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Taconic Orogeny in Pennsylvania: A ~15 –20 m.y. Apennine-style Ordovician event viewed from its Martic hinterland

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ABSTRACT

In Pennsylvania, the Taconic Orogeny lasted from ~461 to ~443 Ma as Cambro-Ordovician slope deposits were deformed into mountains edging the Laurentian craton at the same time that materials from an adjacent deep-water basin were being transported ~50 –70 km across a carbonate platform into foreland basins. This paper focuses on shelf-edge hinterland features, mostly the Martic Zone as a folded, stack of imbricate thrust sheets of slope materials that corresponds to Vermont's Taconic Mountains and Southern Quebec's zone of Taconic allochthons. Work of the last century is summarized, corrected, and combined with a new ~450 Ma radiometric date and fluid inclusion data from the Pequea Mine within the Martic Zone. These and abundant new graptolite and conodont dates in the foreland paint a revised Pennsylvania picture differing from the northern Taconic areas. Differences are: (1) transport of very large allochthonous masses of deep-water material, the Dauphin Formation, far across the carbonate platform, and (2) deformation migrating progressively across that platform during a ~15 –20 m.y. period, incorporating it and its foreland cover into alpine-scale, recumbent folds and thrusts. The scenario has many analogies to Italy's modern Apennine Mountains minus the Latian volcanics.

1. Introduction

1.1. Dating the Taconic Orogeny

Two recent papers ask, "How long does an orogeny last? "(Dewey, 2005) and, "How do orogenies end?" (Karabinos, 2001). Dewey provides one answer to the first question by documenting the Ordovician Grampian Orogeny of Scotland and Ireland as concentrated mostly into an 18 m.y. period while Karabinos documents a comparably short Ordovician Taconic Orogeny in New England and suggests its rather abrupt end was caused by a flip in the subduction zone. Excellent graptolite and conodont time slices of ~1 –2 m.y. in the Ordovician (Cooper, 1999) make these and other Taconic orogenies ideal candidates for exploration of such questions.

Even though the Taconic/Grampian Orogeny was relatively brief on a local scale, the orogeny as a whole was diachronous along the 2000 km Appalachian length, potentially lasting ~70 m.y. (Table 1). Earliest events in the chain may have been arc collisions in Late Cambrian (~500 Ma) to Early Ordovician (~470 Ma) with the most intense activity in late-Middle to Late Ordovician time (~465 to ~445 Ma). The Silurian unconformity at ~443 Ma marked the end of intense activity although lesser disturbances continued for another ~10 –15 m.y. (Table 1). Differences in timing and tectonic style along strike of the orogen probably reflect some combinations of: a collision of outboard terranes with an irregular edge of the Laurentian craton (Rankin, 1976; Thomas, 1977, 2005; Ratcliffe, 2006; Zagorevski et al., 2007), offshore collisions of lesser arcs plus their mainland collisions (Karabinos et al., 1998; van Staal et al., 2004; Hibbard et al., 2007), flipping of subduction zones (Karabinos et al., 1998; Karabinos, 2001), and possible changes in directions of plate convergence.

The present paper examines these issues along a cross -section of the Pennsylvania Piedmont just east of the Susquehanna River to show that the local Taconic orogeny covered a span of ~15 –20 m.y., similar to orogens described by Dewey and by Karabinos (above). These events, centering on the period of most intense tectonism within the more general Taconic time window (Table 1), have a tectonic style different from most other Taconic relics, in being more Apennine than alpine.

2. Regional setting

2.1. The Martic Zone, Martic Line, and Martic Thrust

The focus of this paper is the Martic *Zone*, a feature that takes its name from exposures in Martic Township near Marticville and

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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, et al., 2004
		470–? Ma		Start of strike-slip duplexing	
			455–? Ma	Final phase collision of Victoria arc with Laurentia	
Quebec and eastern Canada	470 Ma			W-directed imbrication of eastern allochthons	Sasseville et al., 2006
		450 Ma		NW-directed re-imbrication of the thrust sheets	
			Early Silurian	Taconic basins of foreland shift NE into E Canada foreland	Ettensohn and Brett, 2002
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 et al., 2002
		452 Ma		Youngest flysch in Taconic belt	Bradley, 1989
Pennsylvania	461–458 Ma			First local basins (Myerstown) in carbonate platform	Ganis et al., 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 Sil. Unconformity	
		450 ± 4 Ma		Pequea Mine: Martic front post-thrusting and folding	Wise and Ganis, this paper
Central Appalachians	488–476 Ma			Arc stage plutons	Sinha, 2004
		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

Martic Forge, about 15 km south of Lancaster (Fig. 1). The zone started along the early Paleozoic shelf edge, a location separating mostly deep-water sedimentary deposits, now schists of the Octoraro Seaway on the south or southeast, from Cambro-Ordovician slope and platform carbonates of the Lancaster–York Platform on the north or northwest (Fig. 1). Subsequently, the Taconic Orogeny piled a series of imbricate thrust sheets of slope materials against and across this shelf edge and then folded and metamorphosed them into the structural complex now known as the Martic *Zone*.

