Geology 133 Field Trip

Cortlandt Igneous Complex, Buchanan, NY
Stony Point Complex, Stony Point, NY
Palisades Intrusive Sheet, Fort Lee, NJ

24-25 April 2010

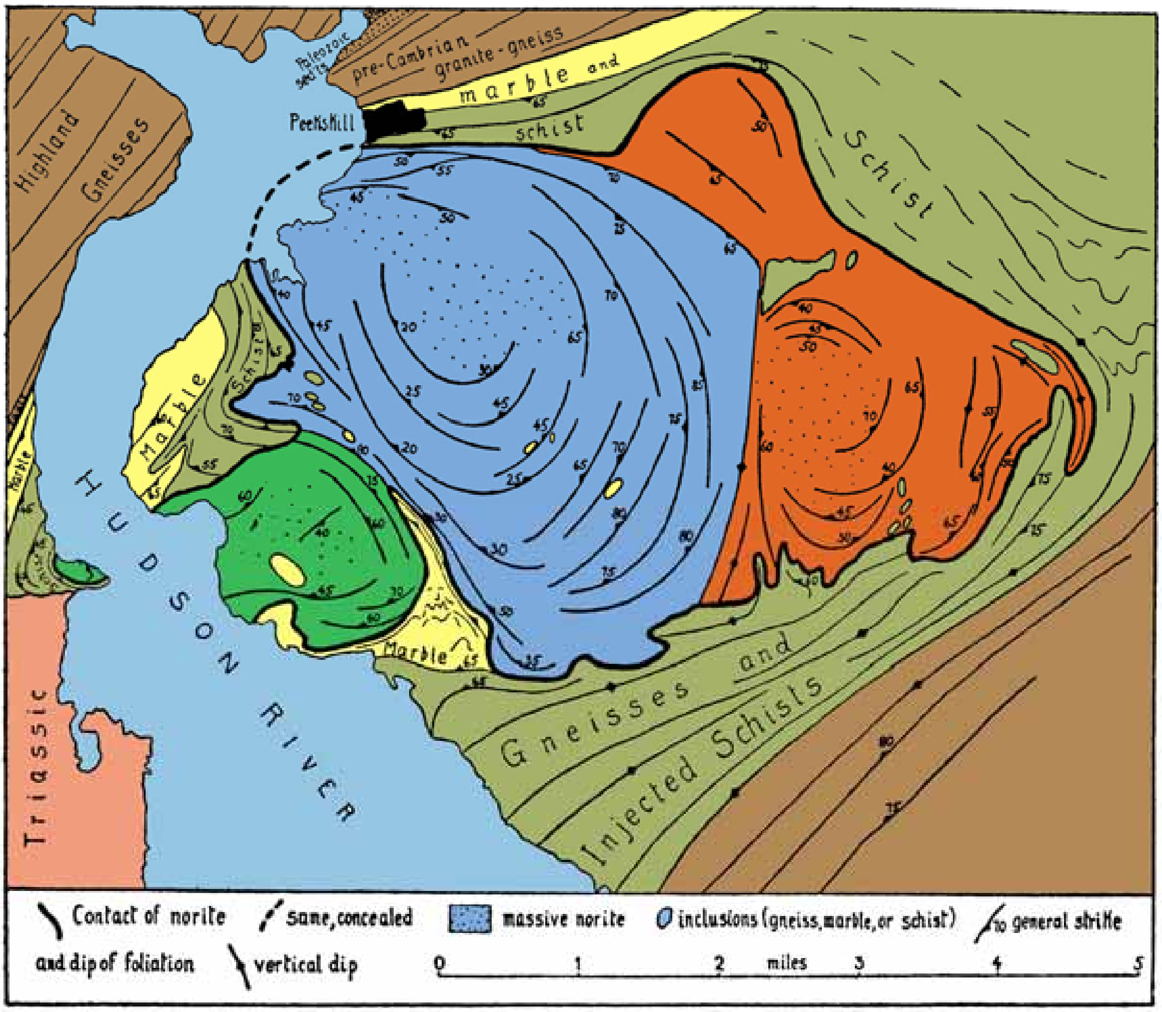

Figure 1. Geological map of the Cortlandt Complex showing the country rock and the Western Funnel (green), Central Basin (blue), and the Eastern Funnel (orange). (Colorized after original drawing by Robert Balk, 1937, Figure 33, p. 92.)

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INTRODUCTION

Welcome Aboard! The scientific goal of **Day One** is to first examine intrusive relationships and igneous phases within the world-renowned Cortlandt Complex south of Peekskill, NY and the Stony Point Complex of Stony Point, NY. (Figure 1, cover.) Ordovician mafic and ultramafic rocks of the Stony Point and the Cortlandt Complexes are not related to mafic intrusive rocks of the Mesozoic Palisades intrusive sheet – the focus of **Day Two**. A discussion on the regional geology, previous and modern studies of the Cortlandt Complex, and field trip stops will follow. For reference, a geologic time scale, specific to the Hudson Valley, is shown in Table 1. Table 2 (also near the end of guidebook) is a detailed description of the stratigraphic units of southeastern New York. Selected references are at the end of this guide.

The Manhattan Prong consists of highly deformed Paleozoic to Proterozoic metasedimentary and metaigneous rocks. These strata constitute the country rocks into which the Cortlandt Complex was intruded at roughly 450 Ma. The Hudson River bounds the Manhattan Prong on the west. Rocks of the Manhattan Prong are unconformably overlain by gently west-dipping Mesozoic reddish sandstone, siltstone, shale, and intercalated mafic volcanic- and shallow-level intrusive rocks that constitute the filling of the Newark Basin (Figure 2). The prong forms a continuous belt northward to the Ramapo fault zone north of which Proterozoic rocks of the Hudson Highlands form an imposing terrain of rugged, glaciated mountains. Stretching from Reading, Pennsylvania northeastward into western Connecticut, this belt of deeply eroded Proterozoic rocks forms the Reading Prong of the New England Uplands.

Channelization of the Hudson into its present valley took the modification of Pleistocene glaciers that helped carve the relatively straight southern part of the Hudson valley. The Hudson's zig-zag course through the highlands may be largely controlled by erosion of intersecting brittle fracture zones in the Proterozoic crust. From the Hudson Highlands southward to Manhattan Island, the Hudson River flows in an essentially straight course along the tilted and eroded unconformity between the Newark Basin and the Manhattan Prong. The ancestral Hudson undoubtedly flowed farther westward from its current path eroding the Millburn, Paterson, and Sparkill gaps in the Watchung mountains and in the Palisades cliffs (Figure 3). Post-glacial flooding of the lower course of the Hudson has produced an estuary (drowned river valley) and has transformed the narrow Hudson Highland section of the river valley into a steep fiord (drowned U-shaped glaciated valley).

The method of analyzing the bedrock underlying a region in terms of "layers" was much emphasized by Levorsen (1933, 1934, 1943, 1960). Sloss (1963) extended Levorsen's approach (but without mentioning Levorsen) and formalized the "layers" by proposing the term "Sequence." The Sloss Sequences refer only to Phanerozoic bedrock underlying the North American craton; the scheme does not include Phanerozoic bedrock outside the limits of the craton nor Proterozoic "basement" nor the Quaternary deposits, which are important geologic components of the New York metropolitan area. Layer IIA(W) in this guide (See Table 2) is synonymous with Sloss's Sauk Sequence and Layer IIB largely matches Sloss's Tippecanoe Sequence. The other layers do not closely match the Sloss arrangement. This is not surprising; the Sloss scheme applies to the interior parts of the craton, and many of the layers shown on our tables (Tables 1, 2) designate strata that were deposited on the ever changing fringe of the craton.

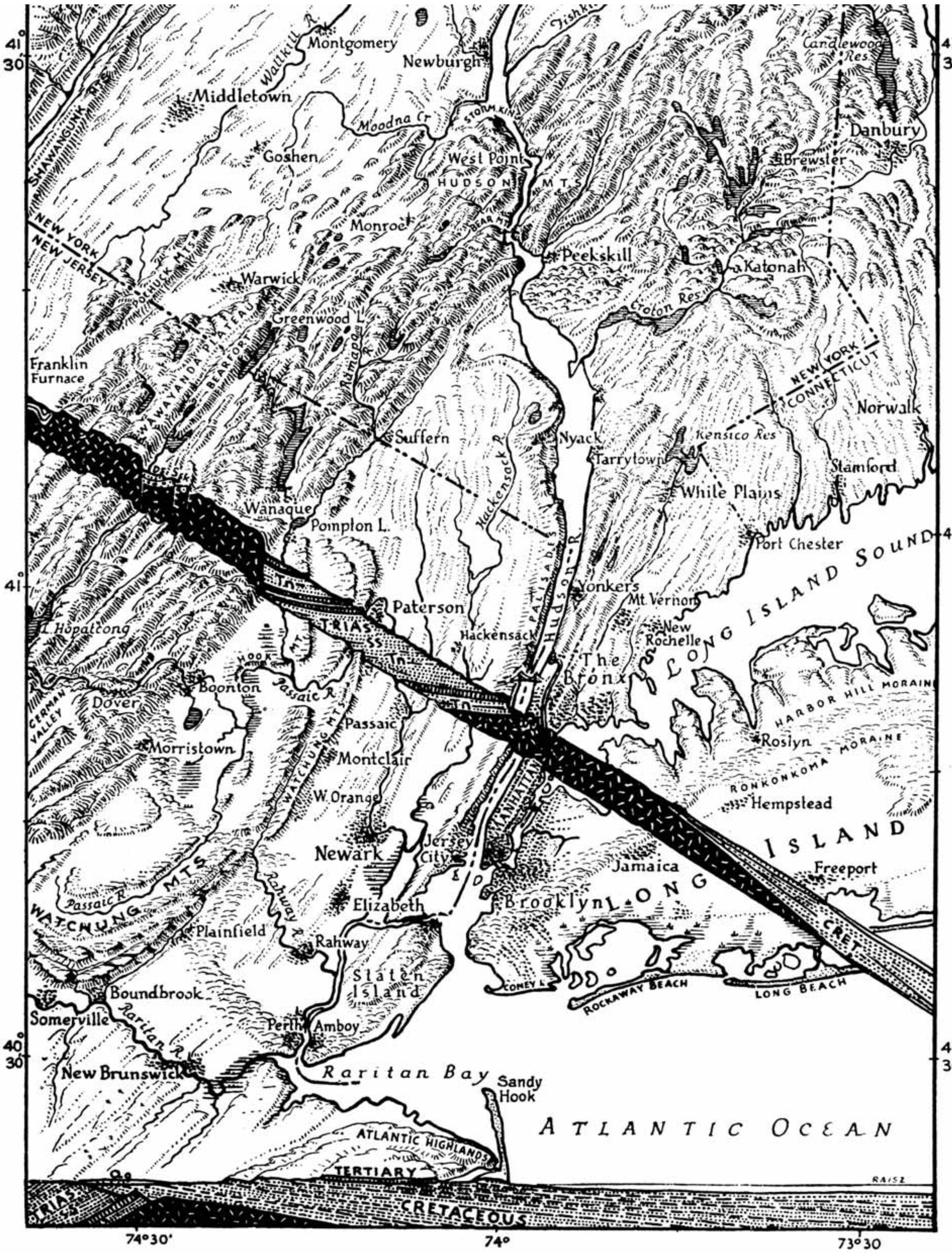


Figure 2. Physiographic block diagram of the lower Hudson River region (drawn by E. Raisz).

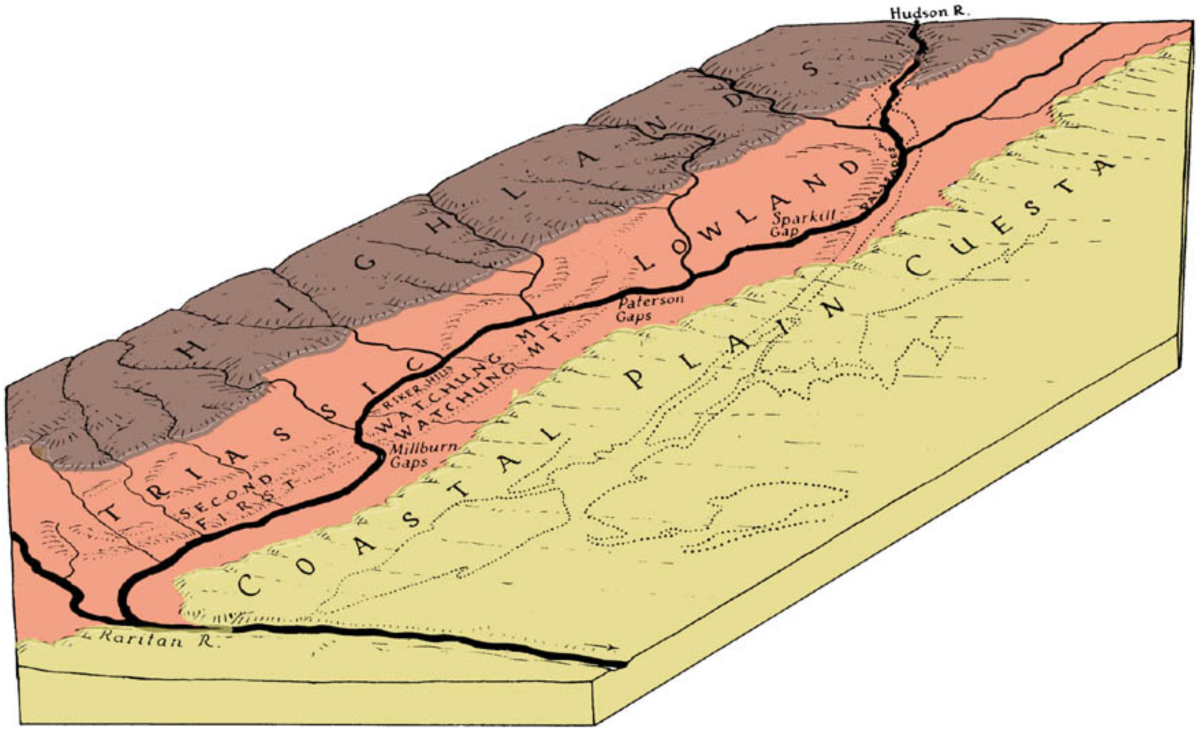


Figure 3. Physiographic diagram of the Hudson Highlands and hypothetical course of the Hudson River in Schooley time. (Colorized from an original drawing by E. Raisz).

BEDROCK UNITS

The bedrock in the vicinity of the Cortlandt Complex includes Layers I and II, the pre-Newark complex of Paleozoic and older metamorphic rocks that underlies the Manhattan Prong of the New England Uplands. (See Table 2.)

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

The rocks of the pre-Newark complex, which are exposed in many parts of Manhattan and the Bronx, in a few places in Queens, and in one place in Brooklyn ("A Rock Grows in Brooklyn!"), are present beneath a cover of younger deposits in Queens and Brooklyn. They have been examined in borings and on-site visits to the shafts- and tunnels of the New York City Aqueduct System and are found to consist of highly deformed and metamorphosed Lower Paleozoic- and older formations. These rocks compose the Manhattan Prong of the New England Upland physiographic province (Figure 4). In New York City, the metamorphic rocks of plunge southward beneath younger rocks to the south of Staten Island and reappear again in the Piedmont of eastern Pennsylvania. Together, they mark the deeply eroded, highly deformed and metamorphosed internal zone of the Appalachian mountain belt that stretches sinuously from Maine southward to Georgia. Along this tract, they have been beveled by Triassic and younger rocks, by Cretaceous and younger sediment of the Atlantic Coastal Plain, and in the northern terranes by Pleistocene strata.

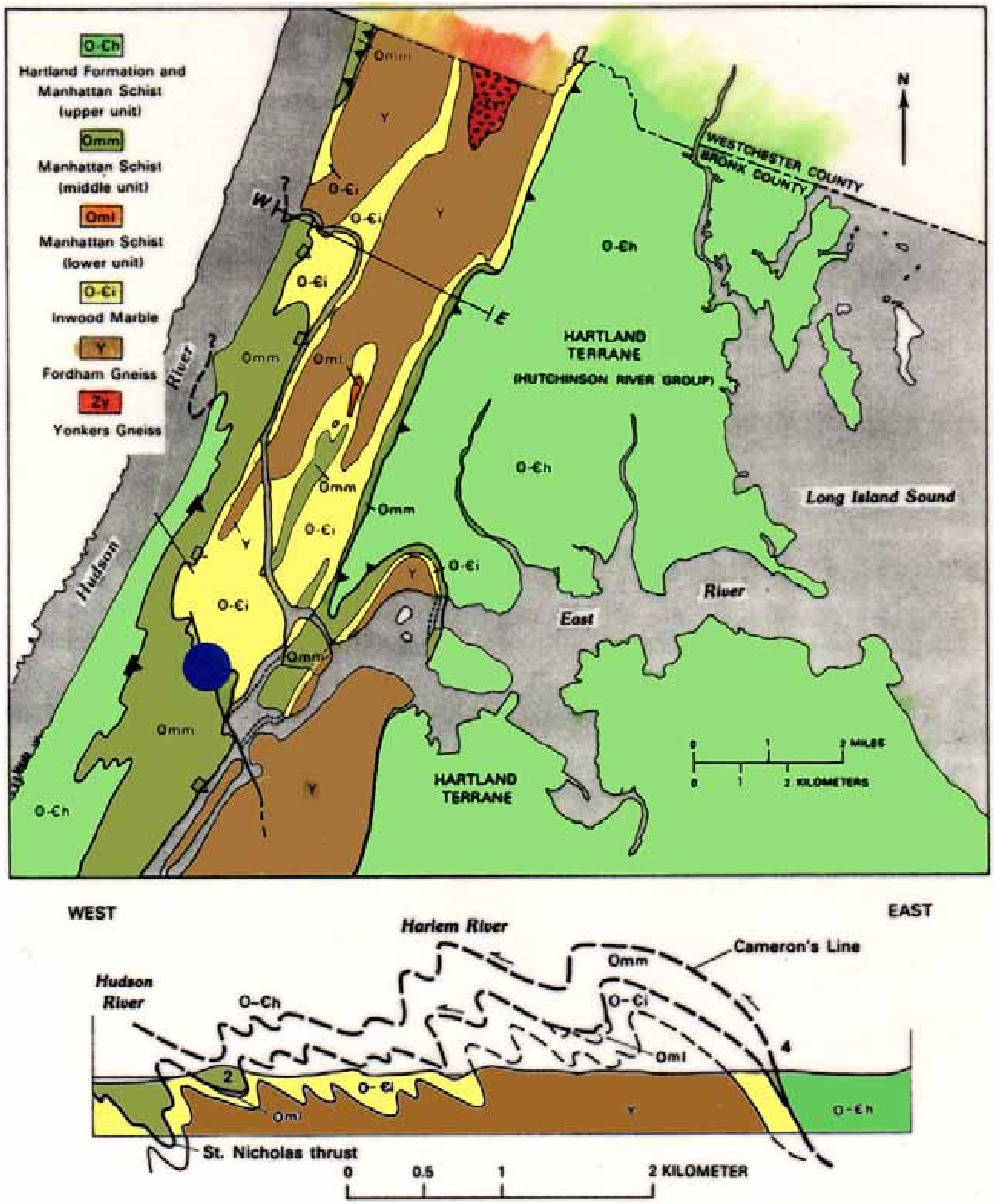


Figure 4. Simplified geologic map of the southern portion of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Blue dot shows location of small January 2001 earthquake along the Manhattanville fault. (Adapted from Merguerian and Baskerville, 1987.)

In the Manhattan Prong, a basal unit (Layer I) of Proterozoic gneiss (the Fordham Gneiss, 1.1 billion years old) is overlain by Layer II, metasedimentary- and metavolcanic rocks that are inferred to have been deposited along the margin of the ancient North American continent in a long-disappeared ocean, the precursor of the modern Atlantic Ocean. This long-lost ocean has been called Iapetus. This layer can be divided into two sub-layers, IIA and IIB (Table 2). The older of these, IIA, is inferred to represent an ancient passive-margin sequence with its various facies spanning the sedimentary realms from near shore (shallow-water deposits) to off shore (deep-water deposits). Thus, Layer IIA can be split into two parts that differ according to their original geographic positions across the inferred ancient passive continental margin.

One part of the older sublayer, part of the **Sauk Sequence**, was deposited on eroded- and submerged Proterozoic crust in shallow water [Layer IIA(W)]. The oldest unit of IIA(W) is the Ned Mountain formation of Brock (1989, 1993) and the Lowerre Quartzite of Late Neoproterozoic to Early Cambrian age. The Ned Mountain consists of metamorphosed rift-facies clastics, volcanic and volcaniclastic rocks. The Lowerre is thin and very discontinuous and represents overlying mature clastics. Occurring above the Lowerre is the Wappinger Limestone and Inwood Marble whose lower part is of Cambrian age and upper part, of Ordovician age. The Inwood and Wappinger strata resulted from the metamorphism of a extensive sheet of dolomitic carbonates and lesser limestone that were formerly deposited in the shallow, Sauk tropical sea that submerged large parts of the North American craton during the early part of the Paleozoic Era. North of New York City, where the metamorphic grade decreases, the equivalent of the Inwood Marble is the Wappinger Limestone, the rock mined at the Tomkins Cove Quarry (visited on our previous trip).

At the same time that Layer IIA(W) was being deposited in shallow water, fine-textured terrigenous- and volcaniclastic sediments and interlayered volcanics of Layer IIA(E) were being deposited farther east, in deeper water. These deep-water deposits form the bulk of the **Taconic Sequence** (Table 2) and the protoliths of what is now the middle unit of the Manhattan Schist (Ꞓ-Om) and the Hartland Formation (Ꞓ-Oh) (Figure 4).

The sediments of the Sauk Sequence were lithified and then experienced uplift and erosion that resulted in local karst topography within the Inwood and correlatives to the north and resulted in a regional disconformity. Submergence of the shallow-water carbonate platform heralded a major bathymetric reversal that was caused by loading of the edge of the continental margin by the encroaching Taconic arc and subduction complex. The reversal from shallow- to deep-water environments resulted in the deep-water infilling of a vast, thick sequence (the **Tippecanoe Sequence**) of terrigenous sediment into a foreland basin (Figure 5) above Layer IIA(W). Immediately above the disconformity surface occurs a thin limestone ("Balmville-type") that is demonstrably interstratified within the typical carbonaceous shales and sandstones of Layer IIB. These interstratified carbonaceous shales and lithic sandstones (graywackes or turbidites) are currently mapped throughout the region as the Normanskill, Martinsburg, Walloomsac, Annsville Phyllite, and as the lower part of the Manhattan Schist.

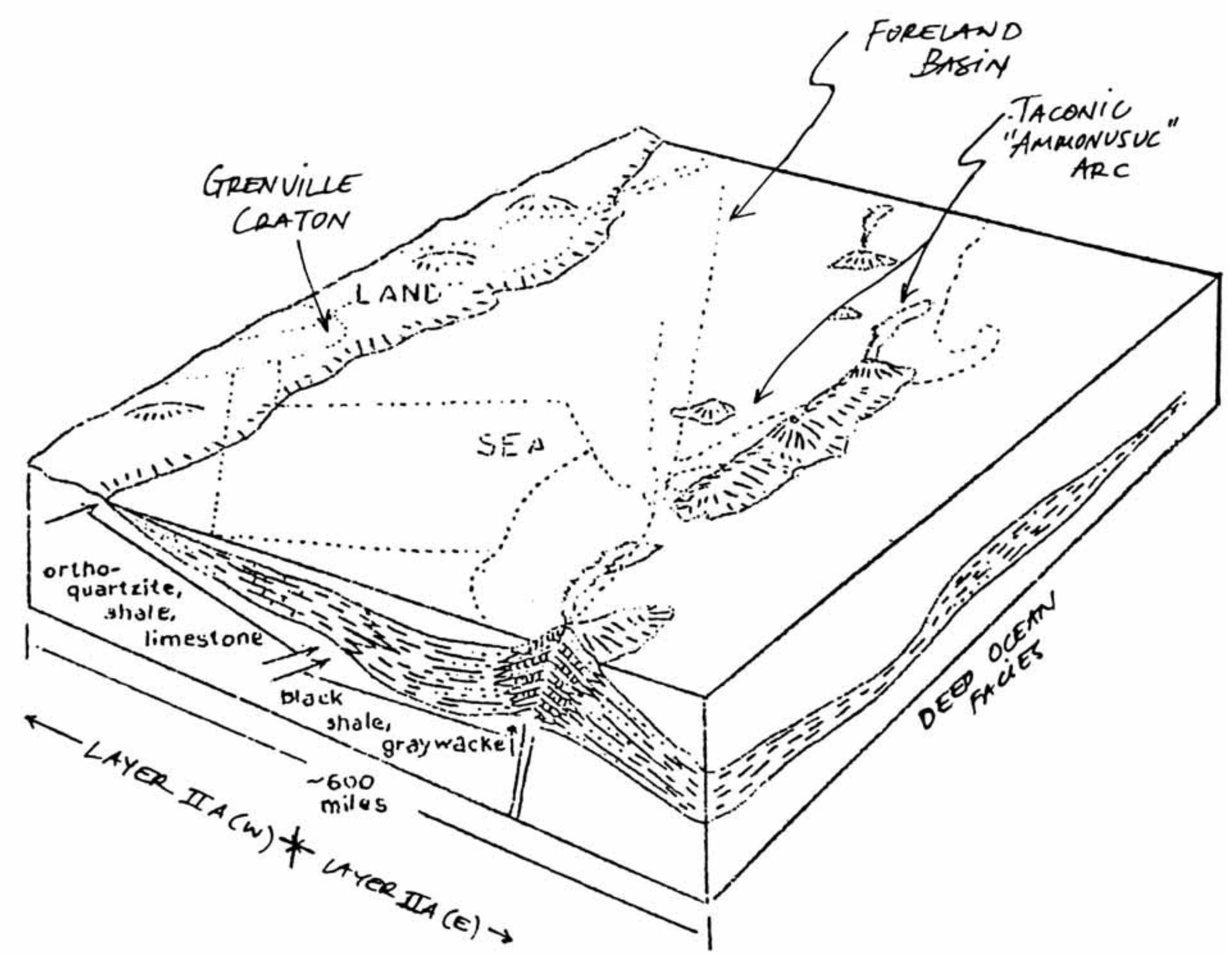


Figure 5. Block diagram showing the Early Paleozoic continental shelf edge of embryonic North America immediately before the deposition of Layer IIB. Current state outlines are dotted. The depositional areas for Layers IIA(W) and IIA(E), and the position of the Taconic arc and foreland basin are shown.

