Geology 133 Field Trip

Cortlandt Igneous Complex, Buchanan, NY

21 April 2008

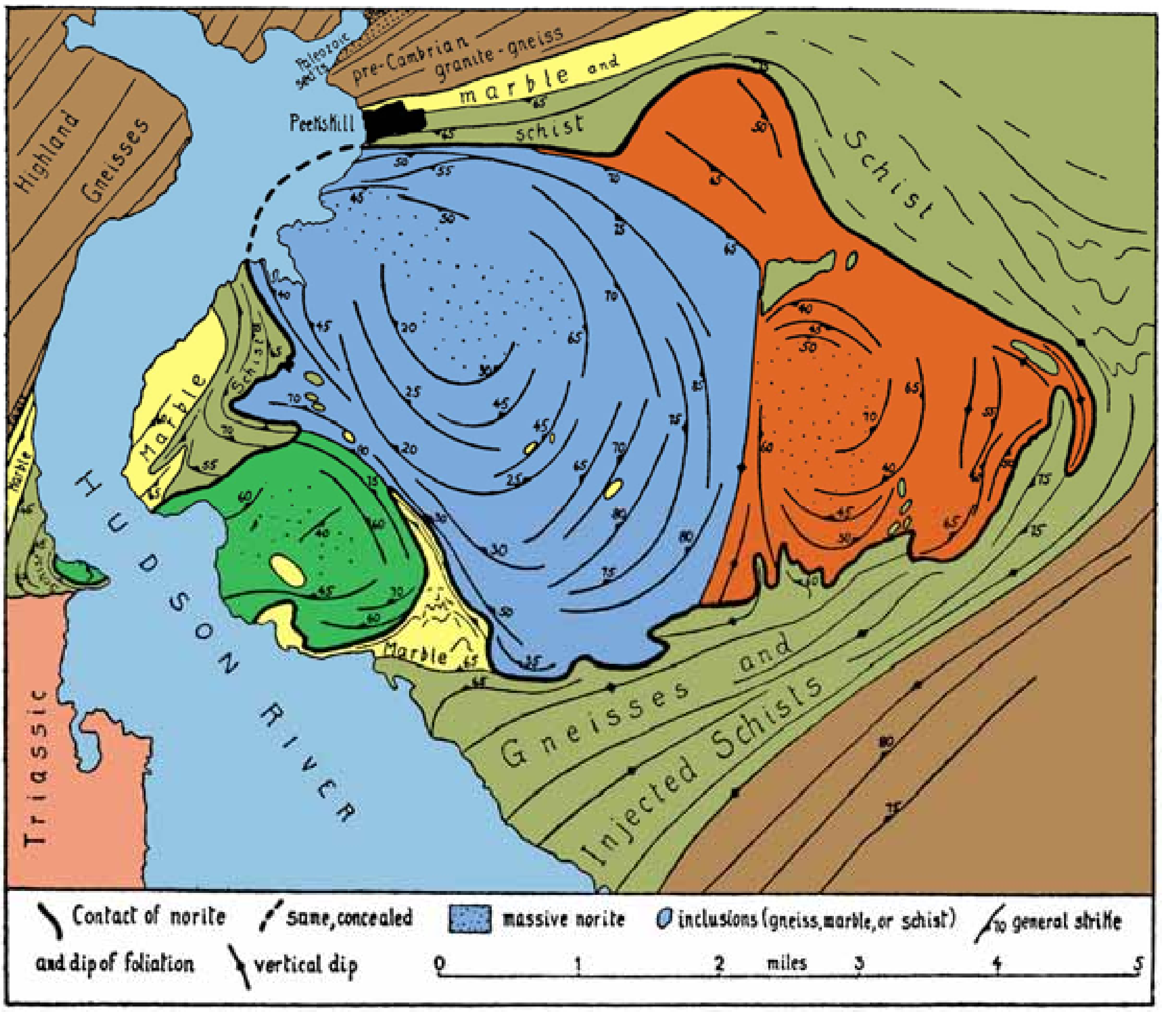

Figure 1. Geological map of the Cortlandt Complex showing the country rock and the Western Funnel (green), Central Basin (blue), and the Eastern Funnel (orange). (Colorized after original drawing by Robert Balk, 1937, Figure 33, p. 92.)

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INTRODUCTION

Welcome Aboard! The scientific goal of this trip is to examine intrusive relationships and igneous phases within the world-renowned Cortlandt Complex south of Peekskill, NY. (Figure 1, cover.) Both mafic and ultramafic rocks studied at the Stony Point Complex are found as separate plutons in the Cortlandt Complex a much larger body found to the east of the river. Today's trip will focus on field relationships at various stops largely from a guidebook by Ratcliffe et al. (1983). 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.

The Manhattan Prong consists of highly deformed Paleozoic- and Proterozoic metamorphic- and igneous rocks. These strata constitute the country rocks into which the Cortlandt Complex was intruded during early Paleozoic time. 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 underlies 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 fringes of the craton.

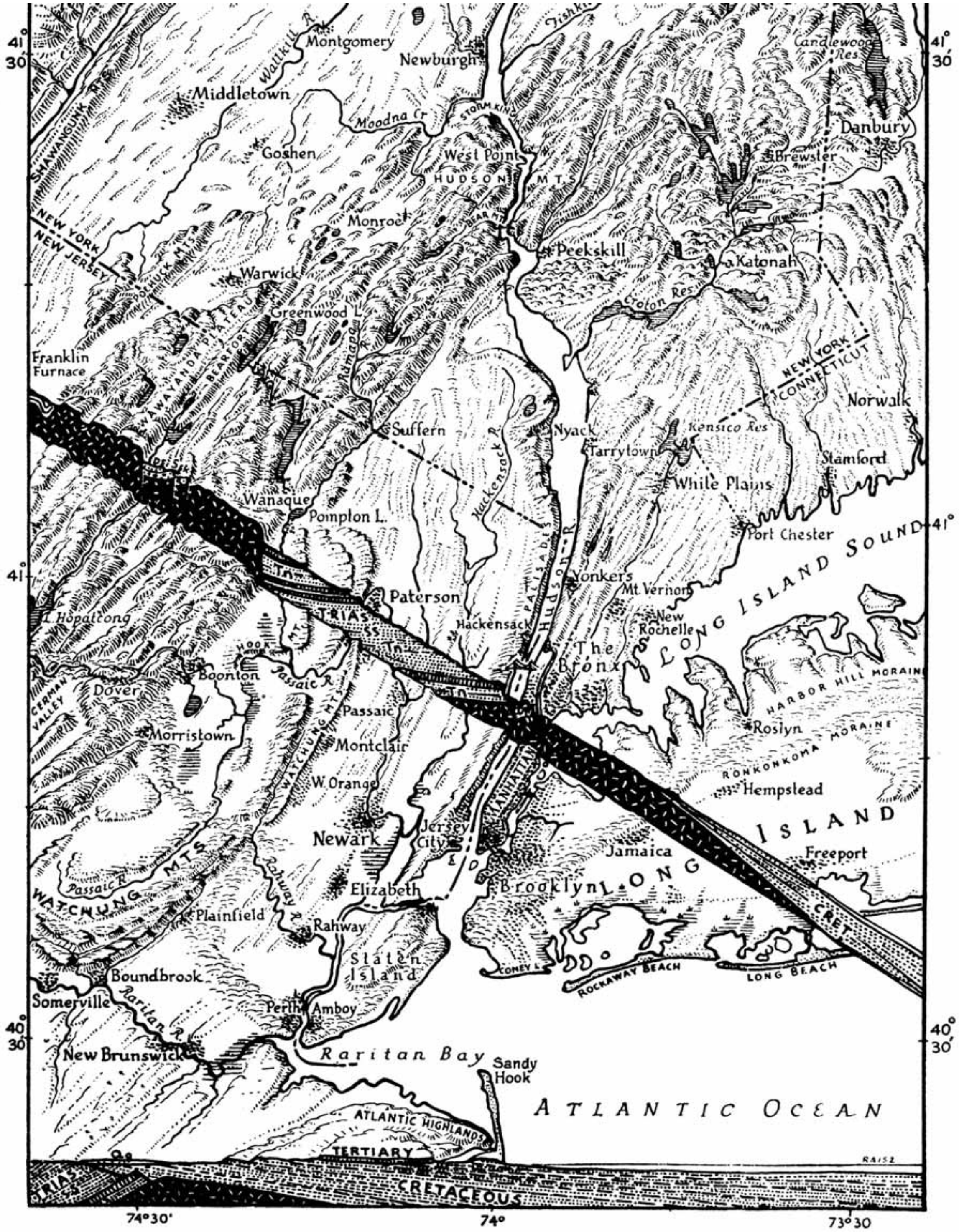


Figure 2. Physiographic block diagram of the lower Hudson River region (drawn by E. Raisz).

