CONTRASTING STYLES OF THE TACONIC OROGENY IN NEW YORK: DEEP- VS. SHALLOW THRUSTS

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INTRODUCTION

The Taconian orogeny in the minds of many geologists is synonymous with the Taconic allochthon, a body of Lower Paleozoic pelitic rocks lying above the virtually coeval Lower Paleozoic carbonate rocks (Figure 1). Starting in the 1930's various challenges were raised to the tectonic-overthrust origin of the Taconic pelitic rocks. Examination of the pelite-carbonate contact failed to disclose mylonite or the kinds of other fault rocks that one would expect to find along a major thrust.

The "to be or not to be" of the Taconic allochthon became a bone of contention among two of the senior members of the faculty in the Department of Geology, Columbia University. Professor G. M. Kay (1935, 1937, 1942) and two doctoral students (W. M. Cady, 1945; and E. P. Kaiser, 1945) working in Vermont, supported the concept of a Taconic allochthon. By contrast, Professor W. H. Bucher (1956, 1957) and two of his doctoral students (J. D. Weaver, 1958; and J. C. Craddock, 1957), argued from studies in New York State that the pelitic rocks are not part of an allocthon but overlie the carbonates along a surface of unconformity.

Subsequent biostratigraphic studies of Ordovician graptolites and detailed geologic mapping of many 7.5-minute quadrangles established the validity of the thrust origin of the Taconic rocks. Application of the sequence-stratigraphic approach and of plate-tectonic concepts to the interpretation of the Early Paleozoic history of the Northern Appalachians has clarified many aspects of the Taconian orogeny. We here review the thrust interpretation of the Taconic allochthon and contrast the temporal relationships associated with "shallow" thrusts in the western foreland basin with those associated with "deep" thrusts in the eastern metamorphic core zone.

REGIONAL GEOLOGIC SETTING

The Lower Paleozoic strata of what is now the Northern Appalachians accumulated along an ancient passive continental margin. During the Cambrian and Ordovician periods, North America lay astride the Earth's Equator; what is now the eastern part of the continent lay in the Southern Hemisphere tropics. The interior of the continent lay to the north, and an open ocean, to the south (Figure 2). Tropical conditions prevailed throughout the time period and a vast sequence of quartzose sands followed by calcareous sediment was deposited above an eroded-and submerged Proterozoic (Grenville) basement complex. The Cambrian- to Ordovician clastics+carbonate passive- continental- margin sequence is known as the **Sauk Sequence** following Sloss (1963).

