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TACONIC EVENTS IN PENNSYLVANIA: DATABLE PHASES OF A ~ 20 M.Y. OROGENY

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ABSTRACT. A suite of well-dated graptolite and conodont locations allows division of about 54 m.y. of Late Cambrian through Late Ordovician events into three time segments in Pennsylvania: 1) Pre-Taconic, offshore deepwater sediments including olistostromes were deposited and deformed in several offshore domains in Iapetus (*sensu lato*) from ~ 497 to ~ 459 Ma; 2) Taconic Phase I began as these rocks were translated onto the foreland as allochthons, some with piggyback basins from ~ 459 to ~ 450 Ma. This was accomplished first by thrusting onto the shelf edge, creating a foreland peripheral bulge and local depositional basins, then by depressing the larger foreland region to allow emplacement of allochthons of the Dauphin Formation (the erroneous "Hamburg klippe" of past literature), and finally with deposition of the thick, widespread fill of the traditional Martinsburg Formation; 3) Taconic Phase II advanced diachronously across the foreland with regional overturning and nappe formation (the classic "Taconic" orogeny in Pennsylvania), driven as the ongoing collision overrode and incorporated the platform and its foreland basin into alpine-scale nappes. This phase started at ~ 459 Ma at the shelf edge and lasted from ~450 to ~ 443 Ma in the present location of the Great Valley foreland and eastward. This series of well-dated events may be a model for timing of a "simple" orogenic cycle in a convergent margin with application to other parts of the Appalachians and beyond.

INTRODUCTION AND BACKGROUND

The Taconic sequence in Pennsylvania is a composite terrane consisting partly of olistostromal units that have themselves been remobilized as allochthons into a foreland basin where they were subsequently buried. Similar complicated geologic histories have been speculated for other terranes in the Appalachians and elsewhere, but rarely in generously fossiliferous successions. Thus, the Pennsylvania Taconics may serve as a guide to cycles and temporal constraints typical of these types of composite terranes.

This paper considers the Taconic orogeny as viewed from the foreland basin and makes only brief correlation with datable events in the hinterland. A companion paper reverses the emphasis, using new data to synthesize and update details of those local events of the hinterland and correlate them with a brief outline of the foreland history presented here (Wise and Ganis, in review JSG).

Geologic Setting

The Martic line (fig. 1) divides the Pennsylvania Piedmont into a lower Paleozoic shelf and foreland on the NW and deeper water, lower Paleozoic clastics of the Iapetian Ocean (*sensu lato*) on the SE. Immediately southeast of the Martic line are the slope and deeper water deposits of the Westminster terrane formed in the Octoraro seaway (Faill, 1997). Farther to the SE, the Pleasant Grove- Drumore – Huntingdon Valley shear zone places this terrane against the Potomac terrane with probable large but undetermined amounts of dextral displacement. The Potomac terrane consists of complex thrust slices of microcontinental fragments, magmatic arcs, and associated basins set in schistose matrices with superimposed, pervasive strike-slip fabric (Gates, 1991; Valentino, 1994; Valentino and others, 1994; Valentino, 1999). These terranes developed during an Iapetian rift phase starting in latest Precambrian or earliest

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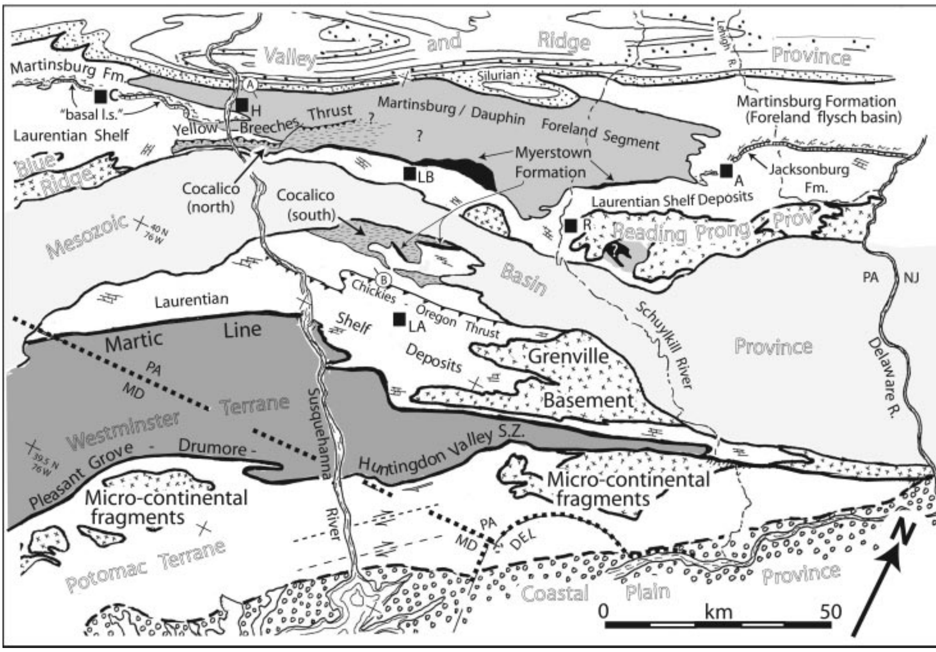

Fig. 1. Tectonic setting of the Martinsburg/Dauphin foreland. The segment, including the Cocalico units, is part of an expanded band of foreland deposition. The transition from platform to foreland, the Myerstown Formation and the "basal Martinsburg limesones" began earlier within a formative foreland sag than the Jacksonburg Formation to the east. A= Allentown; C= Carlisle; H= Harrisburg; LA= Lancaster; LB= Lebanon; R= Reading.

Cambrian and converged onto the Laurentian craton in various episodes of the early Paleozoic including the late Ordovician Taconic orogeny (Faill, 1997a, 1997b). Subsequently, complex mid-Paleozoic structural overprints and intense metamorphism (Srogi, 2004; Bosbyshell, 2004), and strike-slip separation erased much of the record within the hinterland or moved it far to the south. The Pennsylvania foreland was spared the most intense destruction, possibly because of its protected location in the center of the Pennsylvania salient (Wise, 2004). Finally, the late Paleozoic Alleghenian orogeny further telescoped and folded these Taconic and mid-Paleozoic structures (Faill, 1997).