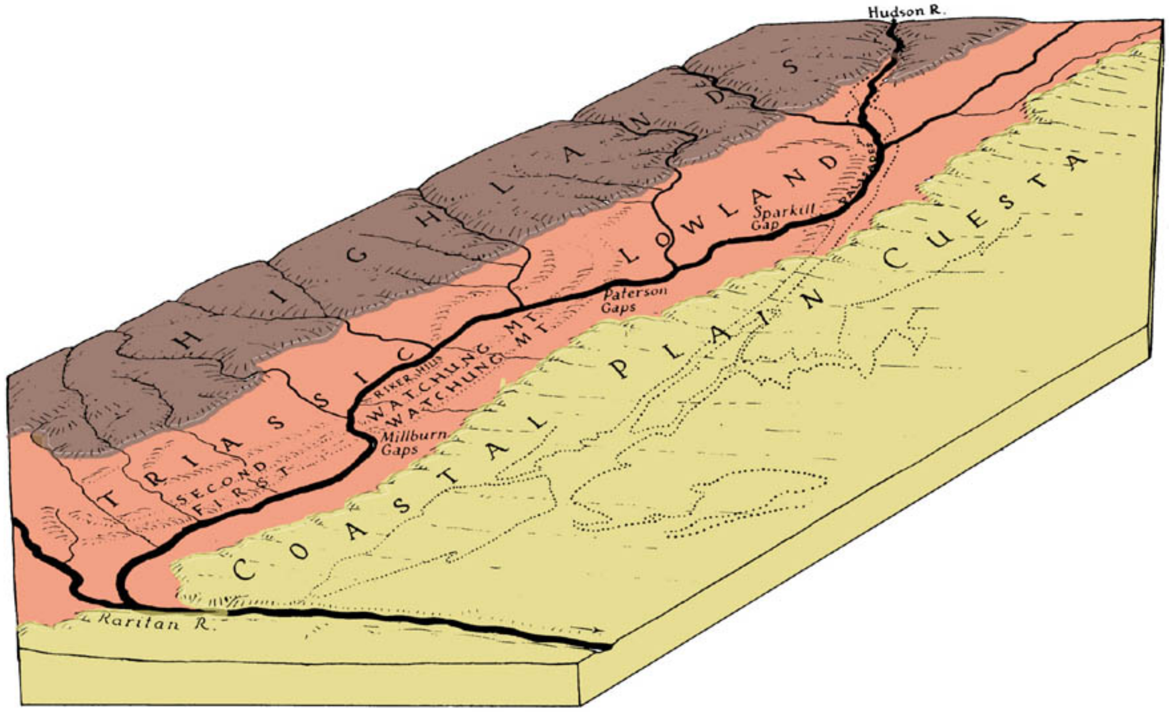


Figure 3. Physiographic diagram of the Hudson Highlands and hypothetical course of the Hudson River in Schooley time. (Colorized from an original drawing by E. Raisz).

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.

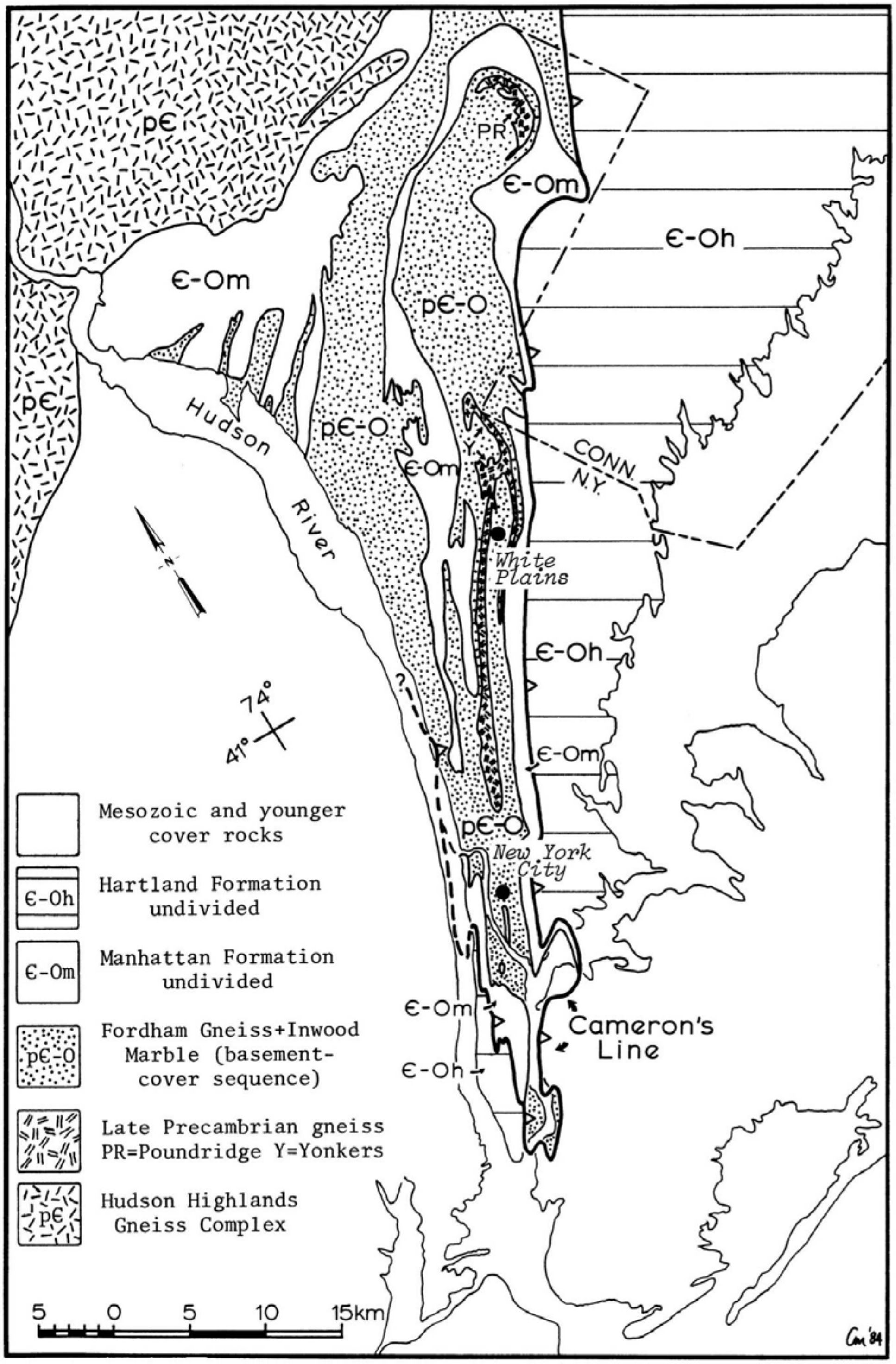


Figure 4. Simplified geologic map of the Manhattan Prong showing the distribution of metamorphic rocks (Layers I and II) ranging from Proterozoic Y through Early Paleozoic in age. Most faults and intrusive rocks have been omitted. (From Mose and Merguerian, 1985.)

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.

Today's trip will examine the crosscutting Cortlandt Complex - an eastward extension of the Stony Point Complex that we visited on our first Petrology field trip on 02 April 2004.

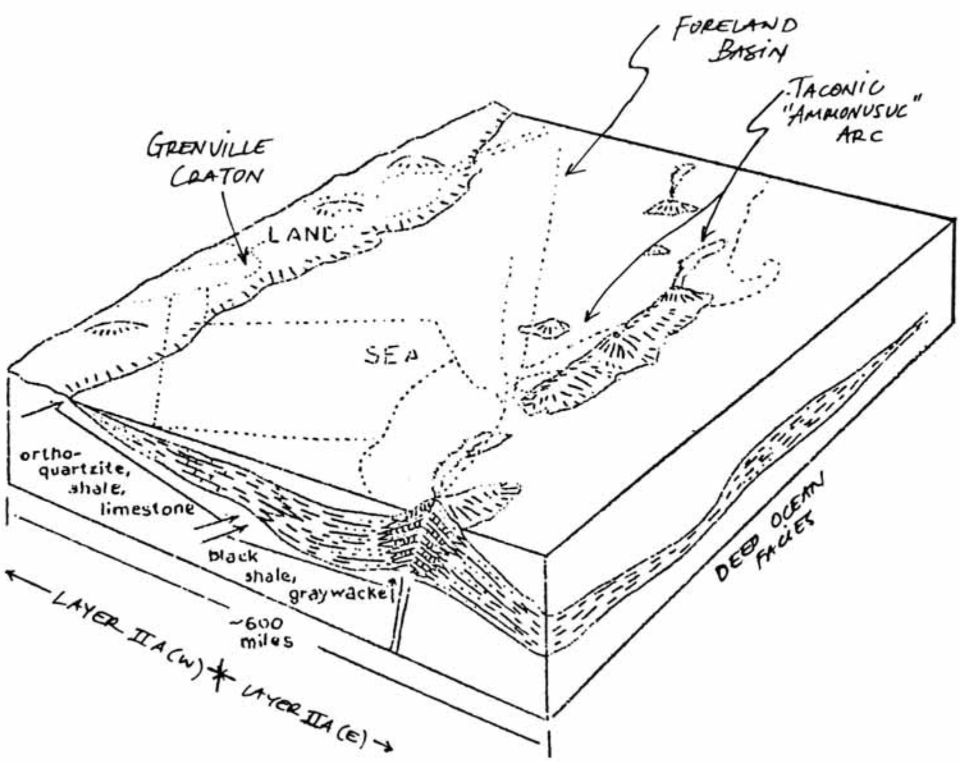


Figure 5. Block diagram showing the Early Paleozoic continental shelf edge of embryonic North America immediately before the deposition of Layer IIB. Current state outlines are dotted. The depositional areas for Layers IIA(W) and IIA(E), and the position of the Taconic arc and foreland basin are shown.

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).