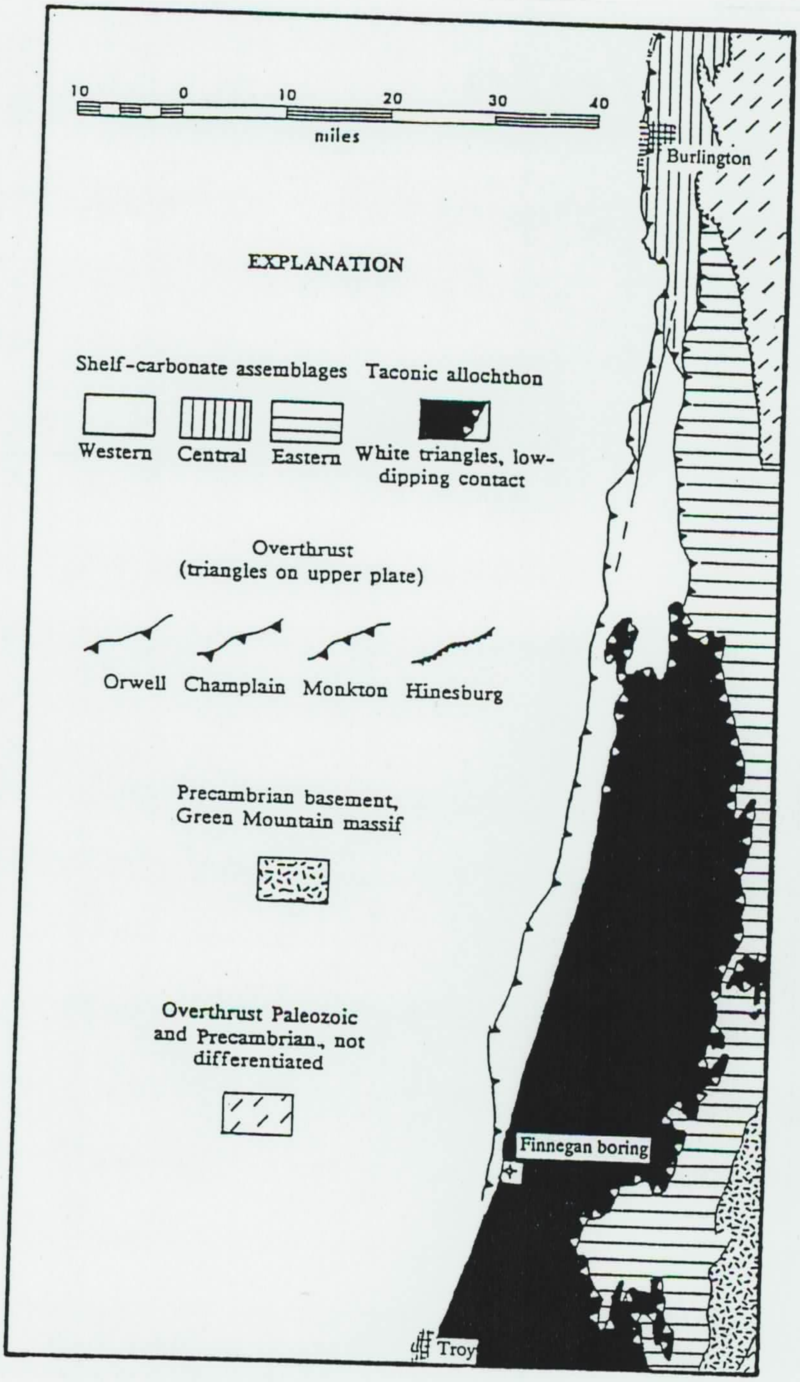

Figure 1. Generalized tectonic map of northern part of Taconic allocthon, eastern New York and vicinity. [J. E. Sanders, 1995, fig. 2, p. 25; compiled from several sources, including A. Keith (1933), Cady (1945), and Stanley and Ratcliffe (1985).]