The strongly deformed and metamorphosed deep-water units south of the Martic line are essentially devoid of recognizable fossils but the shelf and foreland preserve allochthonous fossiliferous correlatives. The complex foreland basin fill comprising the Dauphin Formation allochthonous sheets and their cover of Martinsburg flysch contains a rich graptolite and conodont faunal record with biostratigraphic control on the order of 0.5 to 1.5 m.y. for each biozone (Ross, 1982; Cooper, 1999). Because of this tight control and the ability to correlate simultaneous shelf and foreland events with deep-water events, the pre-Taconic and Taconic history in Pennsylvania may be among the most completely documentable of the various orogenies that comprise the Appalachian Wilson cycle.

Dating

Tectonic events associated with the Taconic orogeny in Pennsylvania can be separated into several diachronous phases. The complex model presented herein is

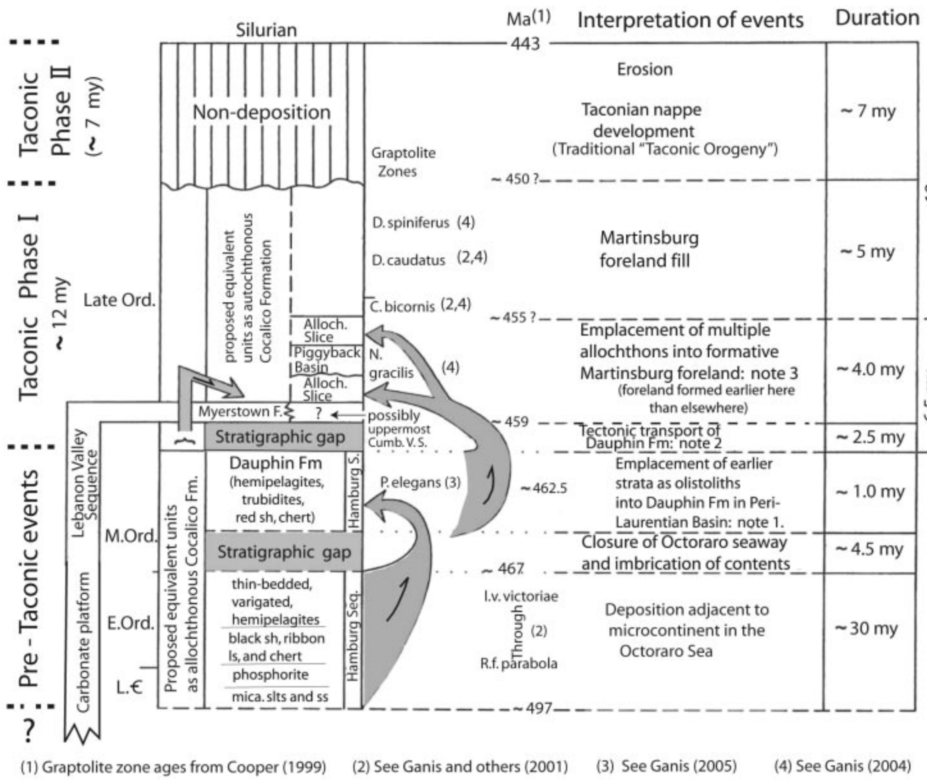

Fig. 2. Fossil-dated relationships among phases of the Taconic orogeny (*senso lato*) in the Martinsburg/Dauphin foreland. Numerical ages are based on world-wide radiometric dating of the fossils (Cooper, 1999). The arrows indicate packages that have been moved as allochthons to be embedded into younger units with fossil-dated matrices. Stratigraphic time gaps of a few m.y. commonly separate the two events. References to fossil dates are at the bottom of figure. Note 1 on figure, the Jonestown volcanics were emplaced into the olistostrome. Note 2 on figure, presumably, this occurred as the Westminster terrane obducted onto the Laurentian margin. Note 3 on figure, in this area the foreland basin formed about one graptolite zone or perhaps 1 to 1.5 m.y. earlier than areas to the east.

based on over 50 fossil localities cropping out in a number of locally named formations and members. To cite and discuss these details in the present text would render it essentially unmanageable for the average reader. Instead, the data are simplified and integrated into figures 2, 3 and 4. The full details behind these figures have been published elsewhere (Ganis and others, 2001; Ganis, ms, 2004; 2005).

Figure 2 represents the fossil-determined dates of events. Figure 3 is an interpretative evolutionary sequence showing how those various sedimentary packages were assembled and brought into the final Mid to Late Ordovician pseudo-stratigraphy of figure 2. Figure 4 expands the lower part of figure 3 with details and dates from figure 2. Additional details supporting these interpretative figures include references that appear on them, in their captions, or as supplementary Appendix notes in the body of this text indicated by an asterisk (*).

Pennsylvania Taconic foreland events can be separated into two major phases. Phase I (marine basin assembly) began with the disruption of the Beekmantown carbonate platform to form local basins, probably as a result of collision at the cratonic edge with associated foreland bulge migration. This phase of marine basin fill continued through the emplacement of massive Dauphin allochthons and their cover