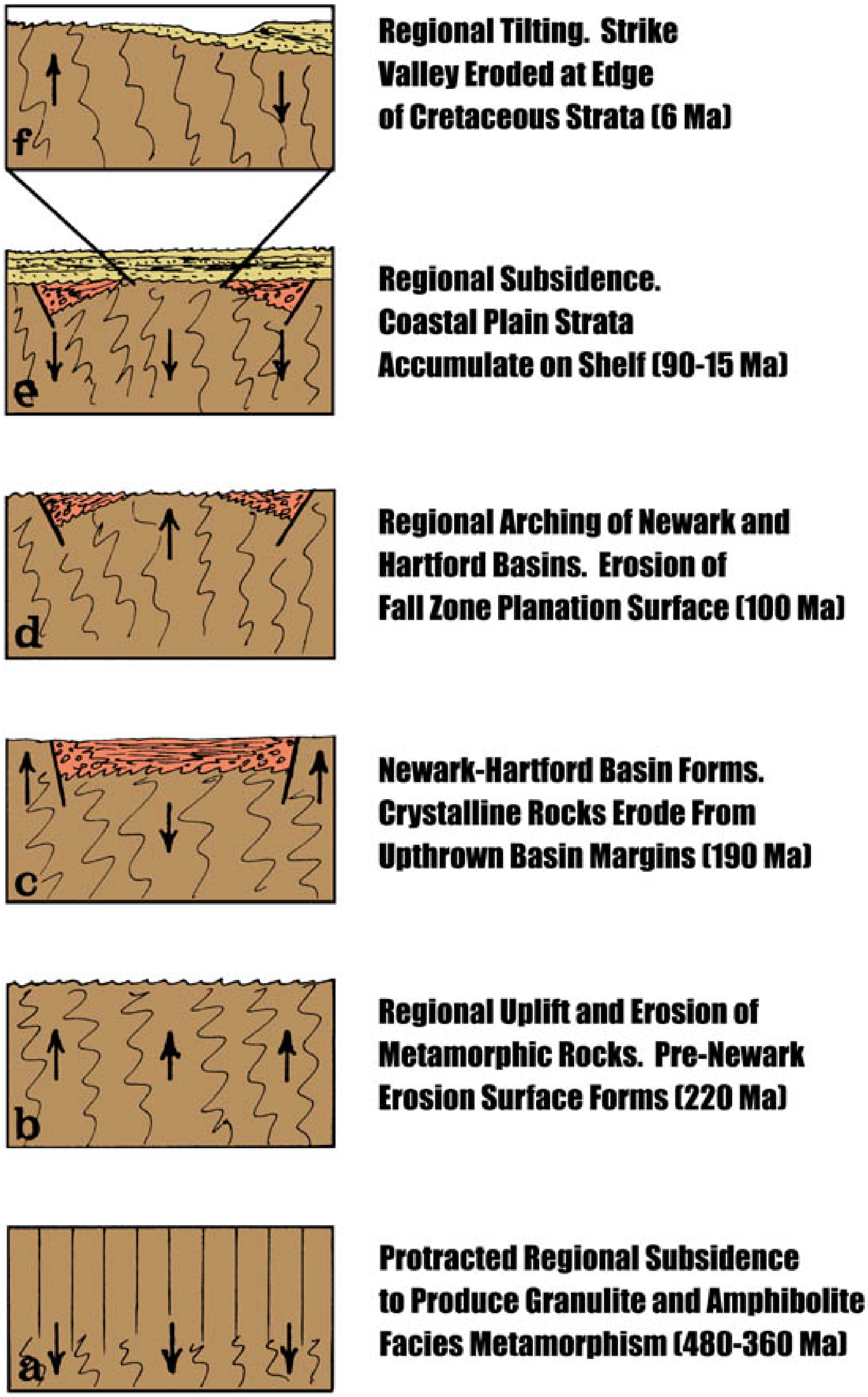


Figure 6. Simplified profile sections showing the development of the New York City region from 365 Ma to 6 Ma. (Colorized from J. E. Sanders sketches.)

GEOLOGY OF THE CORTLANDT COMPLEX

The Cortlandt Complex, a world-class mafic-ultramafic alkalic 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, including 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, 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).

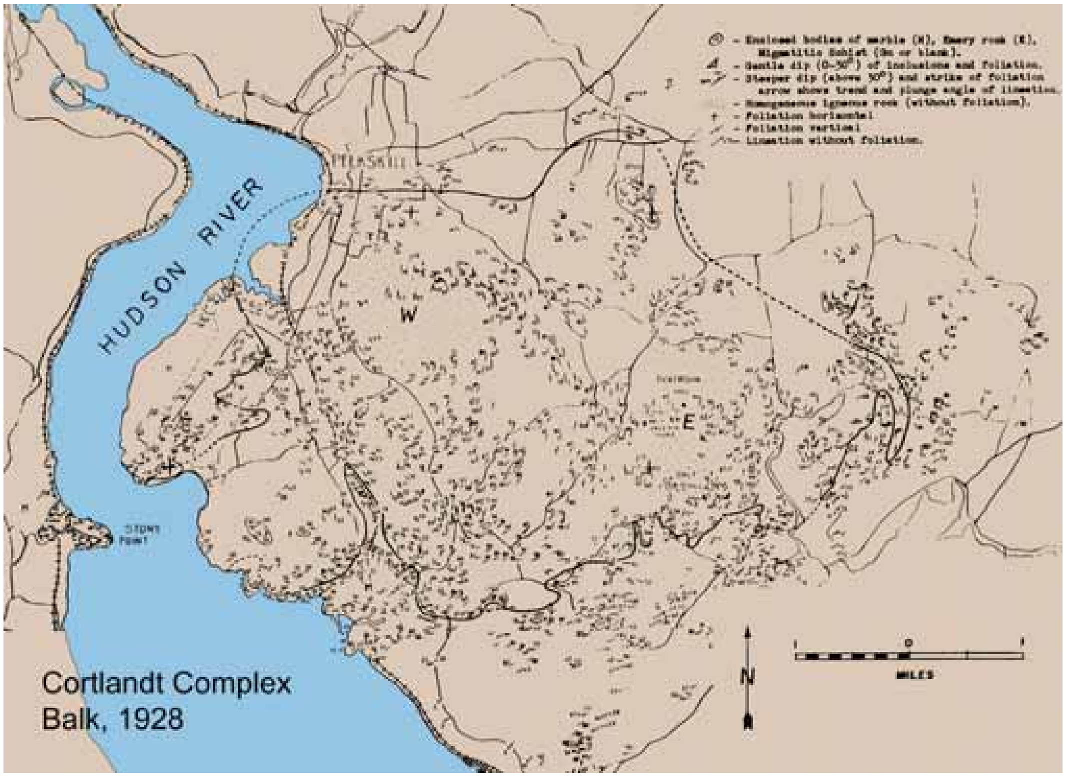


Figure 7. Detailed geological map of the Cortlandt Complex showing the orientation of flow layering and the geometry of internal plutons. (Colorized after Balk, 1927.)

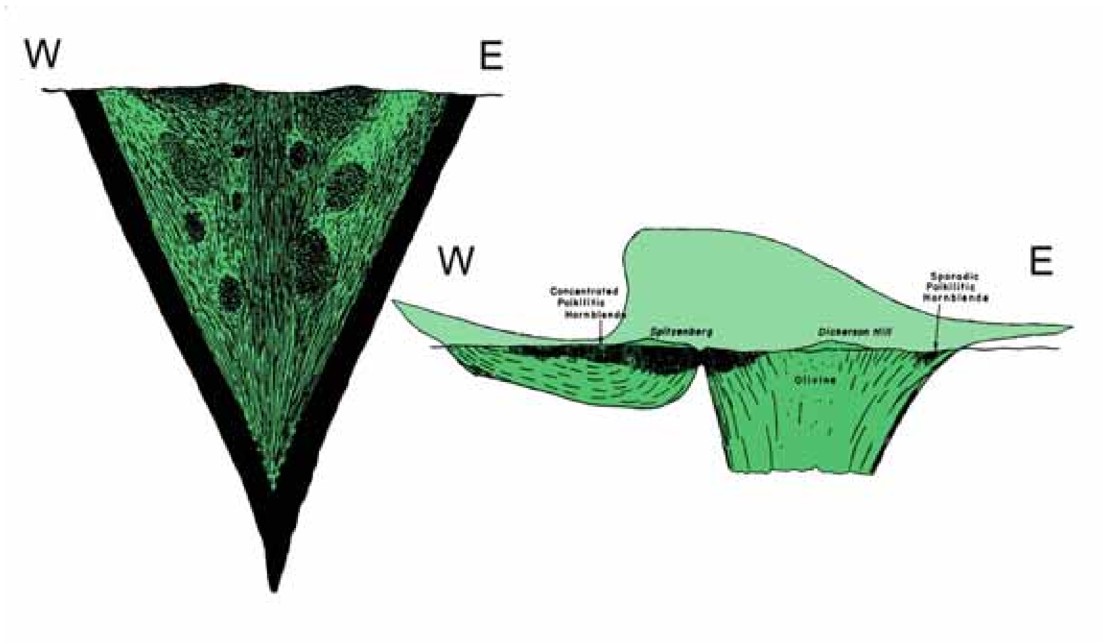


Figure 8. Interpretations of the internal structure of the Cortlandt Complex by Balk (1927) and Steenland and Woollard (1952) on the right.