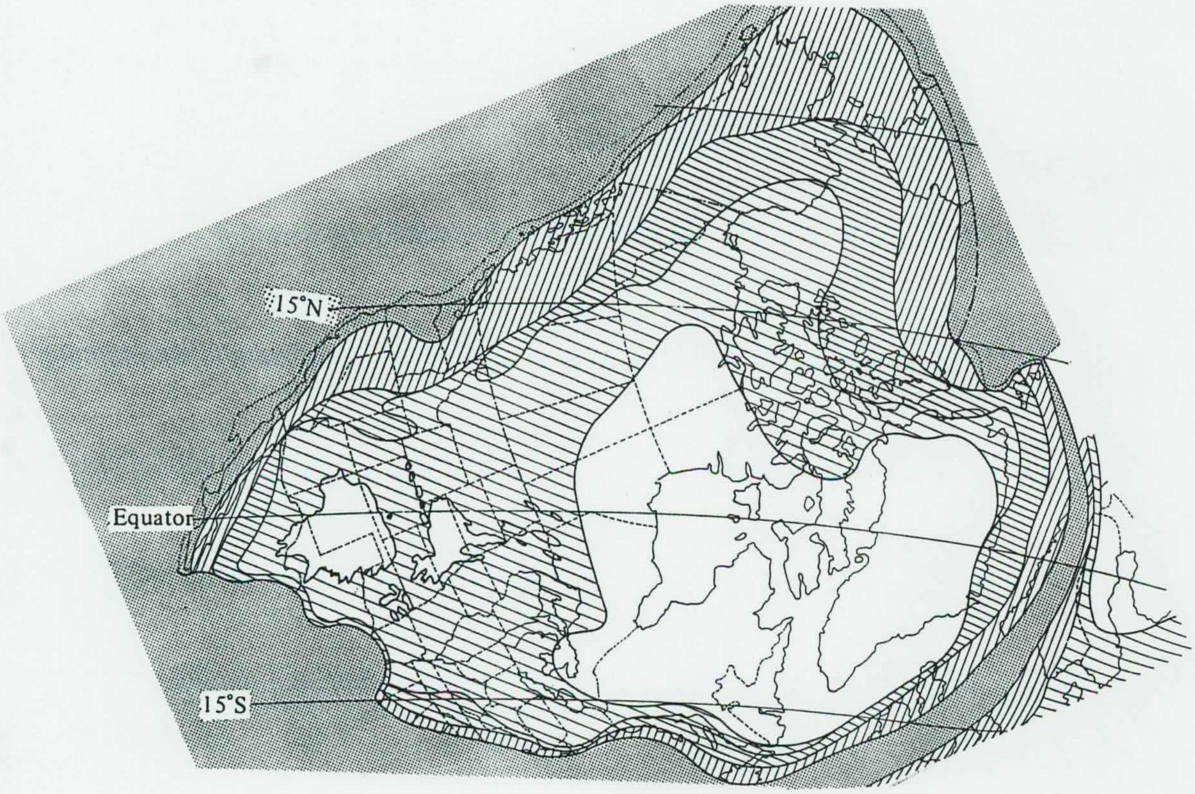

Figure 2. Paleogeographic map showing North America in its Early Paleozoic position astride the Earth's Equator. (C. K. Seyfert and L. A. Sirkin, 1979, figure 10.4b, p. 252.)

Starting in the mid-Ordovician, tectonic plate convergence brought to an end the passive-margin regime that had prevailed since early in the Cambrian Period. An initial, and particularly conspicuous, product of this episode of plate convergence was the appearance of the Northern Appalachian foreland basin. This basin, which developed atop the Sauk Sequence, saw the influx of deep-water pelitic sediments and intercalated turbidites. In New York State this mid-Ordovician assemblage is known as the Normanskill formation and regionally it is named the **Tippecanoe Sequence**. This basin, whose origin has been ascribed to the isostatic effects of thrust loading (Quinlan and Beaumont, 1984) appeared **after** the demise of the carbonate shelf.

The original basis for recognizing Taconian thrusting was the juxtaposition of two suites of Lower Paleozoic strata deposited in contrasting paleogeographic settings. One of these suites consists of Sauk carbonate rocks, mostly dolomitic, that accumulated on a shallow tropical carbonate shelf ("-platform" of some authors). The other is composed of pelitic rocks, deposited beyond the former shelf edge, subsequently interpreted as being products of deposition on a continental rise (B. D. Keith and Friedman, 1973, 1977) and generally referred to informally as the Taconic sequence. During the Taconic Orogeny, both the Sauk and

Tippecanoe sequences became imbricated by low-angle thrusts and older, deeper-water pelites of the **Taconic Sequence** were emplaced within the Northern Appalachian foreland basin.

Considerable confusion has arisen over the stratigraphic- and structural relationships of clastics+carbonates and overlying pelites of the autochthonous Sauk and Tippecanoe sequences and the allochthonous Taconic Sequence. Geologists wanted to know how these two sequences, consisting of strata of essentially the same age, could have arrived at their observed configuration, namely a coeval "shale" sequence above the "carbonate" sequence. Numerous geologists accepted this configuration as being a product of low-angle thrusting of allochthonous Taconic "shales" over autochthonous Cambro-Ordovician carbonates (A. Keith, 1932, 1933; Prindle and Knopf, 1932). Thus, the name **Taconic allochthon** (Kay, 1935) was applied to the body of presumably overthrust pelitic rocks.

THE TACONIC-THRUST CONCEPT

Geologic ideas about the Taconic pelites and their relationship to the Cambro-Ordovician carbonates have pendulated back and forth between establishment- and denial of the concept of low-angle thrusting. During the first swing of the pendulum, all of the stratigraphic units involved were assigned to one of two groups, the aforementioned "pelites" and "carbonates." Given this two-component stratigraphic arrangement, the key to understanding the correct interpretation was held to be the boundary between the pelites above and the carbonate below.

Detailed study of this contact convinced Balk (1932; 1936a, b; 1953) that no basis existed for inferring a large-scale thrust. In short, Balk balked at the idea. Thus, in an early geologic version of that later popular inquiry: "Where's the beef?", Balk asked "Where is the mylonite?". Both Cady and Kaiser correctly understood relationships that were not to be demonstrated to general satisfaction until two decades later. They emphasized the unconformable overlap of a mid-Ordovician black shale across the carbonates and that the contact with the displaced greenish- and reddish Taconic rocks was one of **shale on shale**, not shale on carbonates. Therefore, the evidence of unconformity at the shale/carbonate boundary, emphasized by Bucher and later established as correct, was irrelevant with respect to the thrust. The key Taconian contact was not at the carbonate/"shale" boundary, to which Balk had devoted so much effort.

