Tectonostratigraphy of Paleozoic New York City Schistose Rocks

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Introduction

Long the center of commerce and culture in the United States, Manhattan is an island around which many geologic units and structural features coalesce. Starting in the earliest days of New York City (NYC) field research by naturalists in the 1700s and geologists in the 1800s, the hard crystalline bedrock was always recognized as an excellent substrate for construction of infrastructure. Indeed, Manhattan's underlying durable crystalline structure has enabled the construction of towering skyscrapers and extensive subsurface engineering projects. These have been constructed into crystalline schist and gneiss named the Manhattan Schist formation near the beginning of the twentieth century by F.J.H. Merrill (1898) following the pioneering work of W.W. Mather (1843) who considered the Hudson Schist part of the "Primitive" series.

The subvertical orientation, hardness and stitching granitoid intrusives of Manhattan Schist were perfect for sustaining the load of tall buildings and for supporting surface and subsurface infrastructure projects. After over 200 years of geological field study the pendulum has swung wildly from initial evaluations of a single formation (Manhattan or Hudson Schist) resting above Inwood Marble and older "Primitive" crystalline rock (Fordham-Inwood basement cover sequence) to our subdivision of the Manhattan Schist into regionally traceable essentially coeval lithostratigraphic equivalents with different formational names and former depositional settings. Careful stratigraphic, structural and petrographic analysis has led to recognition of imbricated mylonitic rock units at subdivision boundaries forcing our view that NYC schistose rocks are separated by regionally important ductile faults that distinguish tectonostratigraphic units mapped as the **Manhattan**, **Walloomsac** and **Hartland** formations. These formations are traceable on the ground to far reaching lithostratigraphic correlatives to the north and northeast of NYC where rocks tend to be less metamorphosed and in some instances fossil-bearing.

Over the past two decades, reinterpretations of NYC schistose rocks based on geochemical- and geochronologic studies have tended to ignore the structural, mineralogical and paleontologic work upon which tectonostratigraphic subdivisions have been based and have suggested amalgamation of NYC schistose rocks back to one formation – the Manhattan Schist. Thus, the pendulum has swung wildly back to initial viewpoints and have virtually ignored over a century of geological investigation by many professional geologists. Agreed, part of the problem rests with the structural complexity and degree of metamorphism of the NYC rock mass. One goal of this extended abstract is to address the question of just what the Manhattan Schist represents and to provide evidence for our subdivision into three different ductile fault bounded lower Paleozoic NYC schistose formations.

Understanding the age and protoliths of NYC metamorphic rocks is key to unravelling their tectonic history and we find that the application of a sequence stratigraphy approach leads to a clearer understanding of NYC geology. As such, the following will provide our definition of what rocks constitute the Manhattan Schist and offer along strike correlation of NYC bedrock tectonites using the sequence stratigraphy approach of Sloss (1963).

History and Subdivision of the Manhattan Schist Formation

First studied by naturalists in the 1700's, and by geologists in the 1800's, 1900's and on to the modern day, the bedrock geology of the NYC and vicinity was mapped in systematic detail beginning in the mid- to late 1800's. F.J.H. Merrill was senior author of the United States Geological Survey New York City Folio #83 (1902). In this work and in previous papers (1890, 1898a, b, c), Merrill formally named the Manhattan Schist for exposures on Manhattan Island and outlined the basic stratigraphic framework that successive geologists would test and amplify upon. (See Merguerian and Sanders 1991b and Merguerian and Merguerian 2024b for a more comprehensive discussion of the history of NYC bedrock investigations.)

In 1969, a symposium focusing on the New York City Group of Formations was held at Queens College, NY, a year after hosting a field conference for the New York State Geological Association. Collecting the work of Hall (1968c, 1969), Ratcliffe (1968a, b) and Ratcliffe and Knowles (1969), "de-Grouping" of the New York City Group of Formations resulted. In particular, Leo M. Hall's identification of truncation of subunits of the Fordham Gneiss beneath various members of the Inwood Marble in Westchester County, provided concrete evidence for a major nonconformity between the Proterozoic (Precambrian) rocks of the Fordham and overlying Paleozoic rocks of the Lowerre-Inwood-Manhattan sequence of the Manhattan Prong.

Geochronologic zircon studies of Grauert and Hall (1973) yielded a 1.1 Ga Pb^{207}/Pb^{206} Grenvillian age for the Fordham Gneiss. Paleontologic evidence supported an Early Paleozoic age for the Inwood Marble based on crinoidal stem plates found in the Wappinger Limestone at Verplanck Point, NY (Ratcliffe and Knowles 1969). Based on principles of superposition and interlayering with Inwood Marble, the Manhattan Schist was considered younger than the Inwood and part of a normal stratigraphic sequence, but pre-Silurian based on regional relationships and a late medial Ordovician age of the Taconic unconformity. Thus, by the late 1960’s - early 1970’s an upward-younging model for lower Paleozoic cover was accepted.

Based on his work in the Glenville area of Westchester County, Hall (1968a, b; 1976, 1980) proposed subdivisions of the Manhattan Schist into lithostratigraphically variable members (designated by letters A, B, and C) and correlated parts of the Manhattan Schist with Cambrian rocks of the Taconic allochthon of eastern New York State (Figure 1). He was the first to recognize the lithological differences within the Manhattan Schist allowing for discrimination into members and separated it from rocks of the Hartland Formation. Rb-Sr whole rock ages of 554 +/- 59 Ma on the Manhattan C from White Plains and lithostratigraphic correlatives in NYC showed that Manhattan was no younger than Cambrian and was a time stratigraphic match with elements of the Taconic Sequence (Mose and Merguerian 1985).

For the past five decades we have concentrated our efforts on describing the Paleozoic bedrock geology of NYC and ductile- and brittle faults in the region. As we have published extensively on these topics we refer the interested reader to the Publications Tab at https://www.dukelabs.com. The references in our most recent contributions will help direct you to our many older on-topic NYC publications from 1981 to present (cf - Merguerian 1984, 1994a, 1996c, 2015b; Merguerian and Merguerian 2004, 2016a, b, 2024b, 2025a; Merguerian and Moss 2005, 2006a, 2007; Merguerian and Baskerville 1987 and Merguerian and Sanders 1991b, 1993a). Over the years, we have opined on the former plate-tectonic setting of the Paleozoic bedrock of NYC and to help identify the southernmost extent of the Taconic allochthon (Merguerian 1981a; Merguerian and Sanders 1996b).