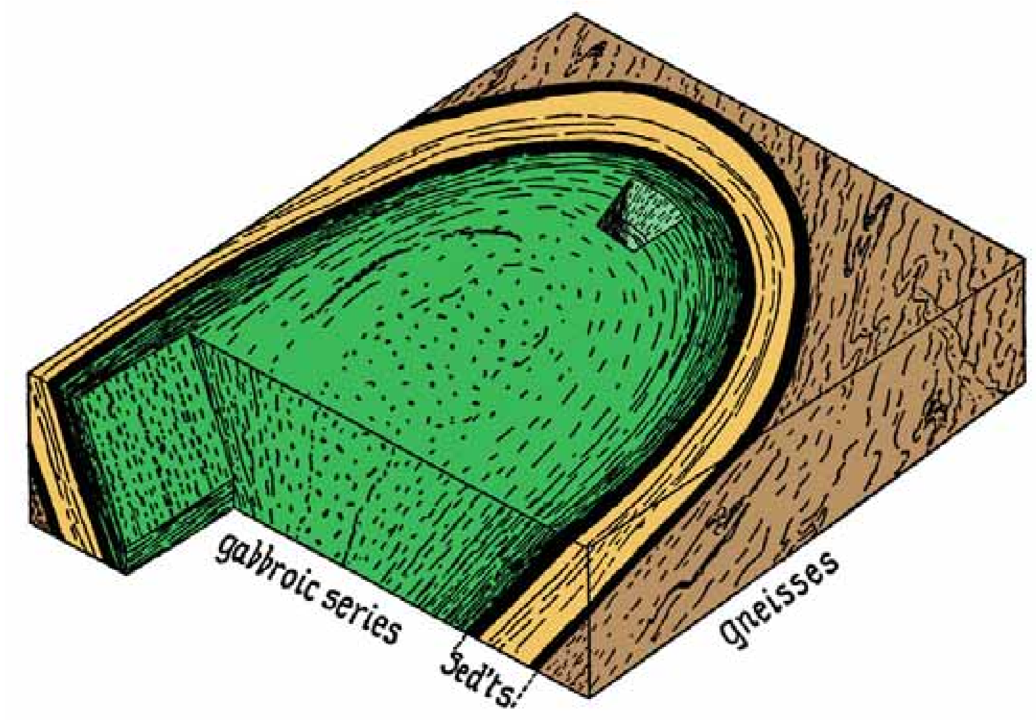


Figure 9. Generalized interpretation of a funnel structure showing flow fabrics in mafic-ultramafic plutons similar to the Cortlandt according to Balk (1937, Figure 34, p. 93). The funnel may be steep or shallow and expose massive igneous rocks of varying composition. Alternatively, the center may be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

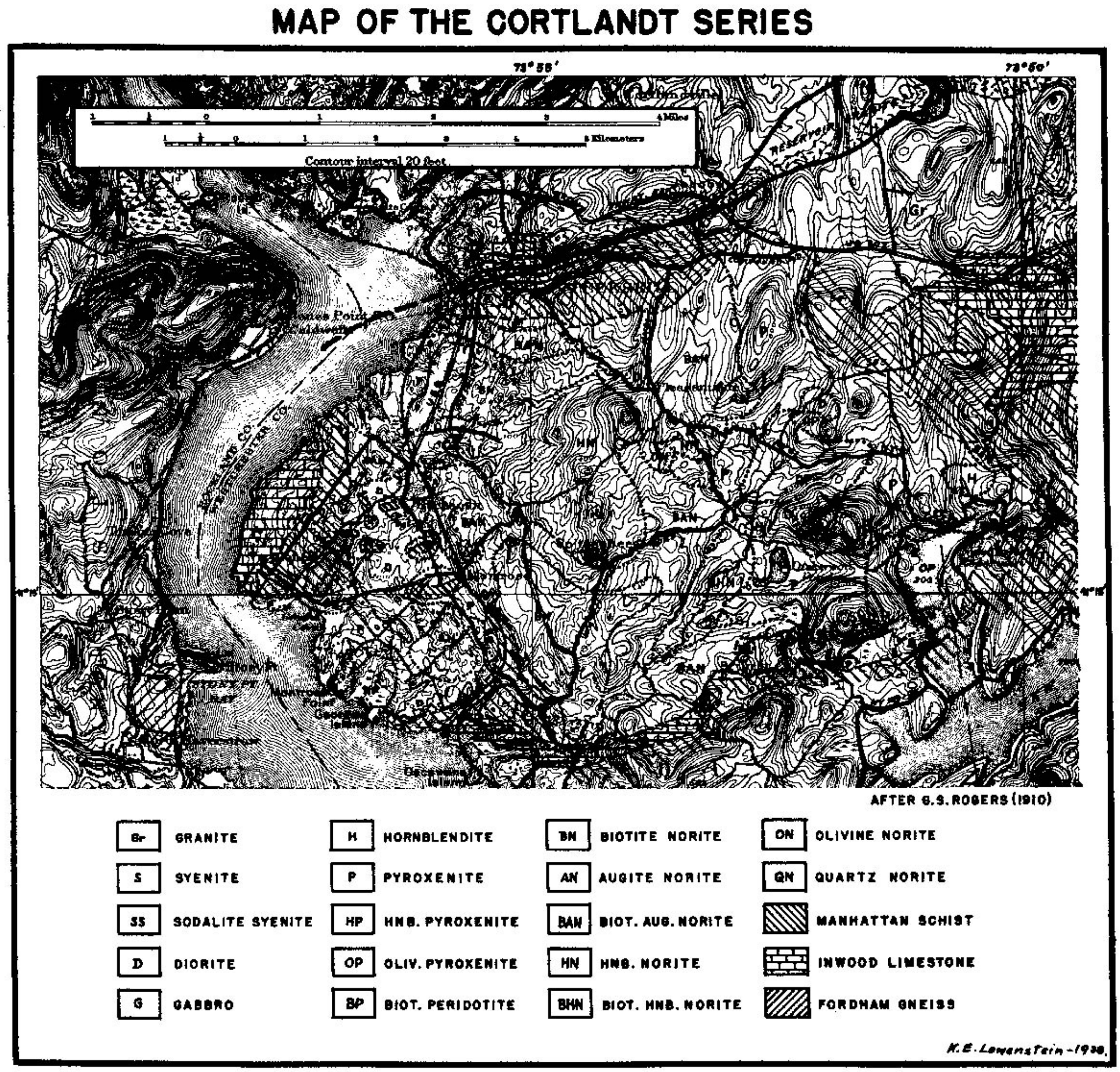


Figure 10. Petrographic map of the Cortlandt Complex by Dr. Kurt E. Lowe of The City College of New York in 1937. The map, after Rogers (1910), shows the great variation in rock types (17 igneous phases) that were found using a purely petrographic approach.

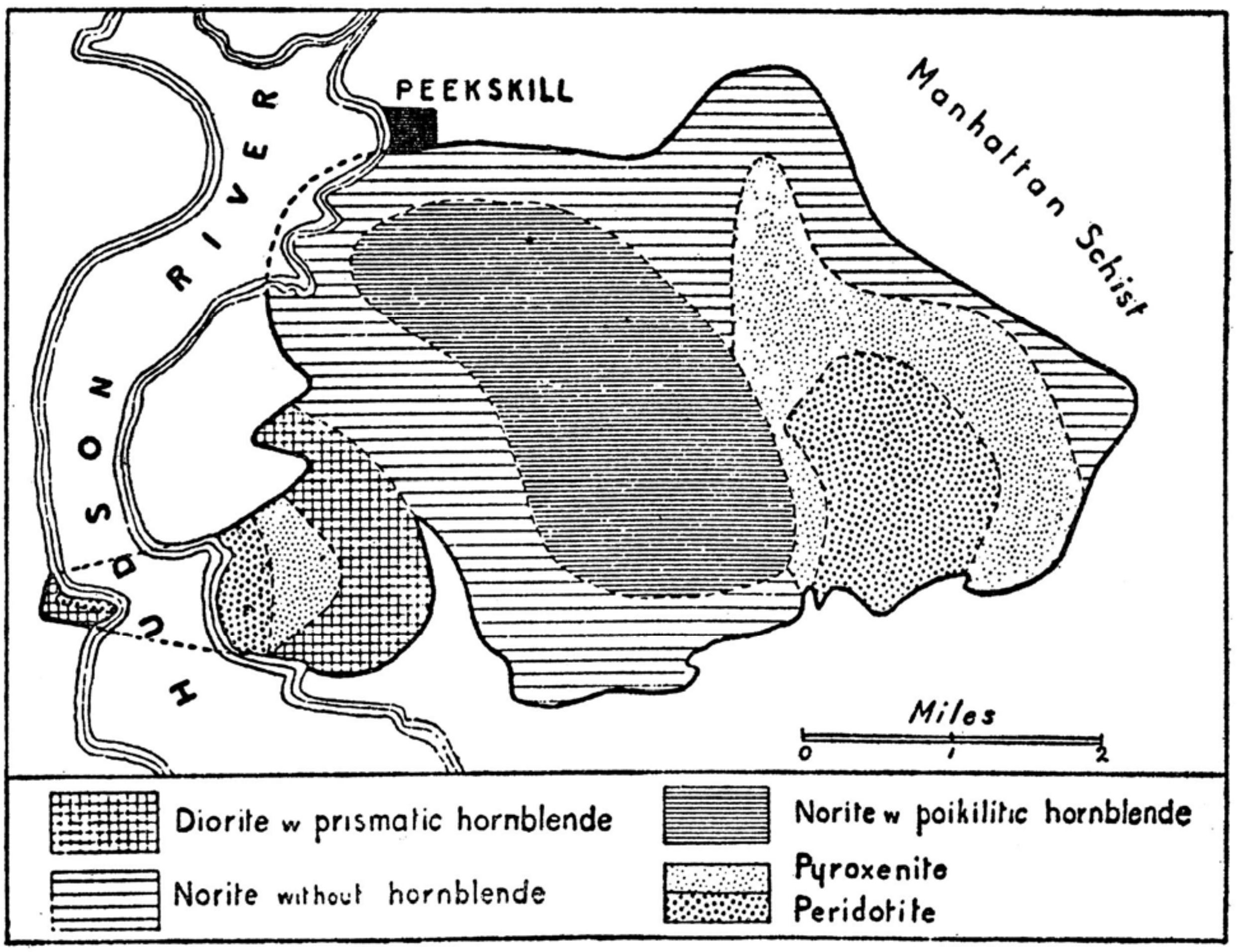


Figure 11. Petrographic map of the Cortlandt Complex according to Shand (1942) showing the connection to the Stony Point Complex and the major plutonic centers.