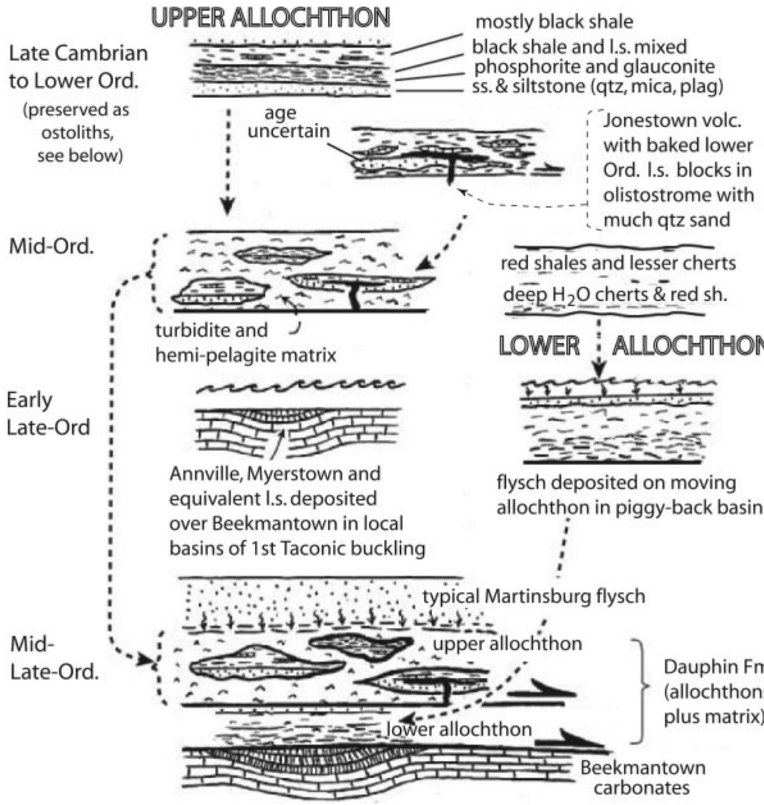

Fig. 3. Assembly of allochthons within allochthons of the Martinsburg / Dauphin foreland. Read top to bottom. Dates are generalized from figure 2 and expanded on figure 4. Pre-Taconic Late Cambrian and Early Ordovician deep-water units became allochthons embedded in Mid –Ordovician deep-water, offshore clastic matrices. With the start of Phase I, these were moved onto and across the Early to Mid-Ordovician platform, some picking up piggy-back cover enroute. These became embedded in new Mid- to Late Ordovician matrices before final emplacement as the two contrasting, major allochthonous sheets comprising this area's Dauphin Formation. After the final emplacement, the sheets were conformably covered by thick Martinsburg flysch. (After Wise and Ganis, fieldtrip guidebook, NE GSA, March 2006). The discrimination of the various major allochthons was based on work in Dauphin, Lebanon, and western Berks counties, Pennsylvania, or the western part of the Dauphin/Martinsburg foreland segment. Other minor allochthons may be identified with further detailed mapping and the allochthon emplacement history in the eastern part of the Dauphin/ Martinsburg foreland segment needs confirmation.

of Martinsburg flysch. Phase II featured the post-marine disruption of the foreland basin to create alpine-scale nappes. At the cratonic edge there is no recognized evidence of an initial Phase I foreland basin. Instead Phase II began immediately with the Martic thrust zone (Wise, 1970; Wise and Ganis, in review). Inboard on the platform, the two phases probably advanced steadily as part of the foreland bulge migration. Prior to both these phases, a Pre-Taconic, Late Cambrian to Mid-Ordovician phase, shifted contents from some offshore basins to other basins, forming complex allochthons that were ultimately preserved as the Phase I Dauphin allochthons.

The Dauphin Formation and the Hamburg "klippe"

Critical to all the following discussion is a definition of the Dauphin Formation (Ganis and others, 2001), a complex assemblage that includes allochthonous sheets of

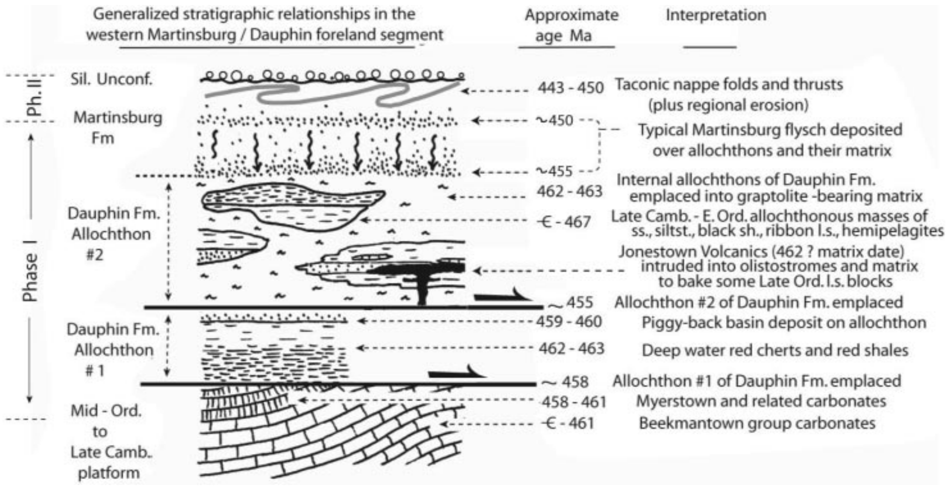

Fig. 4. Dating Taconic events. This figure, an enlargement of the bottom of figure 3, uses the more precise dates of figure 2 to expand the interpretations with details not possible in the limited space of figure 3.

deep-water sediments interbedded and interleaved with datable Martinsburg-*type* flysch deposited over and around the sheets or as piggy-back basin deposits emplaced during their movement into the foreland basin. A further complication is that matrices of some allochthons enclose lesser allochthons and embedded olistoliths, all separately datable by fossils (fig. 2). This complex structural / stratigraphic pile forms the lower part of a foreland basin deposit, namely the Dauphin Formation, emplaced across the carbonate platform between ~ 459 to 455 Ma and covered by the traditional Martinsburg flysch formation between ~ 455 to 450 Ma (fig. 2). The formation takes its name from extensive development throughout Dauphin County, Pennsylvania, and areas to the east (Ganis and others, 2001).

In past literature, the allochthonous masses of the Dauphin Formation, which unknowingly included parts of the Martinsburg Formation, have been identified collectively as the "Hamburg klippe" (Stose, 1946) and likened to the thrust sheets of the Taconic Mountains of New England, now largely isolated by erosion from their roots in the Berkshires (Zen, 1961, 1972; Stanley and Ratcliffe, 1985). In most geologists' minds, the term "klippe" refers to late or post-tectonic erosional or gravitational isolation of large parts of a formerly continuous thrust sheet. Chief Mountain in Montana, Heart Mountain in Wyoming, or the Taconic examples of New England are "poster rocks" for such mental models. Continued use of the term "klippe" for the quite different allochthonous sheets of the Pennsylvania Taconic basin that pre-date the main deformation can only lead to confusion and cloud understanding of their tectonic setting and relationships. In addition much of the past literature contains references to the "Hamburg *sequence*", partly equivalent to the Dauphin Formation, so the continued use of that name seems inevitable. Because the Dauphin Formation represents the end product of amalgamation of several earlier Laurentian outboard sequences, including the Hamburg (see fig. 2), the term "Hamburg sequence" has value when discussing pre-inclusion sequences prior to formation of the Dauphin basin. For the above reasons we suggest abandonment of the term Hamburg "*klippe*" with substitution of terms like "Dauphin Formation" or "allochthons of the Dauphin Formation" but retention of the term "Hamburg *sequence*."