STRATIGRAPHY OF THE GLENVILLE AREA

AGE	FORMATION	MEMBER	BRIEF DESCRIPTION	REGIONAL CORRELATION
UNCERTAIN	HARRISON GNEISS		DARK GRAY BIOTITE AND/OR HORNBLENDE-QUARTZ-FELDSPAR GNEISS WITH SUBORDINATE QUARTZ.	UNCERTAIN. HAWLEY FORMATION (CHIDESTER AND OTHERS, 1967)
UNCERTAIN	HARTLAND FORMATION	S	BROWN OR BROWNISH-TAN WEATHERING GARNET-MUSCOVITE-BIOTITE-QUARTZ-FELDSPAR SCHIST AND MUSCOVITE-BIOTITE-QUARTZ-FELDSPAR GNEISS AND GRANULITE. THE SCHIST COMMONLY CONTAINS SILLIMANITE AND/OR KYANITE.	UNCERTAIN. MORETOWN FORMATION (CHIDESTER AND OTHERS, 1967)
		W	LIGHT GRAY OR WHITE BIOTITE-MUSCOVITE GNEISS WITH LOCAL GARNET	UNCERTAIN; ROWE SCHIST (CHIDESTER AND OTHERS, 1967).
		CP	INTERBEDDED GRAY OR WHITE BIOTITE-MUSCOVITE-GNEISS, BROWN OR RUSTY WEATHERING GARNET-MUSCOVITE-BIOTITE SCHIST WITH LOCAL SILLIMANITE AND/OR KYANITE AND AMPHIBOLITE.	UNCERTAIN
		A	AMPHIBOLITE	UNCERTAIN
UNCERTAIN	MANHATTAN SCHIST	C	PREDOMINANTLY BROWN-WEATHERING FELDSPATHIC SILLIMANITE-GARNET-MUSCOVITE-BIOTITE SCHIST OR SCHISTOSE GNEISS; SILLIMANITE NODULES COMMON. ALTHOUGH SILICEOUS BEDS ARE PROMINENT IN SOME PLACES, BEDDING IS NOT COMMONLY CLEARLY DEFINED.	CORRELATION OF MEMBERS B AND C IS UNCERTAIN BUT THEY MAY BE EQUIVALENT TO THE WARAMAUG FORMATION (GATES AND BRADLEY, 1952), THE HOOSAC FORMATION (CHIDESTER AND OTHERS, 1967), AND LOWER CAMBRIAN AND CAMBRIAN (?) ROCKS OF THE TACONIC SEQUENCE (ZEN, 1967, FIG. 4).
		B	A DISCONTINUOUS UNIT OF AMPHIBOLITE AND MINOR SCHIST; ALTHOUGH THIS UNIT IS COMMONLY AT THE BASE OF MEMBER C, THERE ARE MANY PLACES WHERE IT IS WITHIN MEMBER C.	
MIDDLE ORDOVICIAN		A	GRAY OR DARK GRAY FISSILE SILLIMANITE-GARNET-MUSCOVITE BIOTITE SCHIST WITH INTERBEDDED CALCITE MARBLE LOCALLY AT THE BASE. UNCONFORMITY	BALMVILLE (FISHER, 1962) AND WALLOOMSAC (ZEN AND HARTSHORN, 1966).
LOWER ORDOVICIAN	INWOOD MARBLE	E	GRAY OR WHITE CALCITE MARBLE, COMMONLY TAN WEATHERING	COPAKE LIMESTONE AND ROCHDALE LIMESTONE (KNOPF, 1962).
		D	INTERBEDDED DOLOMITE MARBLE, CALCITE MARBLE AND SOME CALC-SCHIST.	ROCHDALE LIMESTONE AND HALCYON LAKE FORMATION (KNOPF, 1962).
CAMBRIAN		C	WHITE OR BLUE-GRAY CLEAN DOLOMITE MARBLE.	BRIARCLIFF DOLOMITE (KNOPF, 1962).
		B	INTERBEDDED WHITE, GRAY, BUFF, OR PINKISH DOLOMITE MARBLE, TAN AND REDDISH BROWN CALC-SCHIST, PURPLISH-BROWN OR TAN SILICEOUS CALC-SCHIST AND GRANULITES, TAN QUARTZITE, AND CALCITE-DOLOMITE MARBLE; BEDDING ONE HALF INCH TO FOUR FEET THICK IS PRONOUNCED.	PINE PLAINS FORMATION (KNOPF, 1962).
		A	WELL BEDDED WHITE, GRAY, OR BLUE-GRAY DOLOMITE MARBLE.	STISSING DOLOMITE (KNOPF, 1962).
	LOWERRE QUARTZITE		TAN OR BUFF-WEATHERING FELDSPATHIC QUARTZITE AND GRANULITE, MICAEOUS QUARTZITE AND GLASSY QUARTZITE; DARK GRAY, BROWNISH AND LOCALLY RUSTY-WEATHERING GRANULITE AND SCHIST THAT COMMONLY CONTAIN SILLIMANITE ARE LOCALLY PRESENT AT THE BASE. UNCONFORMITY	POUGHQUAG QUARTZITE (KNOPF, 1962).
PRECAMBRIAN	FORDHAM GNEISS	G	INTERBEDDED GRAY GARNET-BIOTITE GNEISS, GRAY BIOTITE-HORNBLENDE GNEISS AND AMPHIBOLITE.	UNKNOWN.
		AMP	PREDOMINANTLY AMPHIBOLITE WITH SOME GRAY BIOTITE-QUARTZ-FELDSPAR GNEISS.	UNKNOWN.
		CS	LIGHT-GRAY, BROWN, WHITE, OR GREENISH CALC-SILICATE ROCK.	UNKNOWN.
		AM	AMPHIBOLITE.	UNKNOWN.
		P	PINKISH BIOTITE-QUARTZ-FELDSPAR GNEISS.	UNKNOWN.

Figure 1 - Correlation chart of the metamorphic rocks of southeastern New York. (From Hall 1968a.)

NYC is situated at the extreme southerly tip of the Manhattan Prong (Figure 2), a northeast-trending, deeply eroded sequence of metamorphosed Proterozoic to early Paleozoic rocks that widen northeastward into the crystalline terranes of New England. Southward from New York City, the rocks of the Manhattan Prong plunge unconformably beneath Cretaceous sedimentary rocks and overlying Pleistocene (glacial) sediments only to reappear in the vicinity of Philadelphia, PA as the Wissahikon Schist.

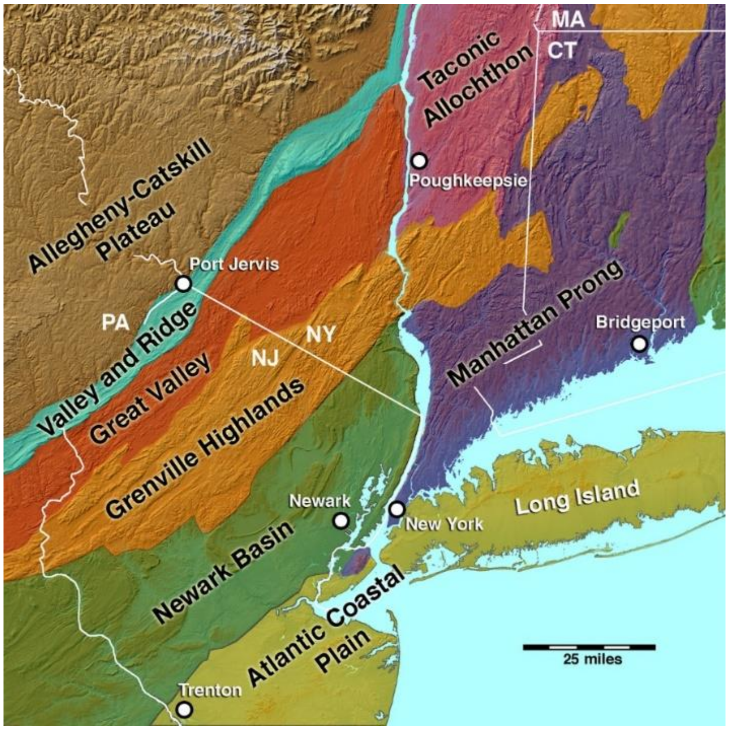

Figure 2 - Physiographic diagram showing the major geological provinces in southern New York, northern New Jersey, and adjoining states. The Manhattan Prong is shown in purple. (From Bennington and Merguerian, 2007.)