Biostratigraphic research on the Ordovician graptolites by W. B. N. Berry (1959; 1960; 1962a, b; 1963a, b; 1970; 1972; 1973) showed that among the "Taconic rocks," not one but **two** pelitic suites are present. These are: (1) the "Taconic" suite spanning the same age range as the carbonates (and then some); and (2) a mid-Ordovician- and younger suite that is **entirely younger than the carbonates** (indeed overlies them unconformably).

Application of the sequence-stratigraphic approach (Sloss, 1963) to the Lower Paleozoic rocks that were affected by the Taconian orogeny helps to clarify these units. Thus, the **Sauk Sequence** designates most of the Cambrian- to Ordovician carbonates and the underlying Cambrian clastics. The **Tippecanoe Sequence** includes a basal limestone unit and the "shales" that are younger than, and were deposited above, the Sauk Sequence. In contrast, the **Taconic Sequence** includes the former off-shelf pelitic strata bearing correlatives of the carbonates. Thus, the top of the Taconic Sequence and the lower part of the Tippecanoe Sequence are the same age (Guo, Sanders, and Friedman, 1990; Figure 3).

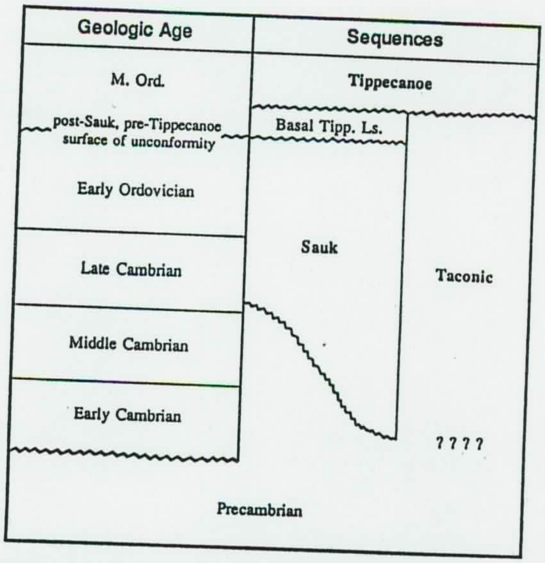

Figure 3. Names of the three stratigraphic sequences applicable to the Lower Paleozoic rocks of eastern New York. (Sanders, 1995, table 1, p. 24.)

THE NON-TECTONIC GRAVITY-DOES-IT-ALL APPROACH

In the 1950's, various European geologists emphasized the view that the mechanism of gravity sliding along the sea floor was the correct interpretation of displaced bodies of rock previously thought to have been thrust. The introduction of this concept to explain the Taconic allochthon (Rodgers, 1952) started a trend that soon became popular (Cady, 1968b). Indeed, gravity displacement down submarine slopes was invoked to explain whole belts of outcrop of the Sauk Sequence (Fisher *in* Rodgers and Fisher 1969; Fisher, Isachsen, and Rickard, 1970; Fisher and Warthin, 1976, Fisher, 1977).

Detailed geologic mapping in the Taconic range began soon after 7.5-minute topographic quadrangle maps became available and the structural evidence soon became unsurmountably in support of hard-rock thrusts. Thus, after enjoying a short-lived popularity, the concept of gravity sliding was challenged by those advocating "hard-rock" thrusting (Bosworth and Kidd, 1985; Stanley and Ratcliffe, 1985; De Angelis, 1987 ms., 1995). To many geologists, subscribing to the older thinking (Zen, 1967; Bird and Dewey, 1975; Ratcliffe and others, 1975) the Taconic orogeny was envisioned as a series of gravity-induced slides (the Low Taconics) and eventual overthrusts (the High Taconics) of the oceanic Taconic sequence above the carbonates of the Sauk Sequence and unconformably overlying foreland-basin flysch of the Tippecanoe Sequence.

Many modern workers [including the two of us, Rowley and Kidd (1981), Stanley and Ratcliffe (1985)] do not believe in gravity sliding as a model for the emplacement of even the structurally lowest Taconic allochthons. Rather, based on stratigraphic- and structural evidence, these modern workers envision **all** Taconic displacements as being the result of continentward thrusting of portions of a subduction complex formed between the oceanward-facing continental margin sequence and the encroaching Taconic arc. This episode of continentward displacement was driven by the encroachment of a volcanic arc (the Ammonoosuc-Bronson Hill Complex) against the passive continental margin of Ordovician North America.