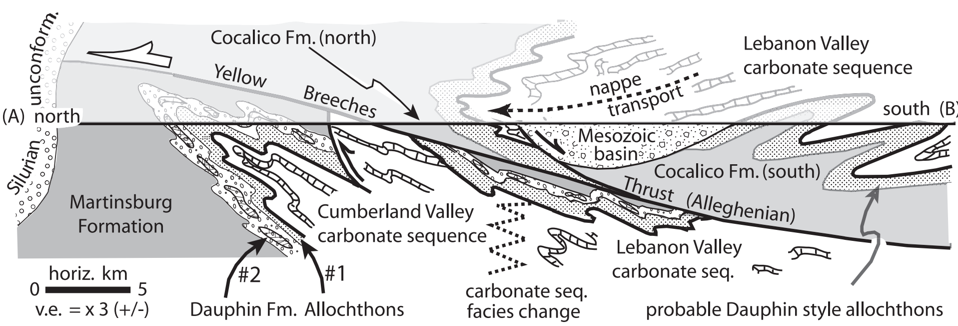

Fig. 5. Schematic cross-section of the Martinsburg/Dauphin foreland along line A-B of figure 1. Faded geometry is above present land surface. The Alleghenian-age Yellow Breeches thrust juxtaposes two strongly overturned to recumbent Taconic anticlinoria. On the north, diagenetic to anchizone metamorphic grade Martinsburg Formation plus two major allochthonous sheets of the Dauphin Formation are repeated across a strongly overturned anticlinorium. The anticlinorium is broken by a relatively small Alleghenian-age thurst that brings up core rocks of the Cumberland Valley carbonate sequence, a western facies. On the south, the Mesozoic basin separates the more-than-recumbent lower limb of a greenschist-grade anticlinorium, into a Cocalico North and Cocalico South portion. Reconnaissance shows Dauphin-like allochthons in both Cocalico areas but details necessary to map a distinct Dauphin-like Formation are not yet available. Here, the core rocks are part of the Lebanon Valley carbonate sequence, an eastern and southern facies. Some type of facies change is required beneath the master thrust.

Phase II: Nappes of the Taconic Alps

Discussion of the complex Taconic history requires retro-deformation of younger structures in order to picture more clearly the original depositional stratigraphy and foreland paleogeography. Accordingly we begin with the final Taconic geometry and its Alleghenian overprint in figure 5, a generalized cross-section of the foreland region along line A-B of figure 1, just east of the Susquehanna River. The geologic map (fig. 1) shows several packages or segments of Ordovician foreland clastics, the Martinsburg/ Dauphin segment on the north and its generally correlative Cocalico segment on the south, the later separated into north (N) and south (S) areas by the Mesozoic basin. In the Alleghenian orogeny the Martinsburg/ Dauphin and the Cocalico segments, previously folded into separate anticlinoria during the Taconic orogeny, were juxtaposed by the Yellow Breeches thrust (figs. 1 and 5), a feature of large but undetermined displacement.

Each of these segments, Martinsburg/Dauphin and Cocalico, is a composite terrane of allochthnous and autochthonous rocks that differ only slightly. The Martinsburg/Dauphin segment, being farther from the hinterland, is at diagenetic to low anchizone metamorphic grade. It is underlain by the Cumberland Valley Cambro-Ordovician carbonate sequence, typical of areas to the west. The Cocalico segment is at greenschist grade and is underlain by the Lebanon Valley carbonate sequence, typical of areas to the east and south. Much of the following discussion of Phases I and II involves the evolution and emplacement of various allochthonous sheets of the Dauphin Formation wherein most details are derived from the Martinsburg / Dauphin segment. Reconnaissance mapping shows similar allochthonous lithologies are present in both Cocalico (N) and (S) but these have yet to be separately mapped and dated as distinct formations of probable Dauphin-like character.

The overturned to recumbent folds of figure 5 are part of a vast system of similar structures, the Lebanon Valley nappes, mapped ~ 100 km to the east and ~ 20 km to the west. The structures continue ~ 30 km to the southeast in Lebanon Valley carbonate sequence rocks as far as the Alleghenian-age Chickies/ Oregon thrust (fig. 1, Meisler and Becher, 1971; summary by Gray and Root, 1999). S-surface patterns of recumbent nappe folds, though distorted by younger deformations, continue the flow pattern southward (fig. 1) through the carbonate shelf and slope deposits of the Lancaster platform, across the Martic line and into steeply dipping roots in the Westminster terrane (Freedman and others, 1964; Wise, 1970; Faill, 1997; Wise and Ganis, in review). These structures, extending nearly 100 km across strike, support and extend Gray's comments in his 1959 discovery paper, "Recent detailed studies in . . . the Great Valley have indicated large-scale recumbent folds, or nappes in the carbonate rocks. The structures are on an alpine scale." In the broadest sense, the Lebanon Valley nappe system might correspond to the Helvetic Alps whereas the Westminster deep-water clastic and schistose roots are more like the Penninic system.

PRE-TACONIC SHELF AND OFFSHORE EVENTS

Several authors have interpreted a complex history of offshore events that preceded the Mid – Late Ordovician Taconic orogeny at various locations along the Appalachians (Hibbard and Samson, 1996; Faill, 1997; van Staal and others, 2004). In most areas, with the exception of Newfoundland, the rock record of those events has been greatly obscured by metamorphism and severe younger deformation. However, the Dauphin allochthons escaped into the foreland basin before most of the obscuring overprint occurred. This preservation including the large number of paleontologic dates and variety of sedimentary facies provides a new window into some early offshore events of the Appalachians.

The Dauphin Allochthons

Faill (1997) suggested that pre-Taconic convergence within the Theic ocean began when the Wilmington island arc complex overrode and metamorphosed basinal strata lying between an arc complex and a Brandywine microcontinent, offshore of Laurentia. This defines the Potomac Orogeny of Hibbard and Samson (1996) at this latitude as a Late Cambrian to Early Ordovician event (Faill, 1997, p. 591) that included overthrusting of the microcontinent (s). The northwest-most Dauphin allochthonons are not metamorphosed beyond low anchizone grade and, therefore, do not appear to be related to the rocks caught up in the Potomac orogeny, indicating the Dauphin allochthons were being deposited elsewhere while the Potomac orogeny was in progress. The basinal strata deposited between a Brandywine or other microcontinent and the Laurentian margin, namely the Westminster terrane (Rodgers, 1970, p. 188), is a better candidate source for these allochthons (see also Lash and Drake, 1984, p. 30). The rocks argue strongly for a microcontinent(s) being positioned off Laurentia at this time (see also Horton and others, 1989; and Faill, 1997). The stratigraphic content of the Dauphin allochthons deposited from Late Cambrian through the early Middle Ordovician (summarized on figs. 2 and 3) indicates a dynamic sedimentary environment more likely to have occurred adjacent to a drifting microcontent than to a stable Laurentian platform.