Bedrock Stratigraphy of New York City

The following section outlines our views on the basement-cover stratigraphy and ductile- and brittle structure of New York City. Figure 3 and Table 1 [at end of this extended abstract] show two basic subdivisions of NYC crystalline bedrock which include a substrate of:

Layer I - Proterozoic Y Basement Rocks of Laurentia. Granulite facies gneiss and cross-cutting metaigneous rocks overlain nonconformably by the cover sequence of Layer II.

Layer II – Proterozoic Z to Lower Paleozoic Cover Sequence. Metaconglomerate, quartzite, dolomitic and calcitic marble, schist, granofels, amphibolite and associated lithotypes. In the NYC area these include from the base upwards [Zn] basal rift-facies of the Ned Mountain Formation of Brock (1989, 1993 ms) which may be basal Manhattan, [Ꞓl] Lowerre Quartzite, [Ꞓ-Oi] Inwood Marble, [Ow] Walloomsac Formation, [Ꞓ-Om] Manhattan Formation and [Ꞓ-Oh] Hartland Formation. These strata were draped across the developing Laurentian passive margin.

Both major rock sequences, described in more detail below, were internally folded and internally sheared and imbricated during Paleozoic orogenesis and cut by younger brittle fractures (fault and joint discontinuities) resulting in a complicated map pattern of polydeformed Proterozoic and Paleozoic metamorphic rocks.

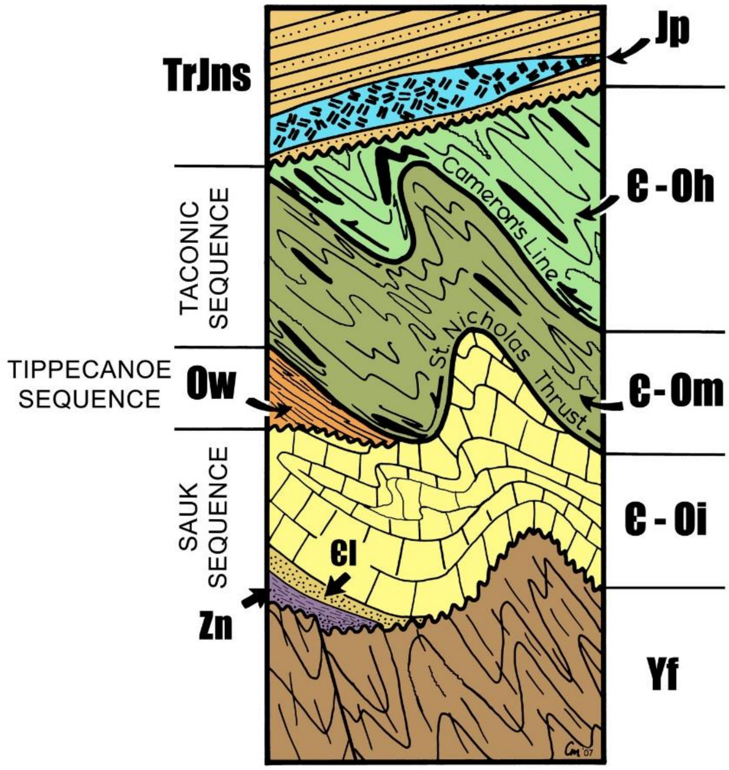

Figure 3 – The product of protracted Taconian deformation, this column illustrates bedrock tectonostratigraphy of New York City as described in text and outlined in Table 1. The polydeformed lower Paleozoic bedrock units are imbricated by the Saint Nicholas thrust and Cameron's Line and nonconformably overlain by west-dipping Triassic and younger strata (TrJns) and the Palisades intrusive sheet (Jp).

Sequence Stratigraphy of Layer II Paleozoic Strata of NYC

Below we combine our scheme of "layers" as in Table 1 [at end of this extended abstract] with the names of Sequences in the sense of Sloss (1963) as applied to eastern New York. Sloss proposed the concept of Sequences for Paleozoic and younger strata found on the North American craton and separated from other groups of strata by a surface of unconformity of regional extent. The oldest of these he named the **Sauk Sequence**. The age range of the Sauk Sequence is from Cambrian (Early, Medial, or Late, depending on locality) through Early Ordovician. The carbonate rocks of the Sauk are typically dolomitic although calcite marble occurs near the top of the sequence throughout NY. In NYC and elsewhere the Sauk overlies Proterozoic Y basement (Fordham in NYC) and metamorphosed rift and mature clastics (Ned Mountain [Zn] and Lowerre [Єl], respectively, where present). The Inwood [Є-Oi] is predominately dolomitic, the remnants of a broad open-ocean transgressive continental margin sequence exposed along the length of the Appalachian chain (Layer IIA[W] of Table 1).

Overlying the Sauk Sequence and separated from it by a surface of unconformity of continent-wide extent is the **Tippecanoe Sequence**. The strata of the Tippecanoe (Unit Ow) have been mapped incorrectly as the Manhattan Schist as they are of medial Ordovician age and consist of basal limestones as contrasted with the Sauk dolostones. Above the basal limestones, the Tippecanoe Sequence consists of a vast sequence of fine-textured pelitic rocks which form the bulk of Layer IIB in our Table 1. Regionally, these are known as the carbonaceous and pyritiferous Normanskill and Martinsburg formations, the products of restricted ocean basin deposition. In NYC, Unit Ow consists of graphitic and pyritic biotite-garnet schist, granofels and calc-silicate rock found with basal calcite marble. It occurs above the depositional contact with the underlying Inwood and on this basis they are considered autocthonous and younger. In NYC, the Sauk-Tippecanoe contact can be observed along the west edge of Boro Hall Park and at an overpass of the Grand Concourse above the Cross-Bronx Expressway (I-95), both in the Bronx. In Manhattan, the contact can be studied along the eastern edge of Marcus Garvey Park (aka Mt. Morris Park), at the northernmost tip of Manhattan beneath the Henry Hudson Bridge in Inwood Park, in borings at the new World Trade Center and elsewhere in borings, shallow building foundation excavations and deep subsurface excavations (Merguerian and Baskerville 1987; Merguerian and Moss 2006a, 2015). This regionally important depositional contact is exposed northeastward throughout NY state including Balmville (Hall 1968a), along the Hudson River shoreline at FDR Veteran's Administration Hospital in Montrose (Merguerian and Sanders, Stop 3, 1994c) and at Verplank, Stony Point and Crugers (Ratcliffe and Knowles 1969).