DEFORMATION OF THE METAMORPHIC INFRASTRUCTURE IN NEW ENGLAND

The Taconic problem in western New England revolves around Cambrian- and younger eugeosynclinal sediments that were displaced continentward to ultimately rest atop middle Ordovician and older deposits of the Appalachian foreland basin (the Tippecanoe Sequence and older Sauk Sequence). To the east, search for the root zone of the Taconic slices has prompted considerable effort on the part of structural geologists for many years. Research has indicated that at the same time as emplacement of Taconic allocthons occurred and somewhat earlier, in the metamorphic infrastructure, an extensive fold belt, a zone of regional metamorphism, and various plutons dated at roughly 470-400 Ma were intruded. Any reasonable understanding of the Taconic Orogeny must reconcile the contrasts in diachroneity of deep-seated vs. supracrustal thrust-related deformation, within- and across the orogen. The following sections attempt to reconcile these temporal differences by first understanding the lithotectonic belts and terrane boundaries of the metamorphic core zone.

A tectonic map of southern New England (Figure 4) includes the territory designated as the metamorphosed root zone for the Taconic allochthons (covered beneath the map explanation in the upper left-hand corner of Figure 4). (See Figure 1 for the position of the Taconic allochthon.) Three major through-going tectonostratigraphic belts (as indicated in Figure 4 by roman