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).

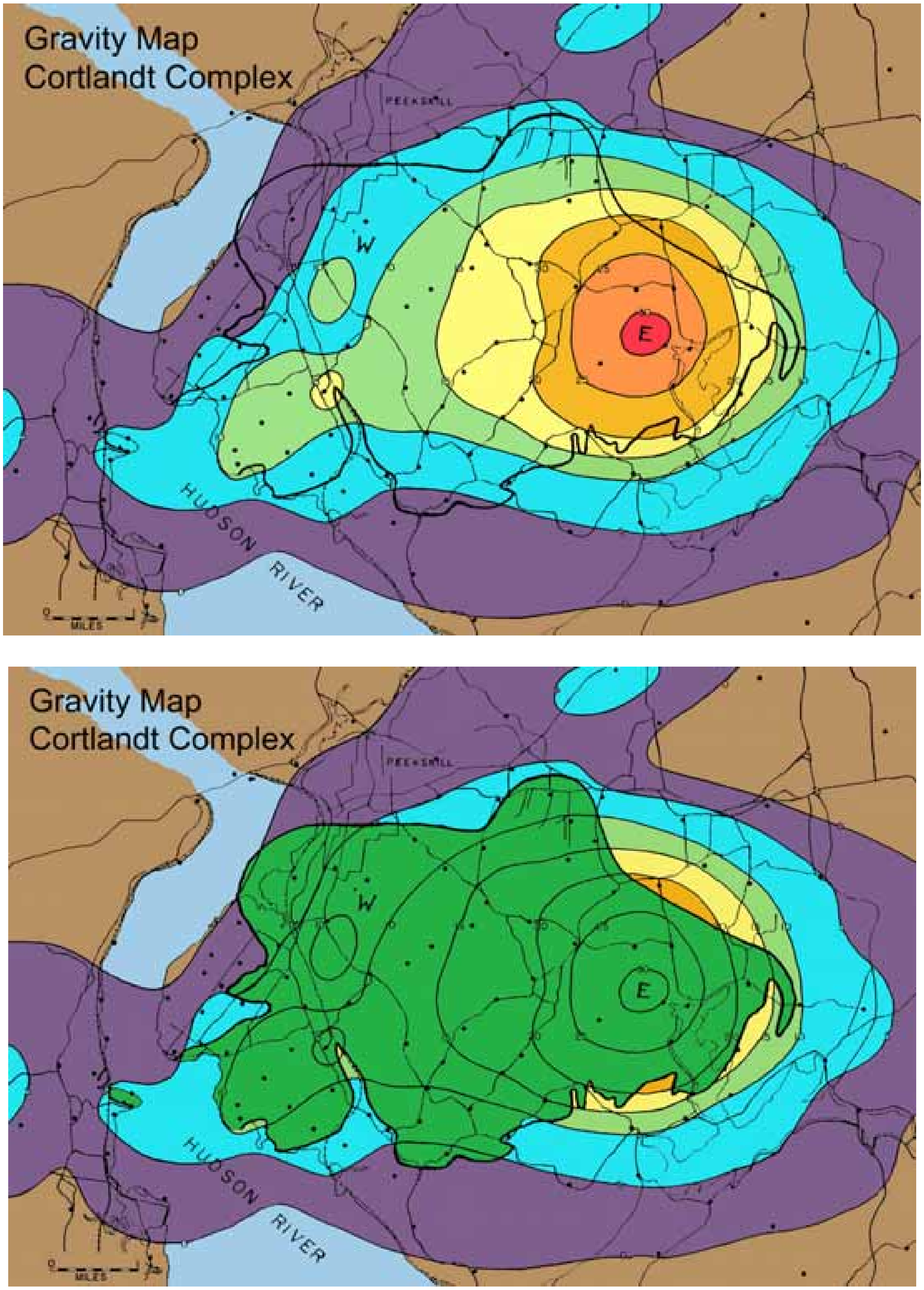


Figure 12. Gravity maps of the Cortlandt Complex. They are colorized to show the overall gravity pattern and the 30 mgal gravity high centered near Dickerson Mountain (the Eastern Funnel of Balk and subsequent workers). The bottom diagram shows the outline of the Cortlandt and its relationship to the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

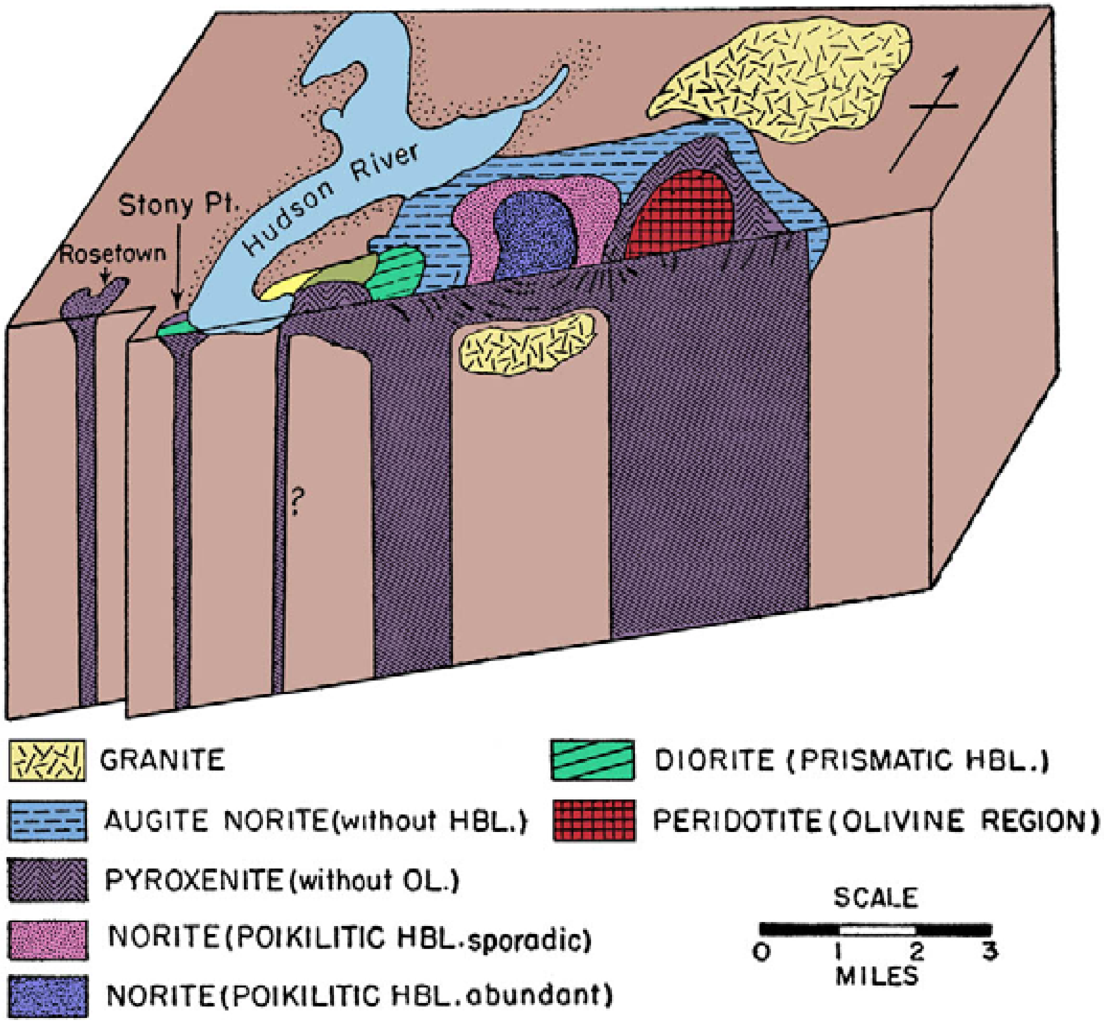
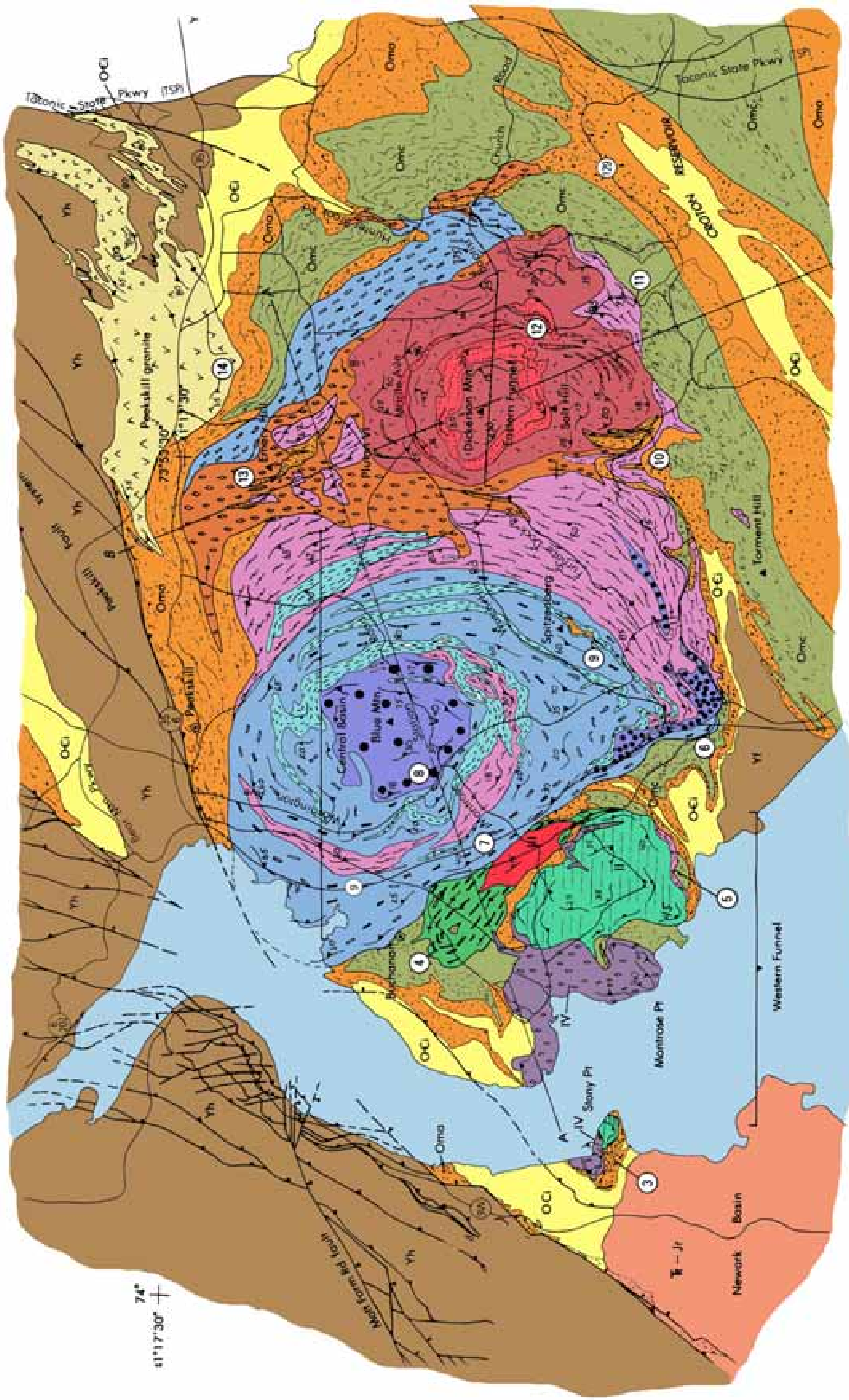