The **Taconic Sequence** [Layer IIA[E] of Table 1] designates the terrigenous pelitic rocks and turbidites the lower part of which are the same age as the carbonate rocks of the Sauk Sequence (Early Cambrian to Early Ordovician). Terrigenous deep-water oceanic pelitic rocks of the Taconic Sequence (Unit Ꞓ-Om in NYC) are found in structural positions above the Sauk Sequence shallow-water shelf sequence and also above the Tippecanoe strata. In New York, such an arrangement was the basis for the interpretation that a large Taconic overthrust had displaced the Taconic strata westward from a root zone east of the Proterozoic massifs on the order of 100 km or more. Regionally the displaced Taconic strata were thus considered to constitute a vast allochthon.

Our lithostratigraphic correlation with highly metamorphosed NYC rocks is driven by on-the-ground continuity of strata northward to less metamorphosed rocks. Indeed, NYC rocks possess the mineralogic and lithologic characteristics that support such far-reaching correlations as proposed in a paper on the geology of Cameron's Line in western Connecticut (Merguerian 1983b) a correlation based on the work of Hatch and others (1968), Hatch and Stanley (1973), Hall (1968a, b, c; 1980) and many others. A stratigraphic correlation chart from that period is included below as Figure 4.

Layer I: Fordham Gneiss - Queens Tunnel Gneiss Basement (Yf; Yq)

The oldest rocks in NYC are a complex cratonic assemblage of Proterozoic Y ortho- and paragneiss, metavolcanic and metagranitoid rocks (Fordham and Queens Tunnel Gneiss). Based on detailed studies and U-Pb age dating in the Queens and Brooklyn subsurface portions of NYC Water Tunnel #3 (Chesman 1996 ms; Merguerian 2000a ms; Brock, Brock, and Merguerian 2001) the Fordham correlative is there known as the Queens Tunnel Complex which consists of predominately massive mesocratic, melanocratic and leucocratic orthogneiss with subordinate schist, granofels, and calc-silicate rock. Grenvillian high-pressure granulite facies metamorphism produced a tough, anhydrous granoblastic rock mass consisting of clino- and orthopyroxene, primary garnet and plagioclase that have resisted hornblende- and biotite-grade Paleozoic (Taconian and younger) retrograde regional metamorphism.

Grenvillian Proterozoic rocks are also exposed along the Hudson Highland-Reading Prong and in the adjacent Manhattan Prong. They also occur in isolated areas such as Snake Hill (Berkey 1933), Stissing Mountain (Knopf 1962), and the Ghent block (Ratcliffe, Bird, and Bahrami 1975). Many of these have been exposed as a result of combined terminal-stage, latest Paleozoic Appalachian overthrusting as well as post-Jurassic faulting (Merguerian and Sanders 1991a).

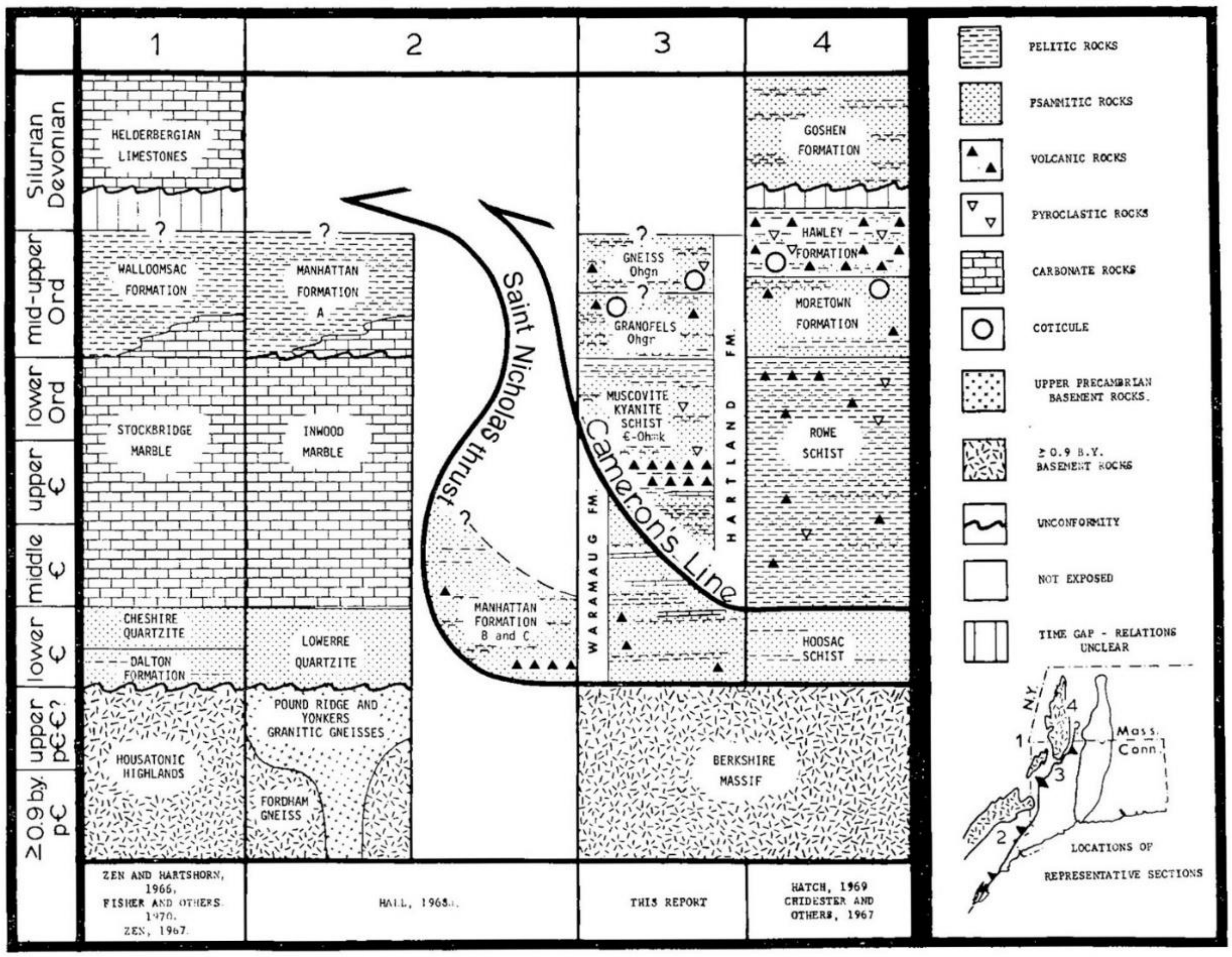

Figure 4 – Correlation chart for southeastern New Yerk and western Connecticut showing the regional correlation of rock units found on either side of the Taconic suture zone defined by the Saint Nicholas thrust and Cameron's Line. (Adapted from Merguerian 1977 ms; 1983b.)