In contrast to the Martic *Zone*, the Martic *Line* of Knopf and Jonas (1929), Stose and Jonas (1939) and of Cloos and Hietanen (1941) is a distinct mappable line drawn just south of the southernmost carbonate exposures of slope deposits on the edge of the Lancaster–York Platform (Fig. 1). In effect, the line is the boundary between the inner and outer Piedmont in this area. The nature of this line has been long debated but is now generally regarded as only more fault contact, the Martic *Thrust*, within an imbricate stack of Taconic thrusts that constitute the Martic *Zone*.

2.2. The Pequea Mine

A key element within the Martic Zone is the long-abandoned Pequea (pronounced "Peck-way") "Silver" Mine that once produced highly argentiferous galena from quartz veins localized along Taconic hinge zones in folded thrust sheets (Fig. 2). The mine was first worked by pre-Colonial natives and later by several centuries of European settlers. It had its greatest activity as a lead source near the time of the Civil War.

The mine lies along Silver Mine Run, a tributary of Pequea Creek, about 15 km S of Lancaster and about 2.5 km NNW of the town of Marticville. The site is an ideal field trip stop, part of a township park with surface workings open to the public. It includes a marked geologic walking trail following the mostly exposed, thrust-repeated or doubled ore zone through two anticlines and an intervening syncline. A simplified for-the-public, geologic guide describes the trail as well as the underground workings and their history (Wise, 2006).

2.3. Regional overview

Readers unfamiliar with local geography, formations, and tectonic history of this area are likely to be overwhelmed by the complexity of Fig. 1 and details of its discussion. The following outline is a distillation of Wise (1970); Rodgers (1970, 1971), Drake et al. (1989); Hatcher et al. (1989a,b, 2007b); Faill (1997a,b, 1998), Ganis et al. (2001), Ganis (2005), Hibbard et al. (2007), Thomas (2005), and Ganis and Wise (2008), all of whom include voluminous supporting bibliographies.

The supercontinent of Rodinia was rifted along its entire length from ~620 to 550 Ma, leaving the Laurentian craton with a ragged, transform-stepped edge. Offshore, a line of microcontinents isolated the Octoraro Seaway, part of the future Westminster Terrane, from the main Iapetian Ocean. As mantle beneath the margin of the Laurentian craton continued to cool and subside, the Lancaster–York carbonate platform developed across its subsiding edge (Fig. 1). The Eocambrian Chickies Quartzite was the initial deposit across the b.y.-old Grenville basement, followed by Lower to Middle Cambrian Antietam Schist and carbonates of the Vintage Dolomite, Kinzers Formation, and Ledger Dolomite (Fig. 2). As the platform edge continued to sink, a widespread slope deposit spread northward and up-stratigraphy to grade into and progressively overlie all the above formations. This deposit, the Conestoga Formation, is a series of euxinic, argillaceous, and quartz arenitic carbonate beds interlayered with carbonaceous phyllites and local olistostromes derived from the shelf edge (Rodgers, 1968; Meisler and Becher, 1971; Gohn, 1976; Rankin et al., 1989). Farther inland, multi-kilometer thicknesses of carbonates were deposited as the Late Cambrian to Middle Ordovician Lebanon Valley sequence (Fig. 1) of Elbrook, Conococheague, and Beekmantown groups (Rankin et al., 1989; Drake et al., 1989).

At ~461 Ma, the appearance of local transitional basins probably reflects initial thrusting along the shelf edge that coincided with emplacement onto the platform of deep-water allochthons from the Octoraro Seaway. Associated with this initial deformation, a peripheral bulge uplifted and subjected several upper Beekmantown units to erosion, producing an unconformity in which

