedings, 6th meeting, p. 61-64.

White, R. S., 1987, When continents rift: Nature, v. 327, p. 191.

Whitney, J. D., 1860, On the stratigraphic position of the sandstone of the Connecticut Valley: Annals of Scientific Discovery, p. 322.

Whittington, D., 1988, Chemical (sic) and physical constraints on petrogenesis and emplacement of ENA olivine diabase magma types, Chapter 23 in Manspeizer, Warren, ed., Triassic-Jurassic rifting, continental breakup and the origin of the Atlantic Ocean and passive margin: Amsterdam, The Netherlands, Elsevier Science Publishers, 998 p. (2 volumes).

Widmer, Kemble, 1964, The geology (sic) and geography of New Jersey: The New Jersey Historical Series, v. 19: Princeton-New York-Toronto-London, D. Van Nostrand Company, Inc., 193 p.

Willard, Bradford; Freedman, J.; McLaughlin, D. B.; and others, 1959, Geology (sic) and mineral resources of Bucks County, Pennsylvania: Pennsylvania Geological Survey, 4th series, Bulletin C9, 243 p.

Witte, W. K., and Kent, D. V., 1989, A middle Carnian to early Norian (225 Ma) paleopole from sediments of the Newark basin, Pennsylvania: Geological Society of America Bulletin, v. 101, p. 1118-1126.

Wolff, M. P., Sichko, M. J., and Leibling, R. S., 1987, Concepts of physical geology--An illustrated overview: Dubuque, IA, Kendall Hunt Publishing Co., 134 p.

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

Woodworth, J. B., 1901, Pleistocene geology of portions of Nassau County and Borough of Queens (N. Y.): New York State Museum Bulletin 48, p. 618-670 (includes geologic map).

Woollard, G. P., 1943, Geologic correlation of areal gravitational and magnetic studies in New Jersey and vicinity: Geological Society of America Bulletin, v. 54, p. 791-818.

Worzel, J. L., and Drake, C. L., 1959, Structure section across the Hudson River at Nyack, N. Y., from seismic observations, p. 1092-1105 in Lowe, K. E., chm. and consulting ed., Modern aspects of the geology of New York City and environs: New York Academy of Sciences Annals, v. 80, art. 4, p. 1047-1169.

Zeigler, P. A., 197, Compressional intra-plate tectonics in the Alpine Foreland: Tectonophysics, v. 137, 420 p.

Zhang, P.; Burchfiel, B. C.; Chen, S.; and Deng, Q., 1989, Extinction of pull-apart basins: Geology, v. 17, p. 814-817.

Filename: OTR24 Palisades.doc