Layers IIA and IIB: Paleozoic Cover Rocks

Hartland Formation (Ꞓ-Oh)

The Hartland Formation consists of gray-weathering, well-layered, fine- to coarse-textured muscovite-quartz-biotite-plagioclase± kyanite±garnet schist, gneiss, and migmatite with cm- and m-scale layers of gray quartzose granofels and greenish amphibolite±biotite±garnet. Known for relatively easy excavation because of pervasive jointing parallel to layering, the unit has been encountered in the East Side Access, Second Avenue Subway, Manhattan Water Tunnels, #7 Line IRT Extension and Con Edison Steam Tunnel projects and crops out mostly east of the Bronx River at the NY Botanical Garden and elsewhere in the eastern Bronx. It has been extended into NYC from western Connecticut and Massachusetts based on lithostratigraphic correlation (Merguerian 1983a) and it is considered a more metamorphosed part of the unrooted pelites, interlayered lithic sandstones and volcanic rocks of the Taconic allochthon (Merguerian and Sanders 1996b).

Manhattan Formation (Ꞓ-Om)

The Manhattan consists of massive rusty- to sometimes maroon-weathering, medium- to coarse-textured, biotite-muscovite-plagioclase-quartz±garnet±kyanite±sillimanite±magnetite± tourmaline gneiss, migmatite, and schist. Characterized by the lack of internal layering except for kyanite± sillimanite+quartz+magnetite interlayers and lenses up to 10 cm thick, cm- to m-scale layers of blackish amphibolite and scarce quartzose granofels, it forms the bulk of exposed Paleozoic metamorphic rocks of northern Manhattan as well as areas of the Bronx and extensions northward into Westchester and Putnam counties. These commonly magnetic allochthonous rocks and the Hartland Formation constitute the **Taconic Sequence** of NYC.

Walloomsac Formation (Ow)

The Walloomsac consists of fissile brown- to rusty-weathering, fine- to medium-textured, biotite-muscovite-quartz-plagioclase±kyanite±sillimanite±garnet±pyrite±graphite schist, granofels and migmatite containing interlayers centimeters to meters thick of plagioclase-quartz-muscovite granofels, layers of diopside±tremolite±phlogopite calcite- and dolomitic marble and greenish calc-silicate rock. Amphibolite is absent although green amphibole+biotite-bearing calc-silicate rocks are locally found. Strongly pleochroic titaniferous reddish-brown biotite, light pinkish garnet as scattered small crystals and porphyroblasts up to 1 cm, graphite and pyrite are diagnostic mineral. The lack of amphibolite and the presence of graphitic schist and interlayered quartz-feldspar granofels invites the interpretation that the unit is correlative with the **Tippecanoe Sequence** consisting of metamorphosed middle Ordovician carbonaceous+pyritic shale and greywacke strata of the autochthonous Annsville and Normanskill formations of SE New York and correlative Martinsburg Formation to the southwest of NYC. Walloomsac rocks are found at many places in Manhattan and the Bronx. They are exposed along the W and E edges of the NY Botanical Garden grounds and extends southward through the Bronx Zoo onto the W and NW edges of Boro Hall Park and on both W and E edges of Crotona Park.

Inwood Marble (Ꞓ-Oi)

Occurring west of the NYBG, white to buff-colored to bluish-gray fine- to coarse-textured dolomitic and lesser interlayered calcitic marble containing dolomite, calcite, diopside, tremolite, phlogopite, muscovite (white mica), and quartz together with accessory graphite, pyrite, tourmaline (dravite-uvite), chlorite and zoisite (Merguerian, Merguerian and Cherukupalli 2011). Layers of fine-textured gray quartzite with a cherty appearance are locally present. The Inwood is correlative with the Cambro-Ordovician carbonate platform or **Sauk Sequence** of the Appalachians. Inwood Marble is exposed mostly in the Inwood section of northern Manhattan, along the shoreline near north end of Inwood Park, Isham Park, Marcus Garvey Park, exposures on I-95 (Cross Bronx Expressway) and underlie the Webster Avenue valley of the Bronx.

Structure and Tectonics

NYC rocks bear evidence for all three Paleozoic orogenic disturbances that together compose the Paleozoic Appalachian orogeny. These events are widely recognized as the Taconic, Acadian and Alleghenian orogenies, all the products of late Proterozoic Rodinian plate separation, subsequent development of a Laurentian trailing edge passive continental margin during Cambrian to early Ordovician time and then a changeover to convergence and collisional assembly and amalgamation of disparate terranes culminating in closure of the proto-Atlantic (Iapetan) ocean by the end of Paleozoic time and subsequent development of the Appalachians.

The rifting of the Proterozoic Y craton of Layer I in latest Proterozoic time thus set the stage for the first of the Paleozoic trailing-edge continental margins of eastern North America. This trailing edge of the Iapetus Ocean, (or Passive Margin I) was to receive clastic, then carbonate sediments of Layer IIA. (See Table 1.) Thus, early into the Paleozoic Era, this part of the Appalachian mountain belt region became the trailing edge of a continental plate, a passive continental margin (Figure 5) adjacent to the ancestral Iapetus Ocean. This tectonic setting persisted until the Taconic orogeny, late in the middle Ordovician Period. Interestingly, the contemporary passive-continental-margin setting of eastern North America, [deformed crystalline basement covered by essentially nondeformed rift and younger sediments that were and continue to be deposited as the margin subsides toward an open ocean to the east] more or less duplicates that of Early Paleozoic time!

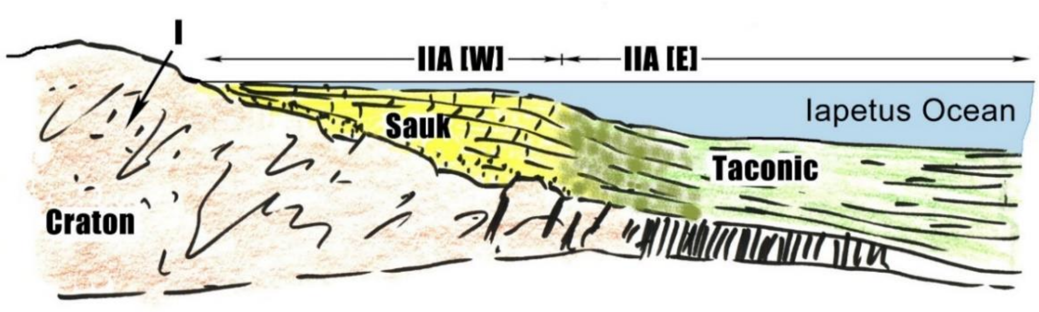

Figure 5 - Diagrammatic sketch of the passive margin of eastern North America in Early Paleozoic time showing the shallow-water (Sauk - yellow) and deep-water (Taconic - light green) depositional areas and the transitional slope-rise (olive green). The colors used above match up with the metamorphic rock products of NYC's Layers I, IIA and IIB. (See Figure 3.)

The Taconic Orogeny in NYC

Bird and Dewey (1975) suggested that the Taconics were part of a huge continentward underwater gravity slide of former deep-water strata into a subsiding deep basin (Tippecanoe in our usage). Robinson and Hall (1980), Hall (1980), Rowley and Kidd (1981), Merguerian (1983b) and Stanley and Ratcliffe (1985) did not believe in gravity sliding as a model for the emplacement of the Taconic allochthons. Rather, based on stratigraphic and structural evidence, these workers all envisioned Taconic displacements as due to continentward overthrusting of a subduction complex formed between the formerly open-ocean passive continental margin sequence, intervening oceanic basin and the encroaching Taconic arc (Figure 6).