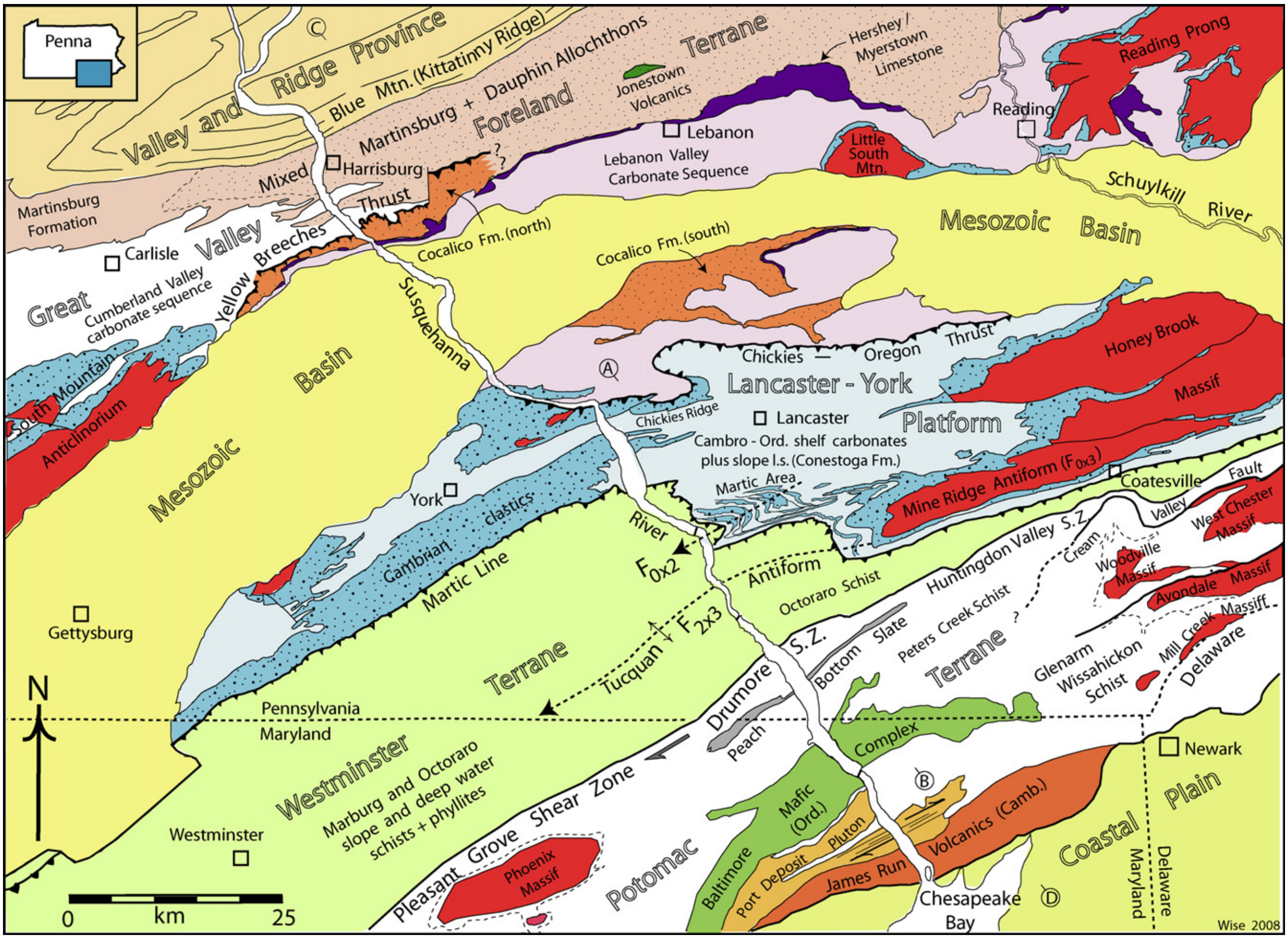

Fig. 1. Lithotectonic map of the Susquehanna Piedmont. Cross section A–B is Fig. 3 and C–D is Fig. 6.

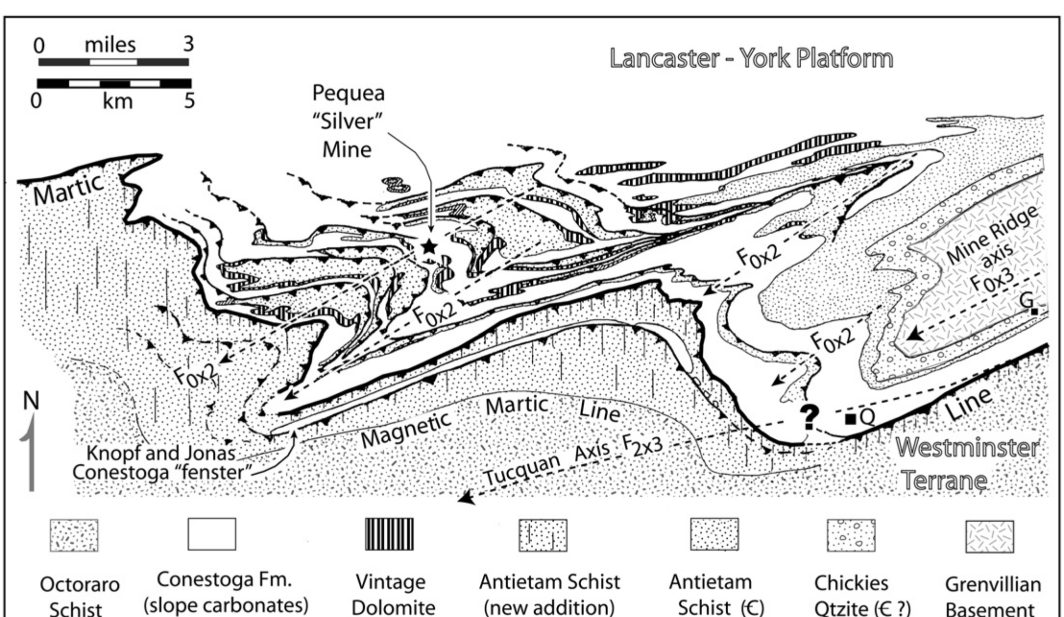

Fig. 2. Two generations of folding superimposed on imbricate thrust sheets along the Martic Zone. Contacts are from Cloos and Hietanen (1941) with thrust and fold markers after Wise (1970). Fold terminology has been updated from but retains the style of Freedman et al. (1964). An alternate style of terminology is included in the text. Q , Quarryville ; G , Greentree.

some beds of the overlying Myerstown-Hershey Formation include dated conglomerate clasts derived from the eroded units. These local basin deposits were followed by final emplacement into the evolving foreland basin of several large and complex allocthons of deep-water materials, the Dauphin Formation. Finally, the late Ordovician Martinsburg flysch or its southern cousin, the Cocalico Formation (Fig. 1) covered the allochthons and continued to fill the foreland basin until ~450 Ma, as indicated by graptolite dates.