Some of the Late Cambrian and Lower Ordovician rocks of the Dauphin sequence are deep-water limestone turbidites that yield Baltoscandian conodonts unrelated to North American midcontinent affinities (Bergström and others, 1972; Repetski, 1984a, 1984b; Ganis and others, 2001; Repetski and Ganis, 2001). This is further evidence that the Dauphin sequence was deposited adjacent to an offshore microcontinent separated from Laurentia by an oceanic barrier.

Westminster Terrane Source Area ?

The Westminster terrane has been interpreted as deposits of the Octoraro sea that once separated Laurentia from a Brandywine or other microcontinent (Faill, 1997). However, no part of the Westminster terrane exposed today has been specifically matched to the Dauphin allochthons: they are "different." This might reflect extreme variability of different parts of the depositional basin coupled with different timing, transport distance, and elevation in the imbricate stack of Taconic allochthons. In addition, major mid-Paleozoic right-lateral displacements of the eastern Piedmont may well have moved the true, more outboard source of the Dauphin allochthons far to the south (Gates, 1991; Valentino and others, 1994; Valentino, 1999).

The Dauphin allochthons are proposed here as the most distal members of the imbricate thrust stack that was structurally detached from the rest of the "different" Westminster terrane. In this interpretation they represent the basinal strata from some unidentified part of the Octoraro sea, dating from Late Cambrian (the arrival of the microcontinent at this paleolatitude?) to early Middle Ordovician (fig. 2). A nearly complete graptoliferous succession from basal to early Middle Ordovician, collectively preserved in a Dauphin olistostrome is described by Ganis and others, 2001, and Ganis, ms, 2004. Conodonts extend this succession downward into the Late Cambrian (J. Repetski, personal communication, 2001).

Another Peri-Laurentian Basin (~ 4.5 m.y. Duration)

The following discussion is illustrated on figure 2. The Octoraro marine basin accumulated sediment for approximately 30 m.y. and then was structurally destroyed as a consequence of microcontinent convergence and closure of the seaway (Ganis and others, 2001; Ganis, ms, 2004). Apparently, closure was nearly complete after about 4.5 m.y., when the olistrostromes of the Dauphin Formation were deposited in a peri-Laurentian basin. This new turbiditic (*1) and hemipelagic (*2) basin received olistolithic structural debris from imbricated (elevated) strata originally deposited adjacent to a microcontinent within the Octoraro sea over the very short interval of one graptolite zone (Ganis, 2005). More distal, pelagic, radiolarian red chert and shale strata (*3) dated with conodonts and graptolites (Ganis, ms, 2004) were also deposited during the same brief interval. Minor eruption and emplacement of basic volcanics (*4) into the olistostrome also occurred during this interval. This peri-Laurentian basin, with its many attributes of trench sedimentation, was probably associated with rollback of the Laurentian margin (discussed below).

PHASE I: LAURENTIAN OBDUCTION, ALLOCHTHON EMPLACEMENT AND BURIAL

Obduction and Allochthon Separation: ~ 2.5 m.y. Duration

The driving mechanism for convergence and obduction was diagrammed by Faill (1997) as rollback of the Laurentian margin beneath the incoming microcontinent and Westminster terrane. The destruction of the peri-Laurentian basin (discussed above) effectively dates formative obduction and arrival of the Westminster terrane via the Martic thrust zone onto the Laurentian margin as the Dauphin allochthons, the "Hamburg klippe" of Stose (1946). The emplacement of these allochthons from the Westminster terrane into the foreland marks the culmination of obduction, separation, and emplacement over a period of about 2.5 million years (fig. 2).

Based on observations in the western half of the Martinsburg/ Dauphin foreland segment, an initially emplaced allochthon of Middle Ordovician pelagites was covered during transport by a turbiditic piggyback basin during the early Late Ordovician [*Nemagraptus gracilis* Zone (Ganis, ms, 2004) at approximately 459 Ma; fig.2]. The disconformity between the allochthon and the piggy-back basin represents a stratigraphic gap of about 2.5 million years for the transport interval. Further allochthons, composed of Middle Ordovician olistostromal hemipelagites and turbidites, were then emplaced above this initial allochthon/ piggyback basin. With only nominal amounts of biostratigraphic control, Root and MacLachlan (1978) described mutiple allochthon emplacements into the Martinsburg basin and drew an early version of this big picture. In similar fashion, Wright and others (1979) proposed the emplacement of *N.*

gracilis age allochthons into the Martinsburg basin in the *Diplograptus multidens* (=*Climacograptus bicornis*) Zone in the eastern part of the Martinsburg/ Dauphin foreland segment.

Platform to Foreland Transition; Allochthon Emplacements ~ 2.5 m.y. Duration

The carbonate platform initially responded to obduction of the Westminster Terrane by subsidence and transition from relatively pure carbonate (*5) deposition to an ever-increasing muddy clastic input. Conodont faunal evidence (Ross and others, 1982) for the basal age of transitional strata (*6) below the allochthons shows it to be older than equivalent strata elsewhere. To the east, the base of equivalent transitional strata (Jacksonburg Formation in fig. 1; *7) below the foreland basin fill (Martinsburg Formation) is younger and has no allochthons emplaced above it. The allochthon's advance apparently created a formative part of the foreland basin subsidence (Ganis, ms, 2004). In effect it produced the forward sag into which the allochthons were emplaced. The irregular rifted margin of late Precambrian-Cambrian Laurentia may have created a long-lived tectonic inheritance that influenced the structural orientation for multiple orogenic elements throughout the Paleozoic (Thomas, 1977, 2006). These included separating and positioning the Brandywine microcontinent(s) for closure of the Octoraro sea, location of the adjacent platform margin shelf break, obduction of the Westminster terrane, and location of the initial foreland sag for later emplacement of the Dauphin allochthons.