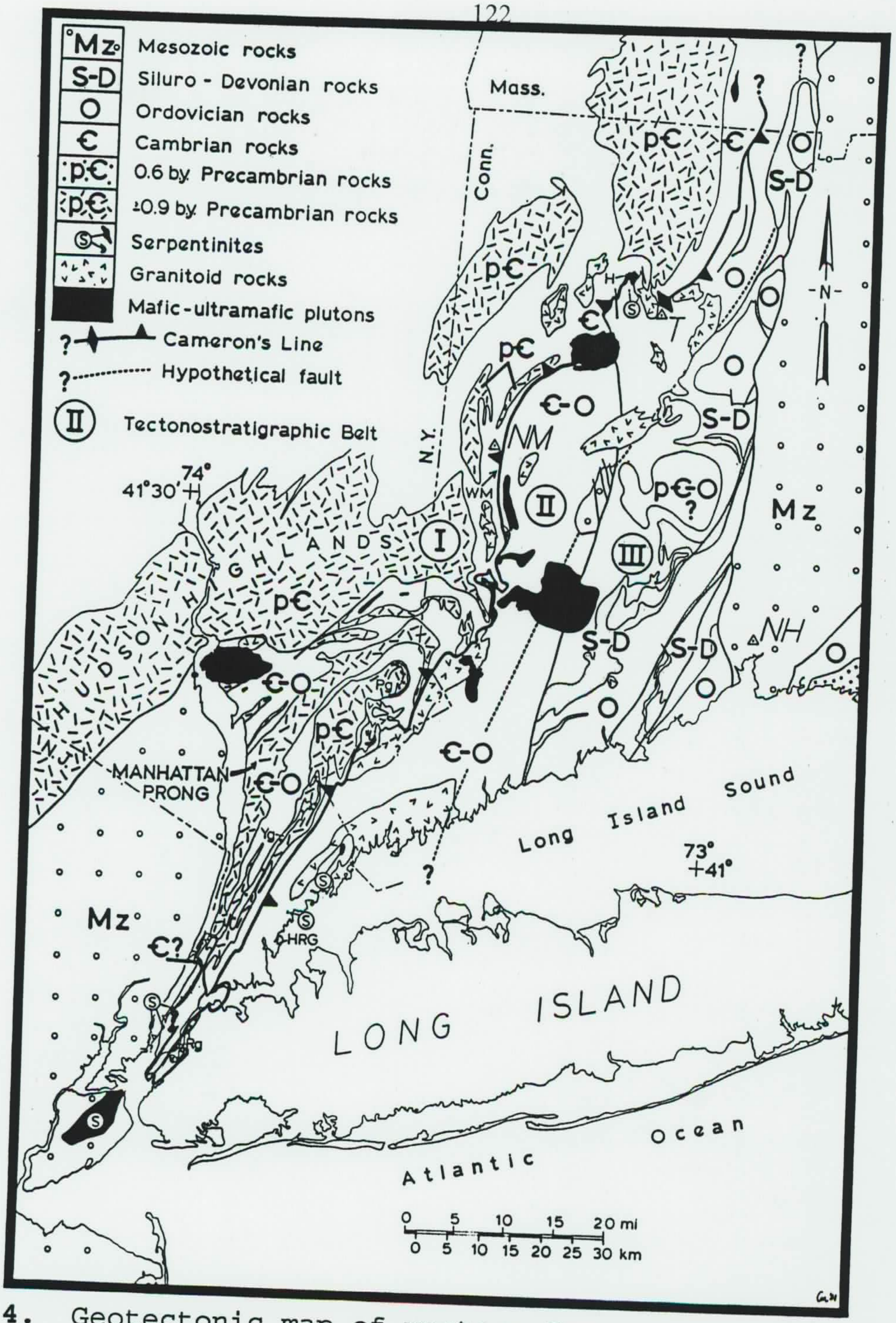

Figure 4. Geotectonic map of western Connecticut and southeastern New York. The Taconic allochthons are covered, in the upper left-hand corner of this figure, by the explanation. (From Merguerian, 1983a.)

numerals I, II, and III), constitute the bedrock units of southern New England. Belt I consists of Proterozoic basement rocks, unconformably overlying autochthonous quartzite, marble, gneiss and schist (metamorphosed products of the Sauk and Tippecanoe sequences), and some allochthonous rocks (Waramaug, Hoosac, and Manhattan [in part] formations of the Taconic

Sequence), originally derived from Belt II. Belt I is truncated along the east by Cameron's Line, a major Taconian ductile shear zone in the New England Appalachians which marks the easternmost extent of basement- and cover rocks.

Belt II, which occurs to the east of Cameron's Line, is underlain by the Hartland Terrane which consists of highly aluminous schist and gneiss, together with amphibolite, coticule, and serpentinite lenses. Merguerian (1983a, 1985a) has interpreted the Hartland Terrane as marking the deeply eroded remains of an internally sheared, continent-facing Taconian subduction complex.

Belt III bounded on the west by a hypothetical fault (dashed line in Figure 4) and cut on the west by the basin-marginal faults of the Hartford Basin. Near New Haven, Connecticut and in the Ordovician gneiss domes extending northward from there, the rocks of Belt III include metamorphosed Ordovician plutonic-, volcanic- and volcaniclastic rocks (Maltby Lake and Allingtown volcanics) which extend northward to merge with the Ammonoosuc- and Bronson-Hill island-arc-terranes of Massachusetts and New Hampshire. Thus, from west to east, Belts I, II, and III mark a transect through collapsed arc-continent collision zone with elements of a passive-continental-margin sequence (Belt I), an intervening subduction complex consisting of former deep-water oceanic strata (Belt II), and a composite arc terrane (Belt III).

Numerous lower Paleozoic calc-alkaline plutons were intruded in close proximity to the Belt I-Belt II boundary (Cameron's Line) in western Connecticut and southeastern New York. (See Figure 4.) Near West Torrington, Connecticut, the Hodges mafic-ultramafic complex and the crosscutting 466±12 Ma Tyler Lake Granite were sequentially intruded across Cameron's Line (Merguerian, 1977 ms.). These plutons are folded along with Cameron's Line in West Torrington, Connecticut. Because of their formerly elongate shapes and because the regional metamorphic fabrics related to the development of Cameron's Line in both the bounding Waramaug and Hartland formations display contact metamorphism, these plutons are interpreted as being late synorogenic. The identification of significant mid-Ordovician plutonism across Cameron's Line (Mose, 1982; Mose and Nagel, 1982; Merguerian and others, 1984; Amenta and Mose, 1985; Baskerville and Mose, 1989) has established a mid-Ordovician- **and possibly older age** for the formation of Cameron's Line and the syntectonic development of regional metamorphic fabrics in the Taconic root zone of western Connecticut.