The same ~450 Ma date from a Pequea Mine monazite indicates that most Taconic imbrication, folding, cleavage, and metamorphism had been completed along the Martic Zone at the same time that the last of the Martinsburg foreland flysch was being deposited as dated by graptolites. During the following ~7 m.y., deformation advanced across the platform to engulf those distal carbonates, allochthons, and foreland flysch into alpine-scale recumbent folds and thrusts of the Lebanon Valley nappes. By ~443 Ma, distal ends of these nappes had been eroded and were beginning to receive unconformable cover by Silurian molasse.

Later Paleozoic deformation camouflaged much of this Taconic mountain system. In mid-Paleozoic, major strike-slip faulting along the Pleasant Grove –Drumore –Huntingdon Valley shear zone (Fig. 1) replaced farther offshore parts of the Taconic hinterland with the Potomac Terrane, a multiply deformed mixture of rifted microcontinent basement slices, mélanges, mafics, ultramafics, and more silicic volcanic and plutionic complexes (Fig. 1). Later, the Alleghenian Orogeny detached basement slabs of the entire Piedmont, carrying them along with their passengers of early and middle Paleozoic structures and lithologies some 100 –200 (+) km onto the Laurentian craton. Folding and thrusting of these slabs and their cover produced all present basement exposures north of the Drumore shear zone, including the Mine Ridge fold and its associated Tucquan ("Tuck-wahn") Antiform (Figs. 1, 2). Many of these Alleghenian thrusts reactivated and further complicated the Taconic Lebanon Valley nappes while others such as the Chickies-Oregon and Yellow Breeches thrusts (Fig. 1) telescoped elements of the Taconian nappe system.

3. Local geology: errors and all

Recognition of the Martic Zone's structure in relation to the overall Taconic Orogeny evolved slowly over the last century and not always unidirectionally. Widespread quadrangle-scale mapping, including structure and stratigraphy, was done in the early 20th century by the likes of George Stose, Anna Jonas (later Stose), and Elenora Bliss Knopf (Stose, 1930; Stose and Jonas, 1927, 1933; Jonas and Stose, 1926, 1930; Knopf and Jonas, 1929).

The 1930s and 1940s saw great debates of whether the Martic Line was a thrust (Knopf and Jonas, 1929; Stose, 1930; Mackin, 1935) or an unconformity (Miller, 1935) with additional mapping and fabric analyses by Cloos and Hietanen (1941). In the foreland, Stose (1946) proposed the Hamburg klippe and compared it to the Taconic klippen of Vermont, an issue that was hotly debated into the 1980s (summary and comments by Ganis et al., 2001).

The 1950s saw discovery and mapping of regional nappes in the Great Valley foreland (Fig. 1) by the Pennsylvania Geological Survey (Gray et al., 1958; Gray, 1959; MacLachlan, 1967; Root and MacLachlan, 1978; summary by Gray and Root, 1999). "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." (Gray, 1959).

The 1960s and 1970s saw: definition of multiple folding across the lower Susquehanna region (Freedman et al., 1964), recognition of platform shelf and slope facies (summarized by Rodgers, 1970, 1971), beginnings of a stratigraphic understanding of the Wissahickon and related schists (Higgins, 1972), and extension of multiple fold interpretations eastward into the Martic and Mine Ridge areas (Wise, 1970).

Subsequently, a host of workers have studied many facets of the region including: an Iaptian transform fault in relation to distinctive curvature of the Pennsylvania Salient (Rankin, 1976; Thomas, 1977; Wise, 2004), recognition of the Pleasant Grove –Drumore –Huntingdon Valley Shear Zone and the nature of the Potomac Terrane (Gates, 1991; Valentino, 1994; Valentino et al., 1994), complex metamorphic relationships (Bukeavich et al., 2006), and new radiometric dating especially in Potomac Terrane areas to the east (Bosbyshell, 1999; Pyle et al., 2006.) Faill's monumental summary (1997a,b, 1998) of this massive literature stands as *the* benchmark of regional knowledge and thinking as of the end of the 20th century. Recently, a new cycle of geologic quadrangle mapping by the Pennsylvania Geological Survey (Blackmer, 2004b) and new regional syntheses and maps (Hibbard et al., 2006; Hatcher et al., 2007b) have begun to further clarify many of these problems.

3.1. Mapped contacts and thrust faults, real and otherwise

Superb mapping of the Martic Zone by Cloos and Hietanen (1941), authenticated almost to the last detail in 1960s thesis mapping by Franklin and Marshall College students, shows an upward sequence of Antietam Schist to Vintage Dolomite to Conestoga Formation, repeated at least six times from east to west along the plunging northern edge of the zone (Fig. 2). This repetition and geometry can only be that of subsequently folded imbricate thrust sheets with axes plunging WSW into and beneath the Westminster Terrane (Figs. 1, 2).

The first thrust sheet below or north of the Martic Line is a folded, 25-km long band of Antietam Schist (Fig. 2). At its eastern end, the schist has a cover of only Conestoga Formation but beyond a tight fold near its western end, a thin band of Vintage Dolomite separates Antietam from Conestoga. This separation persists through all the remaining thrust sheets that lie to the north (i.e., stratigraphically deeper), including the one that hosts the Pequea Mine. A Conestoga sub-crop map (Wise, 1970) shows all the units underlying the Conestoga appearing in stratigraphic succession, younging northward as ~E–W bands extending from the city of York (Fig. 1) to Mine Ridge, evidence that the edge of the Lancaster–York platform trended E–W as it gradually sank and slope deposits of the onlapping Conestoga Formation merged progressively northward into platform carbonates.