As the allochthons advanced a peripheral bulge formed to the northeast (Blackriveran hiatus of Lash and Drake, 1984), uplifting the platform sequence. As that uplift was eroded, clasts from the carbonate platform (*8) were shed as a conglomerate facies (*9) into the sag described above. Eventually the bulge was erosionally reduced to be onlapped by transitional strata (*7).

The Dauphin-style allochthons occur above transitional strata (*6) in the Cocalico segment of the foreland and in the Great Valley west of the Susquehanna River. Stose (1946) correctly identified the Cocalico "Formation" as part of the "Hamburg terrane" based on lithologic similarities. The Taconic (Martinsburg/Cocalico) foreland once extended to the southeast beyond its traditional Martinsburg outcrops in the Great Valley section (see fig. 1) to include areas of the present Cocalico outcrops (fig. 1). The Cocalico, like the Martinsburg/ Dauphin foreland segment of the Great Valley, is also a composite terrane of both allochthonous and autochthonous rock. Its more proximal position relative to the late Taconic tectonic front produced low greenschist grade metamorphism. During the Alleghenian orogeny part of the Cocalico "terrane" was later transported northwestward on the Yellow Breeches thrust (MacLachlan, 1967) into juxtaposition with its less metamorphosed counterpart in the Martinsburg/ Dauphin foreland segment. The main body of the Cocalico, south of the Mesozoic basin in Lancaster County, Pennsylvania, is designated the Cocalico South and its counterpart north of the basin, transported on the Yellow Breeches thrust, the Cocalico North. The Cocalico North rocks contain gradational exposures of the uppermost transitional strata (Myerstown Formation, see note *6) to "Cocalico Martinsburg". The same relationship exists in the Great Valley up into the Martinsburg (*6).

Tectonically distorted graptolites occur in the "Cocalico North" (Willard, 1943; described these as "probably Normanskill"; see also Prouty, 1959, in reference to "Climacograptus", p. 37; and MacLachlan, 1967) above the Myerstown strata in the "Cocalico Martinsburg." Recent collections (fig. 6) permit a provisional date of early Late Ordovician which are dominated by large biserials such as orthograptids, climacograpids, and hallograptids and/or glossograptids, lacks dichograpids, and is typical of the *N. gracilis* or *C. bicornis* Zone. However, most are difficult to taxonomically assign specifically due to marginal preservation and distortion. This age suggests early foreland flysch deposition prior to the emplacement of the Dauphin allochthons

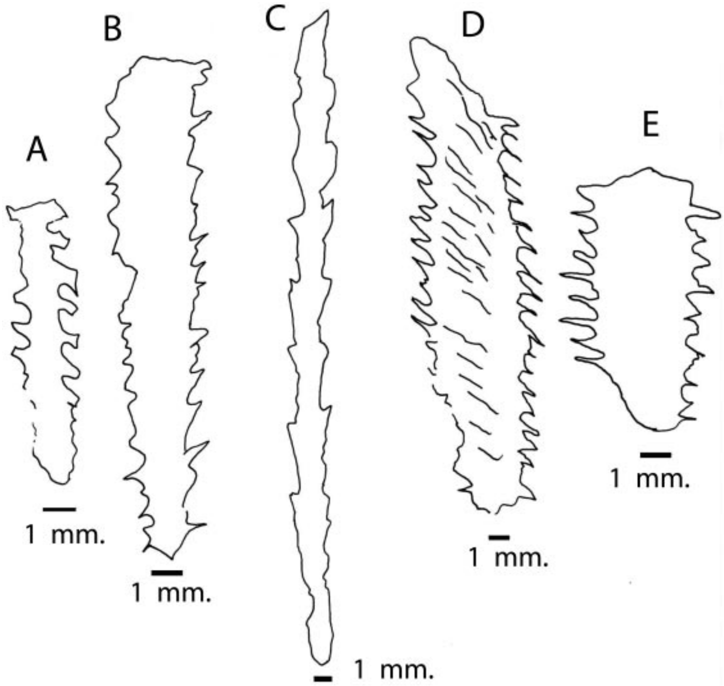

Fig. 6. Graptolites preserved as external molds, tectonically distorted to varying degrees, from the Cocalico North Formation. This figure represents the first clearly documented assessment of graptolite fossils from the Cocalico (see also note *10 in Appendix). It is part of the primary evidence for this paper's correlations of the Martinsburg and Cocalico. Location is roadcut on Chambers Street, Steelton, Pennsylvania (40° 13′ 30.85″; 76° 49′ 26.80″). Each outline has a 1mm bar for scale. (A) a climacograptid, U.S. N.M. 535000; (B) *Orthograptus* cf. *calcaratus* (Lapworth), U.S.N.M. 535001; (C) an orthograptid, highly stretched, U.S.N.M. 535002; (D) a glossograptid, U.S.N.M. 535004; (E) *Hallograptus* sp., U.S.N.M. 535003. U.S.N.M. is United States National Museum, Washington, D.C.

(discussed below). Possible graptolites were reported by Jonas and Stose (1926, 1930), Stose and Jonas (1933), and Stose (1946) from the Cocalico South but are open to question (*10 in Appendix).

Within the regionally overturned package carried by the Yellow Breeches thrust, other parts of the Cocalico North sequence contain higher emplaced allochthonous rocks in the pseudo-stratigraphic pile. Some are lithologically comparable to the Middle Ordovician pelagites north of the Yellow Breeches thrust. The base of the Martinsburg cover above the allochthons is exposed in the Great Valley, north of the Yellow Breeches thrust (Ganis, ms, 2004). Thus, the rough stratigraphic position of the base of the allochthon emplacements can be seen within the Cocalico North package and the Great Valley, whereas its top (the traditional Martinsburg Formation) has been recognized only within the Great Valley. Both positions are graptoliferous and range from within the *N. gracilis* to *C. bicornis* Zone (base) to upper *Climacograptus bicornis* Zone (top; see Ganis, ms, 2004), a span of ~ 2.5 m.y.