Figure 13. Block diagram showing an interpretation by Friedman (1956) showing vertical feeders beneath most of the Cortlandt Complex and a buried granitic mass in the central part to account for the low gravity measured there.

Modern work Nick 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)
Peekskill granite
Croton Reservoir
Church Road
Dickerson Mtn
Eastern Funnel
Salt Hill
Torment Hill
Spitzenberg
Central Basin
Blue Mtn
Buchanan
Montrose Pt
Stony Pt
Western Funnel
Newark Basin
Omc
Oma
O-Ci
Yh

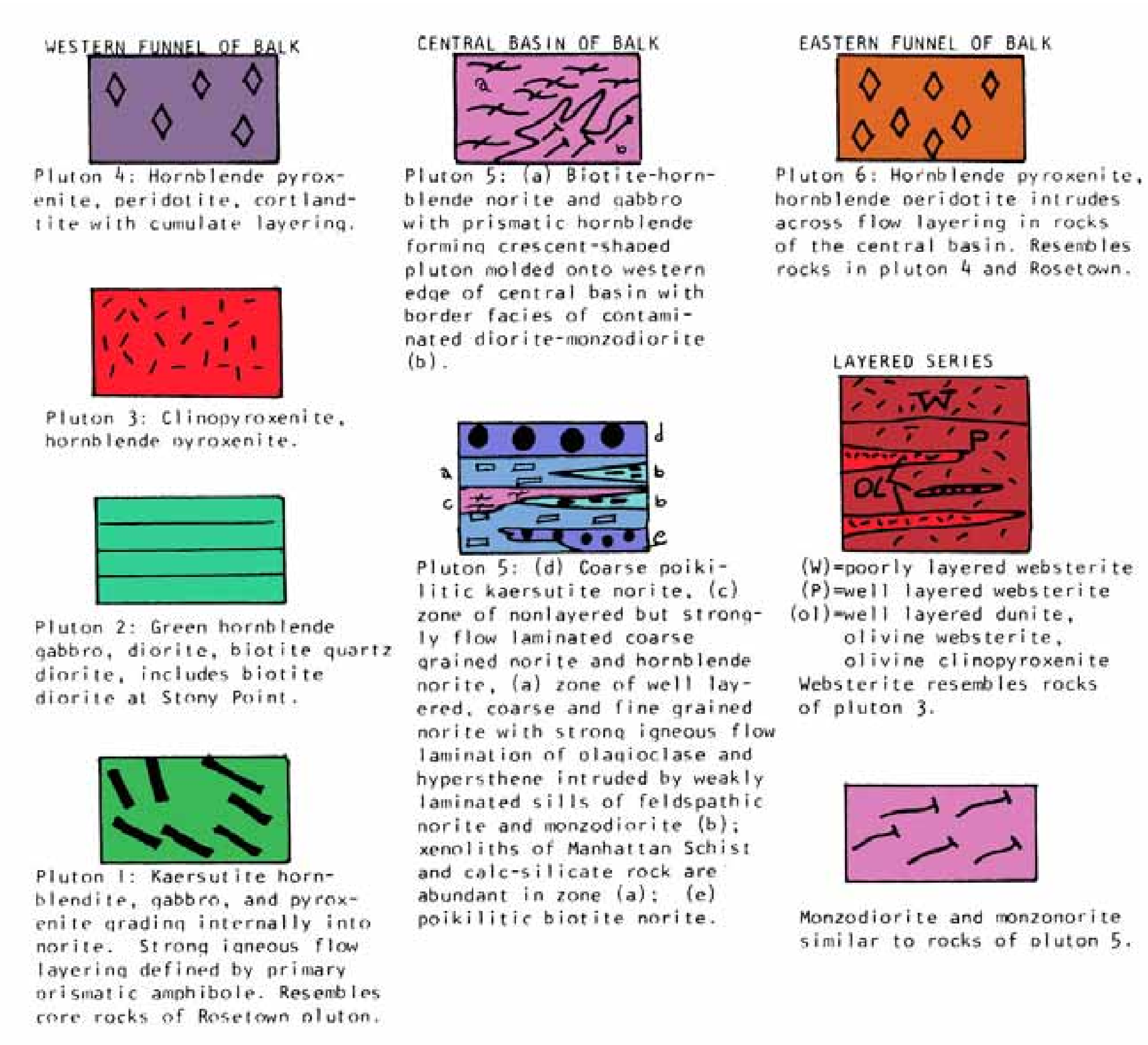


Figure 14. Geologic map of the western and central funnels of the Cortlandt Complex and the Stony Point and Rosetown extensions of the Cortlandt (Ratcliffe and others, 1983).

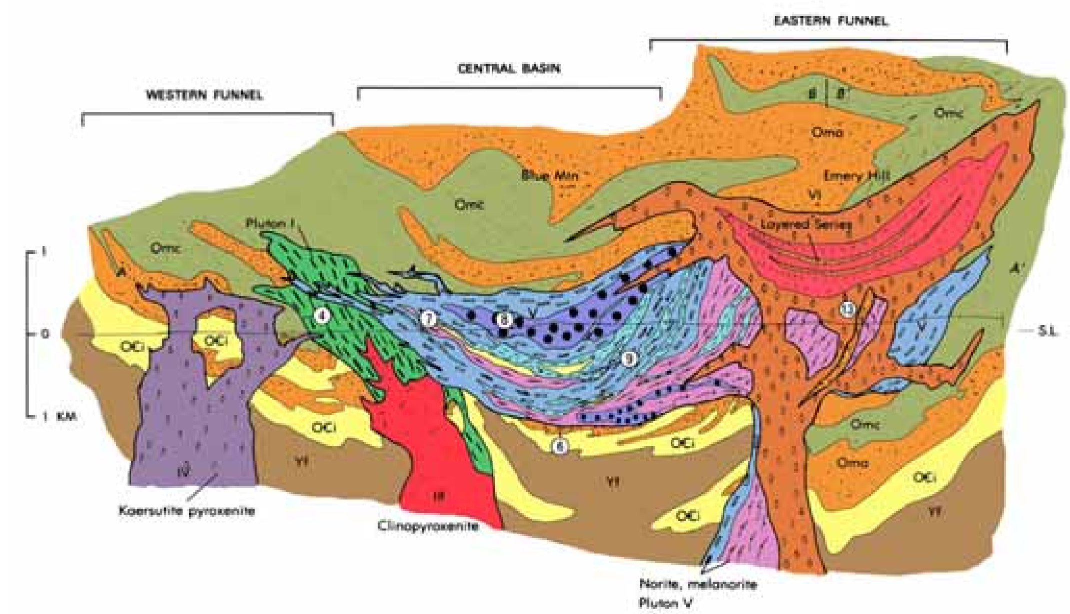


Figure 15. Geologic section oriented SW to NE of the Cortlandt Complex (Section A-A' on Figure 14) showing internal flow structure, cross cutting relationships of the earliest plutons (I, III, and IV), and the general lopolithic form of plutons V and VI of the composite intrusive. Pluton II does not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