All the early Martic workers used the presence of a band of Conestoga carbonates above a schist to identify that schist as "Antietam." Without that carbonate band, the schist became "Wissahickon" or in present terminology, "Octoraro" or "Marburg" (Lyttle and Epstein, 1987; Blackmer, 2004a). However, near the Martic Line, lithologies of the Antietam and "Wissahickon" schists are so similar that Cloos and Hietanen (1941) were unable to separate them. Accordingly, they left a blank spot at the eastern end of the uppermost Antietam sheet where it intersects the Martic Line, a rare but heroic act of honest field mapping indicated by the question mark on Fig. 2. Previously Knopf and Jonas (1929) interpreted a line of valleys (Fig. 2), 1–2 km south of the Martic Line as fensters of Conestoga Fm. exposed by erosion through their proposed "Martic thrust." Using more recent regional views, the passing southward of calcareous Conestoga slope facies into more argillaceous basin facies would support the Knopf and Jonas (1929) name for these schistose carbonates but not necessarily their geometrically strange erosional "fenster" interpretation (Fig. 2). Had Cloos and Hietanen chosen to include these poorly exposed valleys of calcareous schist as Conestoga Formation, their Martic Line probably would have been drawn one thrust sheet farther south.

Thus, the infamous "Martic Thrust" is probably just another thrust contact within a much larger imbricate pile. Cloos and

Hietanen (1941) were quite correct in their inability to distinguish between the two schists; they are essentially the same unit. The question marked contact (Fig. 2) is probably only a minor ramp, formed as one slice of Antietam Schist climbed over the posterior of the next slice to the north.

On a larger scale, the real Martic contact may be nowhere near either of these thrusts. Regional aeromagnetic maps (Bromery et al., 1959) show a distinct break in pattern from "bland" on the north to "curly maple" on the south, about 2 –4 km south of the traditional Martic Line (Fig. 2). Between these two lines there are probably several additional thrust sheets, as yet unidentified without the intervening Conestoga Fm. This boundary, the Magnetic Martic Line (Wise and Kauffman, 1960; Wise, 1970), probably marks the true south contact of the Martic Zone as a whole, bounding mostly imbricated slope deposits on the edge of the Lancaster–York Platform on the north from mostly deep-water Octoraro or Marburg schists of the Westminster Terrane on the south.

3.2. Fold relationships

Folding across the hinterland involved two major superposed phases, each with locally, strongly developed s-surfaces (Fig. 3 after Freedman et al., 1964). In the Westminster Terrane, those authors failed to identify a separate set of locally folded millimeter to centimeter scale quartz bands associated with prograde metamorphism. In retrospect, these initial structures, now identified as S_1, require the main schistosity to be termed S_2 with all other numbers upgraded appropriately, a change that has been made throughout this paper.

These fold descriptions require a dual terminology that must include both the phase of folding and the s-surface that is folded. On all the figures, the *style* of terminology retains that of the original authors. For example $F_{2\times3}$ (read: F 2 by 3) indicates a fold of second cleavage or schistosity (S_2) by a third set of folds (F_3) or deformation (D_3). For those who are more comfortable with an alternate system, a second terminology style is included in parentheses ($F_3(S_2)$).

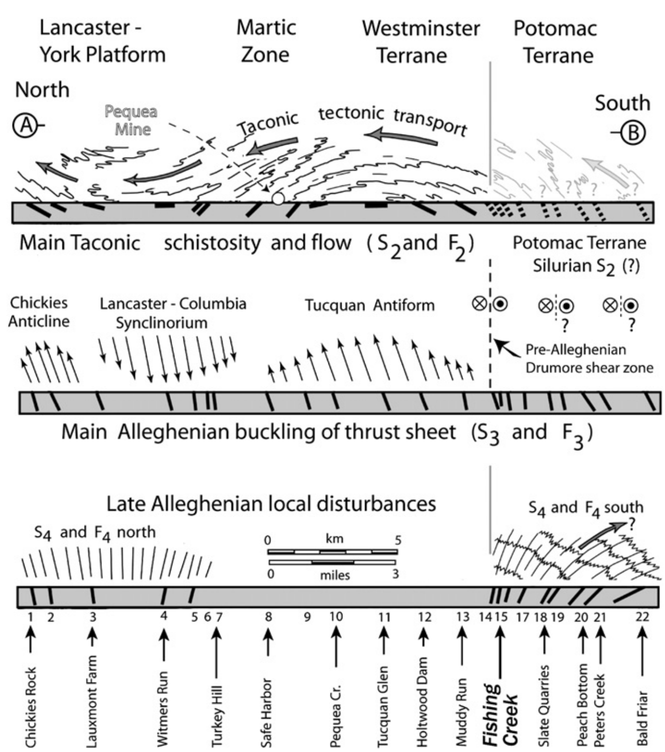

Fig. 3. Multiple fold patterns of the hinterland along line A–B of Fig. 1. Dips of three sets of superposed foliations from 22 fabric stations (Freedman et al., 1964) are plotted separately. This figure, largely after their plot, includes updated fold numbers as well as probable separation of the S_2 pattern by strike-slip displacements of the Potomac Terrane along Fishing Creek as discussed in the text.