Foreland Basin Fill: ~ 5 m.y. Duration

The stratigraphic level covering the upper allochthonous rock emplacement in the western part of the Martinsburg/ Dauphin foreland segment is based in the upper *C. bicornis* Zone (~ 455 Ma; fig. 2 Ganis, ms, 2004). At scattered outcrops through this interval miscellaneous allochthonous rock appears in the basin as boulder deposits and slices that include Lower and Middle Ordovician carbonate boulders and slabs (dated with conodonts, J. Repetski, personal communication, 2001) in a Martinsburg-type shale matrix (dated with graptoilites, Ganis, ms, 2004). At the *C. bicornis-Diplacanthograptus caudatus* Zone (= *Corynoides americanus* Zone) boundary level, foreland fill in the Martinsburg/ Dauphin segment reaches a biostratigraphic position roughly equivalent to the base of the Martinsburg Formation to the northeast (Epstein and Berry, 1973) and southwest (Stephens and Wright, 1981). Above this level, through the range of *Diplacanthograptus spiniferus,* the foreland basin continued to fill with typical Martinsburg flysch, which has an Edenian shelly fauna (*11) in the uppermost part (~ 450 Ma; fig. 2; references in Ganis, ms, 2004). Wright and others (1979) proposed Martinsburg cover above allochthon emplacement between the *D. multidens* (= *C. bicornis*) and *D. spiniferus* zones in the eastern part of the Martinsburg/ Dauphin foreland segment. In short, the Martinsburg fill above the highest allochthons and below the Silurian unconformity took about 5 m.y. to accumulate.

SUMMARY AND SYNTHESIS

Fossiliferous successions in the Pennsylvania Cambro-Ordovician foreland record ~50 m.y. of pre- and syn-Taconic events, a rare example of relatively old orogenic deposits containing abundant, well preserved, high resolution, fossil dates. Relatively pristine allochthons, expelled from roots in subsequently highly deformed, metamorphosed, removed, or destroyed inner Piedmont terranes, provide dateable insight into the pre-metamorphic history of both the offshore Piedmont and its relation to an evolving foreland mountain system. These dates (table 1) show the record of Pennsylvania Taconic orogeny, with preserved portions ranging from ~461 to ~443 Ma, may have started a bit later than some other areas, but went through their intermediate and final stages at about the same time as most other areas of the broader Appalachian orogen.

The Pre-Taconic phase in the L. Cambrian to early Middle Ordovician (~461 Ma) was marked by a long period of deep-water deposition adjacent to both a stable carbonate platform developing on the cratonic margin and an outboard microcontinent. Early tectonism related to the microcontinent, recorded by a change from sandstones and siltstones to phosphorites, deep-water cherts, black shales, deep-water traction limestones, and hemipelagites, was minimal, but the influence of outboard drifting terranes gradually entered the picture. The ~30 m.y. record of these events, as preserved in the allochthons, ends with a sharp break and ~4.5 m.y. time gap at ~467 Ma (fig. 2), interpreted as the first impingment of outboard arc systems beginning to override a drifting microcontinent(s) such as Baltimoria. Inboard of the microcontinent, this began the collapse and closure of the Octoraro seaway lying between it and Laurentia. Tectonic processes steadily accelerated as cratonic rollback drove the microcontinent inward, compressing and thrusting the basinal contents of the seaway. This partial closure produced the 4.5 m.y. stratigraphic gap (fig. 2), that ended with migration of the basin axis to a new area and/or creation of a new, very short-lived (~1 m.y.) basin. Within this transient basin fragments of already imbricated strata were emplaced as olistostromes across lower deposits, more proximal to Laurentia. This last event reveals both the rapidity and complexity of conditions under which these types of olistostromal deposits can form and remobilize.

Taconic Phase I on the Laurentian mainland is first recorded at ~461 Ma. Even though local thin ash from offshore volcanoes had been falling on the Beekmantown carbonate platform for some time (Huff, 1996), this date marks the first major disruption of the broader platform into more local pure carbonate and cement-rock basins. Presumably this was caused by obduction of deepwater strata, including the

Table 1

Summary of dates of Taconic events along the Appalachians

Region	Starting (?) Stages	Intermediate Stages	Final (?) Stages	Event	Reference
Newfoundland	495 - 490 Ma			Obduction of Lushs Bight Fm onto craton	van Staal and others, 2004
		470 - ? Ma		Start of strike-slip duplexing	"
			455 - ? Ma	Final phase collision of Victoria arc with Laurentia	"
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Quebec &	470 Ma			W-directed imbrication of eastern allochthons	Sassevill and others, 2006
eastern Canada		450 Ma		NW-directed re-imbrication of the thrust sheets	"
			Early Silurian	Taconic basins of foreland shift NE into E Canada foreland	Ettinsohn and Brett, 2002
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New England	502 ± 4 Ma			Late Cambrian Mooretown and Cram Hill Volcanics	Ratcliffe, 2006
			443 - 434 Ma	Migmatitic granitic complexes of E. Berkshires	"
	485 - 470 Ma			Shelburne Falls arc collision with Laurentia	Karabinos, 2001
			450 - 440 Ma	Super 40 Ar / super 39 Ar cooling ages	"
		?	454 - 442 Ma	Collision of Bronson Hill arc with Laurentia	Tucker and Robinson, 1990
		463 - 460 Ma		Conodonts in warm seas both sides of Berkshires	Thompson and others, 2002
		452 Ma		Youngest flysch in Taconic belt	Bradley, 1989
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Pennsylvania	461 - 458 Ma			First local basins (Myerstown) in carbonate platform	Ganis and others, 2001; Ganis, 2005
		460 - 459 Ma		Piggy- back basins on Dauphin allochthons in transit	"
		458 - 455 Ma		Dauphin Fm. allochthons emplaced in foreland	"
		455 - 450 Ma		Martinsburg flysch deposited over allochthons	"
			450 - 443 ? Ma	Foreland basin into nappes covered by Silurian Unconformity	"
		450 ± 4 Ma		Pequea Mine: Martic front post-thrusting and folding	Wise and Ganis in review JSG
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Central	488 - 476 Ma			Arc stage plutons	Sinha, 2004
Appalachians		472 - 450 Ma		Syn-orogenic plutons	"
			446 - 441 Ma	Stitching plutons	"
			? 434 - 423 Ma	(?) Extension related Silurian collapse plutons	"
			Early Silurian	Taconic "rebound unconformities" extend S into VA	Dorsch, 2001

above olistostromal deposits, against the Laurentian slope and shelf edges, creating a peripheral bulge and foreland basin sag as they advanced over the next ~2.5 m.y. The first allochthons to enter the newly created basins near the shelf edge formed the substrate for active deposition in a piggyback basin at ~460 Ma. These and other allochthons were later moved into and depositionally buried in the final foreland basin, developing the faux-statigraphy of the Dauphin Formation from ~459 to 455 Ma. Over the following ~5 m.y., the shelf edge orogeny continued to advance northwestward, providing a voluminous supply of flysch for burial of the Dauphin Formation allochthons by the Martinsburg Formation (*senso stricto*). The phase ended at ~450 Ma with deposition of the uppermost graptolite-bearing Martinsburg beds.