Layer V: Newark Strata and the Palisades Intrusive Sheet

The tilted- and eroded remnants of the Newark strata are exposed along the west side of the Hudson River, from Stony Point south to Staten Island. As shown on the diagonal cut-away slice in Figure 3, the Newark strata generally dip about 15° to the northwest.

The formal stratigraphic name for the Newark strata is the Newark Supergroup. Included are various sedimentary formations, of which the basal unit is the Stockton Arkose. Above it is the Lockatong Formation, the unit into which the Palisades Sill has been intruded. Higher up are other sedimentary units and three interbedded sheets of mafic extrusive igneous rock (ancient lava flows), whose tilted edges are resistant and underlie prominent ridges known as the Watchungs (now called the Orange Mountain, Preakness, and Hook Mountain basalts). The age of the sedimentary units beneath the oldest extrusive sheet is Late Triassic. The remainder of the formations are of latest Early Jurassic age (Olsen, 1980).

The Newark sedimentary strata were deposited in a fault-bounded basin to which the sea never gained access (Figure 6). In this basin, the filling strata were deposited in various nonmarine environments, including subaerial fans, streams, and shallow- and deep lakes. Lake levels varied according to changes in climate.

Despite all these environments of deposition, a general pattern prevails in the distribtion of particle sizes. Close to the basin-marginal fault the sedimentary debris is coarse: cobbles and boulders are typical. In the past, most of these coarse rocks have been called "fanglomerates" (literally, conglomerates deposited on fans, usually meaning subaerial fans). Because the evidence about an origin on subaerial fans is not always definitive, we shall refer to these coarse materials by the more-general non-environmental term of basin-marginal rudites.

Another point of general interest about these basin-marginal rudites is their composition. The kinds of clasts indicate what kind of bedrock was being eroded in the elevated basin-marginal blocks. The basin-marginal rudite clasts reveal unroofing of the Proterozoic basement complex in addition to overlying Paleozoic strata. In nearly all of the studied examples, the predominant rock types are Paleozoic carbonates (not metamorphosed), and various terrigenous rocks such as the Silurian sandstones and conglomerates, and Ordovician graywackes. Only rarely (and high in the stratigraphic succession) does one find a clast from the Proterozoic basement. This distribution of clasts implies that during the episode of sediment accumulation, the rivers in the elevated Ramapo Mountains block had not yet cut down through the cover of Paleozoic rocks. The clasts of non-metamorphosed carbonates prove that the elevated Ramapo Mountains block lay northwest of the zones of Paleozoic metamorphism and that prevailing climates were hot and dry to preserve the carbonate clasts.

In contrast to the basin-marginal rudites are the finer sediments that predominate at distances of only 1 or 2 kilometers away from the basin-marginal faults. Outside the basin-marginal zone, sand is typical, silt and clay are abundant, and coarser grain sizes are scarce. Interbedded conglomerate layers consist of well-rounded boulders which, similar to the vertical, internal stratigraphy of the basin-marginal rudites, show increasing clast age higher up in the section (which, because of the westward dip of the strata translates into the proposition that as one goes farther west, one finds older clasts in the Newark conglomerates).

After the Newark strata had been deeply buried, they were elevated and tilted, probably during a period of mid-Jurassic tectonic activities. They were then eroded and truncated to form a surface upon which the Upper Cretaceous and younger coastal-plain strata were deposited (Figure 6, F).

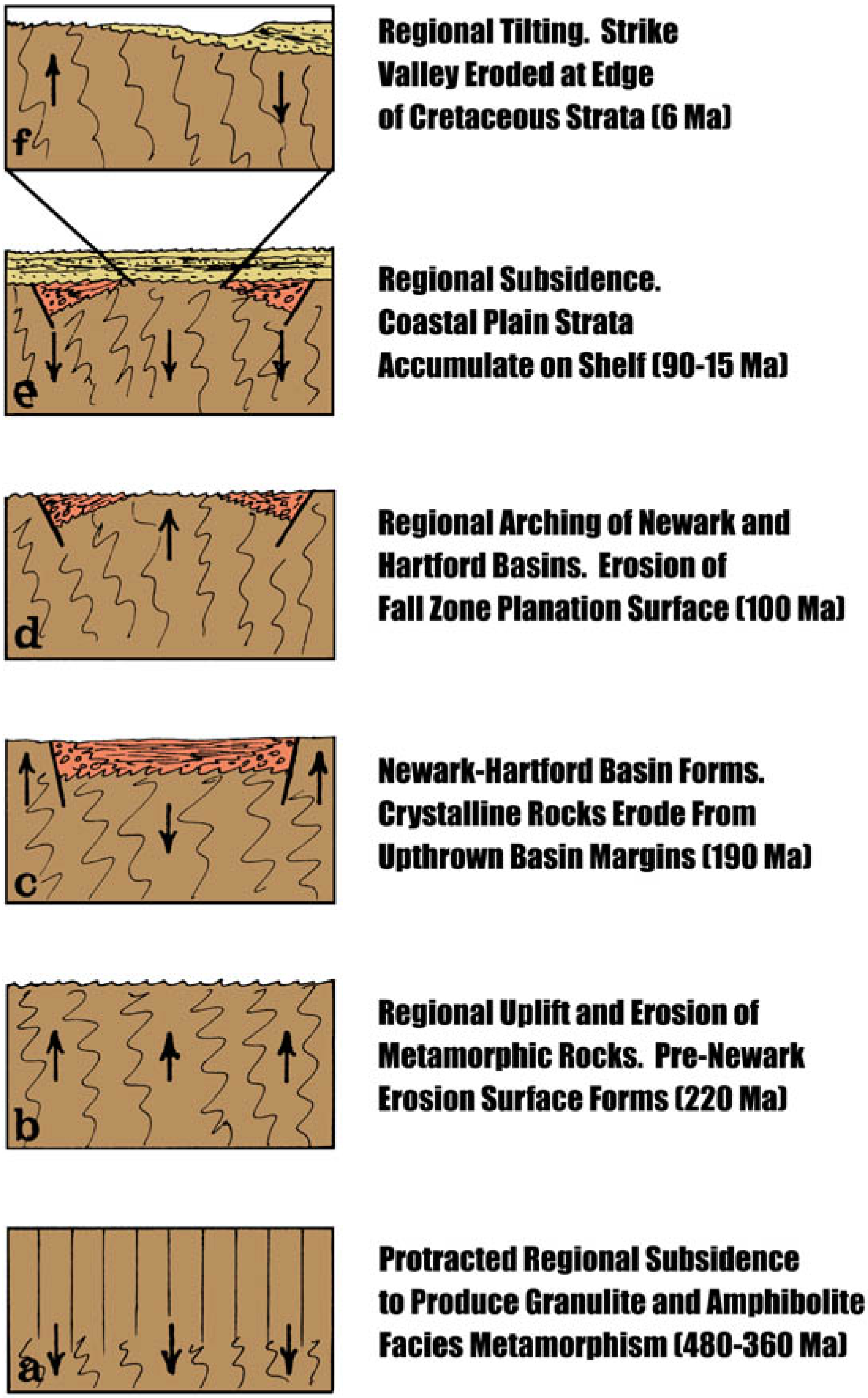


Figure 6. Simplified profile sections showing the development of the New York City region from 365 Ma to 6 Ma. (Colorized from J. E. Sanders sketches.)

GEOLOGY OF THE CORTLANDT COMPLEX

The Cortlandt Complex, a world-class alkalic mafic-ultramafic igneous intrusive, is one of a number of similar plutons that were emplaced across the Taconic suture zone (Cameron's Line) in Medial to Late Ordovician time. These composite mafic-ultramafic intrusives include the Hodges Complex, Mount Prospect Complex and Bedford Augen Gneiss in the western Connecticut highlands as well as the Peach Lake, Croton Falls, Torment Hill, Rosetown and Stony Point Complexes in New York. They are similar in structural setting, mineralogic composition, and age as noted by many workers.

Since the late part of the nineteenth century, geologists interested in igneous rocks have studied the various phases of the Cortlandt Complex near Peekskill, New York. Work by Dana (1881, 1884) and Williams (1884, 1885, 1886, 1888a, b, c) helped set the stage for twentieth-century studies by Rogers (1911a, b), Balk (1928, 1937) and later studies by Shand (1942) and Bucher (1948). K. E. Lowe built on the petrographic mapping of rock types started by Rogers and eventually produced a map (Figure 10) showing 17 different plutonic rock types from syenite to peridotite as small stocks and plutons. No cross section accompanied the map. All workers mention the obvious poikilitic characteristics of the igneous minerals olivine, pyroxene, and amphibole and strong flow layering, particularly in the norite and gabbroic rocks of the central basin.

A structural geologic map of the complex by Balk (Figure 7) identified a western funnel, central basin, and an eastern funnel. Balk's early view of the internal structure was that of a huge deep-seated intrusive with different phases the result of magmatic inhomogeneities and wallrock interactions within a large conical mass (Figures 8, 9). His model envisioned early formed mafic schleiren or knots of material that produced obstructions around which flow-layered norite was emplaced as sheets. Balk's work in similar intrusives showed that structural mapping of internal igneous flow layering could identify the geometry of internal flow in large plutons and allow for identification of subsurface feeders and interpretations on depth of erosion.

Shand (1942) published a simplified map of the Cortlandt Complex (reproduced as Figure 11). His work subdivided the mafic igneous rocks into hornblende-bearing and non-hornblende-bearing phases. His map showed three intrusive centers corresponding to the western funnel, central basin, and eastern funnel of Balk (1937) and provided a connection between the Cortlandt Complex and identical rocks of the Stony Point Complex on the west side of the Hudson River. Shand suggested that rock types found in the central basin of the Cortlandt were the result of fractional crystallization and gravitational settling of an original noritic parental magma that was contaminated by wallrocks to produce hybrid dioritic facies. He also suggested that the poikilitic characteristics of the amphiboles in norites of the central basin were the result of deuteric alteration caused by continuous heat supplied by a vertical conduit beneath the basin. Supported by Bucher's work (1948) the Balk-Shand-Bucher vision of the Cortland has stood the test of time although modern mapping has delineated a more complex internal structure than early workers had visioned and modern geochemical studies have better identified the chemical differention paths and tectonic affinities of the parental and derivative magmas (Bender, 1980; Bender et al., 1982, 1983; Ratcliffe et al., 1982; Tracy et al., 1987).

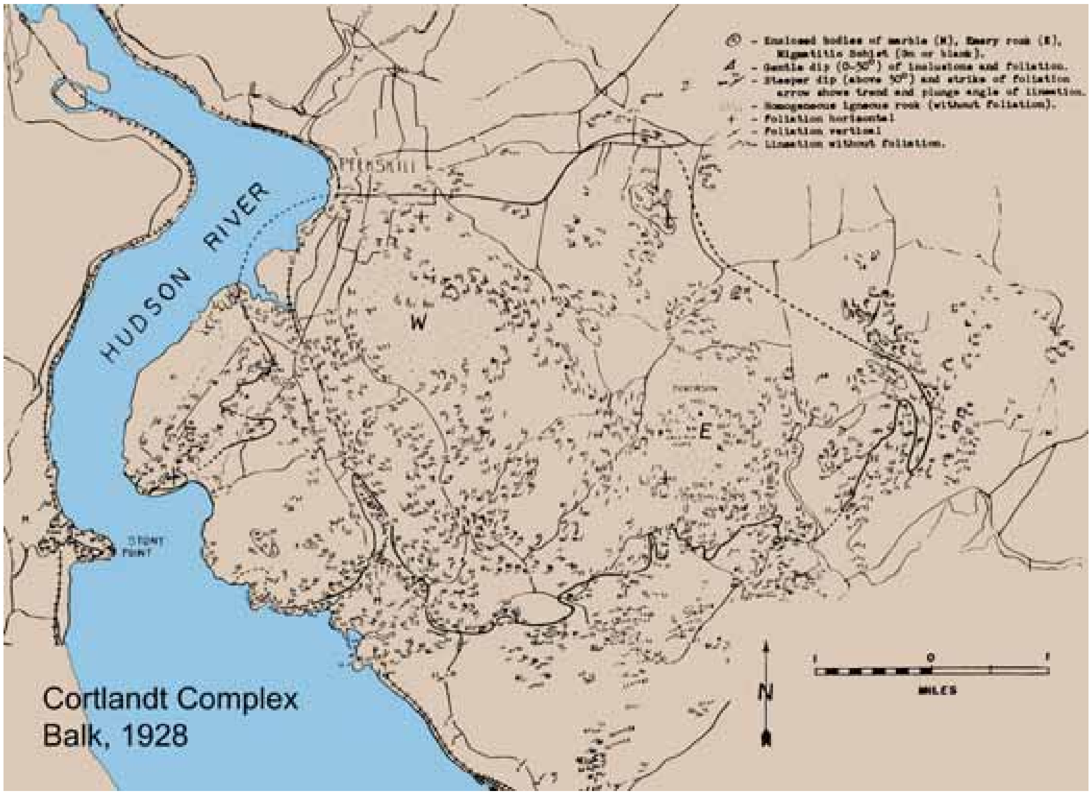


Figure 7. Detailed geological map of the Cortlandt Complex showing the orientation of flow layering and the geometry of internal plutons. (Colorized after Balk, 1927.)

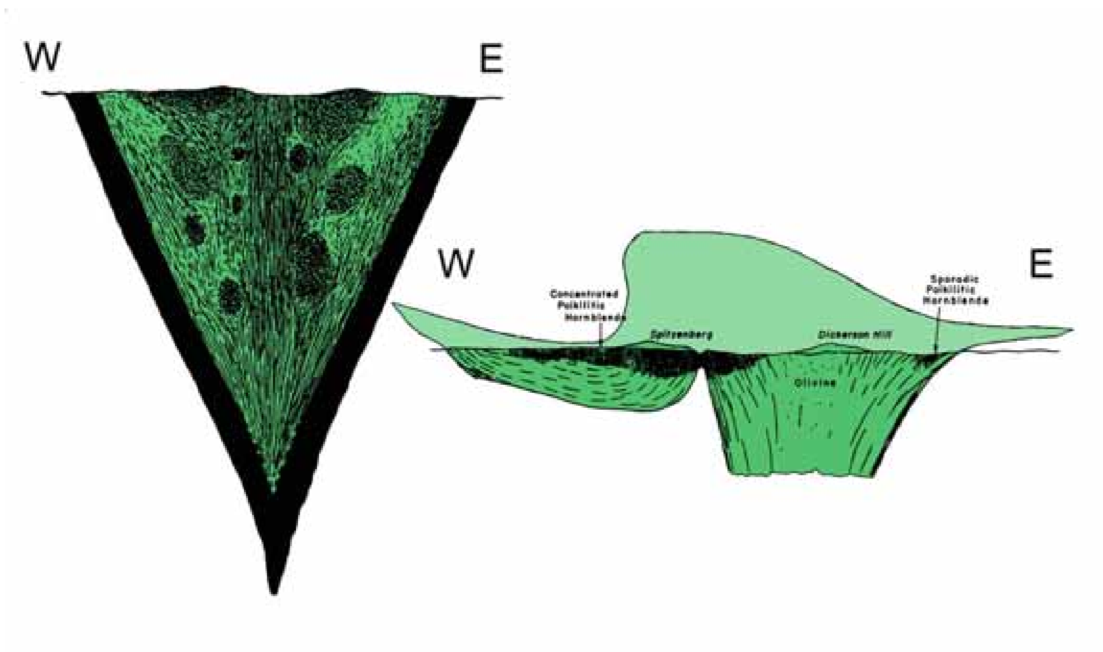


Figure 8. Interpretations of the internal structure of the Cortlandt Complex by Balk (1927) and Steenland and Woollard (1952) on the right.

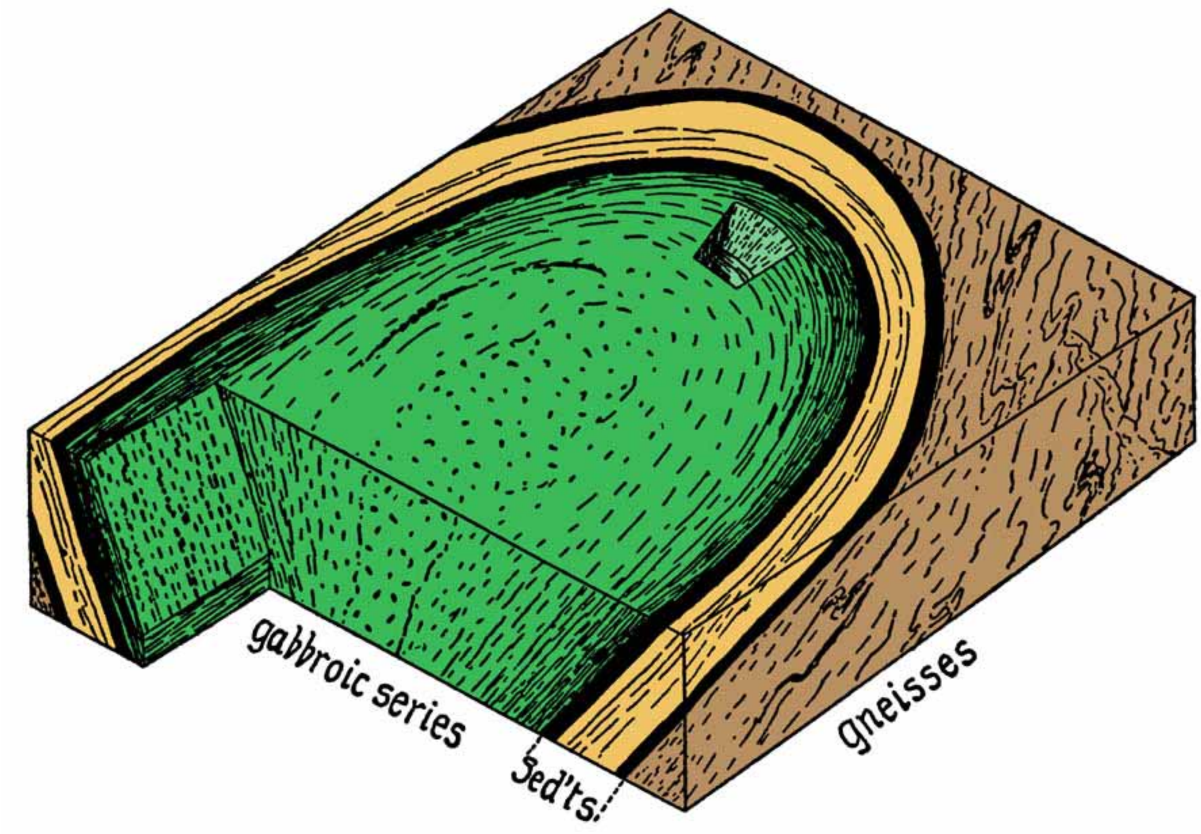


Figure 9. Generalized interpretation of a funnel structure showing flow fabrics in mafic-ultramafic plutons similar to the Cortlandt according to Balk (1937, Figure 34, p. 93). The funnel may be steep or shallow and expose massive igneous rocks of varying composition. Alternatively, the center may be covered by sediment.

By the 1950's geophysical work of Steenland and Woollard (1952) allowed new models of the crustal structure of the Cortlandt Complex. A 30 mgal gravity high was found to occupy the eastern part of the intrusive, centered at Dickerson Mountain, where Balk had identified the Eastern Funnel. The gravity map (colorized in Figure 12a) shows the bulls-eye pattern on the east with some elongation of contours toward the west. Two smaller gravity highs found on the western part of the complex correspond to individual plutons, according to modern mapping. The intrusive model proposed to satisfy the gravity data was that of a steep-walled intrusive on the east and a lopolithic extension to the west. (See Figure 10.)

Friedman (1956) performed important petrographic work on the spinel and emery deposits peripheral to the Cortlandt Complex. He described the contact metamorphic mineralogy and petrographic characteristics of the emery and provided an interpretation (Figure 13) that the Cortlandt was everywhere fed by steep-walled diatremes except for the central part where a buried granitic intrusive (a possible offshoot of the Peekskill granite) held the key to lower than expected gravity readings.

MAP OF THE CORTLANDT SERIES

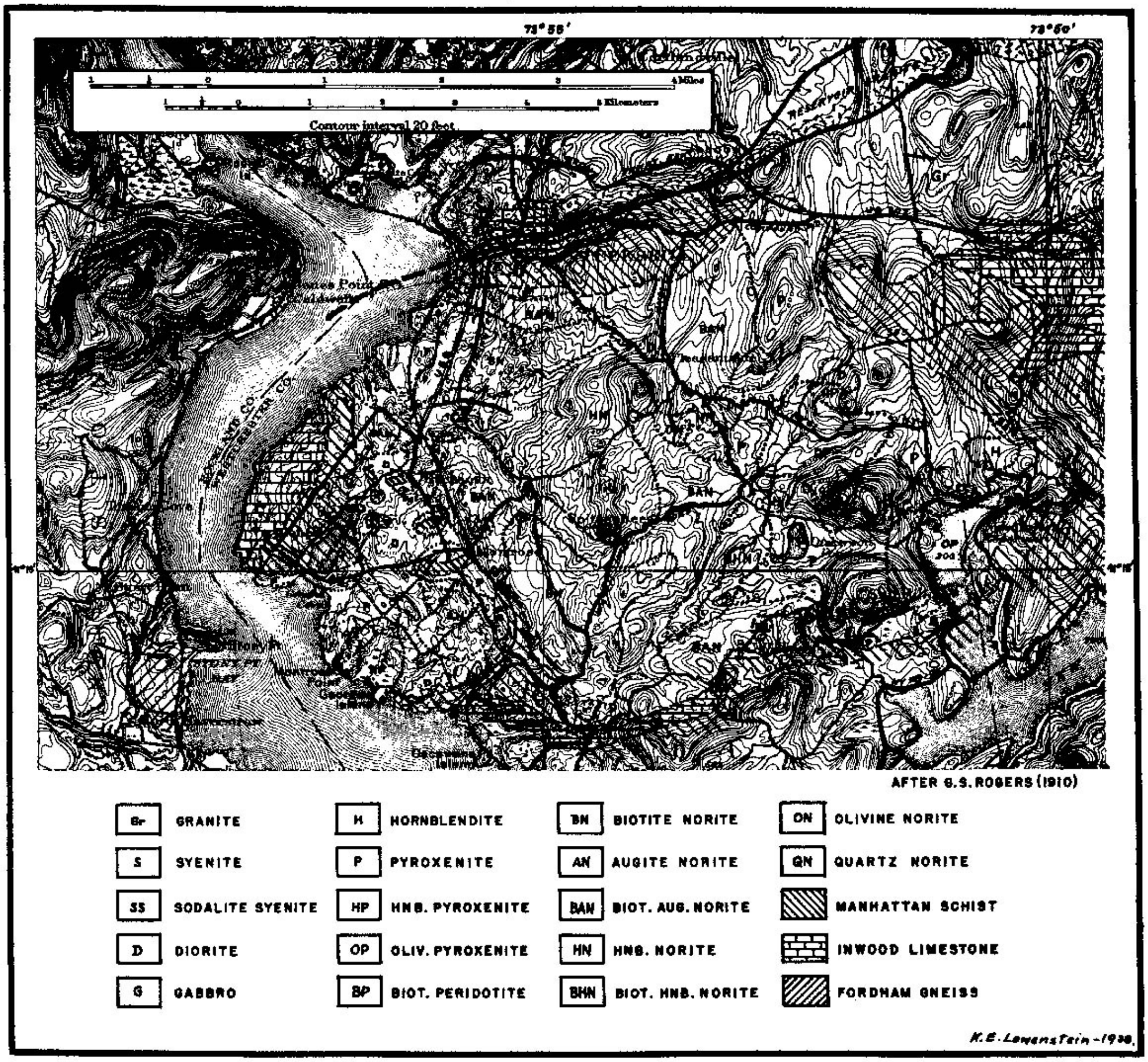


Figure 10. Petrographic map of the Cortlandt Complex by Dr. Kurt E. Lowe of The City College of New York in 1937. The map, after Rogers (1910), shows the great variation in rock types (17 igneous phases) that were found using a purely petrographic approach.