The superposed fold patterns along the Susquehanna River cross-section (Freedman et al., 1964) extend eastward along the Martic Zone to Mine Ridge (Fig. 2, upgraded from Wise, 1970). In the Martic Zone of the Susquehanna cross-section, S_2 schistosity dips smoothly north as axial surfaces of $F_{0\times2}$ ($F_2(S_0)$) folds that broadly deform the imbricate thrust sheets. Regionally, these folds and s-surfaces seem to be part of a single system of N60E -trending $F_{0\times2}$ ($F_2(S_0)$) fold axes and cleavages and a pervasive regional set of N30W tectonic transport lineations (Fig. 4). The pattern shows that the Westminster Terrane and Martic Zone are roots of a regionally pervasive Taconic N30W transport system that extended at least 70 km from the hinterland across strike through the Lebanon Valley nappes.

Like the modern Apennines, the Taconic Orogeny in this area involved very little thrusting of basement sheets. Some broad Taconic folding of basement does occur where axial traces of $F_{0\times2}$ ($F_2(S_0)$) folds on the plunging nose of Mine Ridge (Fig. 2) pass through broad warps of the basement contact with overlying Chickies Formation. At Greentree, "G" on Fig. 2, a small quarry exposes beautifully flow-folded Chickies Quartzite near the basement contact. As shown by S_2 planes wrapping around garnet porphyroblasts, Taconic metamorphism reached garnet-grade conditions in the thrust sheets immediately overlying the west-plunging basement nose (Fig. 5d). However, near the Pequea Mine, ∼10 km to the west along plunge and ∼1–2 km higher in the imbricate stratigraphy, conditions reached only biotite grade.

3.3. Error (!)

In hindsight a significant error is embedded in the 1964 s-surface interpretations of Freedman et al. (1964). Their plot of S_2 (Fig. 3) correctly shows S_2 dip passing smoothly and continuously across the Drumore Shear Zone at Fishing Creek. Subsequently this location has been identified as the boundary between the profoundly different Potomac and Westminster Terranes (Gates, 1991; Valentino et al., 1994; Faill, 1997a, 1998). Rechecking the Freedman et al. stereo plots shows that even though S_2 *dips* remain constant across the contact, their *strikes* change from N60–70E on the north to N30–40E on the south. This impediment to interpretations of large displacement across the Drumore Zone is no longer valid. The displaced true outboard roots of the Pennsylvania Taconic Mountains probably lie somewhere in Virginia or the Carolinas, unrecognized or buried beneath the coastal plain.

3.4. "Curious" cleavage geometry

Alleghenian folding (F_3) of the Mine Ridge anticline created some seemingly strange but very instructive cleavage geometry in Taconic F_2 folds and transport directions. The $F_{0\times3}$ ($F_3(S_0)$) basement antiform of Mine Ridge has an obvious continuation in the Westminster Terrane as the $F_{2\times3}$ ($F_3(S_2)$) or Tucquan antiform (Fig. 1). However, in detail the Tucquan axial trace curves into the south flank of Mine Ridge instead of passing, as might be expected, directly into its plunging nose (Fig. 2). This geometry is possible only if S_0 and S_2 were non-parallel, allowing their respective fold crests to occur at different locations. Taconic thrusting and loading tilted the shelf edge to the south to create a strongly south-dipping imbricate pile (Fig. 5b). Within that pile, nearly recumbent S_2 cleavage and related axial surfaces of F_2 folds deformed the thrust sheets as they cut down-section at angles of ∼20 –30 ° within the overall northward flow and transport geometry (Fig. 5c,d).