Phase II was the most dramatic of the Taconic events wherein the platform/ foreland system was severely folded and uplifted into colossal alpine scale nappes in a mere 7 m.y. By basal Silurian the alpine terrane was under erosional assault and shedding sediment to the Laurentian interior to form the substrate for the next orogeny. Subsequently, during mid-Paleozoic strike-slip deformation, the hinterland source areas were shifted laterally, possibly great distances to the south. Finally, the late Paleozoic Alleghanian orogeny again thrusted and folded the Taconic complex into its present geometry.

The sedimentary record interpreted above seems to require diachronous development of the several phases of the Taconic orogeny but a second data set from the former shelf edge tells a similar story. The Pequea "silver" mine at the Martic Front is a quartz/ galena vein deposit localized in the hinge zones of first generation folds that deform imbricate thrust sheets (Wise, 1970, 2006; and Wise and Ganis, in review JSG). Samples from the mine have yielded a monazite date of 450 +/- 4 Ma (2 σ count precision) and a H_2O/CO_2 fluid inclusion homogenization temperature of 215 to 265° C (Wise and others, 2007), suggesting a depth of ~10 km assuming typical thermal gradients. Meanwhile, 50 km to the NW across the foreland (in today's geometry but probably several hundred km in the Ordovician) the youngest graptolites are recorded in the Martinsburg basin. Thus, even though at the shelf edge Phase II alpine mountains were near maturity at ~450 Ma, Phase I was just ending in the distal foreland. These dates like all the others cited above carry significant error bars but their overall story seem reasonably robust: the Taconic orogeny in Pennsylvania consisted of two phases that swept across the orogen in about 20 m.y.

At first glance, the above interpretation of the Taconic story might seem a radical departure from the classic one of New England. Substitution of deep-water, synorogenic allochthons of the Dauphin Formation for the classic "Hamburg klippe" with all the implications of that term does represent a significant revision. However, the disparity diminishes if the imbricate thrust zone of the Martic shelf-edge is equated with the imbricate thrusts of the New England Taconics while the Dauphin Formation allochthons correspond to the allochthons of the Snake Hill Formation in the Hudson foreland (English and others, 2006). It should be noted that the concept of the "Hamburg klippe" by George Stose in 1946 was controversial from its inception and was frequently challenged (for example, Platt and others, 1972; Root and MacLachlan, 1978).

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Appendix

*1 Nyes Road Member, Dauphin Formation (Ganis and others, 2001).

*2 Shellsville Member, Dauphin Formation (Ganis and others, 2001).

*3 Manada Hill Member, Dauphin Formation (*ibid.*); mostly red or maroon shale and/or radiolarian-bearing chert; sometimes green, purple or tan; sometimes with minor traction generated carbonate beds (Ganis and others, 2001).

*4 Jonestown volcanic complex of amygdaloidal pillow basalts and diabase dikes; emplacement appears to have been in a Dauphin Formation olistostrome and adjacent turbidites (*ibid.*). Some Lower Ordovician carbonate olistoliths have metasomatically altered rims. See also Stose and Jonas (1927); Lash (1984).

*5 Annville Formation.

*6 Myerstown Formation, with minor (cm scale) meta-bentonite beds, is spatially associated with the Dauphin allochthons emplaced above. The probable equivalent in the Cumberland Valley sequence of the Great Valley west of the Susquehanna River is the "basal Martinsburg limestone" of Root (1977), Root and MacLachlan (1978), and Becher and Root (1981) where allochthons were emplaced above in the eastern part of the outcrop area; however, biostratigraphic correlation between the Myerstown and the "basal Martinsburg limestones" awaits confirmation. East of the Susquehanna River in the Great Valley, the unit below the allochthonous rock emplacements is structurally concealed but is presumed to be a transitional limestone equivalent to the "basal Martinsburg limestone".

*7 Jacksonburg Formation with several thick (m-scale) meta-bentonites. (Sherwood, 1964, describe three traceable beds). At a minimum, the lower half of the Myerstown Formation is older than any part of the Jacksonburg Formation (Ross and others, 1982).

*8 The Lower Ordovician Beekmantown Group and older Cambrian Units.

*9 "Hershey Formation", a limestone pebble conglomerate in a black shaly limestone matrix is sometimes separated as a distinct formation from the Myerstown Formation. We prefer to characterize the Hershey conglomerate strata, which has a spotty distribution and an inconsistent stratigraphic position, as a high-energy facies of the Myerstown Formation. Limestone clasts from the Hershey facies have yielded Beekmantown age conodonts (J. Repetski, personal communication, 2001).

*10 Jonas and Stose (1926) reported poorly preserved graptolites of Chazyan age (Middle Ordovician) from the Cocalico South. In 1930 Jonas and Stose mentioned the same graptolite discoveries from " Kissel Hill and near Cocalico Creek 1 mile east of Oregon" but, added clarification that cast doubt on the prior identification in 1926. In the 1930 reference they state, " Further study by Ulrich [Edward O. Ulrich, 1857–1944; paleontologist, United States Geological Survey 1897–1932] has thrown doubt on the earlier identification of these poorly preserved graptolites. . .". Stose and Jonas (1933) again mention, "a few graptolites of uncertain species were collected [in the Cocalico]". However, in 1946 (two years after E. O. Ulrich died) regarding the Cocalico, Stose stated, " A few graptolites collected from the shale were tentatively assigned by Ulrich to the Normanskill". Given the earlier cloud of uncertainty regarding the identity of these supposed graptolites, the reliability (and attribution) of this last age assignment seems suspect. The disposition of the collection is unknown. If graptolites of any kind (other than dendroids) were found, even if unidentifiable, the age could be assigned to Ordovician since younger rocks can be excluded for tectonic reasons.

*11 Shelly fauna in the upper Martinsburg Formation, within the Martinsburg/Dauphin segment, was described from various localites, noteably Swatara Gap in Lebanon County, Pennsylvania by Stose (1930).

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