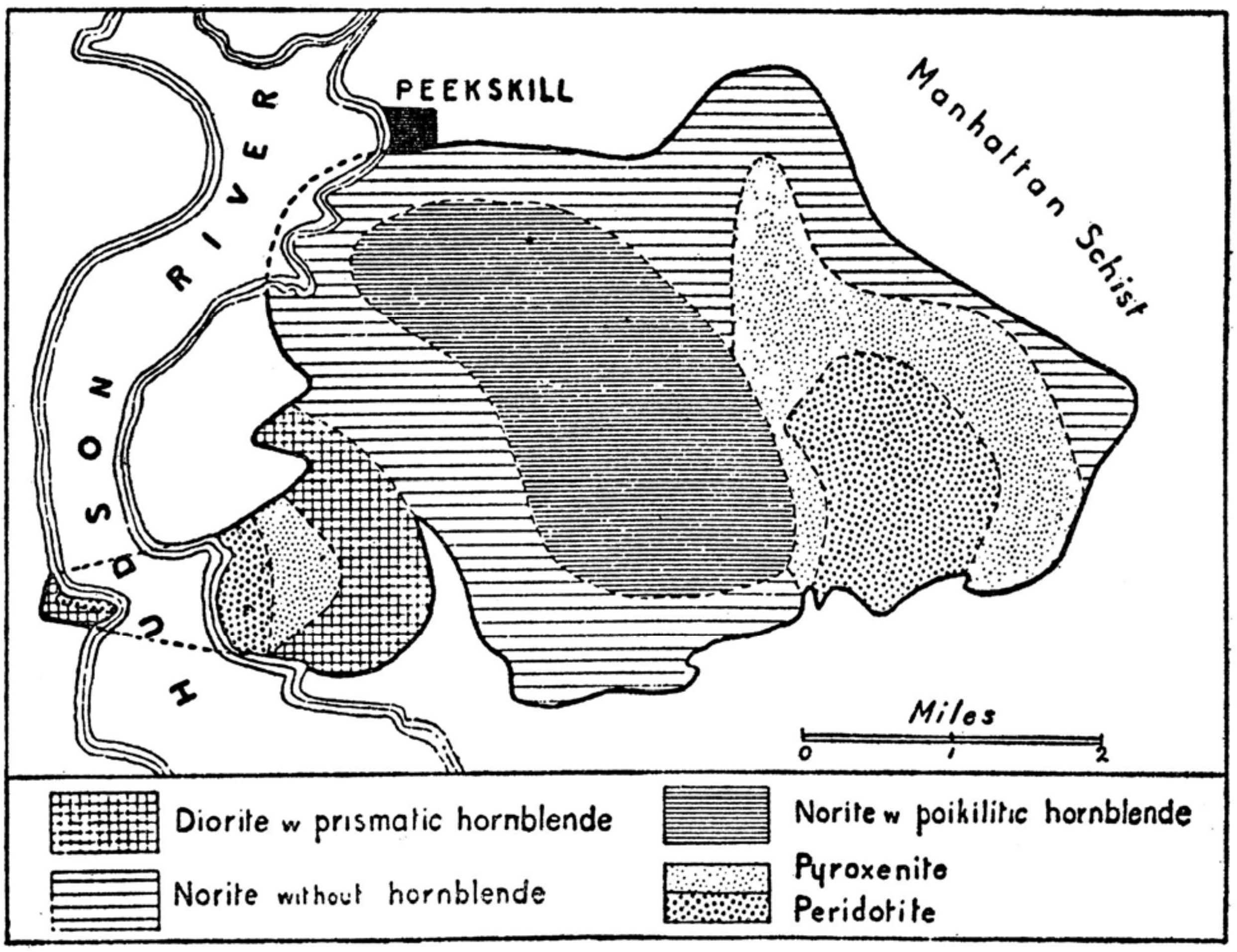


Figure 11. Petrographic map of the Cortlandt Complex according to Shand (1942) showing the connection to the Stony Point Complex and the major plutonic centers.

Modern studies since 1956 have built upon the geological data base of earlier workers and using geochemical- and geochronologic data to supplement detailed field work, Ratcliffe (1968, 1971, 1981) and Ratcliffe et al., (1982, 1983) have better defined the age of intrusion, contact-metamorphic relationships, and internal configuration of the Cortlandt pluton(s). Professor Merguerian first visited the Cortlandt Complex in the early 1970s while a student of Nick Ratcliffe's at The City College of NY. Later, Merguerian went on to map the Hodges Complex, a similar pluton in western Connecticut for his Masters Degree with Nick Ratcliffe as his advisor (Merguerian 1977, Merguerian and Ratcliffe, 1977).

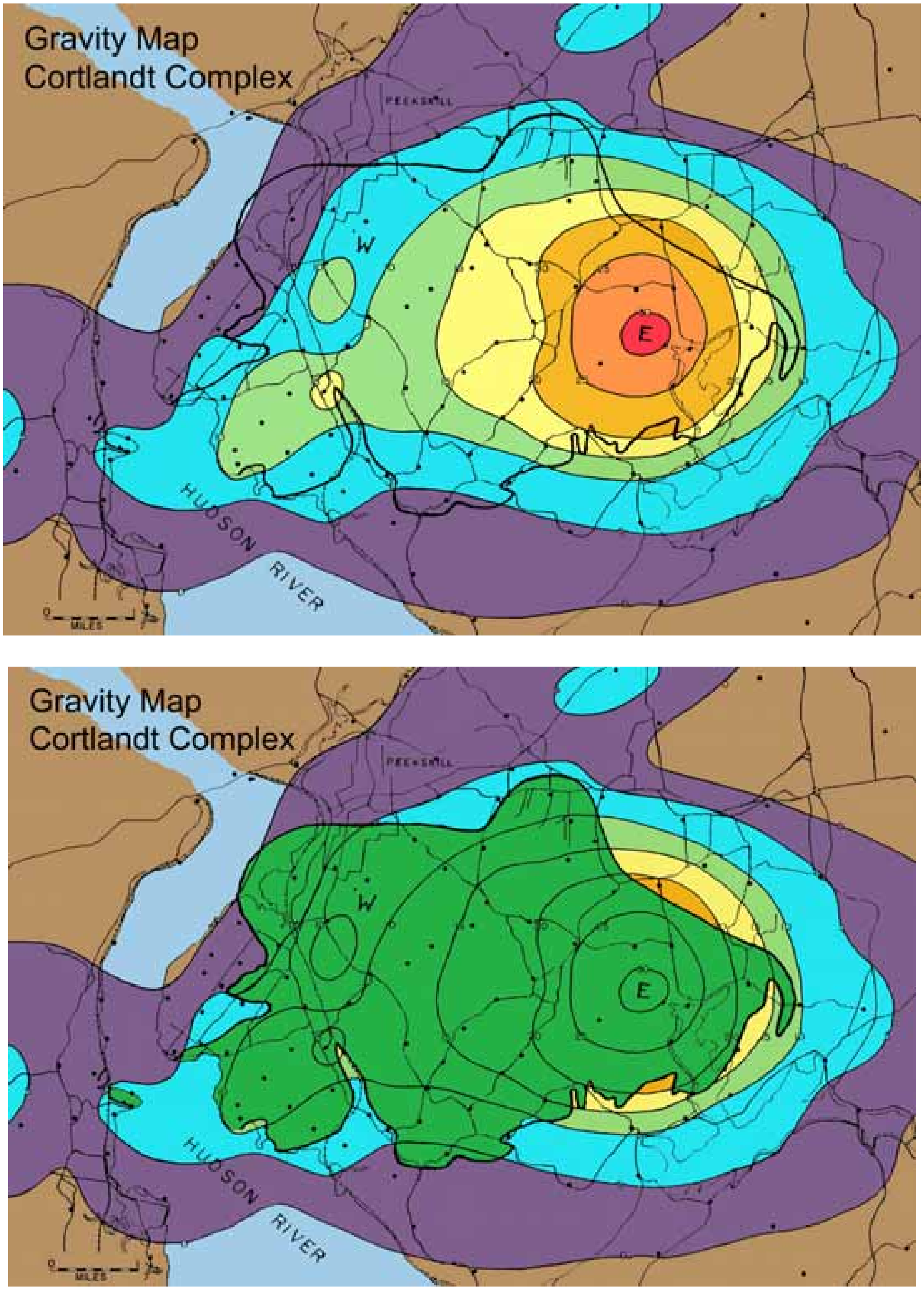


Figure 12. Gravity maps of the Cortlandt Complex. They are colorized to show the overall gravity pattern and the 30 mgal gravity high centered near Dickerson Mountain (the Eastern Funnel of Balk and subsequent workers). The bottom diagram shows the outline of the Cortlandt and its relationship to the overall pattern. Colorized after Steenland and Woollard (1952).

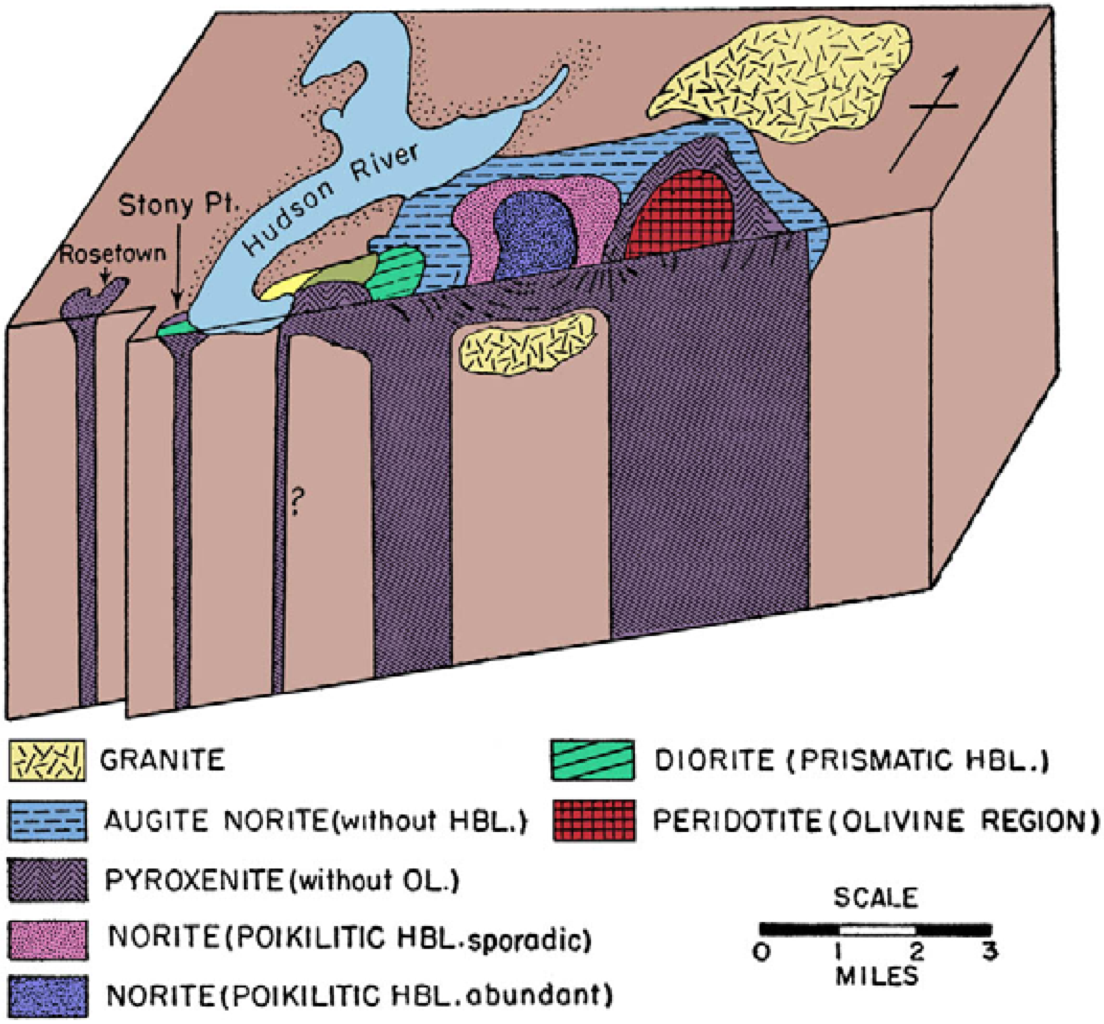
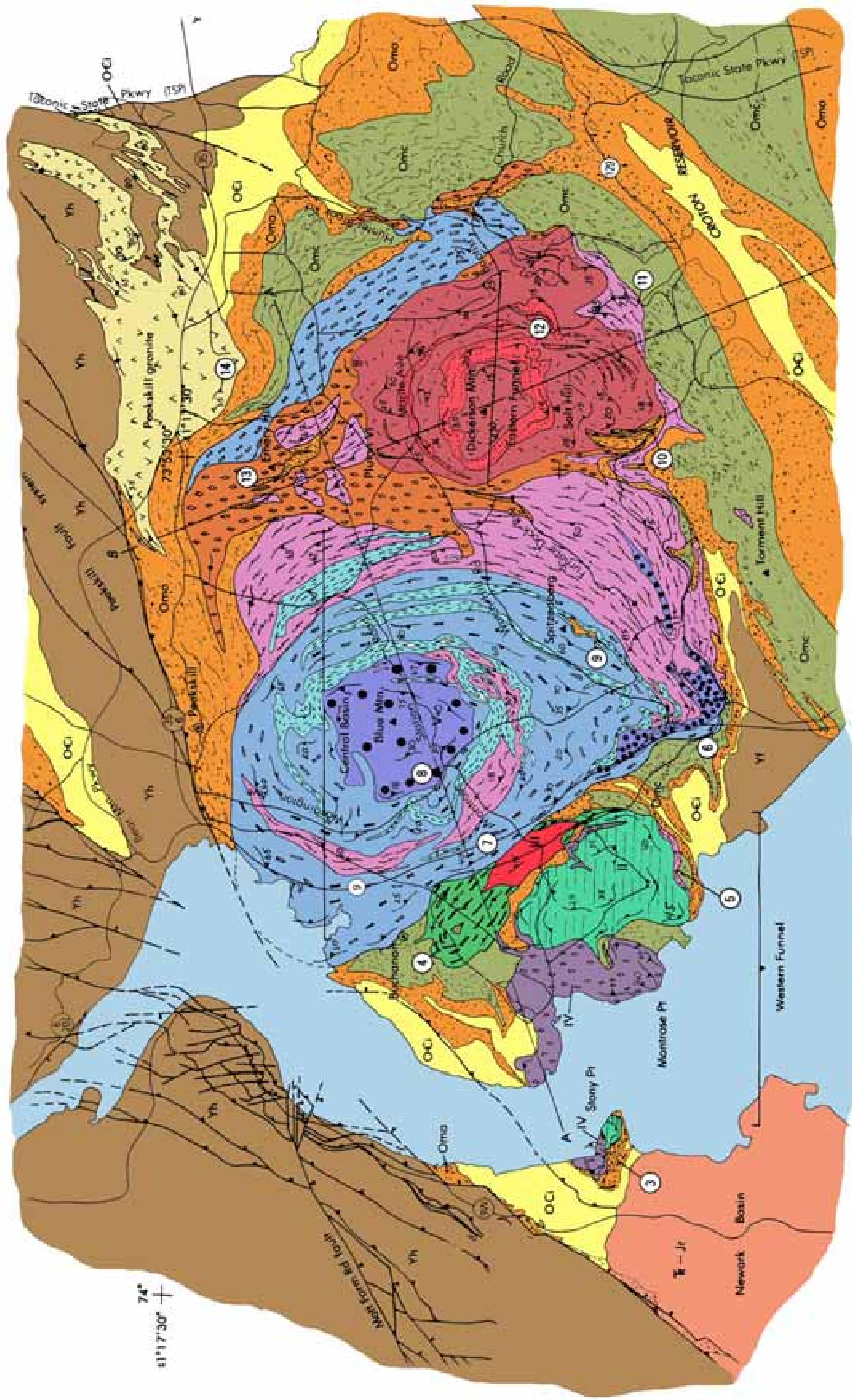


Figure 13. Block diagram showing an interpretation by Friedman (1956) showing vertical feeders beneath most of the Cortlandt Complex and a buried granitic mass in the central part to account for the low gravity measured there.

Studies by Ratcliffe (1968a, b; 1971, 1981) and Ratcliffe at al. (1982, 1983) indicates that the Cortlandt Complex is a lopolithic (inverted mushroom shaped) mass consisting of six temporally related plutons of varying compositions (Figures 14, 15, and 16). Most of the rocks show strong flow layering and the intrusive is thick with xenoliths and screens of country foliated rock. The new mapping corresponds to the contributions of Balk and Rogers but bears little resemblance to the maps of Shand and Bucher. According to Ratcliffe et al. (1983, p. 9) *"The complex is composite and consists of numerous smaller plutons each with its own coherent internal flow structure and comagmatic plutonic rocks showing limited but real* in situ *differentiation as well as textural variations evolving from crystallization of discrete intrusive pulses"*.


Taconic State Pkwy (TSP)
CROTON
RESERVOIR
Peekskill granite
Central Basin
Blue Mtn
Dickerson Mtn
Eastern Funnel
Western Funnel
Montrose Pt
Stony Pt
Newark Basin
Torment Hill
Spitzenberg
Buchanan
Omc
Oma
O-Ci
Yh

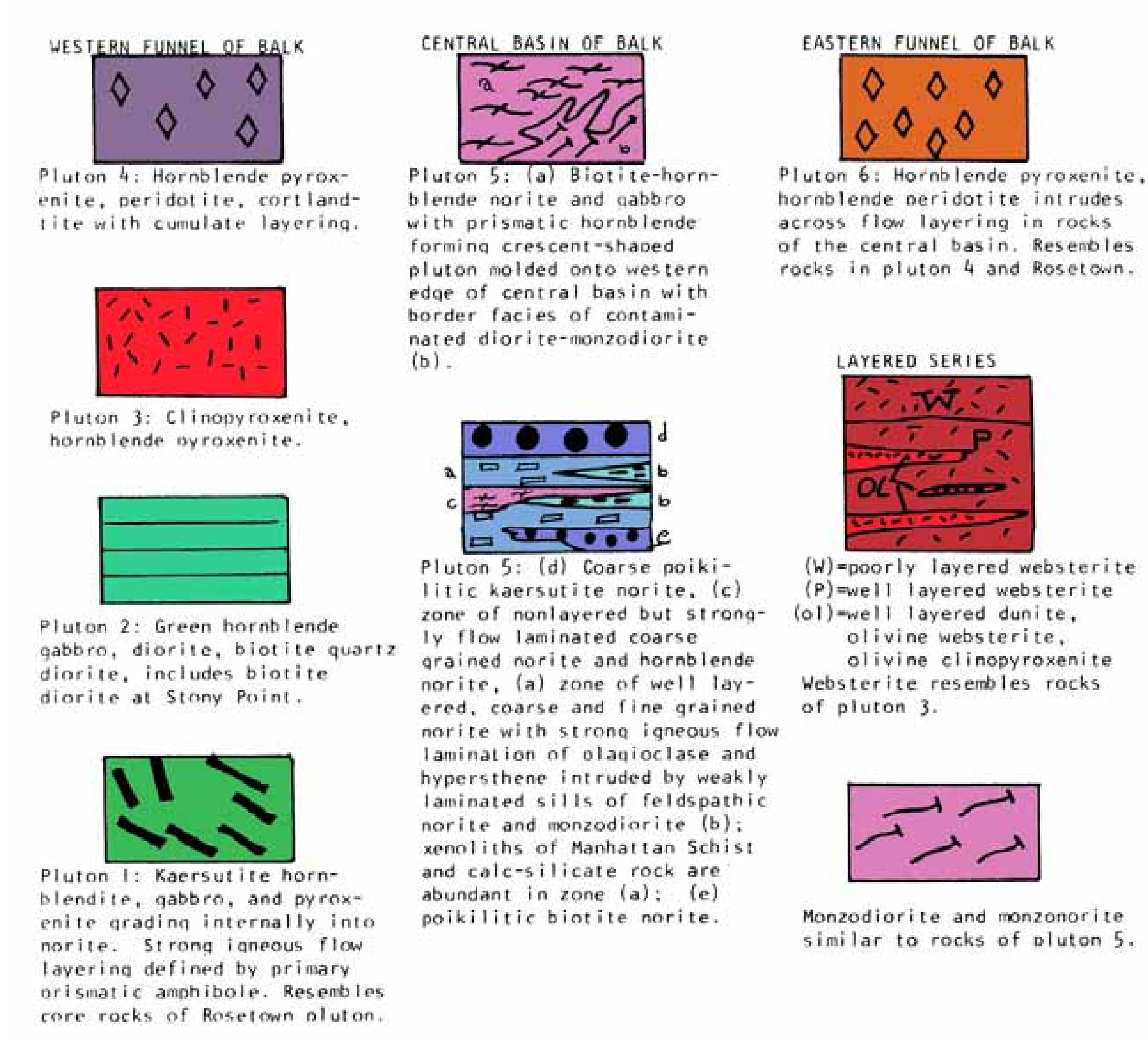


Figure 14. Geologic map of the western and central funnels of the Cortlandt Complex and the Stony Point and Rosetown extensions of the Cortlandt. (Colorized by CM after Ratcliffe et al., 1983.)

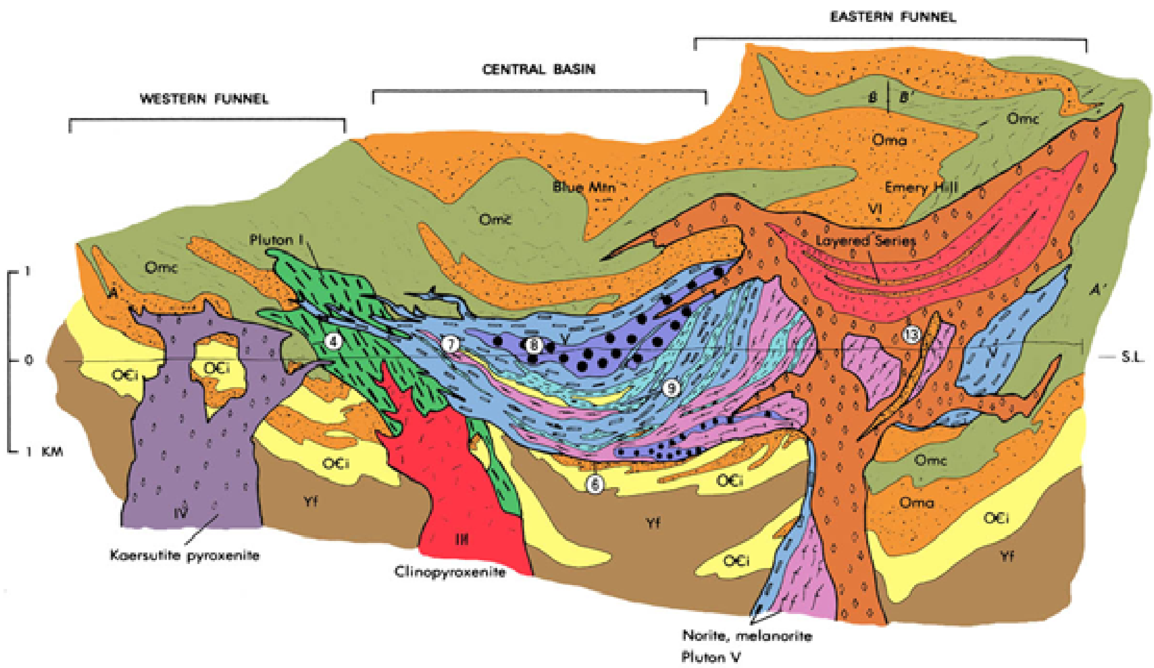


Figure 15. Geologic section oriented SW to NE of the Cortlandt Complex (Section A-A' on Figure 14) showing internal flow structure, cross cutting relationships of the earliest plutons (I, III, and IV), and the general lopolithic form of plutons V and VI of the composite intrusive. Pluton II does not cut line of section. (Colorized by CM after Ratcliffe et al., 1983.)

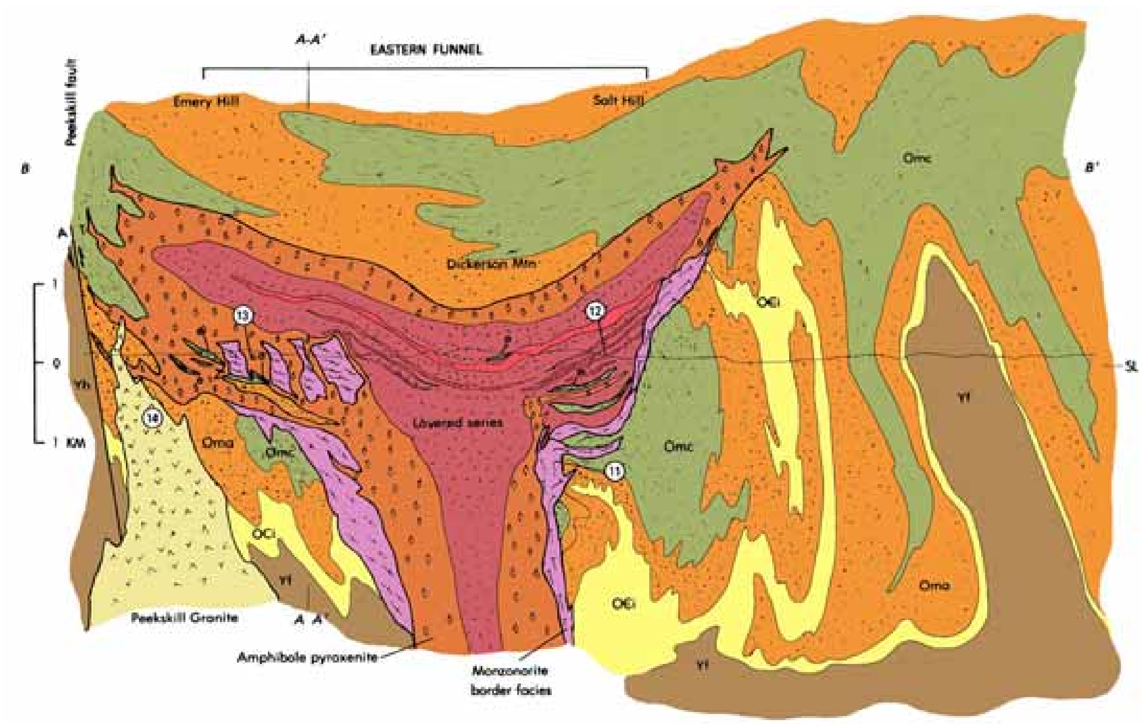


Figure 16. Geologic section oriented NW to SE of the Cortlandt Complex (Section B-B' on Figure 14) showing internal flow structure, cross cutting relationships, and general lopolithic form of Pluton VI of the composite intrusive. (Colorized by CM after Ratcliffe et al., 1983.)

The western funnel of Balk consists of four separate plutons separated by foliated screens and xenoliths of Manhattan Schist and Inwood Marble. Plutons II and IV are also found at Stony Point. These four plutons are interpreted (Figures 14 to 16) as separate but related early intrusives along the western edge of the Cortlandt Complex.

The oldest plutons (Plutons I and II) are the most internally deformed and include many screens and xenoliths of foliated metamorphic rocks that tend to be on strike and traceable to identical rocks outside of the pluton margins. **Pluton I** consists of kaersutite (an alkalic amphibole) hornblendite, gabbro, and pyroxenite that grade internally into norite (an orthopyroxene-bearing gabbro). **Pluton II** consists of a green hornblende gabbro, diorite, and biotite quartz diorite that are correlative with identical rocks at Stony Point on the west side of the Hudson. Both plutons are described as elliptical and funnel-like in shape. They are elongate in a NW-SE direction and dip steeply toward the NE. The hornblendite margin of Pluton I exhibits ESE-plunging primary kaersutitic amphibole flow lineation.