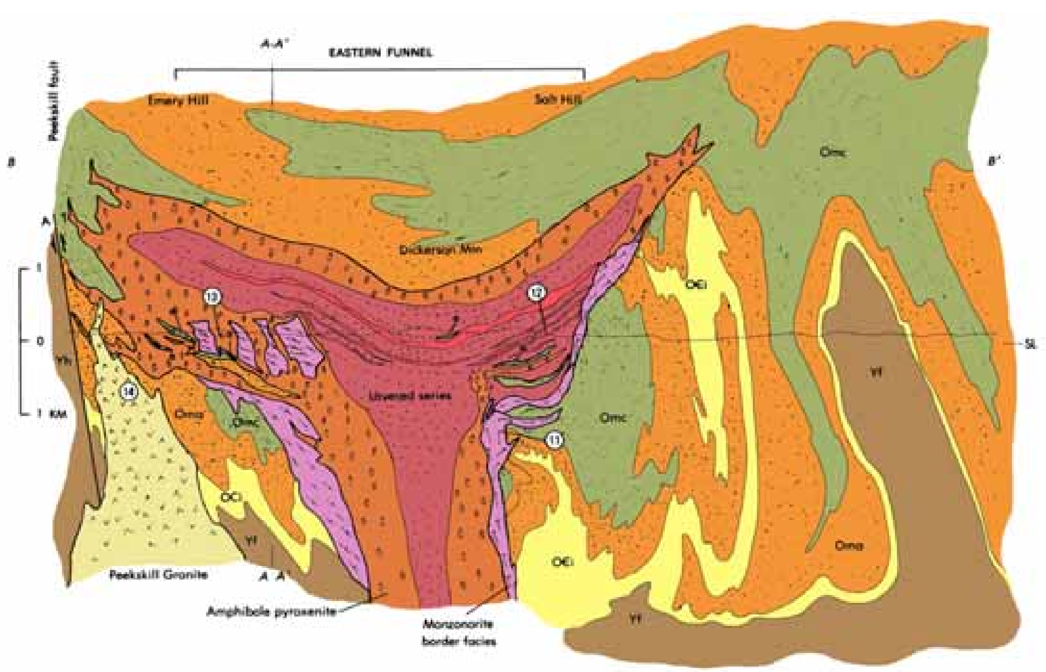


Figure 16. Geologic section oriented NW to SE of the Cortlandt Complex (Section B-B' on Figure 14) showing internal flow structure, cross cutting relationships, and general lopolithic form of Pluton VI of the composite intrusive. (Colorized after Ratcliffe et al., 1983.)

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.

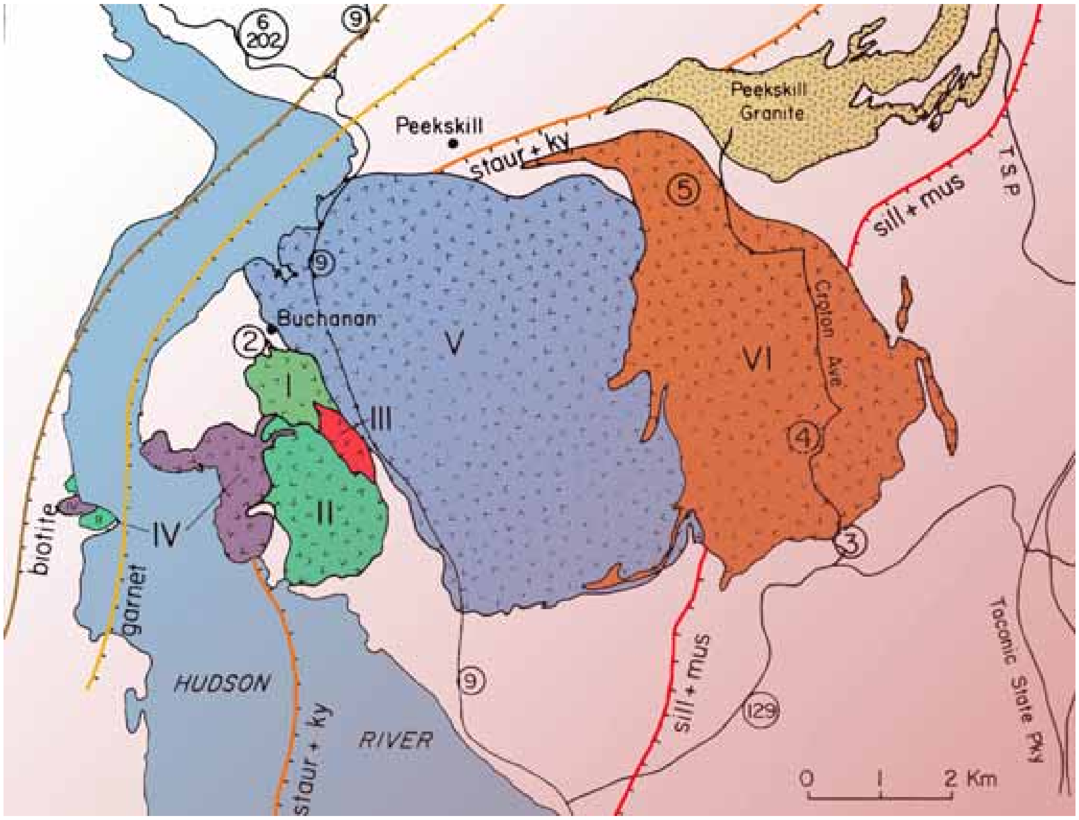


Figure 17. Map showing truncation of Taconian regional isograds by plutons of the Cortlandt Complex. (Colorized from Tracy et al., 1987.)

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.

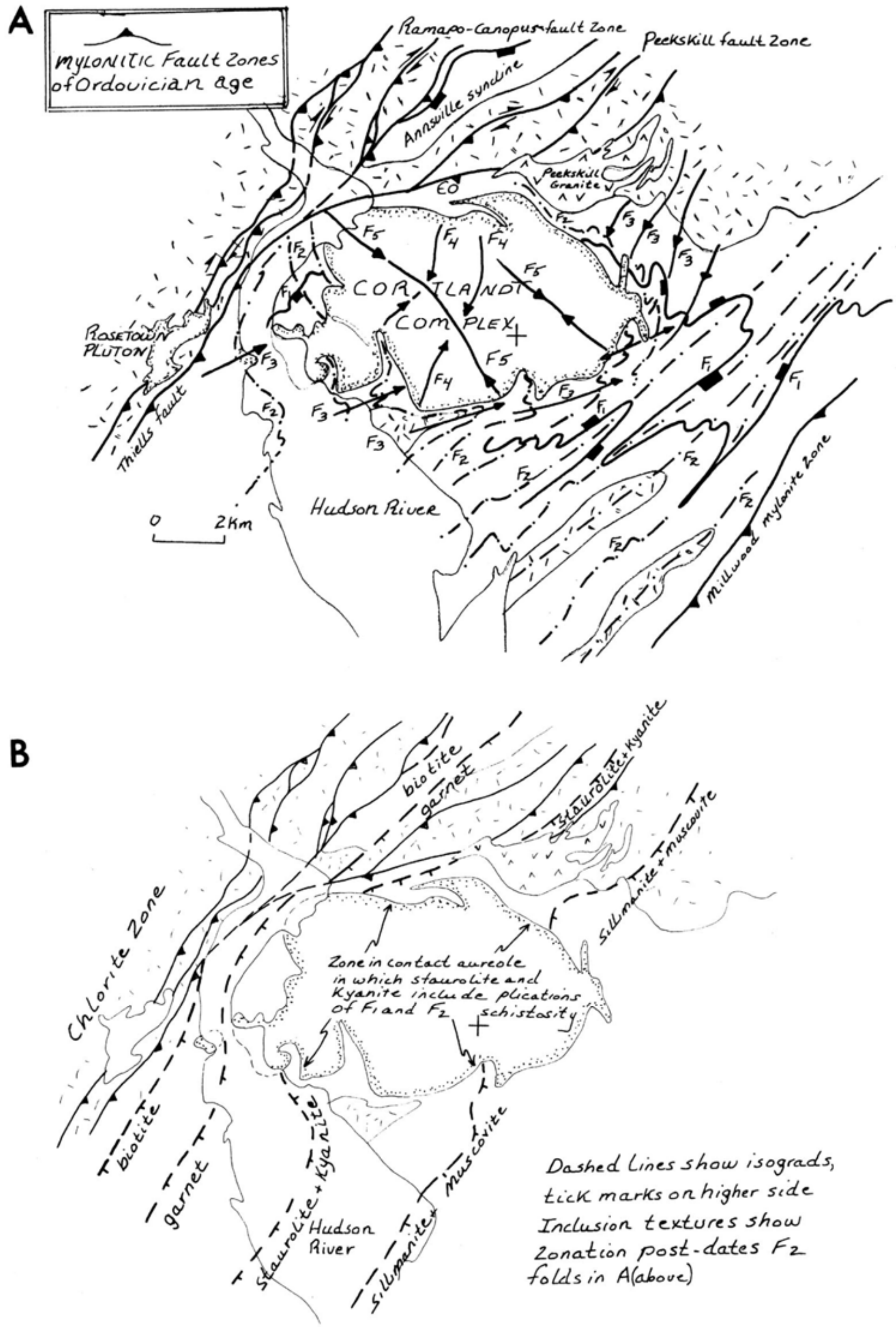


Figure 18. Map A shows F_1 through F_5 axial traces and traces of regional Taconian ductile faults in the vicinity of the Cortlandt Complex. Note that the Cortlandt truncates F_1 through F_3 folds but is deformed by F_4 and F_5. Map B shows truncation of regional isograds and areas where contact assemblages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