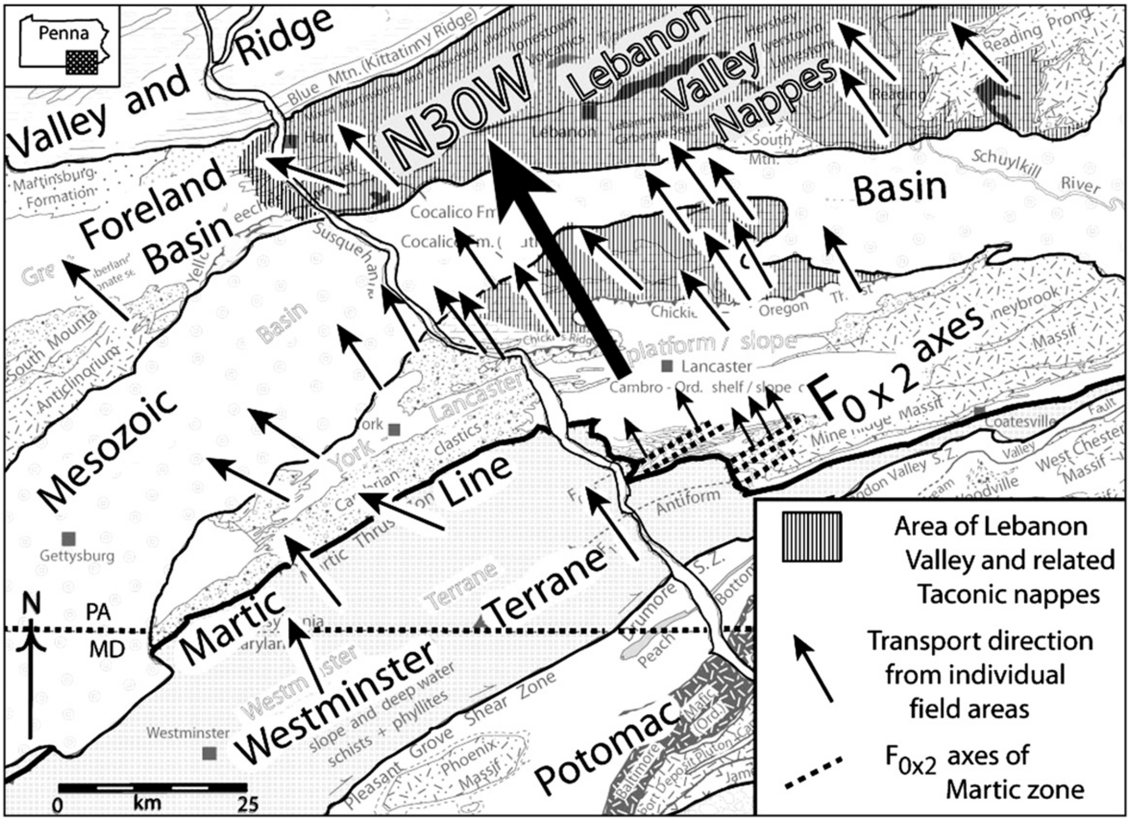

Fig. 4. Comparison of Martic Zone $F_{0\times2}$ folds (S_0 bedding folded along second generation axes) with average regional tectonic transport system trending at N30W. Patterned overprint indicates areas of Lebanon Valley nappe development. Each black arrow represents a transport direction derived from an equal area plot of an individual field area as summarized by Wise and Werner (2004).

Alleghenian deformation on the north flank of the Tucquaqn Antiform (Fig. 6) further rotated those Taconic, near-recumbent F_2 and S_2 structures (Fig. 5d) past recumbency into moderate north dips. The photo from the Pequea Mine area (Fig. 7) shows an example where cleavage in plate-like carbonate clasts of an olistostrome in the Conestoga Formation is nearly perpendicular to bedding. (Visitors to this outcrop continue to debate mechanisms whereby originally slab-like carbonate clasts could have been rotated to this cleavage position without disrupting the delicate adjacent bedding or leaving evidence of major pressure solution. Commonly invoked

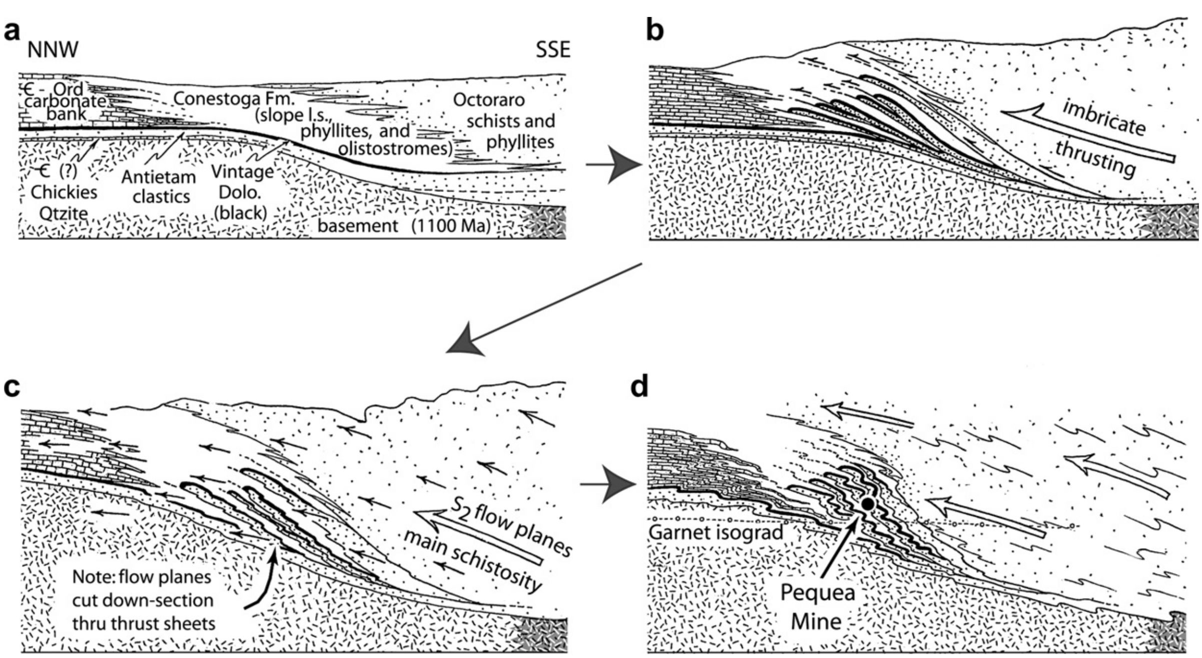

Fig. 5. Schematic diagrams illustrating Taconic evolution of the Martic Zone. Note the s-surfaces and flow structures cut *down-section* to the N through south-tilted thrust sheets as discussed in the text.