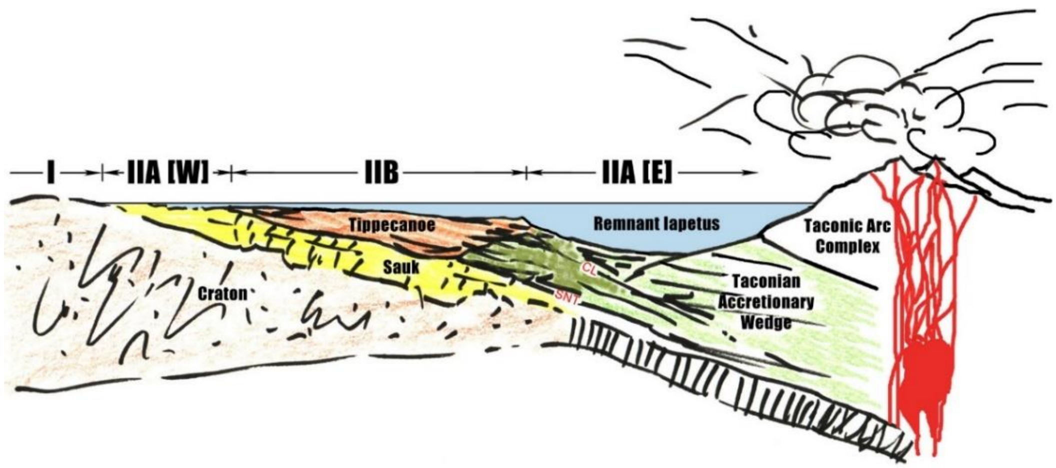

Figure 6 – Diagrammatic sketch showing the Taconic Orogeny in NYC just before final suturing of the arc complex and Taconian accretionary wedge with the collapsed passive continental margin of North America. Deep-seated metamorphic recrystallization of NYC tectonites and imbrication of Sauk, Tippecanoe, and Taconic elements of the former margin and deep-water realm along the Saint Nicholas thrust and Cameron's Line are shown here just before final docking of the arc complex. In red lettering, SNT = Saint Nicholas thrust; CL = Cameron's Line.

Paleogeographic reconstructions show that North America straddled the paleo equator during and after the Taconian arc-continent collision with continentward structural vergence and overthrusting of strata within a convergent accretionary prism that formerly separated the passive Laurentian margin and arc complex. The timing (~450 Ma) of this collisional event is based on paleontologic (conodont and graptolite) studies at the base of the Tippecanoe strata in the foreland basin and equivalents east of the Green Mountain massif (Potter, 1972; Ratcliffe, Harris and Walsh 1999) and U-Pb zircon and titanite geochronological data from widely separated plutons that cross-cut and contact metamorphose the suture zone (Ratcliffe and others 2012).

Rowley and Kidd (1981) identified the most suitable modern analog for the Appalachian Taconic orogeny as the area of Timor, a volcanic island chain NW of the passive continental margin that of NW Australia (Figure 7). There, as was the case during the Taconian event in NYC, the continental margin draping sediment sequence is being subducted beneath upper plate of the Timor volcanic arc complex.

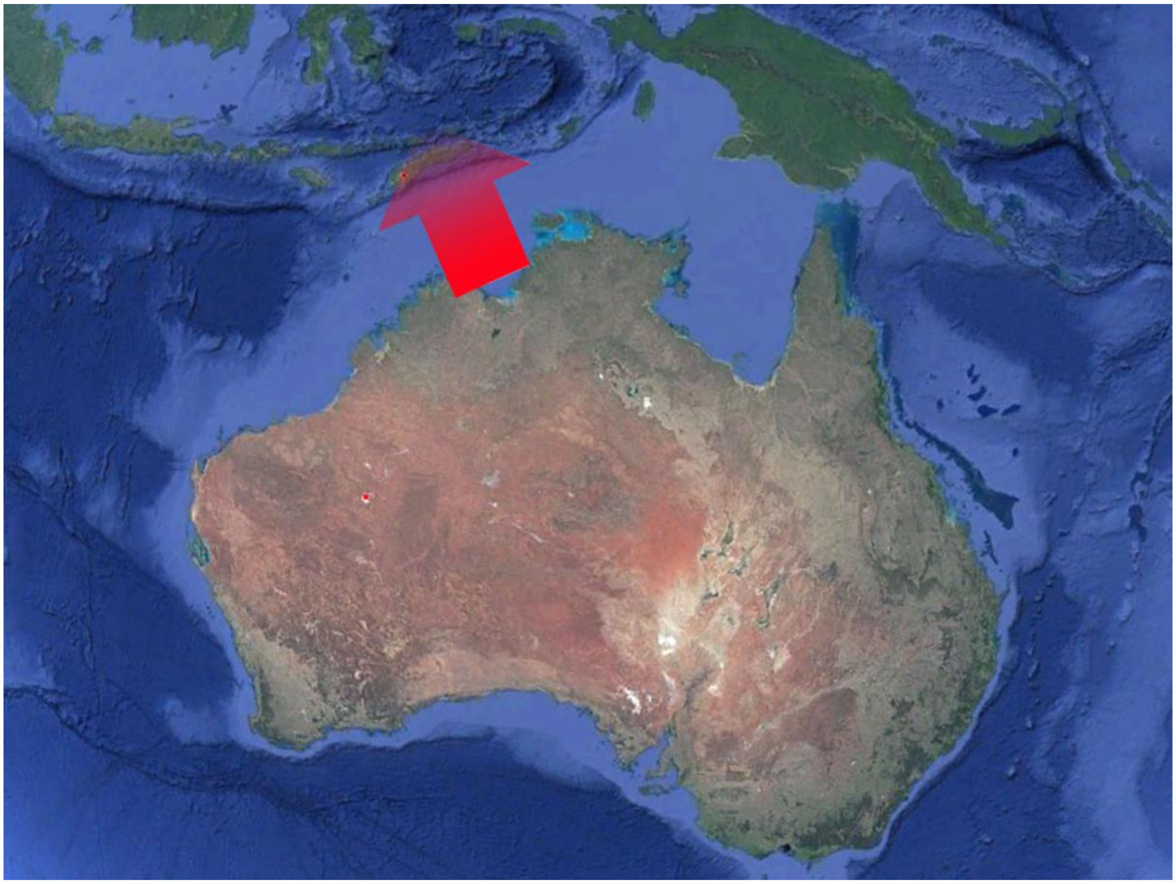

Figure 7 – In this modern analog of the Taconic orogeny of eastern North America, a view of the current arc-continent subduction zone of the Timor-Australian collision zone where the shelf edge of NW Australia is subducting northwestward beneath the Timor arc complex. Eventually, this will lead to an arc-continent collision not unlike the medial Ordovician Taconic orogeny in NYC. (Google Earth.)