Pluton III consists of clinopyroxenite and hornblende pyroxenite (websterite). It cuts across the core of Pluton I and sends apophyses (offshoots) into Pluton II. The clinopyroxenite pluton is centered above a +15 mgal gravity high (Steenland and Woolard, 1952, Figs 7 and 9) suggesting it may by the main feeder zone for plutons I through III.

Pluton IV consists of coarse-textured amphibole pyroxenite and amphibole peridotite (the type Cortlandtite of Williams, 1886) that display cumulate-type layering produced by crystals settling through the magma. Internal structures show intrusive centers at Stony Point ant at Montrose (Ratcliffe et al., 1983). Pluton IV is texturally dominated by poikilitic kaersutite amphibole enclosing cumulate magnesian olivine, hypersthene, and augite.

Pluton V underlies the central basin of Balk (See Figure 15) and clearly crosscuts plutons I and III of the western funnel. Lopolithic in shape, pluton V consists of biotite-hornblende norite and -gabbro, and coarse poikilitic kaersutite norite and occurs as a relatively thin western flange of a spoon-shaped concordant pluton originating from an eastern intrusive center, as first suggested by Bucher (1948) based on the gravity data of Steenland and Woollard (1952). This pluton contains abundant xenoliths and screens ranging from cm to 100s of m in thickness of Walloomsac schist and Inwood Marble. Newly recognized zones of monzodiorite and feldspathic quartz norite form irregular, discordant units within the norite and coarse poikilitic kaersutite norite is concentrated in the basin center. The main norite pluton shows evidence of injection under compression in the form of bent crystals of plagioclase and biotite and delicate folds in igneous flow layering.

Pluton VI occupies the eastern "funnel" of Balk (See Figure 16) and is composed of amphibole pyroxenite and peridotite which engulfs abundant cognate xenoliths of Pluton V and xenoliths of Manhattan Schist. The schistose xenoliths show evidence for replacement by spinel-emery, producing a number of small mines in the periphery of pluton VI. Funnel-like in shape, pluton VI exhibits a border phase of poorly layered olivine-kaersutite pyroxenite, kaersutite pyroxenite, and pyroxene (kaersutite) hornblendite. In the central layered series rock types include websterite, olivine websterite, and interlayered olivine clinopyroxenite, wehrlite, and dunite. Plagioclase is typically absent and tends to be less than 10% except for areas rich in cumulates.

Gravitational settling of the pyroxenitic central core of the pluton is associated with graded layers and trough banding. Well-layered peridotite 68 m thick underlies black coarse-grained websterite 204 m thick on Dickerson Mountain. The peridotite contains layers of wehrlite, olivine pyroxenite, and dunite 0.5 to 1.0 m in thickness. Below this coarse-textured greenish clinopyroxenite with interlayered olivine clinopyroxenite, peridotite, and dunite about 374 m thick is exposed (Ratcliffe et al., 1983). Coarse greenish pyroxenite extends to the wall of the pluton east of the Croton Reservoir.

The **Peekskill Granite** crops out to the north and west of the Cortland Complex (Figure 14). It consists of bioitite-muscovite granite adamellite and granodiorite with a bulbous western end and central mass which sends wedge-like dikes northeastward into Proterozoic gneiss. No genetic connection has been demonstrated for the Peekskill and Cortlandt Complexes and they appear to be of different ages. Rb/Sr dating yields a Devonian age for the Peekskill intrusive. Yet there are REE and major element similarities with granodiorites of the Rosetown pluton, a similar mafic-ultramafic pluton found west of the Stony Point complex on the west side of the Hudson (Ratcliffe et al., 1983).

The results of geochronologic dating of various phases of the Cortlandt Complex indicate that the plutons were intruded roughly 430 to 470 Ma (million years ago). Because the intrusives are surrounded by contact aureoles, 25 to 50 meters thick, in which rocks of the Manhattan Prong, which already possessed a regional metamorphic fabric related to the Taconic orogeny, have been subjected to contact metamorphism, these radiometric dates on the intrusive rocks set a medial Ordovician minimum age for the Taconic event. Such a date corroborates estimates from structural- and paleontologic studies farther to the north along the sole thrusts of the Taconic Mountains.

The Cortlandt plutons cut the Taconian regional metamorphic fabrics and ductile shear zones in the country rock. They also crosscut and deform Taconian regional isograds (Figure 17) and cause overgrowths on plicated S_2 regional fabrics in the bounding rocks. This and the map evidence (Figure 18a, b) show that the Cortlandt intrusives are well bracketed with respect to regional structural deformation. The intrusives shoulder and deform F_3 axial traces and are deformed by F_4 and F_5 open folds. The fact that Cortlandt rocks have not been regionally metamorphosed and are only mildly folded indicates that they were intruded during the waning stages of the Taconic orogeny and lay outside the domain of Acadian (Devonian) metamorphism. Perhaps the open F_4 folds are the result of Acadian orogeny. Kyanite, sillimanite, staurolite, and garnet overprinting S_3 fabrics within the contact aureole of the Cortlandt Complex. These discoveries are the basis for the interpretation that the complex was intruded at former depths of 25 kilometers in the Manhattan Prong. Figures 18c and 18d show the intricate folds of the metamorphic rocks in the vicinity of the Cortlandt Complex with the plutons removed.

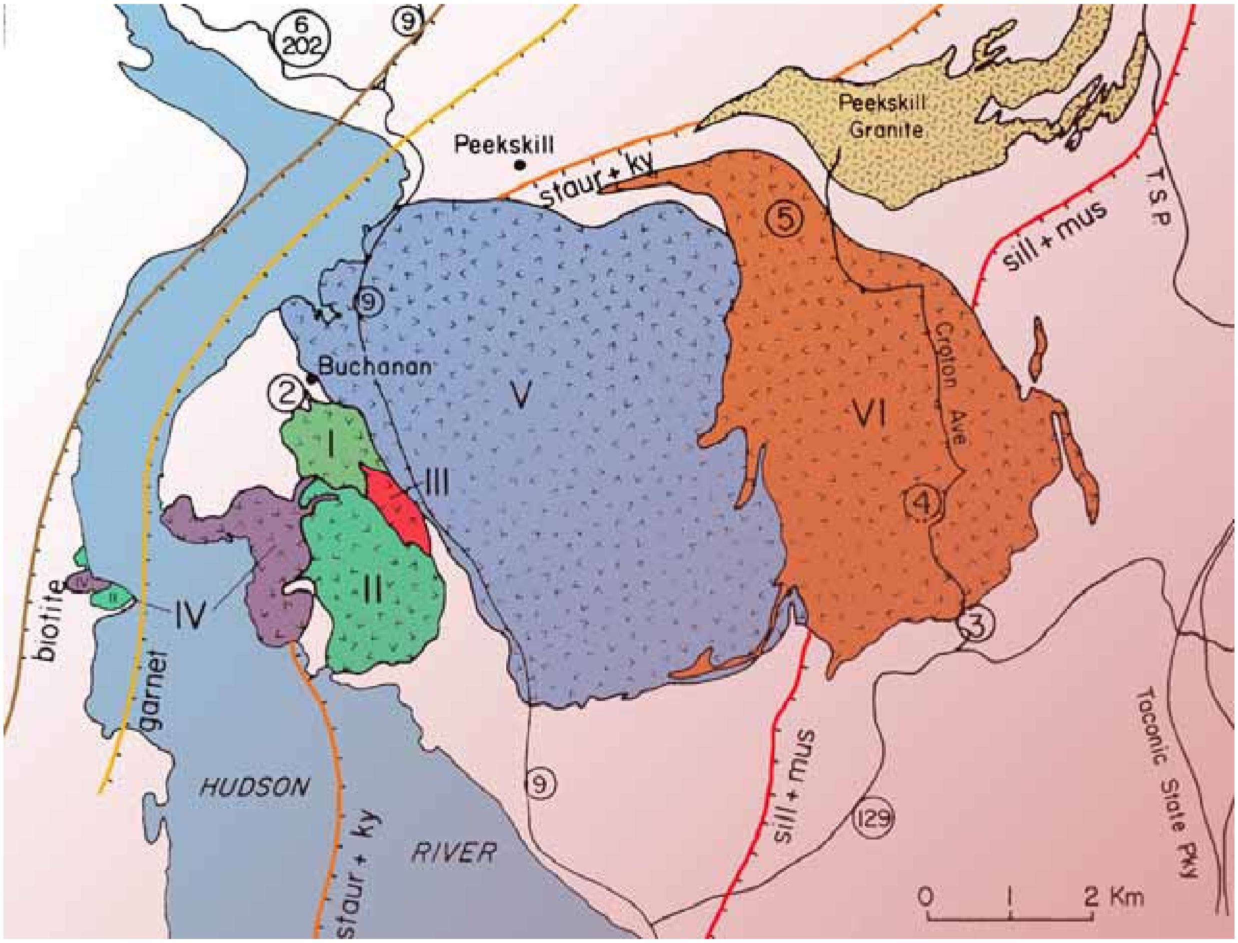


Figure 17. Map showing truncation of Taconian regional isograds by plutons of the Cortlandt Complex. (Colorized by CM from Tracy et al., 1987.)

Intrusive Model for the Cortlandt Complex

The detailed mapping of Ratcliffe has allowed a four phase sequential view of the intrusive history of the igneous complex (Figure 20). The first stage (A) involves early intrusion of kaersutitic gabbros and ultramafic plutons (Plutons I through IV) along the west edge of the Cortlandt Complex as well as across the Hudson at Stony Point. The second stage (B) involves the intrusion of intermediate aged norite, monzonorite, and hybrid rocks (Pluton V) as a large spoon-shaped lopolithic mass to form the Central Basin. The third stage (C) encompasses the late intrusion of parental kaersutite pyroxenite in various phases (Pluton VI) from a plutonic center at the Eastern Funnel of Balk. Sills of websterite and dunite were formed at this time. The final stage sees the injection of lamprophyre dikes along conjugate fractures (D).

Dissimilarities in age and chemistry preclude any connection between the Devonian Peekskill Granite and the Cortlandt Complex.

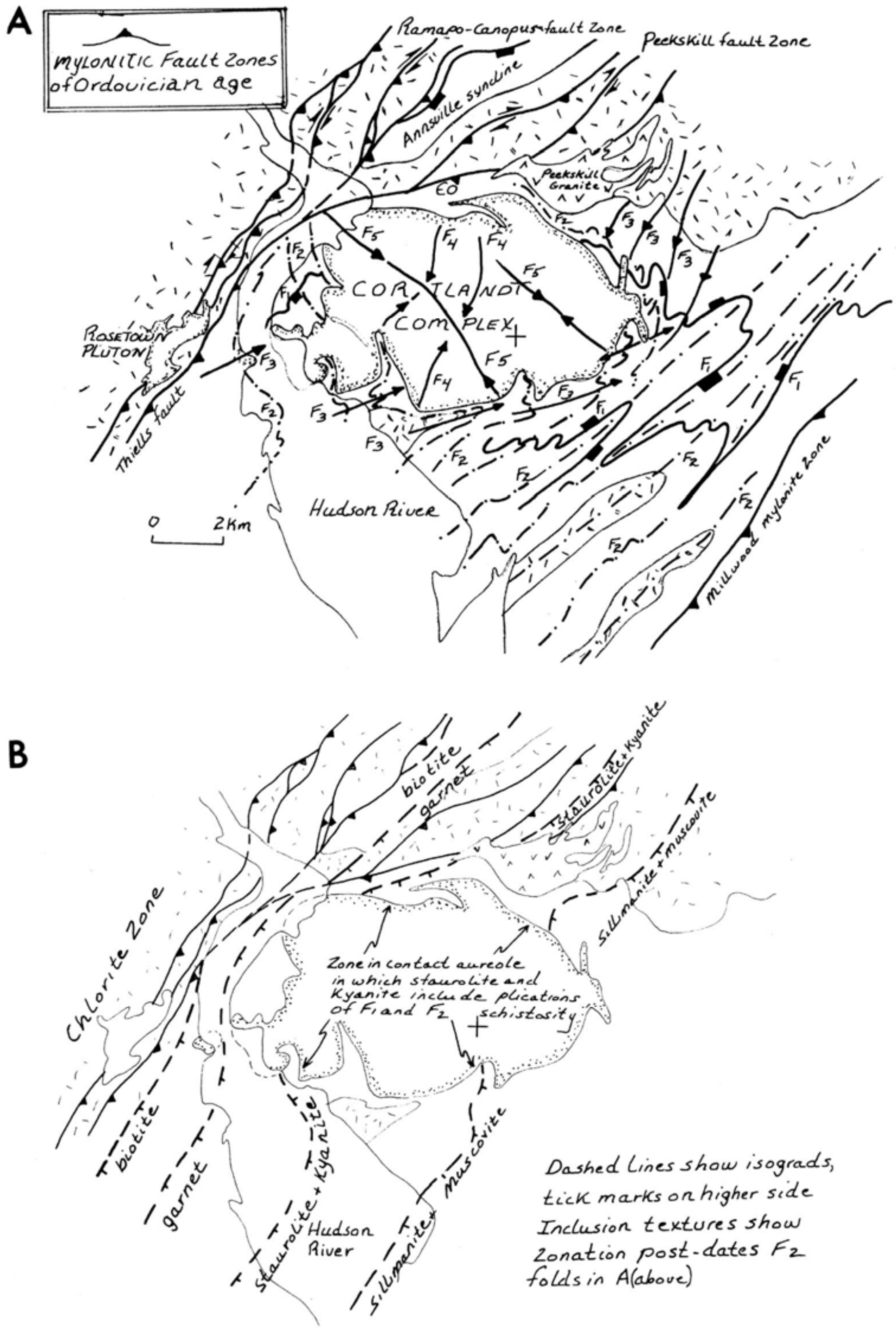


Figure 18. Map A shows F_1 through F_5 axial traces and traces of regional Taconian ductile faults in the vicinity of the Cortlandt Complex. Note that the Cortlandt truncates F_1 through F_3 folds but is deformed by F_4 and F_5. Map B shows truncation of regional isograds and areas where contact assemblages overgrow S_2 and probably S_3 fabrics. (From Ratcliffe et al., 1983, Fig. 9.)

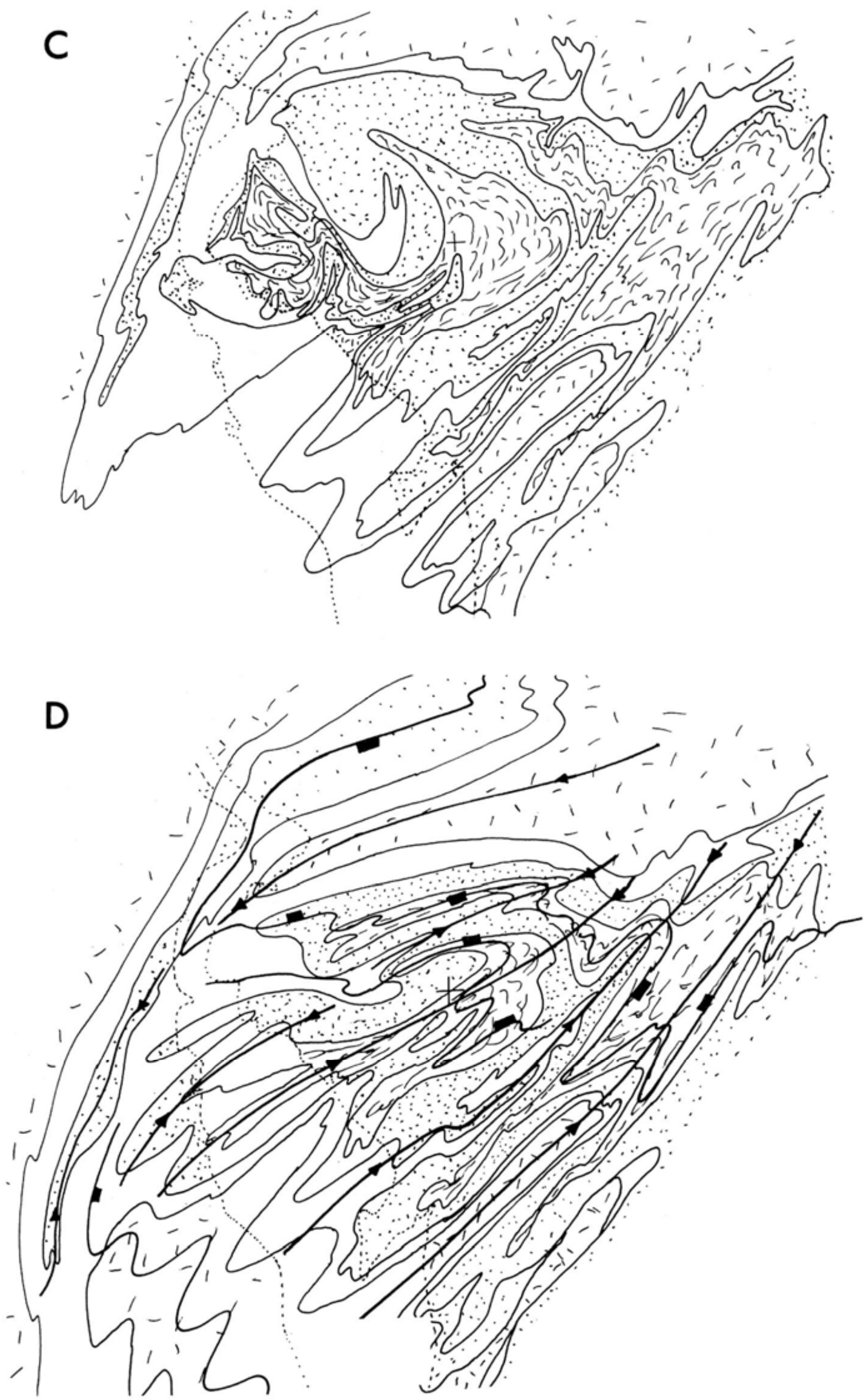


Figure 19. Map C shows the effects of F_1, F_2, and F_3 folds in metamorphic rocks of the Fordham Gneiss (hashed pattern), Inwood Marble (unpatterned), Walloomsac [=Manhattan A] (stipled), and Manhattan Schist (dashed) with Cortlandt Complex removed. Map D is a view of F_1 and F_2 patterns before injection of the Cortlandt Complex. Map created by structural mapping and tracing screens and xenoliths through complex. (From Ratcliffe et al., 1983, Fig 9.)

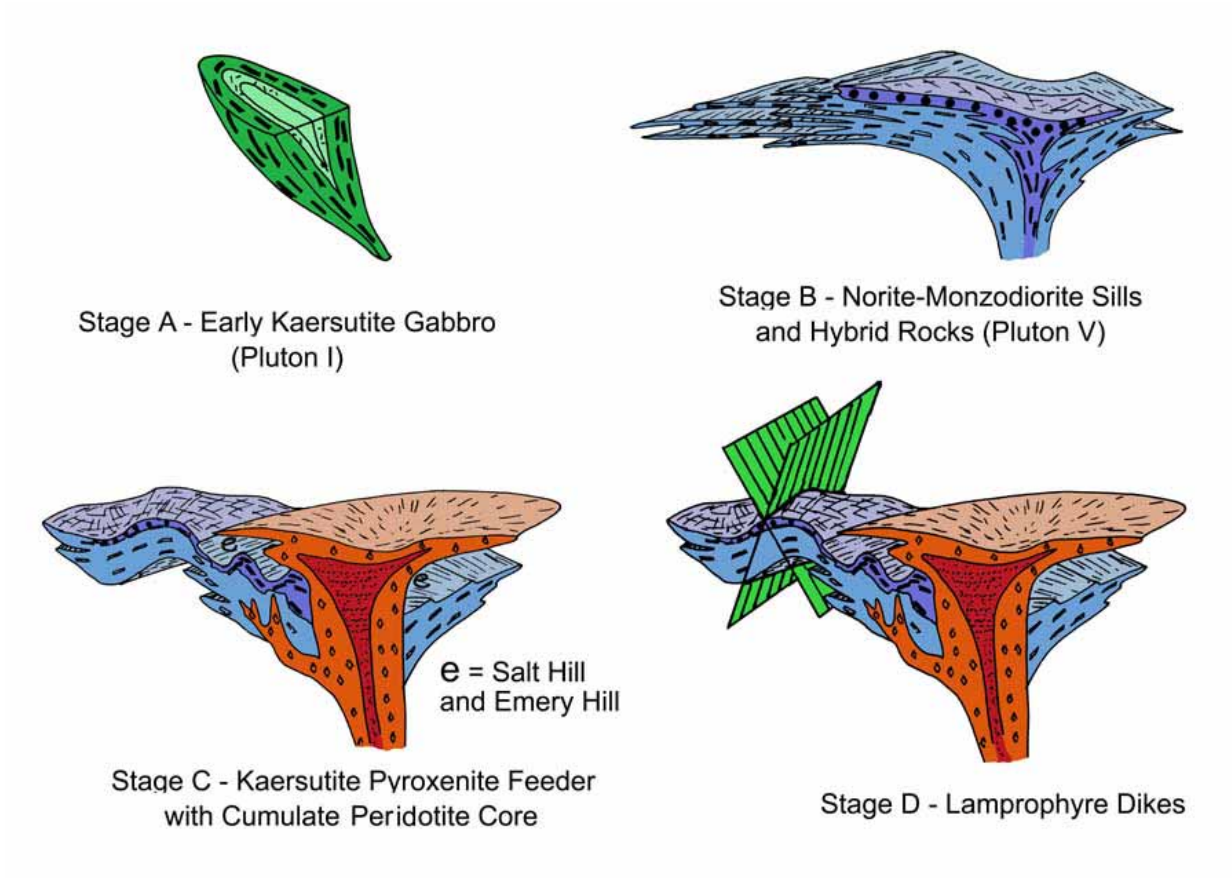


Figure 20. Sequential diagram showing the evolution of the Cortlandt intrusive suite as a four stage process. (Colorized by CM from Ratcliffe et al., 1983, p. 22, fig. 8.)

The fact that the Cortlandt rocks have not been regionally metamorphosed indicates that they were intruded during the waning stages of the Taconic orogeny and lay outside the domain of Devonian metamorphism. Studies of the stability fields of minerals found within the contact aureole of the Cortlandt Complex are the basis for the interpretation that the complex was intruded at depths of 25 kilometers into the Manhattan Prong.

Our field trip today will visit as many stops as possible starting with a number of localities from Merguerian and Sanders (1992, 1994a), new localities studied during an April 2004 trip with Hofstra student Meaghan Baldwin, and localities from a field guide prepared by Ratcliffe et al. (1983) for a trip prepared for the 1983 Northeastern Section meeting of the Geological Society of America. I have attached the appropriate stop descriptions at the end of this guide for you to follow along for today's trip to the Cortlandt Complex and beyond.

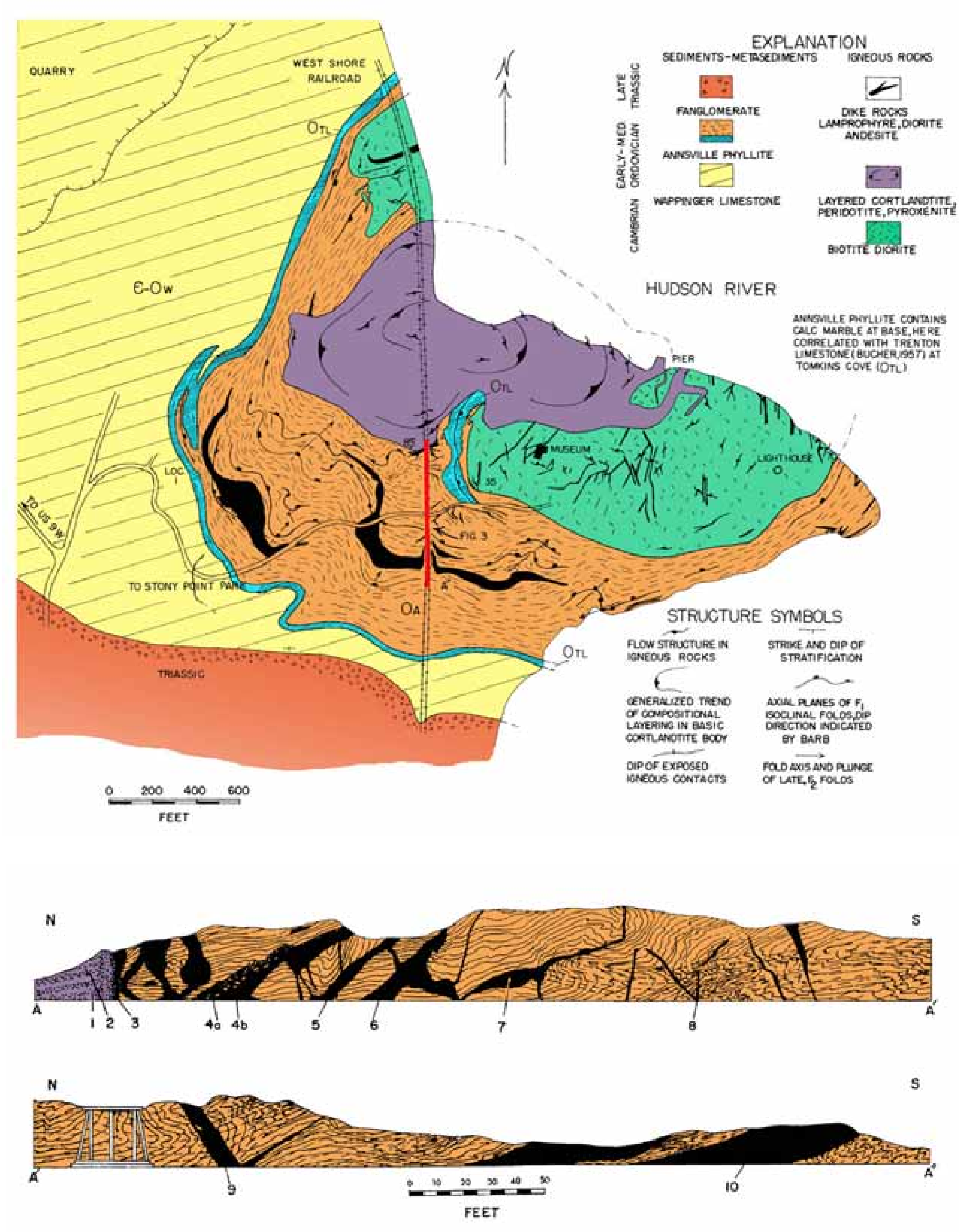


Figure 21. Geologic map and sections from Stony Point showing plutonic rocks and their contact with metamorphosed bedrock. (Colorized by CM from Ratcliffe, 1968.)