THE TACONIC OROGENY IN NEW YORK CITY

The Taconic problem in New York City focuses on ductile-fault imbrication of three lithologically distinct amphibolite-grade rock sequences formerly deposited as temporally correlative lithotopes across the Cambro-Ordovician shelf edge of embryonic

North America. The former shelf **(Sauk Sequence)** is preserved as the Cambro-Ordovician Inwood Marble (Є-Oi) which is locally interlayered with autochthonous calcite-marble bearing Middle Ordovician Manhattan Schist (Om) of the **Tippecanoe Sequence**. The Saint Nicholas thrust (Taconic frontal thrust) separates lower-plate **Tippecanoe** (Om) and **Sauk** (Є-Oi) rocks from upper-plate gneiss, schist, and amphibolite of the former Cambro-Ordovician slope- and rise (Manhattan Formation; Є-Om). The structurally higher ductile fault mapped as Cameron's Line, juxtaposes muscovite-rich schist and gneiss, amphibolite, serpentinite, and coticule of a former deep-water realm (Hartland Terrane; Є-Oh) with Є-Om rocks. Combined as the Manhattan Schist Formation by past workers, the subunits Є-Om and Є-Oh are here considered to be allochthonous, ductile-fault-bounded facies of the **Taconic Sequence**.

During Ordovician Taconian arc-continent suturing, the Saint Nicholas thrust and Cameron's Line juxtaposed former shelf-, rise-, and deep-water facies in a continentward-facing subduction complex. The two Taconian terrane boundaries now occur as steeply oriented, highly laminated, migmatized, complexly folded-and annealed zones of commingled mylonitic rocks. They developed during progressive synmetamorphic ductile deformation ($F_1 + F_2$) which culminated in two internally sheared structural sheets now roughly oriented N50°W, 25°SW (Merguerian, 1983b). Both ductile-fault zones are characterized by penetrative F_2 isoclinal- and shear folds, mica- and feldspar porphyroclasts, polygonized quartz ribbons, products of lit-par-lit granitization, local lenses and layers up to 10 cm thick of kyanite+quartz±magnetite, and local tectonic mélange.

Thus, the "good old Manhattan Schist" (Om) is the metamorphosed equivalent of the foreland-basin-filling Normanskill strata (i. e., that part whose protoliths belong to the Tippecanoe Sequence, and were deposited unconformably above the basal Tippecanoe limestones), whereas the overlying schistose rocks are the metamorphosed equivalent of two parts of the Taconic Sequence [= the Waramaug (Hoosac) formation (Є-Om) and Hartland Terrane (Є-Oh)], whose protoliths are basically coeval with the Inwood Marble and owe their structural positions above the marble (and also above unit Om of the Manhattan Schist) to displacement along two ductile thrusts, the St. Nicholas thrust below, and the Cameron's Line thrust above.

TECTONIC MODEL

Available geochronologic data from plutons which crosscut Cameron's Line in western Connecticut and New York City together verify that the compressive ductile deformation in the metamorphic- and igneous Taconic root zones of these seperated areas of the orogen leads the supracrustal emplacement of Taconian thrust sheets by a minimum of 20 Ma. Mylonitic rocks at terrane boundaries (Cameron's Line) are cut by deformed middle

Ordovician plutons. In New England, the polydeformed internal massifs presumably mark the deeper levels of a continentward-facing accretionary complex within which subduction and ductile deformation of oceanic deposits preceded collision of the Taconian arc terrane. In our view, final docking of the Taconic-arc terrane resulted in cratonward thrusting of the shallower levels of the subduction complex as the Taconic slices.

Taconian imbrication of the Sauk carbonate platform and emplacement of "hard-rock sedimentary" Taconic slices preceded thrusts in the metamorphic core zone indicating that deformation and "lock-up" of the infrastructure preceded emplacement of the Taconian slices. A major difference between these two portions of the orogen is that the infrastructure is tectonically thinned and shows none of the stratal duplication that exists in the foreland basin. Clearly, in the infrastructure, metamorphism and tectonism were synchronous. We envision that deep-seated compressional deformation begins in the upper plate (infrastructure) at the leading edge of the subducting plate by some 20 Ma, then steps outward to effect the strata on the subducting plate as convergence continues. Final closure of the collisional zone eventually results in consolidation- and thrusting of the upper levels of a mature, internally deformed subduction complex within an imbricated foreland basin. Thus, we here envision that Taconian convergent tectonics developed diachronously both across and within the orogen. Such upward-younging of the deformational front may yield a geometrically predictable vertical pattern of diachroneity in arc-continent collision zones of similar polarity. The deformation of the Antler orogeny of the western Cordillera exhibits similar diachronous patterns (Merguerian, 1985b).

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