Discussion

The Taconic problem in NYC, focuses on ductile-fault imbrication of three lithologically distinct Cambro-Ordovician upper amphibolite-grade schistose-rock sequences formerly deposited across the shelf edge of embryonic North America. During mid-Ordovician Taconian arc-continent suturing, the St. Nicholas Thrust (SNT) and Cameron's Line (CL) imbricated metamorphosed shelf-, rise-, and deep-water lithotopes in a continentward-facing subduction complex. The Cambro-Ordovician Inwood Marble (Ꞓ-Oi) of the Sauk Sequence is overlain by autochthonous calcite-marble bearing medial Ordovician Manhattan Schist (Ow) of the Tippecanoe Sequence. The SNT (Taconic frontal thrust) separates upper-plate gneiss, schist, and amphibolite of the former late Proterozoic(?) to Cambro-Ordovician slope- and rise (Manhattan Formation; Ꞓ-Om) above Tippecanoe (Ow) and Sauk (Ꞓ-Oi) rocks. A structurally higher ductile fault (CL), juxtaposes muscovite-rich schist, granofels, gneiss, amphibolite, serpentinite, and coticule of a former deeper-water realm (Hartland Formation; Ꞓ-Oh). As such, the subunits Ꞓ-Om and Ꞓ-Oh should be considered to be ductile-fault-bound tectonostratigraphic units of the Taconic Sequence.

Geochemical study of Manhattan, Hoosac vs. Rowe-Moretown (Hartland) metavolcanic rocks by Ratcliffe and others (2018) in southern New England indicate that Manhattan and correlative Waramaug and Hoosac rocks both contain correlative rift-related metabasalts which is not surprising since they are continuous on the ground from New York City northeastward through western Connecticut, New Hampshire and Vermont. As such they show rifted Laurentian margin ancestry. Yet, they are distinct from metavolcanic rocks analyzed in the allochthonous rocks found east of Cameron's Line (Hartland and correlatives) which show clear arc-oceanic parentage. These data suggest that the accreted margin contains both peri-Laurentian and Iapetan components within the suture zone which traverses NYC as the Saint Nicholas thrust and Cameron's Line. These are both elements of the Taconian suture, a zone which includes scattered, serpentinite bodies (Merguerian and Moss 2005, 2007). Stanley and Ratcliffe (1985) called this a cryptic suture because of tectonic intercalation of continent derived metasediments and arc- ocean floor components during collision.

The development of plate tectonic theories to better explain the mountain building process has been strengthened by remapping of former geologic terrains and also by studying modern convergent margins. One such study that stands out was an investigation of deep-sea drilling and study of core from the Nankai Trough area of the Shikoku subduction zone in southwestern Japan (Moore and Karig 1976).

Two figures from their paper are combined below as Figure 8 which demonstrate the shallow level isoclinal folding and imbrication of sedimentary strata detected in the upper levels of thrust sheets within the upper plate subduction complex.

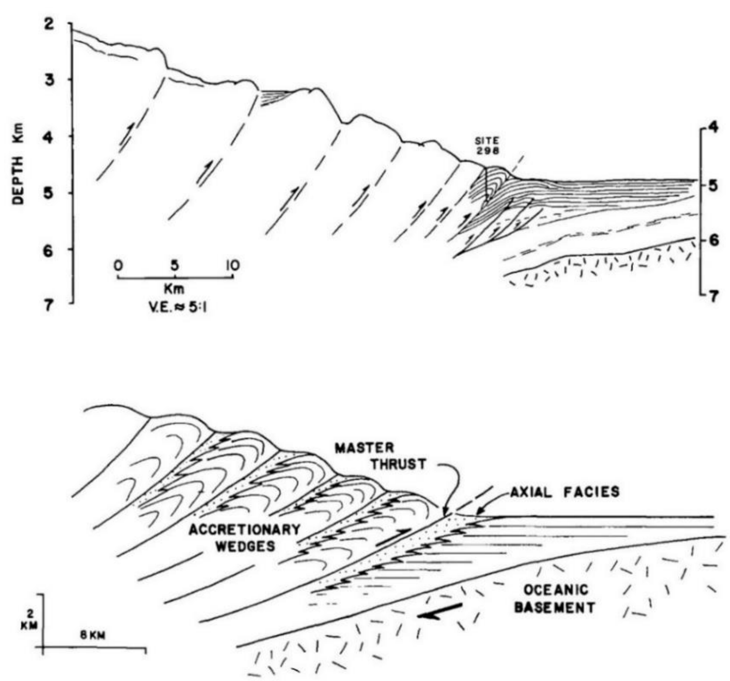

Figure 8 – Two views of internal structure of the trench wall of accretionary wedge associated with modern subduction in the Shikoku subduction zone of the Japanese trench based on drilling (Sites 297, 298). Their study of bedding-cleavage relationships demonstrated that isoclinal folding and imbrication of strata took place in concert with thrust faulting in the upper plate at high crustal levels (5-6 km). (From Moore and Karig, 1976, figs 11, 12.)

Our model of the Taconic orogeny takes into account the juxtaposition of strata during deep-seated convergent tectonics and gives reverence to how complex the original starting strata may have been even before the obscurities introduced by metamorphism. As such, traditional formational mapping in uplifted mobile belts produced in arc-continent or arc-arc convergent margin settings may be best understood by abandoning simple layer-cake stratigraphic models and entertaining the idea that shear zones and thrust faults may be more pervasive than outcrop mapping may indicate – even away from major shear zones. Indeed, the field geologist in deeply eroded core zones of mountain belts may inquire "are there shear zones around every outcrop"? We have experienced many waves of confusion in the field trying to determine which formation is which but we should be open to imbrication (mixed zones) at major tectonic boundaries and intimate shearing of strata at the small scales as they steepen and descend to the deeper levels of a subduction zone, especially in light of the fold-thrust complexities of starting materials within the developing subduction complex at depths of 5-6 km much less the complexities introduced by the deeper (~24 km) realms experienced by NYC allochthonous rocks (Merguerian and Moss 2015).

One rock cut in the western metamorphic belt of the Sierra Nevada of California has changed our philosophy on bedrock mapping of metamorphic rocks at major convergent boundaries. There, Permo-Triassic chert and argillite of the Calaveras Complex were overthrust by twice deformed lower Paleozoic quartzite, orthogneiss and schist of the Shoo Fly Complex in the western foothills of the Sierra Nevada metamorphic belt (Merguerian 1985 ms, 1985b; Schweickert, Merguerian and Bogen 1988). A new back road constructed in 1981 (CM Stop SF1178) exposed a 40m-long transect across the thrust zone in biotite-grade rocks which displayed intimate m-scale imbrication of rocks from both formations as shown in the image and field sketch of Figure 9. One can only imagine the complications introduced to strata in the upper plate and trench wall introduced by protracted shearing during subduction to the deeper (~24 km) levels of the suture zone. (See Figure 8.) Thus, in our view, it is no surprise in NYC that confusion exists at the outcrop scale. The spatial coincidence of zones of mylonite and annealed mylonite help to better identify tectonostratigraphic boundaries in these areas and decreases the need for coin-tossing where bounding strata have been commingled by shearing at rheologically diverse lithologic boundaries (Merguerian and Sanders 1998).