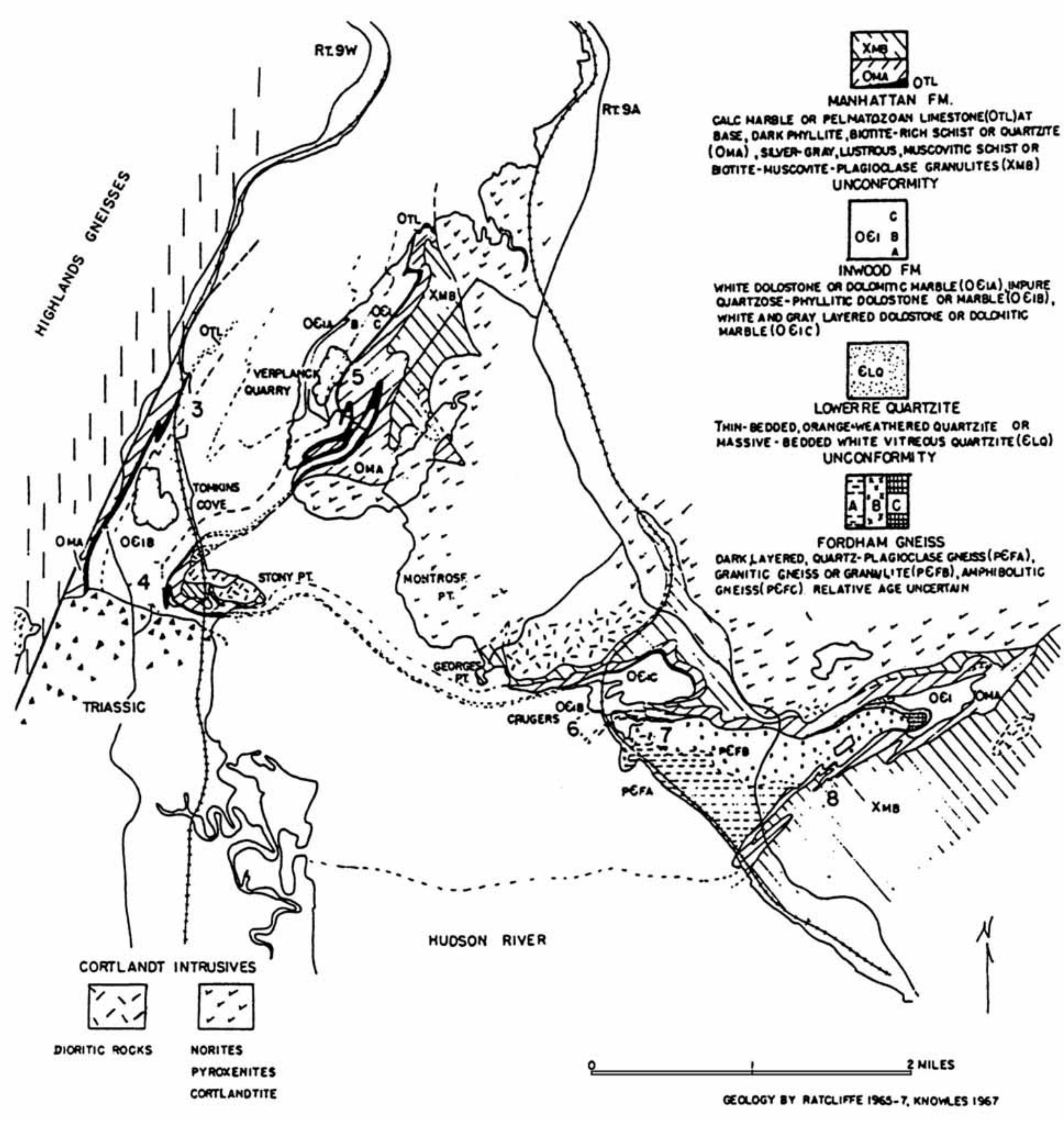


Figure 22. Geologic map of the west edge of the Cortlandt intrusives showing the lithic subdivisions of the Manhattan and Inwood Formations. Note the position of the Tomkins Cove Quarry on the west side of the Hudson, north of Stony Point. (From Ratcliffe, 1968.)

FIELD TRIP STOPS

Stops 1-6 include a road log and are modified from field guides to Peekskill Hollow by Merguerian and Sanders (1992) and a guide to Bear Mountain and vicinity by Merguerian and Sanders (1994a). After these six stop descriptions I have attached descriptions for two additional stops without a road log on the west side of the Hudson River from Merguerian and Sanders (1993).

STOP 1 - Igneous flow layering in norite, west edge of Pluton V of the Cortlandt Complex. [UTM Coordinates: 588.94E / 4568.78N, Peekskill quadrangle.]

The purpose of this stop is to examine flow layering in igneous rocks of Pluton V (norite) of the Cortlandt Complex. (Stop 1 is located at the 25° flow layering symbol between Stops 4 and 9 on Figure 14.) We are situated at the western edge of the Central Basin of Balk (1927). Here notice the well-developed, northeast-dipping coarse- to medium-textured norite with an igneous flow layering oriented N30°W, 26° NE. The layers consist of plagioclase laths (reddish tint) and hypersthene (an orthopyroxene). Note the northeast-dipping lithologic contact between texturally and mineralogically different phases within the igneous rock, the presence of schlieren (mafic clots), and the compact, dense mafic rock here. Note the crossbeds and local tight folds of mafic mineral layering.

During intrusion, the refractory nature of these dense, iron+magnesium enriched mafic rocks resulted in great contrasts in temperature across their boundary with the adjacent country rocks. The chilling, progressive effects of contact metamorphism will be examined in detail and discussed at Stop 5 from the Ratcliffe et al. (1983) trip stop (below).

20.0 Continue west on Bleakley Avenue. Note more coarse-textured mafic rocks on R.
20.3 Traffic light at entrance to Indian Point Nuclear Generating Station (Turn on your geiger counters.) Turn L onto Broadway headed toward Verplanck and note Cortlandt rocks on both sides of road.
20.6 Powerlines by transformer station on L.
20.8 Indian Point 3 entrance on R.
21.1 Schistose crop on R is Stop 2.

STOP 2 – Foliated Graphitic Manhattan Slate/Phyllite = Walloomsac Formation. [UTM Coordinates: 587.67E / 4567.90N, Peekskill quadrangle.]

Highly flattened lustrous fine grained graphitic slate and phyllite is exposed along the west side of Broadway in a steeply inclined cut. By rubbing your finger in certain spots a black smudge from the graphite is evident. The highly flattened regional foliation is oriented N9°E, 70°SE. The rocks are internally folded by tight south-plunging isoclinal folds and exhibit a strong intersection lineation. Both the lineation and the foliation along the exposure are warped by open, steep east-plunging folds with axial surfaces oriented N80°W, 77°NE.

21.5 Turn R onto 11th Street.
21.6 Pull over to side of road for Stop 3.

STOP 3 - Glaciated Inwood Marble and Manhattan Schist? [UTM Coordinates: 587.29E / 4567.44N, Peekskill quadrangle.]

On the north side of 11th Street, note the low, rounded knoll underlain by calcite marble (Inwood or Balmville?) with interlayers of mica-tremolite schist. Here, the marble is fine-textured and foliated but late south-plunging folds warp the lithologic layering. The vertical foliation in the marble strikes N15°E but is locally variable. Glacial striae on the marble here are oriented S17°W.

On the south side of the street both marble plus schist? (or is it phyllite?) show glacial striae and grooves trending S7° to 18°W. According to Ratcliffe et al., (1983) the Manhattan Schist member A (of Hall, 1968) is weakly metamorphosed here. In our opinion, the rock is technically a compact, carbonaceous- and pyritiferous phyllite or slate showing none of the coarse mica textures typical of schist. Siltstone interlayers noted by Meaghan Baldwin during a field trip in April 2004, are tightly folded about folds with axial surfaces parallel to the penetrative muscovite+graphite slaty cleavage which is oriented N60°E, 77°SE. Oxidation of abundant fine-textured pyrite in the rock has created a deep iron-stained weathering color.

This stop is included to examine the Walloomsac Formation (or Manhattan A) and to take a sample to compare it to the Annsville Phyllite at its type locality (Stop 5). Of geologic significance, Stop 3 is one of the few places where the low regional metamorphic grade allows one to examine the contact between the Cambro-Ordovician carbonates and their Medial Ordovician pelitic cover rocks. As such, the stratigraphic contact here is overturned and dips toward the southeast. We suspect that the calcite marble exposed here should be assigned to the Balmville. If so, then within the marble at this exposure, is the sequence boundary between the Sauk Sequence (dolomitic marbles) and the basal limestone of the Tippecanoe Sequence.

16.2 Continue E on Eleventh Street.
16.25 Turn R onto Broadway (southbound toward Verplanck).
16.4 Traffic light, Eighth Street.
16.5 Turn L in front of Verplanck Post Office at Sixth Street.
16.7 Traffic light at Westchester Avenue.
16.9 Crossing Lake Meahagh.
17.1 Outcrop on R by curve before going uphill.
17.3 Sunset Road on R.
17.4 Blinker light Tate Avenue. Sixth Street is now Kings Ferry Road.
17.5 Outcrop of mafic rocks on R.
17.55 Bannon Road on L.
17.6 Traffic light on curve to R.
17.9 Montrose Point Road to R. Outcrop of mafic rock on curve to L (recently brushed back for our viewing pleasure).

18.1 Crest of hill. Mafic rock exposed on R.
18.3 Traffic light at intersection of NY 9A (New York-Albany Post Road). Turn R onto NY 9A southbound.
18.4 Travis Avenue on R.
18.55 Mafic rocks on L.
18.9 Dutch Street on R for Georges Island Park.
19.0 Entrance on R for Franklin Delano Roosevelt Veterans hospital for Stop 3.
19.05 Guard house on R.
19.1 Bear L at double blinker light.
19.5 Parking Lot F, after D, and E, on L. Continue on main road.
19.7 Turn L following sign to Picnic Area and River Front Area.
19.75 Where road starts downhill, exposure on R of Cortlandt diorite.
19.8 Small knoll on R by gate is Manhattan Schist (Lower Member). We have just crossed the contact between the diorite and the schist.
19.9 Park in parking lot at bottom, by river for Stop 3.

STOP 4 - Glaciated Manhattan-Inwood contact and the Cortlandt Complex, Franklin Delano Roosevelt Veterans Hospital. [UTM Coordinates: Traverse from 589.55E / 4565.1N to 589.1E / 4565.1N, Haverstraw quadrangle.]

Walk back uphill on the paved road to the glaciated knoll of bedrock. The rounded knoll has been sculpted by glacial ice coming from two directions. As a result, two roche moutonnées intersect so that the asymmetry of the first has been modified by the ice that formed the second. The obvious grooves, oriented N15°E to S15°W at north end of the outcrop that swing to S10°W at the south end, are products of the most-recent glaciation. These grooves all but mask an older general rounding to the surface of the bedrock knoll, which resulted from glacial flow N47°W to S47°E. Thus, according to our scheme, we see the results of the last two (youngest) glaciations. In the somewhat comparable bi-directional bedrock knoll in Inwood Park that we discovered on our On-The-Rocks Manhattan trip, the inferred order of glacial sculpting is the reverse: the older feature sculpted by ice flowing NNE to SSW was modified by ice flowing from NW to SE.

The Manhattan Schist (Member A) bedrock is a fine-textured, highly laminated mica schist with cm-scale quartzose interlayers and thinner, discontinuous calcareous interlayers now metamorphosed to calc-silicate rock. The schist has been thoroughly recrystallized and peppered with small garnets in the micaceous layers. The pervasive enrichment in garnet is undoubtedly a result of post-regional-foliation contact metamorphism at the margins of one of the plutons of the Cortlandt Complex. Note that the Cortlandt kaersutite-biotite diorite crops out immediately up the road (we noted an exposure in the road log). Therefore, the contact between the "city rock" of the pluton and the "country rock" of which this knoll is a part, would be mapped through the bushes to our east. Note that no garnets are present in the quartzose- and calcareous interlayers. This distribution of garnets illustrates the phenomenon of compositional restriction (namely, no alumina, no garnets!).

The bedrock here has been disharmonically folded; within the foliation are numerous tight- to isoclinal folds (some with floating hinges and sheared-out limbs). Locally, elliptical quartzose pods up to 30 cm long are strung out within the foliation. As a result of refolding and the forceful intrusion of the adjacent Cortlandt Complex, the orientations of the early folds are variable. Nevertheless, they typically plunge N85°W. All of these early structures have been refolded by open folds with axial surfaces trending N75°E, 82°SE and plunging steeply into S45°W. Note how the quartzose layers behaved in a brittle fashion, forming boudins and how the adjacent schistose rocks illustrate ductile flow.

One interesting feature is a small vein of quartz oriented N72°W, 90° on the upper surface of the bedrock knoll. Because it cuts all of the previously mentioned structural features, the vein is obviously a late structure. Note the two tapered "wedges" of quartz that seem to have been displaced roughly 6 cm in a left-lateral sense, thus suggesting the presence of a small strike-slip fault. Careful examination shows that a strike-slip fault interpretation is all wet. The central vein can not be traced very far beyond these two quartz "wedges." The "apparent offset" is not real because the lenticular pods project, with smaller offshoots directly across the thin vein. A preferred interpretation is that the vein, lenticular pods, and their offshoots were all formed at the same time. The veins are fillings of pre-existing- or developing cracks or joints.

Walk toward the water's edge and up the trail to see an important stratigraphic contact exposed along the edge of the river. Rarely seen by mortals, the contact between the Cambro-Ordovician Inwood Marble and the overlying Manhattan Schist (Member A) crops out in this vicinity. Forming a ledge along the east side of the trail the Manhattan A is a highly laminated, muscovite-rich phyllite with mm-scale calcareous laminae. The contact-induced garnet, so numerous on the knoll, are virtually absent here. This absence demonstrates that contact metamorphism is a spatially limited phenomenon. The foliation and subparallel bedding (compositional layering) are oriented N67°E, 67°NW; a strong stretching-type lineation extends downdip. The Manhattan A is a direct lithostratigraphic correlative of the Annsville Phyllite. The top of the bedrock surface has been glacially polished and grooved. The orientation of the glacial grooves here implies ice flow from N10°E to S10°W, the same direction indicated by the youngest grooves observed at the previous glacially sculpted knoll.

The Inwood-Manhattan A contact is exposed at the water's edge a little farther up the trail and to the left. Here is a unique place where you can actually put a finger on the original medial Ordovician depositional contact between the carbonate-shale protoliths of the Inwood-Manhattan A sequence. We point to the calcareous interlayers in the Manhattan A as evidence of a gradational sedimentary contact between the marble and phyllite. Not far from here, a short distance north, at the Verplanck Point quarry (between Stops 2 and 3) is a famous fossil locality for the Inwood Marble. Pelmatazoan stem plates, of early Paleozoic age, were discovered in the Inwood Marble near the Inwood-Manhattan A contact (Paige, 1956).

The Inwood consists of interlayered dolomitic (buff-colored) and calcite (white- to gray-colored) marble with bedding and foliation parallel, oriented N70°E, 67°NW. An F_2 isoclinal fold, roughly 1 meter long and 15 cm wide, is visible on the top surface of the outcrop. The axial surface of the fold is oriented EW, 71°N with a fold axis plunging 64° into N70°W. Shearing along the limbs is spaced 12-15 centimeters and show 1-3 cm scale right-lateral offset. Joints, oriented N19°W, 87°SW, are prominent in the Inwood at this locality. Vestiges of post-Pleistocene Indian clam bakes can be found at this location! Note the oyster-shell middens decaying out of the soil above the Inwood on the slope leading down to the exposure.

Scramble along the outcrop to the Manhattan A and observe the parallelism of the metamorphic fabric with the foliation in the Inwood. Also note the total lack of garnet and relative low-grade of the micaceous phyllite compared to the garnetiferous Manhattan A exposed on the trail above, a function of relative distance from the edge of the Cortlandt intrusives. Looking south down the axis of the Hudson, Croton Point (On-The-Rocks Trip to Croton Point and Peekskill Hollow) is in the distance to the left (east) and the eroded tilted edges of the strata filling the Newark Basin dip to the right (on the west side of the river).

From here, scramble back up to the trail and walk uphill to the next exposure of Manhattan A in the distance. Here, the Manhattan has been thoroughly recrystallized, and in micaceous layers, garnet is once again abundant. We have re-entered the contact aureole. Briefly, note the abundance of isoclinal folds and the lithologic differences between these rocks and their previously examined counterparts. Follow the trail uphill and to the north. Turn right past the small pond and follow the dirt trail uphill to see the contact between the Manhattan Schist and kaersutite (an alkalic amphibole) diorite (Pluton II) of the Cortlandt Complex. Here, the texture of the diorite is very coarse to pegmatitic. Such textures are inferred to be the result of the availability of abundant water that during contact metamorphism, was flushed from the country rock inward toward the city rock of the pluton. A beautiful example of Bowen's reaction relationship is found here: large, euhedral amphiboles reacted with the magma to form coarse rims of platy biotite.

At the contact, the Manhattan has been thoroughly altered. The contact product is a kyanite-sillimanite-garnet-biotite-plagioclase hornfels. In the cores of the kyanites can be found relict staurolite. The contact-induced development of kyanite is noteworthy in that it marks the westernmost regional presence of this important aluminosilicate index mineral. Studies in geobarometry, comparing contact-induced metamorphic assemblages to those in Manhattan Schist outside the contact aureole, led Ratcliffe and others (1983) to propose that the Cortlandt Complex was intruded at depths of roughly 25 km. Thus, as we traverse across the bedrock surface east of the Hudson River this morning, we are examining a deeply eroded horizontal cross section of the Earth's crust that during the waning stages of the Taconic orogeny, experienced intense folding, and significant mafic-ultramafic intrusive activity.

19.9 Drive back up hill from Stop 4. At yield sign, bear R to retrace route toward toward exit and Route 9A.
20.6 Guard shack.
20.7 Junction with 9A north, turn L.
20.75 Road on L to Georges Island Park.
21.1 Cortlandt plutonic rocks exposed on R.
21.3 Traffic light, Kings Ferry Road on L (to Verplanck).
21.6 Lake Street, Village of Buchanan, New York.
22.0 Bottom of hill.
22.1 Traffic signal for Tate Avenue. New roadcut of norites on R.
22.35 Bleakley Avenue on L.
22.5 Bridge under AMTRAK RR.
22.6 Turn L into Westchester (Triple Bypass) Diner on L. **[REST STOP II].**

22.8 Turn L out of parking lot and continue ahead for entrance to US 9 North.
22.95 At traffic light, turn R then get set for immediate L under bridge.
23.0 As promised, turn L onto ramp.
23.4 Light pole by blocked off ramp, new cuts on R for mafic rock. Keep R by new entrance ramp.
23.8 Stop on R just before new bridge for Stop 5.

STOP 5 - Poikilitic, flow-layered Cortlandt norite (Pluton V) with spectacular xenolith of contact-metamorphosed Inwood Marble. [UTM Coordinates: 589.65E / 4570.3N, Peekskill quadrangle.]

Just a quick stop here to examine more of the norites of the Central Basin of Balk (1927). As a result of the extensive shrub clipping and dirt removal by JES and CM in May 1990 (Stop 7 of On-The-Rocks Trip #10), and abundant rain this spring and summer, previously hidden geologic details of this new roadcut have emerged for our view. The mafic rocks before you are orthopyroxene-bearing gabbro (norite) of Pluton V of the Cortlandt Complex. Here, the mafic rocks exhibit poikiloblasts of primary igneous kaersutitic amphibole ranging from 1-4 cm and averaging 2 cm in size. Often confused with metamorphic overgrowths (called porphyroblasts) illustrating sieve texture, true poikilitic textures result from late crystallization of residual magma which produces ghost-like crystals (in this case, amphiboles) that enclose early, preformed crystals of the host igneous rock. In this case, primary kaersutite encloses flow- oriented plagioclase and two pyroxenes. The roadcut before you offers a textbook example of this unique igneous texture.

Of particular interest here, the poikiloblasts enclose flow-layered norite with the layering (oriented N62°E, 32°SE) defined by alternating bands of plagioclase laths (the reddish mineral = bytownite), and clino- and orthopyroxene. Note, later, that as we drive northward on Route 9, we can see that the igneous layers begin to dip more toward the east and southeast. This change in attitude of the layers is the basis for Balk's Central Basin, in which he inferred that the attitudes of the flow layers define a conical structure. (See Figures 8, 9.)

Cameras ready for an additional "textbook" shot, note the elongate xenolith of folded, contact metamorphosed Inwood (Wappinger equivalent) Marble. The xenolith is roughly 3 m long by 1.5 m high and marks a tight fold of the foliation and parallel compositional layering in the marble. Note how the axial surface of the fold parallels the flow layering of the adjacent norite. The metamorphic + compositional layering is 2-3 cm in thickness and shows contact metamorphism to greenish diopsidic calc-silicate rock within the exposure. Cortlandt norite has intruded into the axial region of the fold producing a "micro-phaccolith" according to On-The-Rocker Bob Cassie and locally has squirted across the metamorphosed layering forming an apophyse extending roughly 15 cm deep into the xenolith. What is more, the norite is chilled against the xenolith with an obvious decrease in grain size within 3-4 cm of the xenolith contact. Note the pyrite crystallized along steep joints at the grass level. Such layers of pyrite are very common. As the paper-thin layer of pyrite decomposes, it forms a limonite coating on joint faces which colors the rocks a yellowish brown. Although such color changes commonly are cited as evidence that the silicate minerals are being decomposed (changed by chemical weathering), in reality, the silicates can be fresh just behind the iron-stained joint faces on which limonite has formed be destruction of pyrite.

Based on crosscutting geologic relationships noted above (intrusion of norite into axial surface and apophyse), the chilled margin, and the general orientation of the elongate xenolith parallel to the mafic flow layering, the xenolith must have been folded before or possibly during the late stages of the intrusion. If so, then the regional foliation in the marble (as sampled in the xenolith) had been already folded at the time of intrusion of the Cortlandt Complex, as discussed earlier under Geologic Background. According to Ratcliffe and others (1983), the xenoliths may represent pieces of country rock, plucked during sill-like, concordant injections of magma. Many xenoliths of the Inwood are known in this area.

24.6 Reboard vans and continue past bridge for another pull-over stop.
24.7 Note new cuts on both sides or road. Good cumulate layers visible dipping SE at about 75°. Fewer joints here compared to the Tate Avenue rocks. Layering is great here. Dip down to about 30° near the second bridge.
24.9 Note exit on R exposes a new cut with glacial polish.
25.3 Pass exit for Main Street, NY 35, US 6-US 202 on R. High cuts on R consist of light Proterozoic granitoid gneiss, granite, and amphibolite. Keep to L for US 6 and 202. Do not take Bear Mountain Parkway.
26.0 Turn L at light. Keep R for US 9 Northbound upon crossing bridge over Annsville Creek.
26.2 Bear R for to US 9 North.
26.4 Proterozoic rock on L beneath till.
26.8 Turn R onto Roa Hook Road.
27.0 Turn R at Stop sign onto Albany Post Road (Eastbound).
27.1 Pull over to R before large cut exposed on both sides of Albany Post Road for Stop 6.

STOP 6 - Type locality of Annsville Phyllite, Annsville, NY. [UTM Coordinates: 590.00E / 4573.19N, Peekskill quadrangle.]

This large roadcut exposes the Annsville Phyllite of Medial Ordovician age. We are in the town of Annsville and you are therefore in the type locality of this distinctive, black to dark-gray carbonaceous rock unit. Here, the lithology holds up a ridge bifurcated by Sprout Brook to the west and Peekskill Hollow Creek to the east. The cut exposes a rather monotonous, steeply dipping and highly cleaved sequence of uniform micaceous slate and lustrous, flaggy phyllite that extends northeastward toward Gallows Hill. On the north side of the cut try to identify compositional layering (bedding) in the form of gray siltstone interlayers about 1 cm thick and convince yourself that bedding and slaty (phyllitic) cleavage are subparallel. They strike N50°E and dip 77°SE. CM argues that the presence of a steep down-dip intersection lineation and mineral streaking within the slaty cleavage indicates the presence of non-obvious intrafolial F_1 isoclinal folds that are probably best observed on top of the outcrop. In a few places isoclinal folds (probably F_2 or second generation) of thin quartz veins occur showing SE plunges. There is a sub-horizontal rock cleavage that is axial planar to kink bands and crenulations of the slaty cleavage and late joints that trend N28°E, 32°NW. The overall structure of the ridge is probably that of a synform overturned to the northwest.

On the S side of the cut, at the E end, isoclinal folds of the foliation plunge steeply northward and display a sub-parallel stretching lineation. At the W end, cm-scale siltstone interlayers parallel the slaty cleavage and may represent thin, fine-textured distal graywackes.

The Annsville Phyllite is considered to be equivalent to the upper part (Penn Argyl carbonaceous shale member) of the Martinsburg Formation (Tippecanoe Sequence, Middle Ordovician). Compare these rocks to those sampled at Stops 2 and 3 and appreciate the reason why the Annsville Phyllite is regarded as being the lithostratigraphic equivalent of the Middle Ordovician part of the Manhattan Schist. Of interest to Pleistocene enthusiasts, these very rock exposures could be the source for the dark, carbonaceous boulders and pebbles that have been eroded out of the lower tan-gray till at Teller's Point (Merguerian and Sanders 1992, Stop 2).

Go west over the Hudson River to visit the last two stops for today.

STOP 7 - Non-marine lacustrine facies in lower part of Newark Supergroup (Stockton? or Passaic? Formation), Lowland Park, Stony Point. [UTM Coordinates: 585.05E / 4564.2N, Haverstraw quadrangle.]