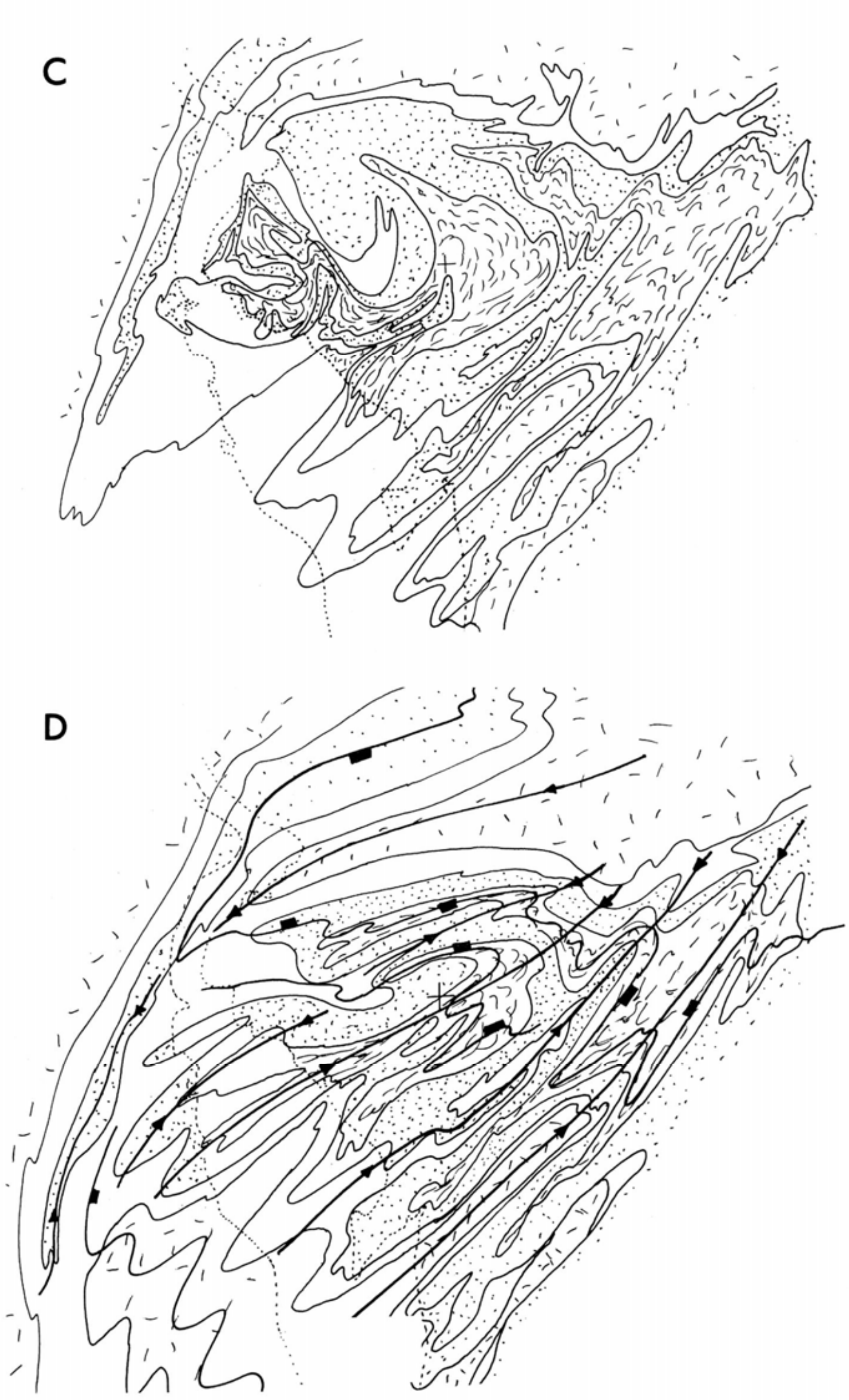


Figure 19. Map C shows the effects of F_1, F_2, and F_3 folds in metamorphic rocks of the Fordham Gneiss (hashed pattern), Inwood Marble (unpatterned), Walloomsac [=Manhattan A] (stipled), and Manhattan Schist (dashed) with Cortlandt Complex removed. Map D is a view of F_1 and F_2 patterns before injection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

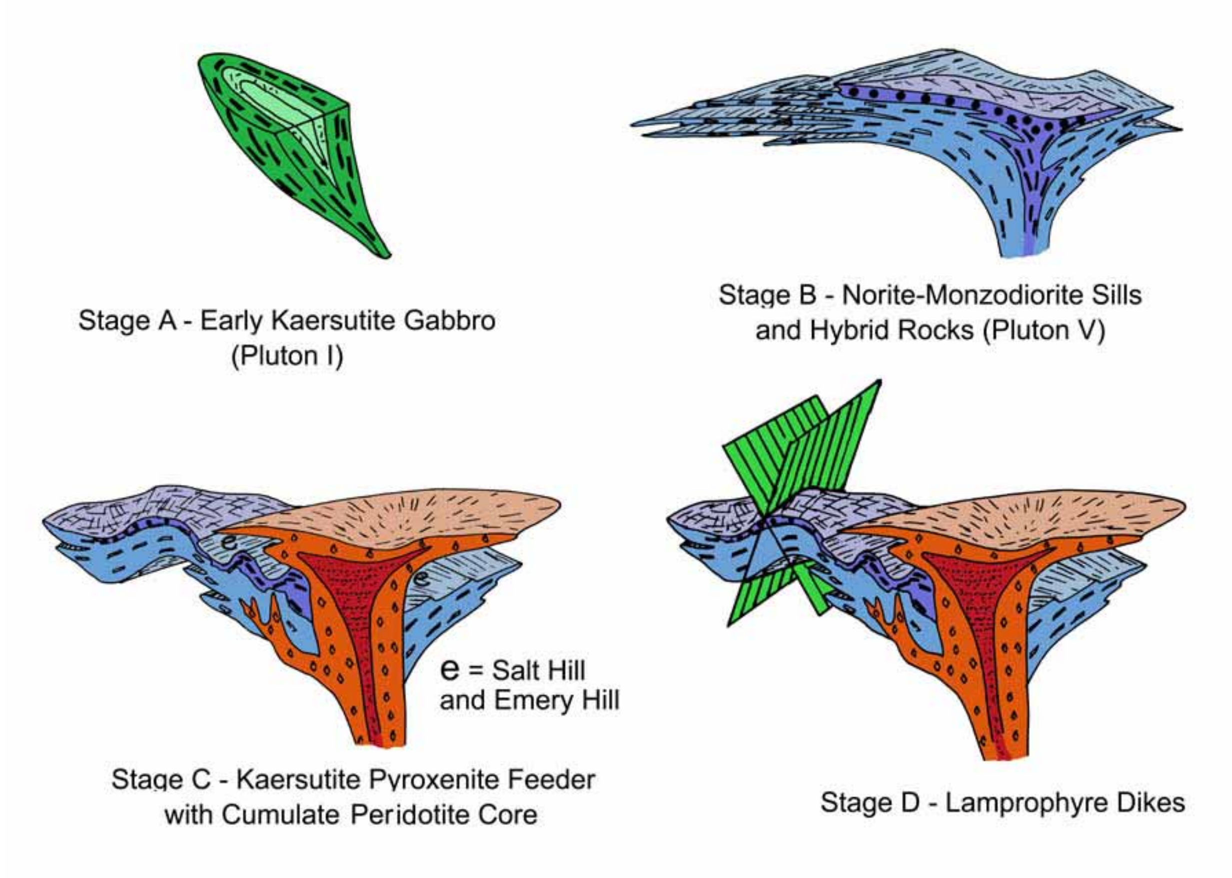


Figure 20. Sequential diagram showing the evolution of the Cortlandt intrusive suite as a four stage process. (Colorized from Ratcliffe et al., 1983, p. 22, fig. 8.)

Our field trip today will visit as many stops as possible starting with a number of localities from Merguerian and Sanders (1992, 1994), 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 the Peekskill Granite.

TABLES

Table 01 - GEOLOGIC TIME CHART

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

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

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

Table 02

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

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

LAYER VII - QUATERNARY SEDIMENTS

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

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IV - COAL MEASURES AND RELATED STRATA (Carboniferous)

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

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

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

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

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

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

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

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

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

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

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

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

LAYER IIA[W] - SAUK SEQUENCE **LAYER IIA[E] - TACONIC SEQUENCE**

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

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

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

LAYER I - PROTEROZOIC BASEMENT ROCKS

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

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

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

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

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

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FIELD TRIP STOPS

The first few 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 nine additional stops from a guide by Ratcliffe et al., (1983). We will not be able to make all of the 15 stops in today's trip but I provide the extra "field nuggets" in case you come up here on your own someday.

STOP 1 - Igneous flow layering in norite, west edge Pluton V of 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), 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).

These six stops offer a prelude to the attached field trip (Stops 4 to 12) to the Cortlandt Complex conducted by Ratcliffe et al. (1983).