Although attenuated to a great degree, perhaps because of the high-standing history of the NY promontory (after all, little to no Cambrian clastic strata exist in NYC) and all three Sequence elements (Sauk, Tippecanoe, and Taconic) occur in extremely thin belts traversing NYC. There, they are separated by zones of imbricated mylonitic rocks with local serpentinite thus marking the Taconian cryptic suture. Serpentinites are locally associated within the Manhattan at the Manhattan-Walloomsac contact (Saint Nicholas thrust) but occur mostly within Hartland rocks and at the Hartland-Manhattan ductile contact defined by Cameron's Line.

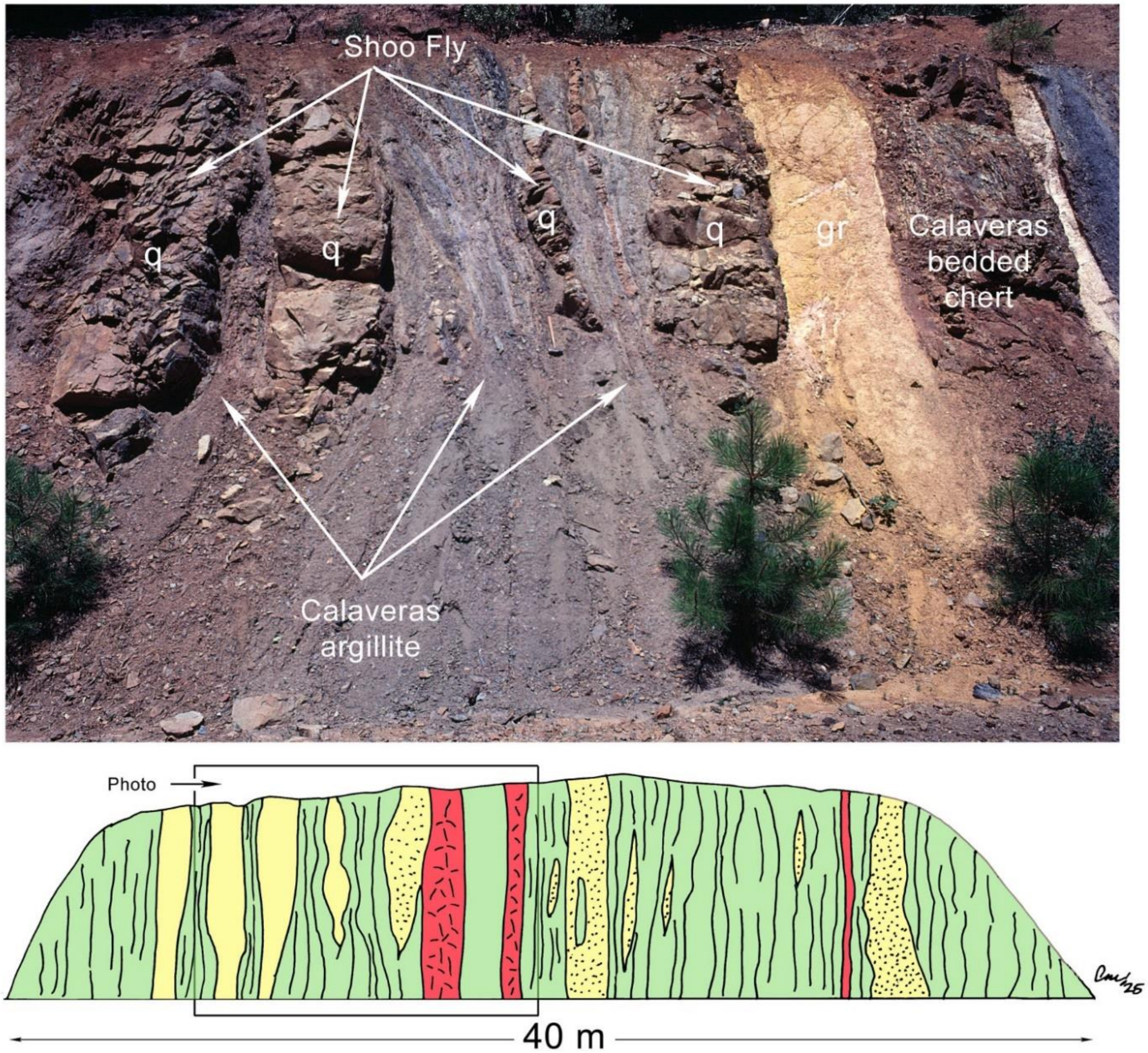

Figure 9 - Southwestward view of 40-m long exposure across the Permo-Triassic Calaveras-Shoo Fly thrust in Lake Eleanor SW quadrangle (Tuolumne County; UTM 240.2E/4185.3N). Note the tectonic intercalation of Shoo Fly (yellow - stippled pattern indicates remnant clastic textures; solid yellow is massive chert and quartzite) and Calaveras Complex (green – argillites and bedded chert) found at the Calaveras-Shoo Fly thrust (Merguerian 1985 ms, 1985b). The main thrust fabric is oriented N64°W, 90° with the main belts of Shoo Fly found to the N (R) and Calaveras to the S (L). Red designates granitoids of the Sierra Nevada batholith.

Table 1 - Generalized Descriptions of Major Geologic "Layers", SE New York State and Vicinity (Adapted from Merguerian and Sanders 1991, 1993a, b)

This abbreviated geological table is derived from the On-The-Rocks Field Trip Program of the NY Academy of Sciences conducted by Drs. John E. Sanders and Charles Merguerian between 1988 and 1998. In Stenoan and Huttonian delight, we here present the lower two layers of a seven-layer cake model which proved effective in simplifying the complex geology of the region.

[**Taconic orogeny**; ~450 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.	Walloomsac Schist
Normanskill Fm.	Annsville Phyllite

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

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

LAYER IIA [W] **SAUK SEQUENCE**	**LAYER IIA [E]** **TACONIC SEQUENCE**
Western shallow-water platform (L. Cambrian - M. Ordovician)	**Eastern deep-water zone** (L. Cambrian-M. Ordovician)
Copake Limestone (Stockbridge and Rochdale Limestone Inwood Marble) Halcyon Lake Fm. Briarcliff Dolostone Pine Plains Fm.	 (Ꞓ-Oh) Hartland Fm. (Ꞓ-Om) Manhattan Fm.

Stissing Dolostone (Zn) Ned Mtn Fm.
Wappinger Limestone
Poughquag Quartzite
Lowerre Quartzite

[**Pre-Iapetus Rifting Event**; extensional tectonics, volcanism, rift-facies sedimentation, and plutonic igneous activity precedes development of Iapetus ocean basin. Extensional interval yields protoliths of Proterozoic X Pound Ridge and Yonkers gneisses and possibly the Ned Mountain Formation of presumable Proterozoic Z age (Brock 1989, 1993).

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

LAYER I - PROTEROZOIC Y and Z BASEMENT ROCKS

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

[**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 Queens Tunnel orthogneiss complex in the subsurface of western Long Island (Queens and Brooklyn Sections, NYC Water Tunnel #3, Stage 2), the Hudson Highland-Reading Prong terrane and associated gneisses and the New Milford, Housatonic, Berkshire, and Green Mountain massifs in New England]

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. North of NYC, Adirondack sequences expose Proterozoic X, Y and Z strata and Archean rocks as well – providing a source of polymict detrital zircons spanning these ages.

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