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

Reddish-brown siltstones and associated gray carbonate rocks about 1250 ft. above base of Newark succession and 3 miles SE of Ramapo fault (Figure 23). Lithologically, these strata are ancient mudstones and nonmarine limestones that were deposited in the offshore parts of a lake. We assign them to the Brunswick (on the presumption that we are above the level of the Lockatong Formation; if they are below the Lockatong, then they belong in the Stockton). The greenish nodules are composed of calcite; they are caliche--the products of upward movement- and evaporation at the surface of water in the ancient soil in a semi-arid climate zone (Figure 24). James Gates Percival (1842, p. 316-317) first noticed carbonate nodules in the "Secondary" strata underlying the lowland of central Connecticut (now designated as the Hartford basin). J. F. Hubert (1978) made a detailed study of comparable ancient caliche in the New Haven Arkose exposed in new cuts at Mt. Carmel, Hamden.

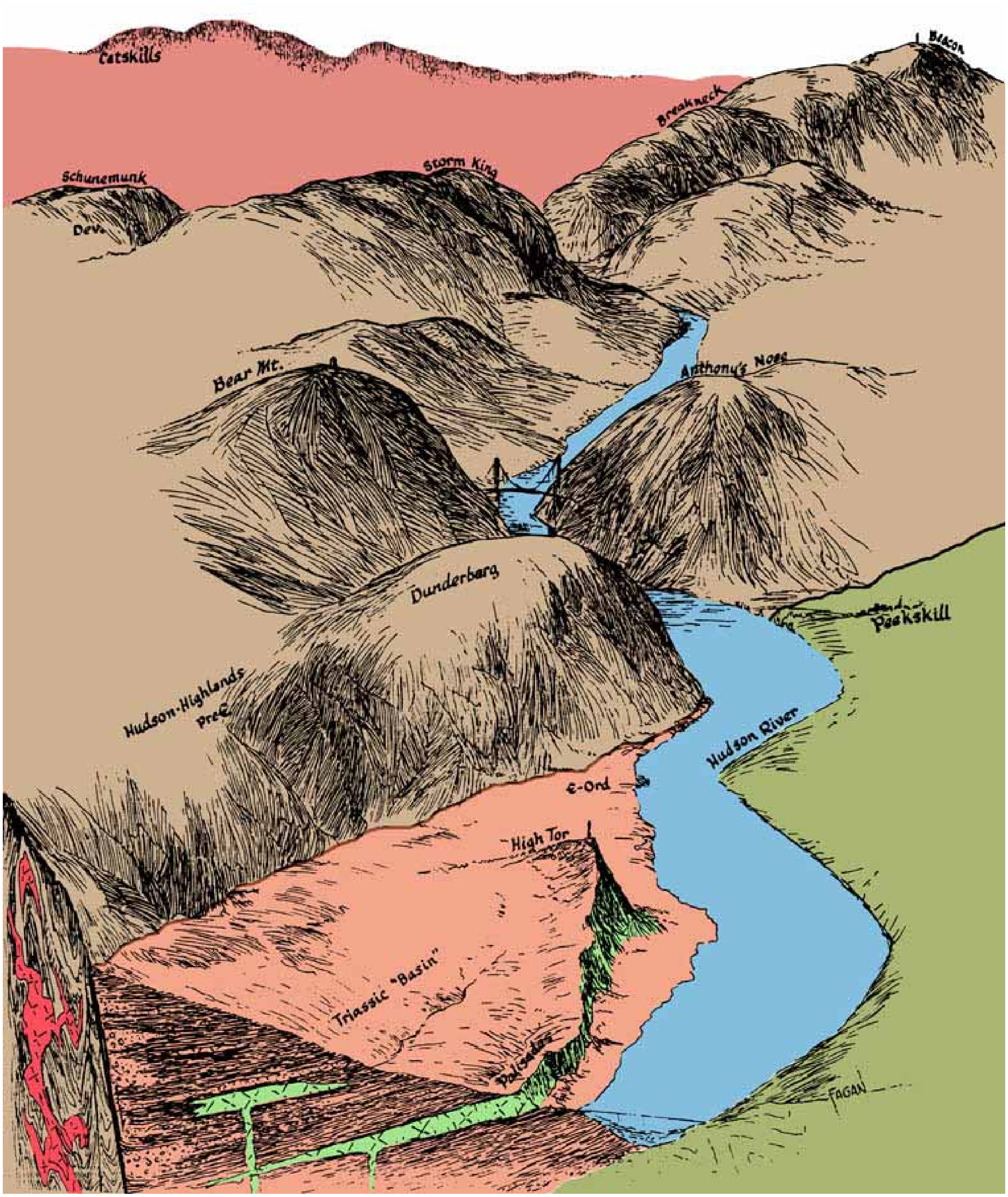


Figure 23. Physiographic sketch of the Hudson Highlands and the Newark Basin showing the course of the Hudson River. (Colorized by Nicole Barth after original drawing by Jack Fagan.)

Figure 24. View of east end of exposure at Lowland park showing the interbedded red siltstones and layers of caliche. Note the abundant nodular caliche in the red siltstone layer near the center of the image. Digital image by C. Merguerian.

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

STOP 8 - Stony Point Battlefield and west edge of Cortlandt intrusives. [UTM Coordinates: 585.62E / 4565.8N, Haverstraw quadrangle.]

We plan to make three small traverses at Stony Point State Park; one south of along the railroad cut to see conglomerate of the Newark Basin, one along the railroad cut that exposes intrusive rocks of the Stony Point-Cortlandt Complex and, a walk through the famous Stony Point battleground.

Along the east side of the CONRAIL tracks south of the entrance to the Stony Point State Historic Park, in a low knoll are exposed red-colored rudites forming the near-basal part of the sedimentary fill of the Newark Basin. Here, in deeply iron-stained exposures on both sides of the active rail, angular 3 to 6 cm clasts of gray-colored Wappinger Limestone are set in a reddish sandstone matrix. Flattened chips of Annsville Phyllite are scarce. Crudely developed beds strike roughly N60°W and dip 35°SW. Compared to the basin-marginal rudites exposed near Suffern, New York, which consist of rounded- to angular boulders of Proterozoic gneiss together with quartzite, Green Pond Conglomerate, limestone, reddish shale, and arkose, the clasts in this exposure are essentially monomict except for rare, but important, clasts of contact-metamorphosed Manhattan Schist (Annsville correlative) and fine-grained Stony Point dike rocks (Nicholas Ratcliffe, personal communication, 4/94). A likely explanation for this exposure is that during the early Mesozoic episode of uplift, erosion, and deposition in what is now preserved as the northern part of the Newark Basin, the adjacent elevated area had not yet been denuded below the stratigraphic level of the Cambro-Ordovician carbonate rocks that formerly covered the Proterozoic basement complex and at this locality that the clasts have traveled a very small distance.

Walk back on the tracks beneath the bridge at the entrance to Stony Point Park. Here, dike rocks and two stock-like masses of mafic- to ultramafic plutonic rock, representing westerly appendages of the Cortlandt Complex across the Hudson River, cut across isoclinally folded, probable lower Paleozoic rocks of the Annsville Phyllite and Inwood Marble. (Refer back to Figures 17 and 19.) Regionally, the country rocks are less-metamorphosed equivalents of the Manhattan Schist and Inwood Marble, respectively, as suggested by stratigraphic- and paleontologic data from the Tomkins Cove and Verplanck quarries on either side of the Hudson River (Figure 25). Here, the Annsville contains sillimanite (a very high-grade metamorphic index mineral) near the contact with the hornblende pyroxenite (Cortlandtite) intrusives. Poikiloblastic muscovite (related to post-intrusive regional cooling) overgrows the sillimanite contact assemblages (Ratcliffe and others, 1983). This is the type locality for poikilitic Cortlandtite as described by Williams (1885).

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

Afterward, walk through the gate to the Stony Point Battlefield exhibit (Figure 26) and walk through the outdoor exhibit in order to relive the important battle that took place here in July, 1779. We will examine features of Pluton II of the Stony Point Complex. Look for xenoliths, and flow features in the biotite diorite pluton. Note the glaciated knolls of diorite that show many crosscutting fine-grained dike rocks, areas of garnet-rich assimilated schist, and late stage leucocratic dikes and fracture filling. On the north side of the promontory, the careful observer will find a few outcrops of the ultramafic rocks of Pluton IV. On the glaciated surfaces of the diorite near the lighthouse, grooves are oriented N3°W.

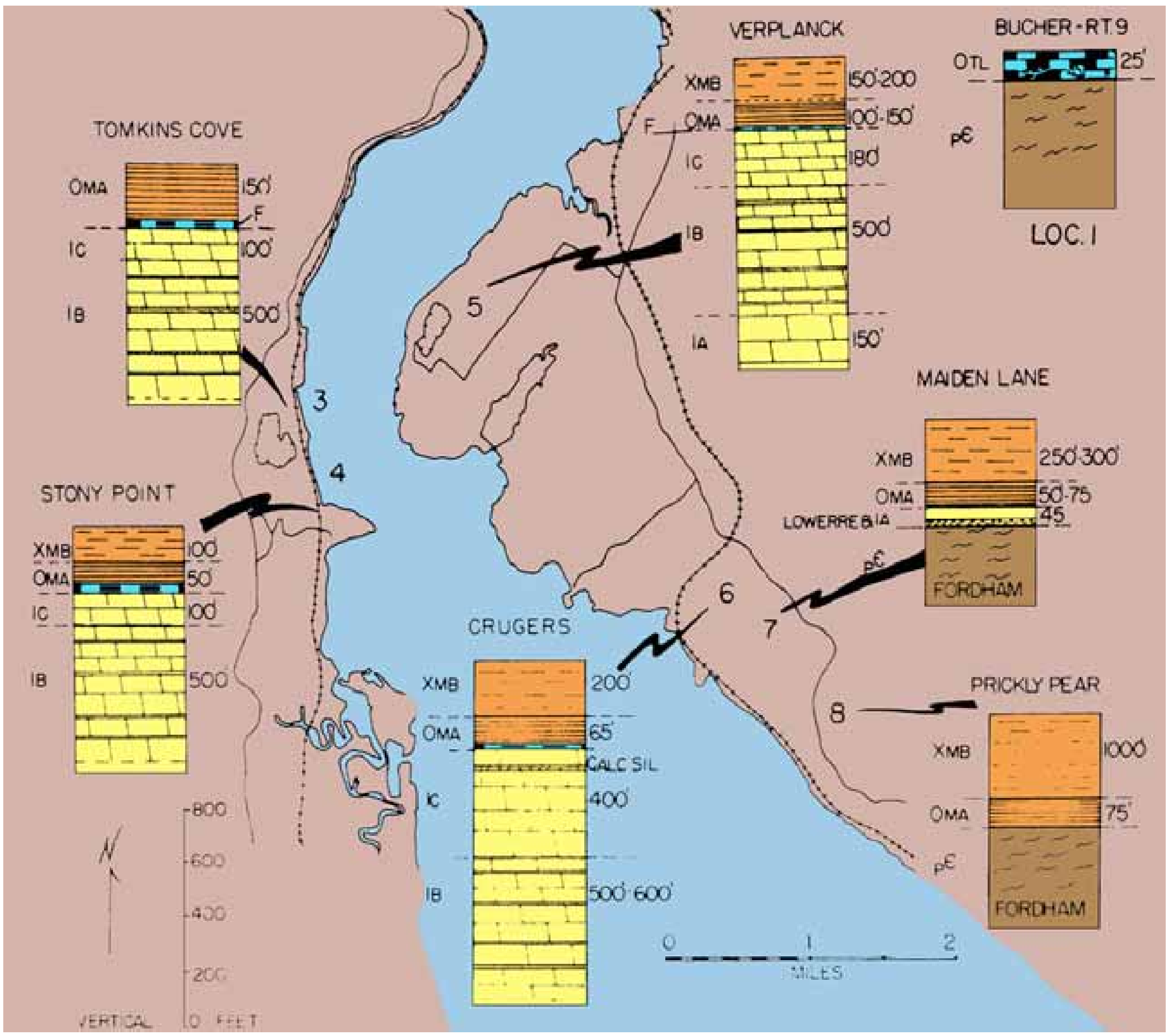


Figure 25. Location map of measured sections showing the subdivisions of the Manhattan and Inwood (and correlative Annsville and Wappinger Group) on the east and west sides of the Hudson River. Locality 4 on this map correspond to our Field Stop 8. (Colorized from Ratcliffe and Knowles, 1969; their figure 6.)

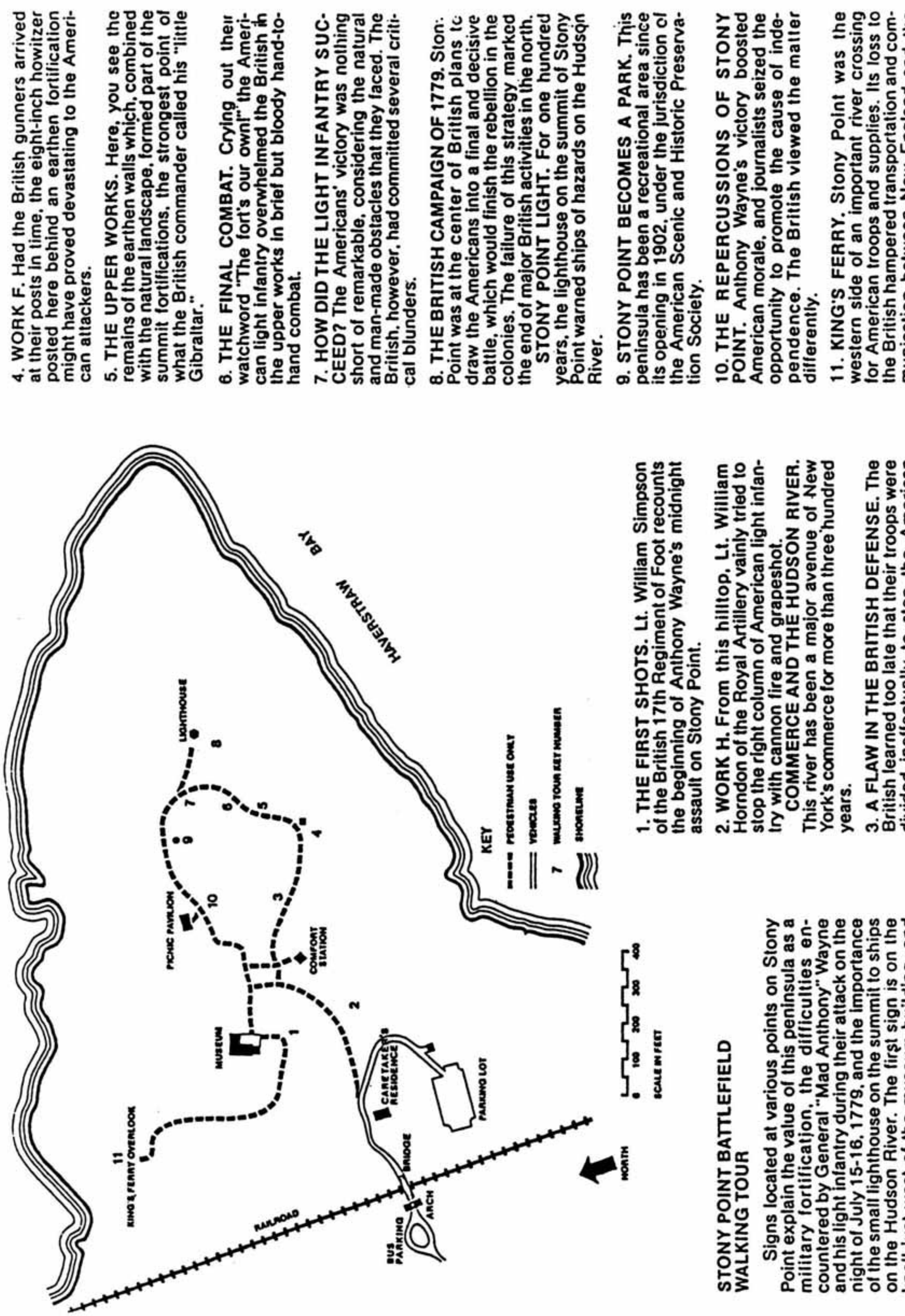


Figure 26. Sketch map of Stony Point State Park showing the walking tour of the battlefield.

DAY TWO

Day Two of this weekend's field trip is intended to introduce the participants to the rocks (both sedimentary and igneous) that filled the Newark Basin (See Figure 2.) which subsided rapidly within the Appalachian highlands during the Late Triassic and Early Jurassic periods, approximately 200 million years ago. The eroded edges of these regionally NW-dipping basin-filling strata underlie the region lying between the Ramapo Fault of New Jersey and Rockland County, New York, on the NW, and the Hudson River between Stony Point, New York and Hoboken, New Jersey, on the SE. Many of the basin-filling strata are sedimentary rocks that tend to form lowlands. With them are four topographically prominent ridges that are underlain by mafic igneous rocks. From SE to NW, these are the Palisades sheet and the First-, Second-, and Third Watchung Mountains. The Palisades is an intrusive; the others are extrusive.

Remember, Table 1 is a geologic time scale with emphasis on the subdivisions shown on the bedrock maps herein, with estimates of numbers of years for their boundaries, and a list of some important local geologic events. It shows the general relationships of the units mentioned in our discussion. Table 2 summarizes the major local geologic units (stratigraphy) in terms of layers designated by Roman numerals.

Of particular interest today are the features found at the base of the Palisades sheet, the relationships between the extrusive sheets and the sedimentary strata, and the changes that can be observed within the sedimentary strata as one approaches the basin-marginal Ramapo fault.

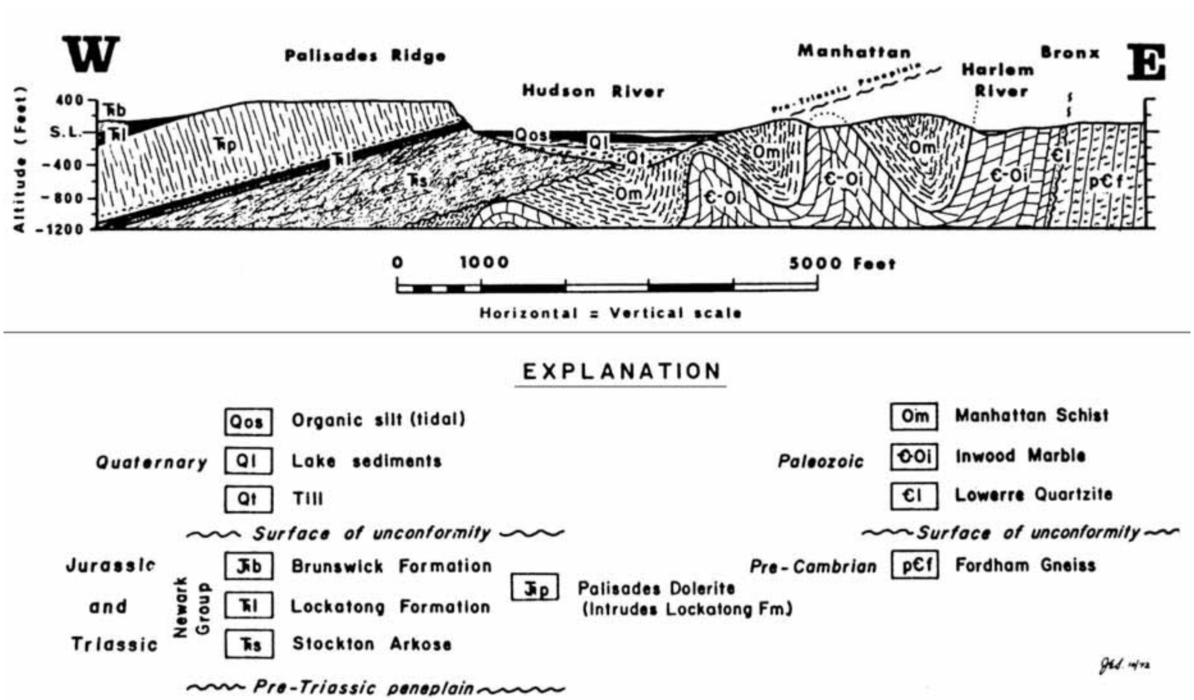


Figure 27. Profile-section across Hudson River at the George Washington Bridge. Topography from United States Geological Survey Central Park 7.5-minute quadrangle. (J. E. Sanders, 1974a, fig. 3, p. 11.)

In order to get to the time when the rock units beneath us formed, we need to leap backward in time to the Proterozoic and Paleozoic eras. Midway across the GWB (Figure 27), we make a time leap forward from the Paleozoic into the Mesozoic, here represented by dominantly red-colored sedimentary rocks and intercalated mafic igneous rocks, which dip gently about 12° northwestward. The land surface is formed by the eroded edges of the strata, once formerly much more extensive than today, that filled the Newark Basin (Figure 28). The prominent cliff on the west bank of the Hudson River, the Palisades (Figure 29), is formed by the resistant edge of the igneous rock of the Palisades tabular intrusive sheet. (For many years, the Palisades has been referred to by many as a sill [a concordant tabular pluton]. Because this sheet is locally discordant and concave upward in profile its proper technical name should be changed to lopolith.) The composition of this mafic rock is quite similar to the mafic rocks of the oceanic crust. Mafic rocks are named by their crystal size: gabbro is the coarse variety; dolerite, an intermediate variety with triangular interlocking crystals; and basalt, the fine variety.

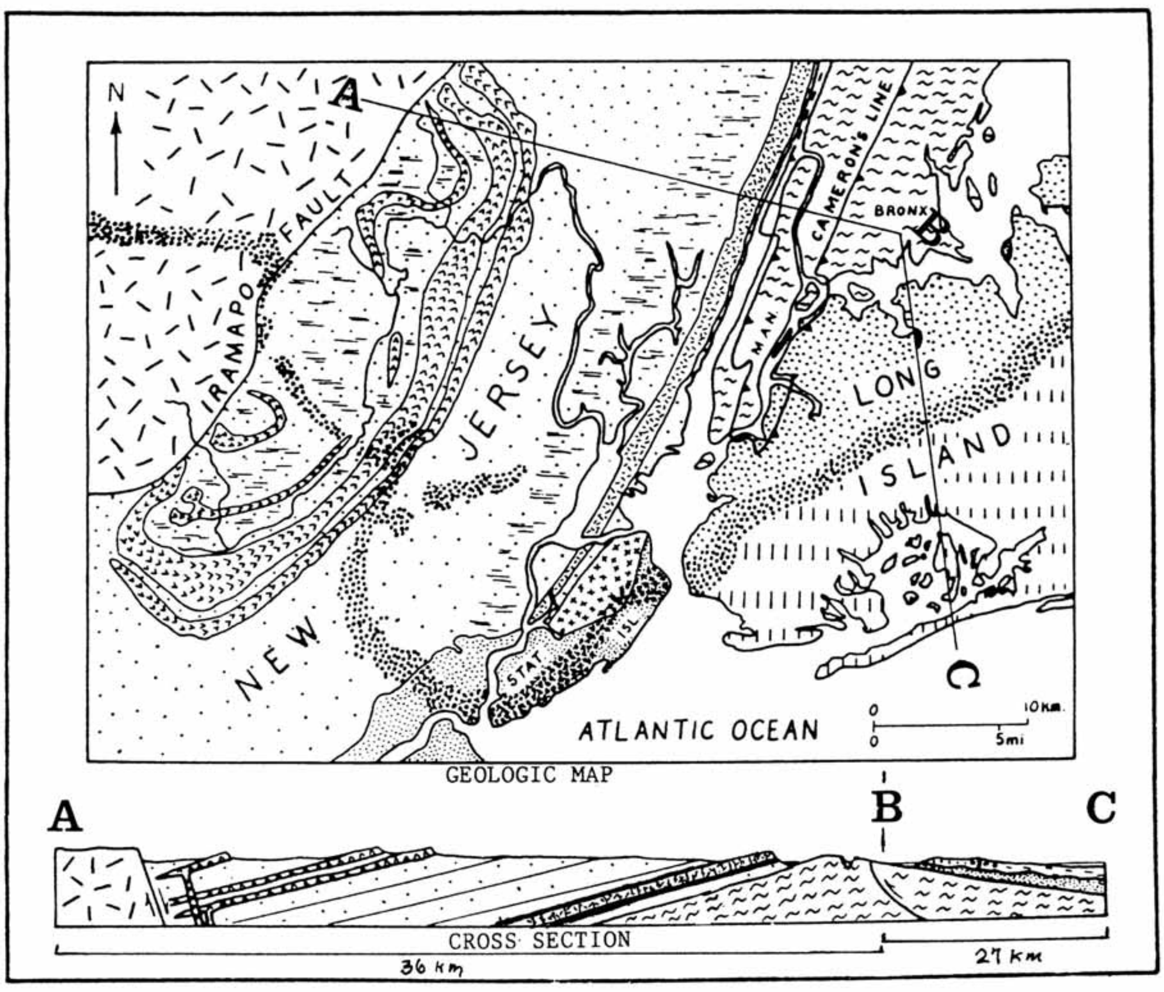


Figure 28. Sketch map and geologic profile-section, southeastern New York and adjacent New Jersey. Note lack of correspondence in scale between profile-section and map, with resulting expansion of the length of AB and shortening of line segment BC. (M. P. Wolff, M. J. Sichko, and R. S. Leibling, 1987, fig. 14.2A, p. 126.)

Because of the prevailing northwest dip in the central part of the trip area (See cut-away slice on Figures 1 and 27.), as we drive northwestward during the course of today's trip, we will encounter successively younger strata among the Newark basin-filling strata. Geologists refer to traverses across the strike of strata starting with older strata and encountering successively younger strata as "traversing up section" (the "section" referring to the succession of strata, and the "up" to the progression from older strata to younger). By contrast, they refer to the reverse, that is, a traverse progressing from younger strata to older, as "traversing down section").

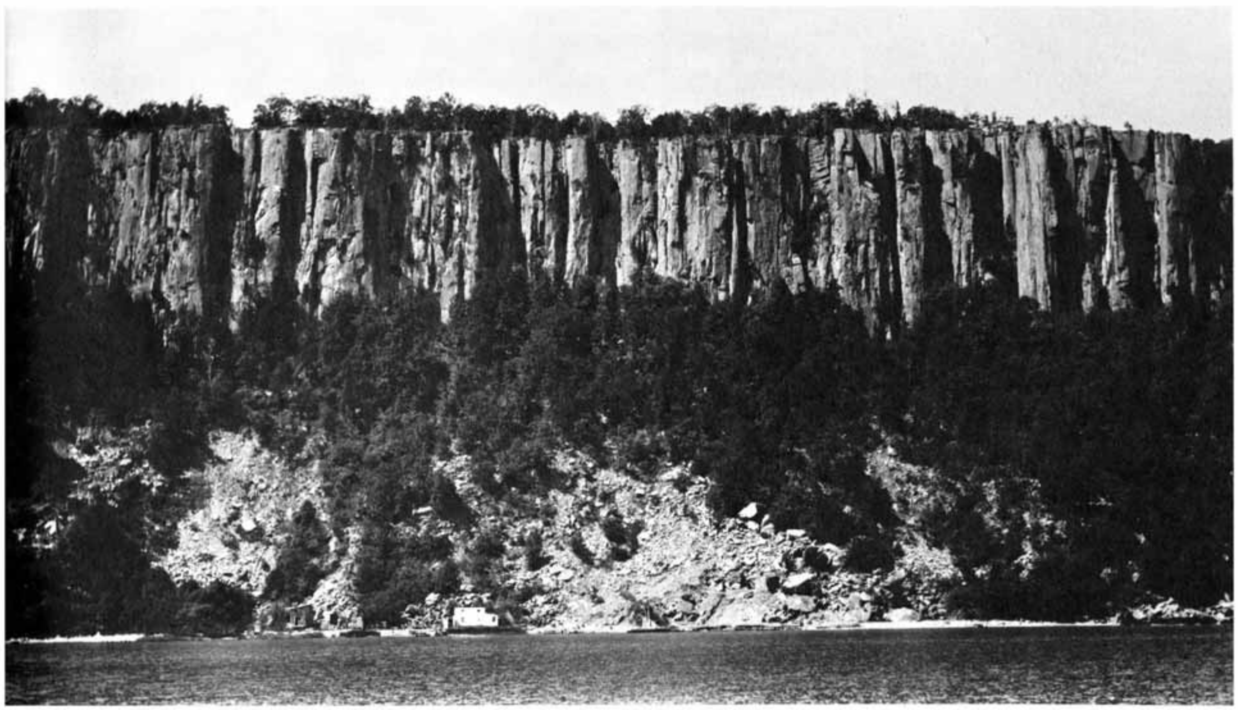


Figure 29. View of Palisades from above the Hudson River looking west. The nearly vertical columns of rock are bounded by steep joints that formed during contraction when the magma solidified to form the mafic igneous rock. (J. E. Sanders, 1981, fig. 6-26a, p. 165.)

We will make our first stop at the western footing of the GWB to examine the contact relationships at the base of the Palisades intrusive sheet and study the formation it intruded, the Lockatong. From there, we will traverse westward past the upper contact of the sheet and drive past west-dipping sedimentary rocks of the Newark Supergroup on our way to stops to examine the three sheets of extrusive mafic igneous rock constituting the Orange Mountain Formation ("First Watchung basalt" of older usage), the Preakness Formation (former "Second Watchung basalt"), and Hook Mountain Formation (formerly "Third Watchung basalt"; each "basalt" named after one of the Watchung mountains that were numbered from east to west). These curvilinear mountain ridges are truncated on the northwest by the Ramapo fault (See Figures 1 and 27.) and we will end our day by examining the Newark Basin sequence in exposures close to the Ramapo fault.

GEOLOGIC BACKGROUND

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

PHYSIOGRAPHIC SETTING

The general physiographic name for the region we shall visit today is Newark Basin lowland. But, as we shall see, strictly speaking, the term lowland is appropriate for only parts of the region, for example the Hackensack Meadowlands ("the Swamp" according to New York's Governor Pataki), which lies close to sea level; and the Great Swamp south of Morristown, where most ground altitudes fall within the range of 150 to 250 ft. Much of the area underlain by Newark strata is enclosed on the NE and SE sides by the topographically prominent Palisades ridge. The region that includes the Great Swamp is bounded on the NW by the highlands province and is enclosed on the SW, SE, and NW by the three curvilinear ridges known as the Watchung Mountains (Figure 30).

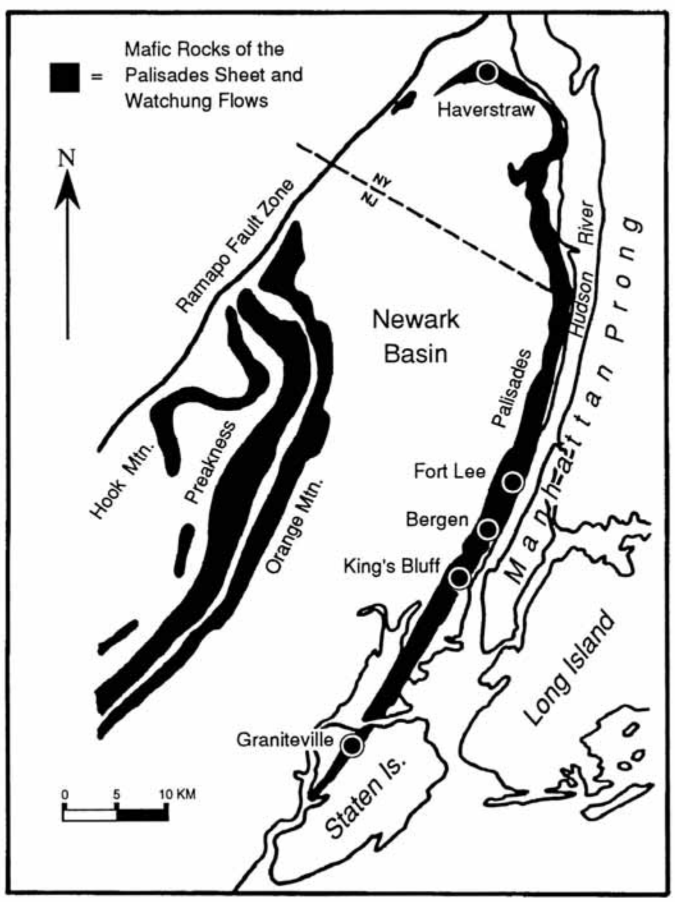


Figure 30. Index map showing the northern half of the Newark-Delaware Basin, the Palisades intrusive sheet, Watchung basalts, and place-names mentioned in the text. (After K. R. Walker, 1969, fig. 1, p. 6.)

We discuss these features from SE to NW, beginning with the Palisades Ridge. From Haverstraw, Rockland Co., NY, to Hoboken, Bergen Co., NJ, the Palisades ridge trends along the W shore of the Hudson River. But to both N and S, the ridge and river diverge. To the north, beyond Haverstraw, Rockland County, NY, the Palisades ridge curves around from its river-parallel NNE-SSW trend to a NW-SE trend. Thus, the ridge swings away from the river and strikes toward the Ramapo Range, the part of the Highlands province lying NW of the Newark Lowland.

To the S, the opposite situation exists. Instead of the ridge going away from the river, the river goes away from the ridge. At King's Bluff (alt. 180 ft) (above the Lincoln Tunnel), the NNE-SSW trend of the Palisades persists, but the Hudson River bends to the left about 20° and follows a course that is close to N-S. From Hoboken SSW to Bayonne is a triangular patch of low ground between the Palisades and Upper New York Bay. This low area is occupied by railroad yards, docks, and tank farms. At the gap used by the railroad leading to the Greenville Yards [UTM grid 577E - 4503N, Jersey City 7.5-minute quadrangle], the altitude of the crest of the Palisades is 50 to 60 ft. At Bergen Point, Bayonne, [UTM grid 573.8 E - 4499.6N, Elizabeth 7.5-min. quadrangle] on the N shore of the Kill van Kull (locally the boundary between Hudson Co., NJ and Richmond Co., NY), the altitude of the top of the top of the Palisades is between 30 and 40 ft.

Although the trend of the SSW decline in altitudes or the top of the Palisades ridge is accurate on a regional scale, a few notable exceptions exist. For example, the altitude of the highest point on the Palisades ridge, at High Tor, S of Haverstraw [UTM grid coordinates 586.76E - 4559.88N, Haverstraw 7.5-min. quadrangle] is more than 840 but less than 850 ft. From here to Hook Mountain State Park, the aspect is typical Palisades: columnar-jointed igneous rock. The altitude of the crest of Hook Mountain [UTM 590.8E - 4552.7N, Nyack 7.5-min. quadrangle] is more than 730 but less than 740 ft. From Hook Mountain State Park southward, especially around Nyack, to Sparkill Gap at Piermont [UTM 590.5E - 4542.6N Nyack 7.5-min. quadrangle], the ridge is an irregular low, wooded feature that does not display prominent jointed igneous rock (Figure 6). Farther south, the crestal altitudes of cliffs at Tallman Mountain State Park [Nyack 7.5-min. quadrangle] are 160 to 170 ft. Here, faults have dropped the igneous rock downward (Thompson, 1959). Just S of NJ-NY state line, 0.25 km NNW of the State Line Lookout [UTM 591.95E, 4538.15 N, Yonkers 7.5-min. quadrangle], the crestal altitude is 520 ft. Apart from the irregularity near Nyack, the Palisades ridge displays prominent rocky columns set apart by the columnar joints. At the Bergen/Hudson Co. Line, North Bergen, NJ, the crestal altitude is about 180 ft.

On Staten Island, NE of Travis Avenue and SE of Victory Boulevard [UTM 570E - 594.2N, Arthur Kill 7.5-min. quadrangle], the igneous rock of the Palisades lies at sea level; intertidal salt marshes overlap it. Just SW of the village of Travis, the SSW trend of the ridge carries it beneath the Arthur Kill and beyond into New Jersey. The SSW gradient of the crest of the ridge is about 800 feet in 40 miles, or 20 feet per mile.

The wide lowland between the Palisades Ridge and the First Watchung Mountain is underlain by topographically weak sandstones and mudstones. Local relief of up to 150 ft exists between the crests of ridges underlain by sandstone and adjacent lowlands underlain by mudstones. Large drumlins form the predominant landscape features.

The Watchung Mountains are curvilinear ridges underlain by tilted sheets of mafic igneous rock that are topographically resistant. The curvature of the three Watchung ridges is generally concordant with that of the Palisades ridge. Altitudes along the crests of the First- and Second Watchungs lie in the 550- to 650-foot range. No regional gradient comparable to that of the Palisades is present. Geologically, the Watchungs differ from the Palisades in consisting not of tilted sheets of topographically resistant intrusive igneous rocks, as in the Palisades, but of tilted sheets of extrusive igneous rock, former lava flows. The important of this difference will become apparent farther along in our discussion on the subject of basin-floor subsidence during deposition of the Newark strata.

In the swampy lowland enclosed between the Watchung ridges and the marginal highlands, ground elevations lie in the range of 150 to 250 feet. A terminal-moraine ridge crosses this intermontane lowland from Morristown to Summit, New Jersey.

Not including the Delaware River, five important rivers head in the highlands lying NW of the outcrop belt of the Newark strata and flow into- or across the Newark lowland. From NE to SW, these are the Ramapo, Pequannock, Rockaway, Whippany, and Raritan. The drainage areas of three other rivers, the Hackensack, Saddle, and Passaic, are confined chiefly to the Newark lowland.

The Ramapo River heads in Central Valley (near the toll plaza, close to the junction of the NYS Thruway and Rte. 17), and flows S and SE through the highlands underlain by Proterozoic rocks. The Ramapo enters Newark lowland at Suffern. Here, it turns SW and flows along the boundary between the lowland and the Ramapo Range to its junction with the Pequannock at Pompton Plains [UTM 560.4E - 4535.8N, Pompton Plains 7.5-min. quadrangle]. Within the Newark lowland, the Pequannock locally forms the boundary between Passaic and Morris counties. The combined flow of the Ramapo and Pequannock forms the short Pompton River, which ends at Two Bridges in the Town of Caldwell, Essex County, where it joins the Passaic River [UTM 561.2E - 4522.3N, Pompton Plains 7.5-min. quadrangle].

The Passaic River originates in the Great Swamp near Bernardsville and New Vernon, an area underlain by Newark strata, and flows generally northeastward; much of its course lies within the low area enclosed by the curving Watchung ridges. The combined Passaic-Pompton rivers flow out of this lowland through prominent topographic gaps: through Preakness Mountain (Second Watchung) at Little Falls [UTM 564.5E - 4525.6N, Paterson 7.5-min. quadrangle] and through the First Watchung Mountain (Orange Mountain) at Passaic Falls (Great Falls), Paterson [Stop 4; UTM 568.9 E - 4529.5N, Paterson 7.5-min. quadrangle (See Figure 3.)] At Passaic, the Saddle River joins the Passaic River. Newark Bay has formed where the confluence of the Passaic River and the Hackensack River has been submerged.

Newark Strata and the Palisades Intrusive Sheet

Because our discussion of Layer V (the Newark strata and the Palisades intrusive sheet) is so long winded and includes so many topics that we have subdivided it into subsections as follows: General Geologic Relationships, Stratigraphic Relationships, Paleogeographic Relationships, Associated Mafic Igneous Rocks, and Tectonic History.

General Geologic Relationships

The Newark strata of Layer V constitute one of the significant "layers of geology" (Levorsen, 1933, 1934, 1943, 1945, 1948, 1954, 1960, 1964) in the New York City region. As mentioned, Newark strata of Layer V nonconformably overlie the older metamorphic terrane of the Manhattan Prong of Layers I and II. In turn, Layer V is overlain in angular unconformity by the virtually horizontal Upper Cretaceous sediments of the Atlantic Coastal-Plain succession of Layer VI, 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. For example, in an outlier at Sand Hill, NJ, Upper Cretaceous strata rest on the exposed edge of the Rocky Hill-Palisades intrusive sheet, a relationship that gives a vague limit for the date of deformation of the Newark rocks (Widmer, 1964). The area of our field trip is shown on the geologic map of the Newark 1° by 2° quadrangle compiled by Lyttle and Epstein (1987).

A well-developed strike valley exists at the base of the Newark strata. The Hudson River follows this strike valley from Haverstraw, NY to Hoboken, NJ. At Hoboken, the Hudson bends to its left, and flows to the south. By doing so, it leaves the strike valley and flows across the metamorphic rocks. (See Figure 3.) In Jersey City, NJ, and on Staten Island, the rocks of the Manhattan Prong are present on the W side of the Hudson River. Farther upstream, the rocks of the Manhattan Prong form the E bank of the Hudson.

Where the Hudson River leaves the basal-Newark strike valley, this strike valley disappears from the modern landscape but does not disappear geologically. The basal-Newark strike valley, filled by Upper Cretaceous- and younger sediments, continues to the SW in the subsurface (Lovegreen, 1974 ms.). This buried subsurface valley extends across western Staten Island. Its continuation, if any, to the SW in New Jersey has not as yet been identified.

Stratigraphic Relationships

Proposed by W. C. Redfield in 1856, the name Newark, from Newark, New Jersey, is a venerable one in American stratigraphy. 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 assigned to the strata composing the Newark Supergroup has oscillated back and forth like a geological pendulum. During the 19th century, based on studies of fossil fish collected from them (Redfield, 1856, 1857), they were assigned to the Jurassic. By contrast, dinosaur remains and -footprints suggested Late Triassic. Given this situation, some geologists classified these strata as 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 (Cook, 1968, 1879, 1882, 1887, 1888, 1889). By contrast, Kümmel (1897, 1898, 1898a, 1898b) initially used only "Newark." When he became associated with the U. S. Geological Survey Folio projects, however, he used "Triassic" (Kümmel, 1914).

But compulsive 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 which they supposed marked the end of the Triassic Period, they decided that, by definition, all the Newark strata had to be of Late Triassic age (i. e., they had been affected by the period-ending "Palisades Disturbance"). Thus, they started a line of thought that lasted 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 this analogy, "we" is all geologists trained in the United States, "kindergarten" is the first-year college 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 (Cornet and Traverse, 1975; McDonald, 1975 ms., 1982, 1992; Cornet, 1977 ms.; Olsen, 1978, 1980a, 1980b, 1984 ms.; Olsen, McCune, and Thomson, 1982; Olsen and McCune, 1991; Fowell and Olsen, 1993) have re-established what the real old-timers knew all along: the age range of the Newark strata is Late Triassic through 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; named by Paul Olsen, the Orange Mountain Basalt, Preakness Basalt, and Hook Mountain Basalt, respectively) and/or the distinctive black argillites of the Lockatong Formation are present, the Newark sedimentary strata are easy to subdivide. But where one is faced with an isolated exposure of a non-fossiliferous 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 mineralogic- or lithologic criteria may prove to be helpful for stratigraphic assignment.

The basal formation, the Stockton, typically consists of gray- to buff-colored coarse, even pebbly arkose (geologists' name for a variety of sandstone that contains notable quantities of feldspar; depending upon personal preferences, "notable" ranges from 25% to 33% or more). Also present within the Stockton are many layers of reddish-brown sandstone and -siltstone that are not easy to distinguish from the typical strata of the thick Passaic Formation. (See Table of Formations above and Figure 31.) In wells drilled on Staten Island, some difficulty has arisen over how to distinguish the gray Upper Cretaceous sands, which unconformably overlie the Stockton, from the light-colored parts of the Stockton. Experienced geologists rely on the feldspar content. The compositionally mature Upper Cretaceous sands lack feldspar whereas the compositionally immature Stockton contains large quantities of feldspar.

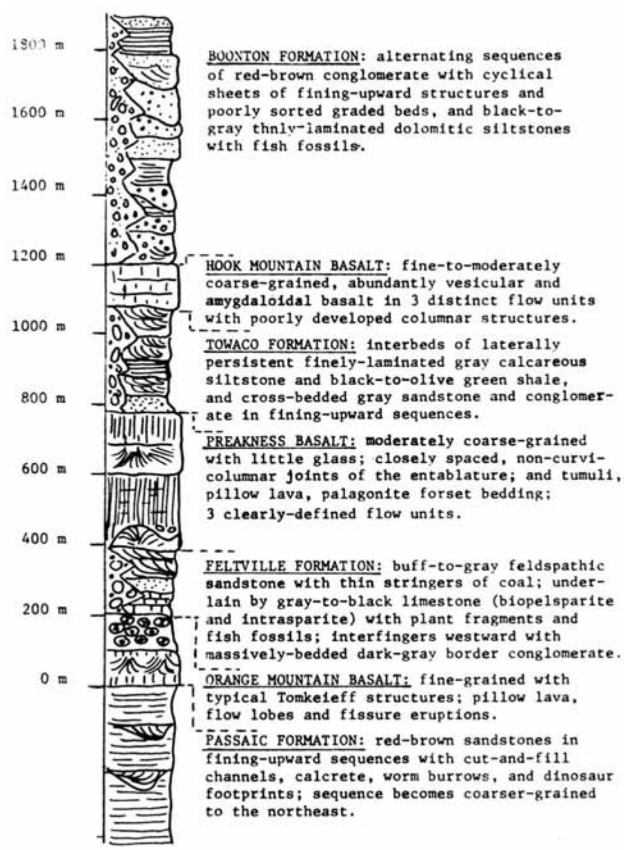


Figure 31. Columnar section of Newark Supergroup from upper part of Passaic Formation to Boonton Formation. (Warren Manspeizer, 1980, fig. 5, p. 319)

The next formation going upward in the Newark Supergroup is the Lockatong, which typically consists of a dark-gray- to black, tough-to-break 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.

Above the Lockatong is the Passaic Formation (lower part of former Brunswick Formation, now the Brunswick Group), whose thickness in the Watchung syncline Olsen estimates at about 6000 m, is more covered than exposed. The predominant aspect of the Passaic Formation is its characteristic red-brown color. This color has left its imprint on most of the Pleistocene sediments.

Paleogeographic Relationships

Of special interest in the understanding of any sedimentary rock is the general paleogeographic (or paleoecologic) setting in which its antecedent sediments were deposited. For example, was the setting in the sea (marine) or in some inland continental basin (nonmarine)? Was the site of deposition in the tropics? In an ancient temperate zone? In a polar region? Where was it situated with respect to a former continental margin?

All available evidence demonstrates that the Newark basins were filled with nonmarine sediments. An attribute of great significance in any nonmarine setting is the hydrologic situation. Was water abundant or scarce? Was rainfall distributed seasonally? In the following paragraphs, we discuss some hydrologic possibilities in nonmarine basins in general terms and then review some of the relationships between water and deposition of sediments.

Hydrologic Situation in Nonmarine Basins. In addition to its importance as a medium for sedimentation, water controls organisms. If water is present, plants grow. If not, no plants can survive. And, without plants, no animals can exist. Dinosaur footprints found in some Newark strata imply that dinosaurs were numerous, which in turn, must have meant that vegetation, hence water, was plentiful. How can evidence for abundant water implied by the large number of dinosaurs to make footprints and for lack of water implied by the footprints themselves be reconciled? Several such ways are possible. These include: permanent through-flowing rivers that head in areas where rainfall is abundant; ground water flowing basinward in shallow aquifers consisting of tongues of coarse sediments that extend from the marginal highland out into the basin-floor lowland; contrasting wet- and dry seasons; and climatic changes involving a shift from dry to wet and back to dry again.

The Nile River, Egypt, is an example of a permanent, through-flowing river that arises in a wet-climate zone and flows across a desert with enough discharge so that it does not dry out. As pictures taken from satellites amply demonstrate, the banks of the Nile are lined with trees. Only a short distance away from the river is a treeless desert. As pointed out by the pioneer American meteorologist, William Ferrel (1863), the annual flood of the Nile is controlled by the northward migration of the zone of vertically rising air that is associated with the sub-solar point (place on Earth where the Sun's rays arrive at normal incidence). This zone of updrafts is also a zone of torrential rainfall; it is known as the Intertropical Convergence Zone (abbreviated ITCZ). According to Ferrel, during Northern-Hemisphere summer, when the ITCZ migrates northward away from the Equator, following the Sun, its torrential downpours soak the Ethiopian Highlands, the headwaters of the Blue Nile (Figure 32). The flood subsides when the ITCZ migrates southward taking its rainfall with it.

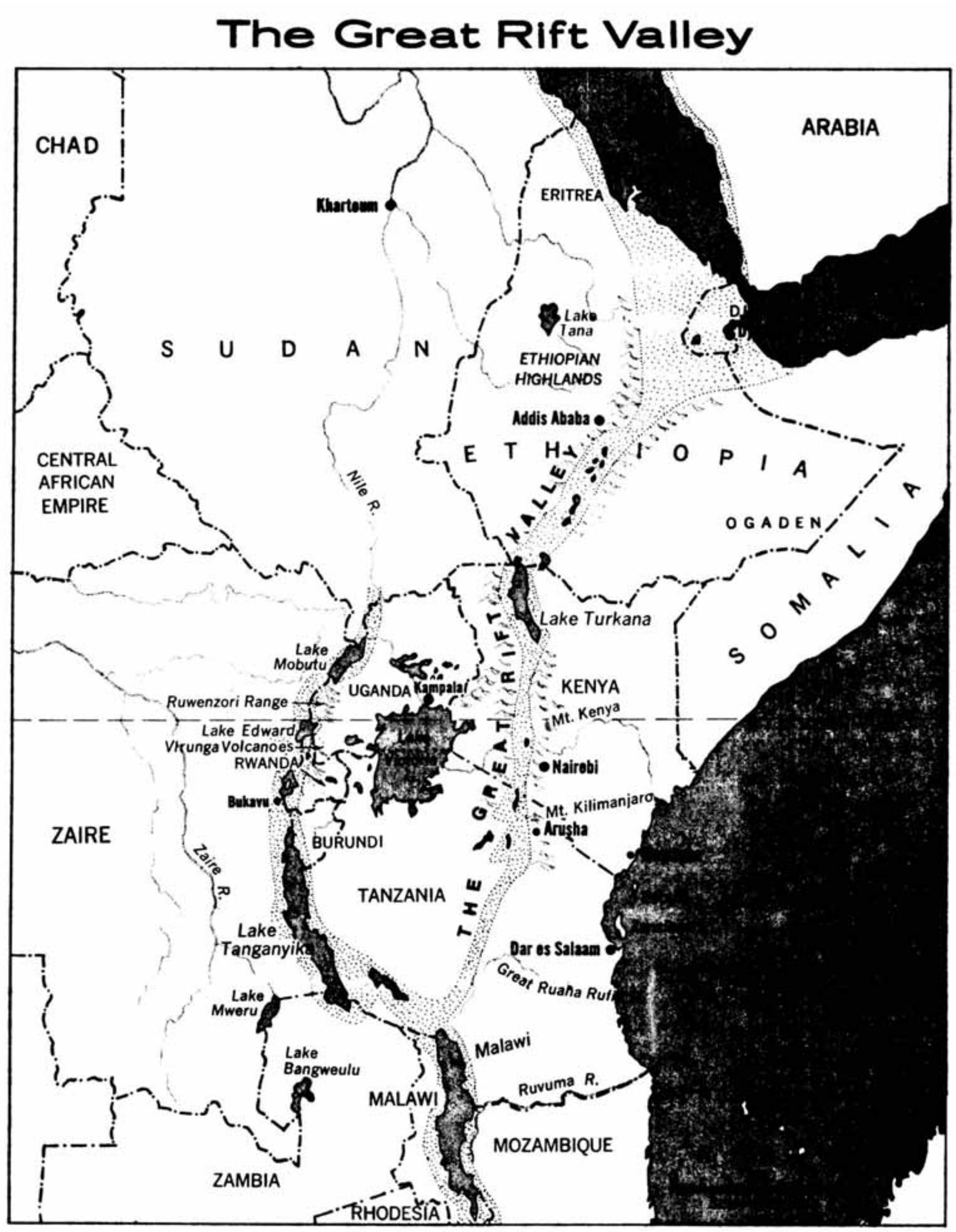


Figure 32. Map of northeastern Africa showing The Great Rift Valley extending from Tanzania to the Red Sea and the Ethiopian Highlands, headwaters of the Blue Nile. (Tanzania Geological Survey map.)

Similarly, the ITCZ migrates southward into the Southern Hemisphere during Northern-Hemisphere winter (southern Summer). Accordingly, at the extremes of this annual migration only a single rainy season takes place. Localities in between experience two rainy seasons, one when the ITCZ passes over from N to S, and the other, when it comes back headed from S to N.

Another way is for water to be abundantly supplied to a desert is to move underground within tongues of coarse, permeable sediment that extend into the basin-floor desert from the basin-marginal highlands. Abundant rainfall in the highlands that recharges these shallow aquifers can be transported in the subsurface into a desert area. An example is the tropical "rain" forest at Lake Manyara National Park, Tanzania (35°50'E, 03°20'S; Figure 33). This forest is a distinct anomaly; it grows within an area where rainfall is a rarity; the surrounding territory is a bone-dry desert. But in the midst of this desert is a tract that is so lushly vegetated that it supports an abundant fauna including herds of large vertebrates. The plants are able to grow here because their roots derive water from shallow aquifers in the basin-marginal fan sediments. The aquifers are recharged in the highland at the margin of the basin. Thus, the Lake Manyara tropical "rain forest" is really a tropical "ground-water" forest.

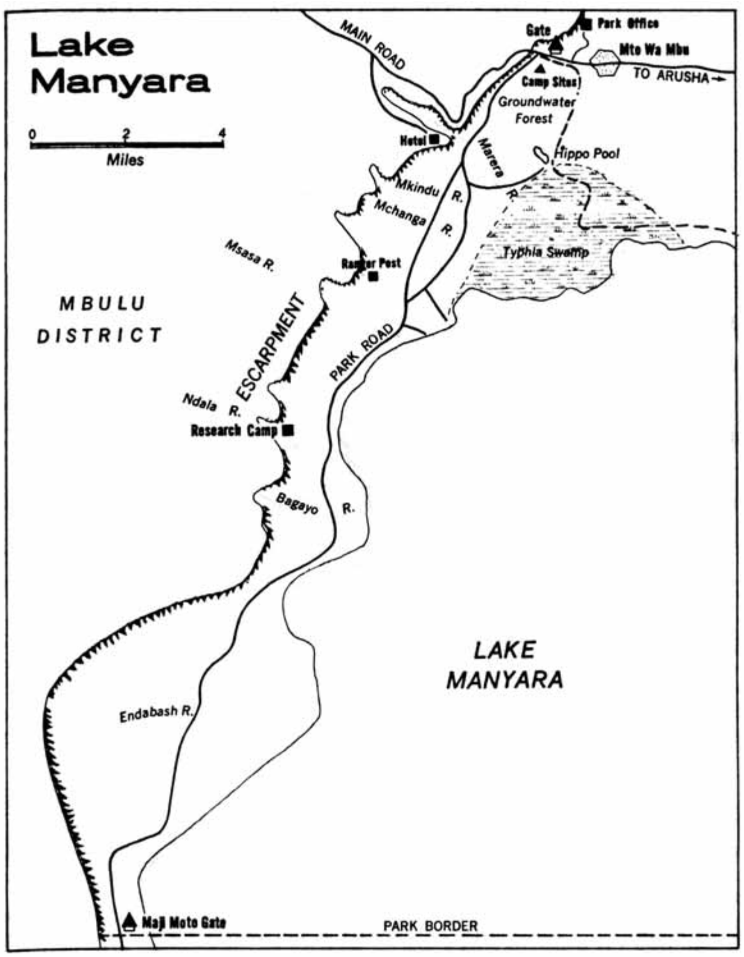


Figure 33. Map of northeastern part of Lake Manyara Park, Tanzania, showing Typhia Swamp and Groundwater Forest. (Tanzania Park Service map.)

Another way in which water can appear in an otherwise-dry setting is for wet- and dry seasons to alternate. Rainfall could come more or less regularly during one- or two short seasons. The monsoon belt of India is an example of a region receiving one-season rainfall. As with the Nile floods, the monsoon season in India accompanies the annual northward migration toward the Tropic of Cancer of the ITCZ (Friedman, Sanders, and Kopaska- Merkel, 1992, p. 282-286).

Still-another way is for the climate to change. During the Pleistocene Epoch, the tropical regions experienced dramatic shifts from wet times, known as pluvials, and dry times (interpluvials). The arid times in the tropics coincide with glacial-age climates elsewhere. The accompanying high winds propelled much dust high into the stratosphere, where the high-altitude winds sent it around the world. Interglacial times in the tropics were marked by abundant rainfall and lush vegetation; under these conditions, the amount of atmospheric dust was greatly diminished. [These times of contrasting abundance of atmospheric dust have been logged in the latest ice cores drilled in Greenland. Zones of dusty ice can be recognized by their higher electrical conductivity (related to the feldspar content in the dust). Continuous resistivity logging enables a graph to be constructed that shows dust content vs. depth (and down to a certain level, at least, depth is a direct function of age). The Greenland ice dated as having been deposited during the last glacial episode shows many sharply defined zones of dusty ice (implying glacial climate) alternating with zones low in dust, which imply non-glacial climate (Taylor and others, 1993). An astonishing attribute of this electrical-resistivity logging of the ice cores is the abruptness of the change from dusty zones to low-dust zones. These imply that the climate shift from one mode to the other was very rapid (within a few tens of years).]

As we shall see, the strata that filled the Newark basin were deposited under contrasting hydrologic settings. Some of them were deposited in a deep lake that may have filled much of the basin, just as Pleistocene Lake Bonneville filled the Great Salt Lake lowland in north-central Utah 20,000 yrs ago. Typical deep-lake deposits are microlaminated black shales containing abundant remains of fossil fish. Other strata accumulated subaerially in a dry climate. Typical features of such strata are desiccation cracks, dinosaur footprints, and paleosol caliche. 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 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-modeling gurus who claimed that the Milankovitch periodicities break down within a few million years have been using the wrong numbers in their formulae.

Associated Mafic Igneous Rocks

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). The significance of these contrasting kinds of sheets will become apparent from the following discussion, which begins with the Palisades sheet.

The Palisades Intrusive Sheet. The world-renowned mafic Palisades intrusive sheet is continuously exposed along the east edge 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 2.) 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 its paleoflow direction with possible feeder on Staten Island. Then follows contact relationshps, chilled-margin facies, discordant contacts, and clastic dikes. These raise the issue of the state of lithification of the sediments at time of intrusion and provide another way of estimating the depth of intrusion.

"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. The author of a recent article on the Palisades Sill berates his readers with "four common misconceptions" the first of which is:

"that the Palisades Sill extends only from Staten Island to near Suffern, New York (Fig. 1), and that the intrusion (sic) is largely sill-like as viewed along strike. Although the Palisades generally is conformable (sic) within the Newark Supergroup in northern New Jersey, it clearly is discordant at its northern end (Fig. 1). In addition, drill-hole (sic) and geophysical data show that the Palisades reemerges from beneath Cretaceous sedimentary cover as the Rocky Hill diabase in the central Newark basin (Fig. 1; Lewis, 1907). Post-intrusion normal faulting again reexposes the Palisades Sill farther west as the Lambertville Sill (Husch, Sturgis, and Bambrick, 1984). Both of these diabase bodies are discordant, particularly at their southwestern ends. Thus, the expanded Palisades body, exposed over a strike length of about 150 km (Fig. 1), is not a sill at many localities and would better be described as a sheet" (Husch, 1990, p. 699). What Husch wrote about the sheet in central New Jersey is accurate, but we think that in the other direction, Husch has joined the flock who have lost sight of the importance of strike and dip.

[Explanation of (sic's): No. 1, after "intrusion" is there because the correct word should be intrusive; intrusion is a process; an intrusive is a body of rock that results from the process intrusion. How many geologists do you know who don't know their processes from their products in the ground? No. 2, after "conformable" is there because the correct word should be concordant. The (sic) means that we have copied faithfully what the author wrote, but are signalling our contention that wrong usage exists.]

We think that all the along strike diagrams that have been drawn in 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). 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) the result of a change from a concordant- to a discordant sheet and thus that it climbs in the stratigraphic succession from near the bottom to up near the top, but rather 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?

Because this sheet of mafic igneous rocks is not concordant along its strike length (Figure 34), 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 34.) 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 30.)

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.

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.

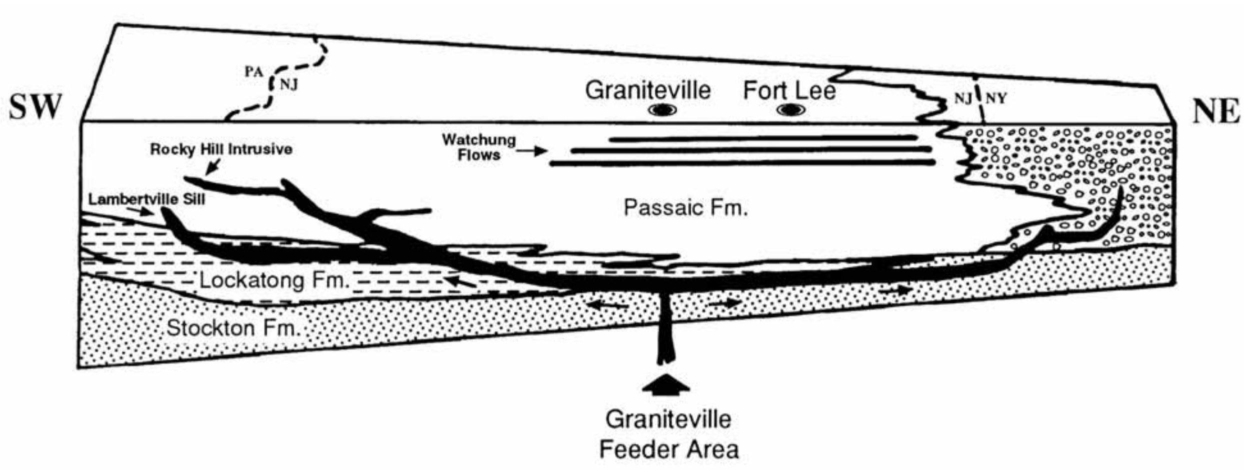


Figure 34. Block diagram showing SW- to NE-trending longitudinal profile (not to scale) of the Palisades intrusive sheet of the Newark Basin and its extension southward into the Delaware Subbasin showing, with arrows, our interpreted paleoflow patterns. Note the overall lopolithic form to the intrusive 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).

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 (Figure 35). 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 in glassy basalt and a pipe amygdale in the base of the Palisades sheet, together 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.

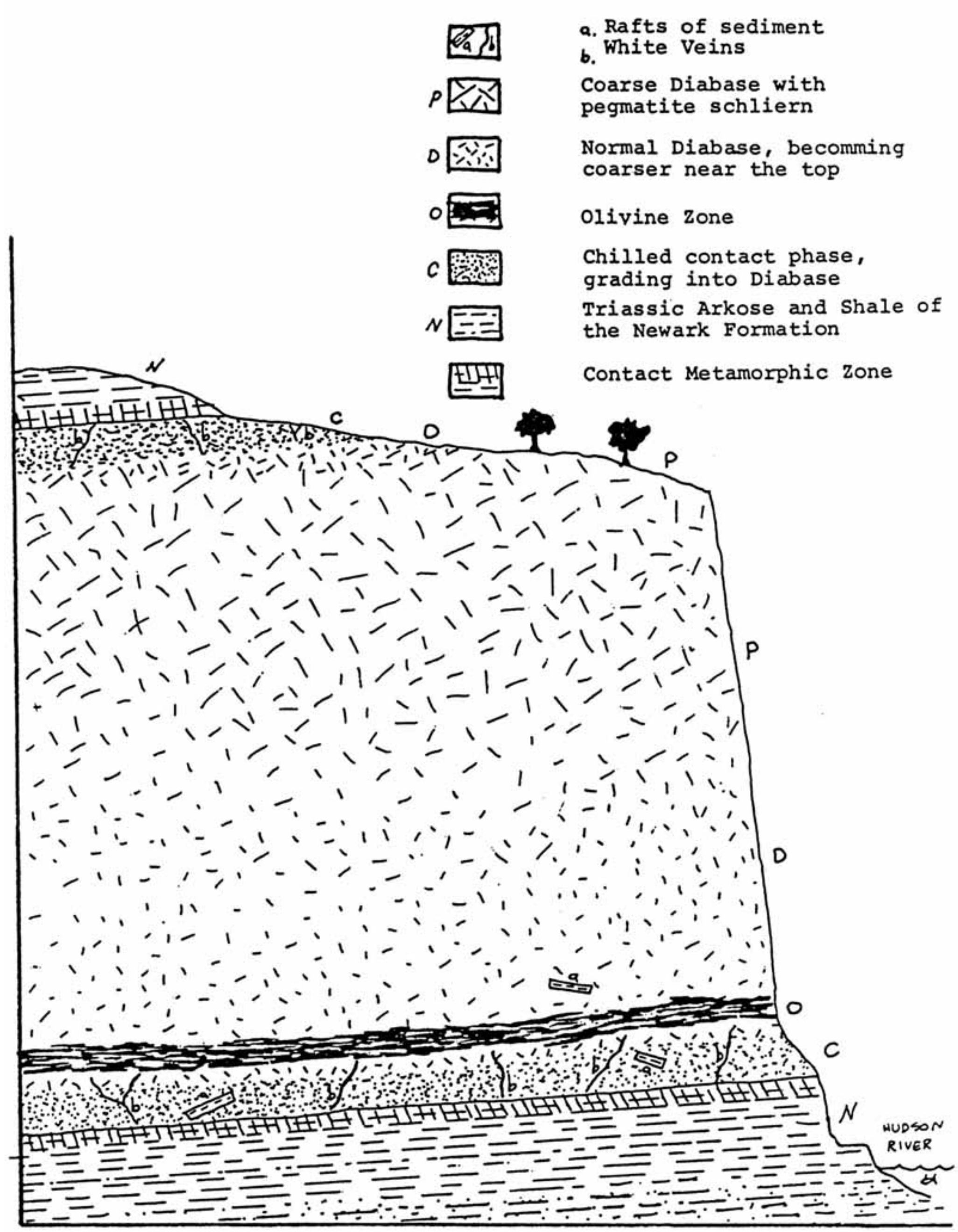


Figure 35. Schematic profile-section through Palisades intrusive sheet, New Jersey. (M. J. Sichko.)

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 36), 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 (Figure 37). (See also Figure 5.) 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 arches (Figure 38).

Figure 36. 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).

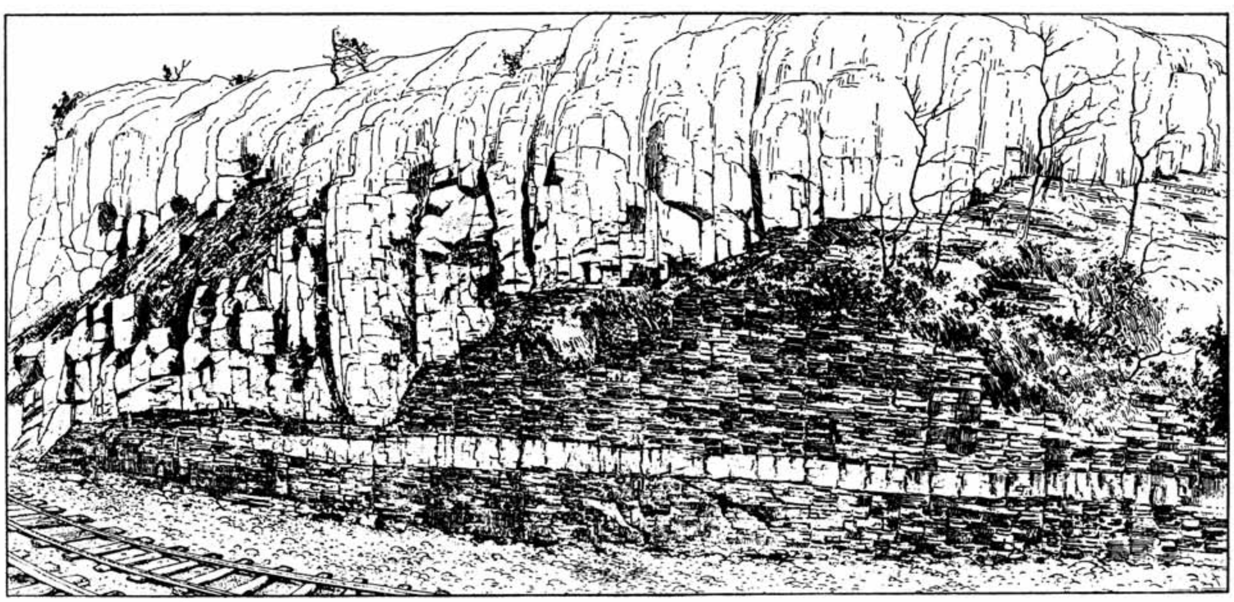


Figure 37. Sketch of Palisades diabase showing lateral ascent of the contact across the strata of the Newark Supergroup. (N. H. Darton, in F. J. H. Merrill and others, 1902, fig. 7, p. 8.)

Figure 38. View of a broad E-W-trending arch of the underlying Lockatong in discordant contact with the leading edge of a north-directed ramp. Hammer handle is 40 cm in length and rests immediately above chilled Palisades basalt contact with the Lockatong. (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 (Figure 39). 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 horizontally 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 (Stop 1 for today's trip), 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 37.) 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.

Figure 39. View of an upright chevron fold gently plunging into N75°W in contact-metamorphosed strata of the Lockatong Formation. The black arrow, which was drawn immediately above the Palisades-Lockatong contact, shows the interpreted flow direction of the Palisades magma. The exposure is immediately north of the George Washington Bridge on the Palisades Interstate Park access road in Fort Lee, New Jersey. Knife (scale) is 9 cm in length. (CM photograph).

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) 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 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 30.) 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 34.) 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 (Figure 40). 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 into the Palisades chilled zone (Figure 41). 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 sandy interlayers that had been vaporized by magmatic heat. In the following and in the description for Stop 1, 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.

Figure 40. View of a feldspathic sand "apophyse" intruded upward, beyond level of hammer, from contact- metamorphosed Lockatong into chilled Palisades basalt. The hammer handle is 40 cm in length and rests on the basal contact of the Palisades chilled-margin basalt. (CM photograph.)

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(?).

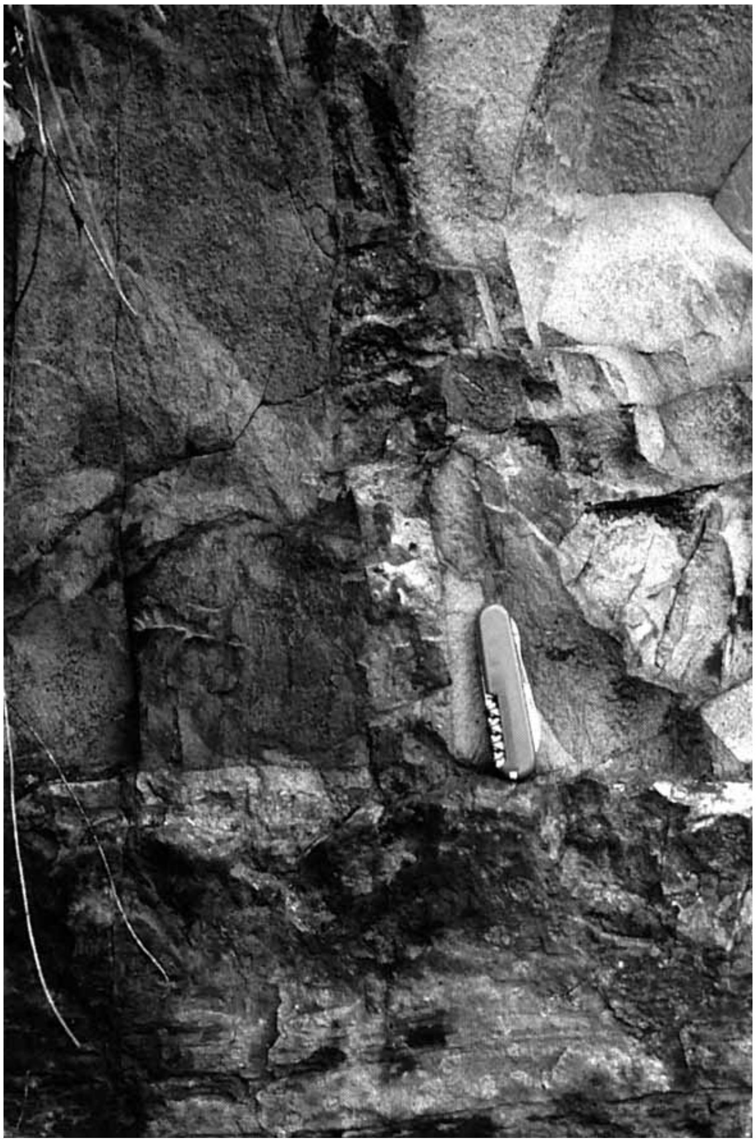


Figure 41. View of a 3-cm-thick feldspathic "clastic dike" that has intruded the Palisades chilled margin. Knife (scale) is 9 cm in length. (CM photograph.)

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 appeared. 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.

An analogous situation, from a quarry in West Rock in New Haven, CT, in the Hartford Basin, was reported by Walton and O'Sullivan (1950). There, a layer of conglomeratic arkose produced a branching, irregular clastic dike exhibiting sharp contacts which was intruded upward more than 10 m into the dolerite sill. The 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.

As noted above, the Newark mafic igneous rocks include both intrusives (the Palisades mafic intrusive sheet) and extrusives (forming 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 igneous geologists has been proof of consanguinity between the Watchung extrusives and phases of the Palisades intrusive. The Palisades mafic sheet was intruded into the base of the Newark Supergroup during the Sinemurian age of the Early Jurassic (roughly 201 ñ1 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.

An important point to be established about the Palisades intrusive is the timing of the intrusion relative to extrusion of one or more of the Watchung extrusive sheets. 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).

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 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.

So enough of all this geologic background, let’s see where we are going today.

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 Passaic River); Orange Mountain and Passaic formations; evidence for faults.

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.]

Exposures along the Palisades Interstate Park access road beneath the George Washington Bridge feature 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)]. The Palisades Intrusive Sheet is one of the world's premier examples of a large sheet of mafic intrusive igneous rock. The tilted- and eroded edge of the mafic rock is expressed in the landscape as the Palisades ridge along the west side of the Hudson River.

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. Our investigations indicate that the sedimentary strata have been contact metamorphosed and that many parts of the contact with the Palisades intrusive are discordant. The strata also display evidence of ductile folding, the probable result of mechanical contrasts between the higher-density magmatic fluid and the contact-heated sediments.

The zone containing abundant olivine crystals is present near the park entrance. Because the olivine-rich rock crumbles much more readily than the rock above it 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 geology students know, an excellent exposure of the olivine zone is present to the south in 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.

Another general feature of the igneous rock is its pattern of columnar joints. One of the characteristics of such 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 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.

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 and then sank, as the result of density contrast, into 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, this version of the crystal-settling concept has been challenged (Husch, 1990). The alternate 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 for pyroxene (not olivine) to crystallize and for the pyroxene crystals 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 magma that underwent olivine accumulation prior to its emplacement within the Palisades."

From this, one may conclude that Husch 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 from a later injection of magma unlike the one 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."

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. In order to appreciate the fine points of what is up coming, 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 of light gray 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 and mudflat to lacustrine (transgressive) facies; 2, a microlaminated 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 or gray-red siltstone or sandstone (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 35).

"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 (5000 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 environ-ment (which are named autocyclic).

Immediately north of the George Washington Bridge is a spectacular exposure of the basal contact of the Palisades intrusive sheet. 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 36). 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 apophyses" (See Figure 22.) and clastic dikes. (See Figure 23.)

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 under the heading Layer V (above), in the Fort Lee area, we have noticed that the intrusive cuts across the bedding at a high angle in a ramp-like fashion toward the north. (See Figure 18.) In addition, immediately beneath the basal contact of the intrusive sheet, the sedimentary strata are broadly arched (See Figure 20.), disposed in tight, chevron folds with vertical, east-west-trending axial surfaces (See Figure 21.), and we have noted asymmetric intrafolial z-folds in the bounding argillites. We have argued (See above.) 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. (See Figure 16.) 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, paleoflow indicators should indicate the magma moved from NE to SW.

STOP 2 - Pillow basalt of Orange Mountain Formation ("First Watchung Basalt"). East side of McBride Avenue ~0.7 mile 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 37).

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: 569.00E / 4529.45N, Paterson quadrangle.]

Consult Figure 11 for a general columnar section of the strata of the Newark Supergroup from the top of the Passaic Formation to the Boonton Formation. Figure 38 is a sketch of the exposure in the Municipal Parking Lot.

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 planar 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 39-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.

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 39-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 lava flowed. According to Manspeizer (1980, fig. 6, p. 319), pipe amgydales here are bent over toward the NE. (See Figure 38.) 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 here onlapped 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. [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 / 4529.65 N, Paterson quadrangle.]

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 Zambezi River in southeastern Africa (Zambia/Zimbabwe).

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). 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 10 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 Folio. JES interprets 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.) CM and JES think that the northward- and upward shift of the basal contact of the extrusive rock is evidence for two other small faults.

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 contact. These give way upward to a zone about 5 m thick that is characterized by large polygonal columns. 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?

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.

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
(Triassic)		activity both extrusive and intrusive. Newark basins form and fill with non-marine sediments.
PALEOZOIC	245	

(Permian)		Pre-Newark erosion surface formed.
	260	**Appalachian orogeny.** (Terminal stage.) Folding, overthrusting, and metamorphism of Rhode Island coal basins; granites intruded.
(Carboniferous)		Faulting, folding, and metamorphism in New York City area. Southeastern New York undergoes continued uplift and erosion.
(Devonian)	365	**Acadian orogeny.** Deep burial of sedimentary strata. Faulting, folding, and metamorphism in New York City area. Peekskill Granite and Acadian granites intruded.
(Silurian)		
	440	**Taconic orogeny.** Intense deformation and metamorphism.
	450	Cortlandt Complex and related rocks intrude Taconian suture zone. (Cameron's Line). Arc-continent collision.
(Ordovician)		Great overthrusting from ocean toward continent. Taconic deep-water strata thrust above shallow-water strata. Ultramafic rocks (oceanic lithosphere) sliced off and transported above deposits of continental shelf.
(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 the Fall Zone planation surface].

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

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

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

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

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

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

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

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IIA[W] - SAUK SEQUENCE

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

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

LAYER IIA[E] - TACONIC SEQUENCE

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

Stockbridge
or Inwood Marbles

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

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

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

LAYER I - PROTEROZOIC BASEMENT ROCKS

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

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

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

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

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

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