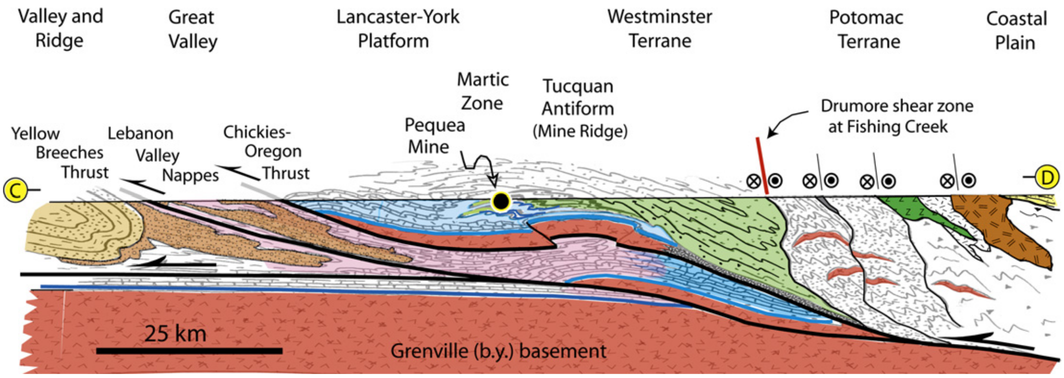

Fig. 6. Schematic post-Alleghenian cross section of the Susquehanna Piedmont. This section along line C–D has the same color scheme as Fig. 1. It shows massive transport to the N of giant sheets of the upper few kilometers of basement that carried on their surface Taconic-modified covering platform and slope deposits as well as the accreted Potomac Terrane.

mechanisms involve book-shelf rotation and differential slip between plate-like clasts as well as minor pressure solution.) Whatever the mechanism, this geometry in an isolated outcrop would be interpreted ordinarily as south-verging structures in right-side-up beds located near a fold hinge (cleavage is ~90° to bedding). Indeed, these were and still are right-side-up, south-dipping beds within the Taconic imbricate thrust sheets but they and their formerly near-recumbent cleavage (Fig. 5d) have been tilted an additional 20–30° to the north on the north flank of the Alleghenian Tucquan antiform (Fig. 6).

4. Post-Taconic features

A variety of structures overprint the Taconic fabric. In the mid-Paleozoic, pervasive right-lateral shearing affected much of the Appalachian hinterland in general (Hatcher, 2002, 2007b), locally substituting the Potomac Terrane (Fig. 1) for part of the Taconic hinterland (Gates, 1991; Valentino, 1994, 1999). Associated strike-slip strain patterns persist on a much smaller scale through the Westminster Terrane and southern parts of the Lancaster–York Platform (MacLachlan, 1990).

Beneath the Great Valley (Fig. 1), Grenvillian basement is at depths of 10–12 km (Faill, 1997) and probably continues its slope southeastward beneath much of the Piedmont. Thus, the appearance of basement at the present surface in the Reading Prong and the Honey Brook / Mine Ridge massifs requires regional Alleghenian detachment with massive transport and overthrusting of a huge slab(s) of the upper basement along with their cover of folded Taconic thrusts, platform, slope deposits, and accreted Potomac Terrane (Fig. 6). Total transport of this and related basement sheets must be 100–200 km or more (Faill, 1998). It is unlikely that any presently exposed Paleozoic rocks of the Pennsylvania Piedmont are even slightly autochthonous. In reality, the deeper basement surface in Fig. 6 is probably broken and has many deflected thrusts much like those described for the Virginia to Georgia foreland by Hatcher et al. (2007a).

The Mine Ridge basement (Figs. 1, 2) has a distinctive fold geometry definable by Alleghenian deformation of its S_2 surfaces. Folded imbricate sheets on its plunging nose have well defined $F_{0\times2}$ ($F_2(S_0)$) axes (Fig. 2) with axial planes and S_2 cleavages dipping consistently ~20–40° N, i.e., there has been *little or no* post-S_2 differential rotation or folding on the plunging nose of this F_3 basement anticline. However, the same S_2 surfaces are *sharply* folded over the south side of the same fold at the level of the basement contact but only mildly rotated over its north edge (data and contoured dips shown in Wise, 1970). Thus, Mine Ridge is a somewhat asymmetric Alleghenian-age box or buckle fold of a basement slab that was embedded above and below within a weak matrix of carbonates and schists (Fig. 6). Continuing bedding-parallel compression probably created the present fold geometry. Attempts to draw cross-sections of this fold with its ~ 10-km wide, flat top seem most realistic when using slab thicknesses of ~3–4 km. The fold's character, location, and trend may reflect its location along the ancient basement edge of the platform with much greater rotation of its south limb.

Eastward and northward, the Mine Ridge basement slab(s) probably widens and/or splays into other Alleghenian basement thrust sheets to form the Honey Brook Massif and the Reading Prong Province of New England (Fig. 1). The slab(s) probably ends westward within the Lancaster seismic zone (Wise and Faill, 2002), the most active seismic area in Pennsylvania. This < 5-km deep, diffuse seismic zone extends from the Martic area through Lancaster to the vicinity of Reading (Fig. 1) and trends obliquely across all other recognized shallow structures that seem capable of seismic localization. The zone is interpreted as the result of modern regional N70E–S70W compression acting on the western edge of a strong slab embedded in weaker rocks, thus localizing strain and producing the seismic pattern. In this interpretation, Little South Mountain (Fig. 1) is an isolated, exposed corner fragment of that slab.

Fig. 7. Olistostrome of platform carbonate clasts embedded in slope deposits of the Conestoga Fm. Location is along a road 200 m east of the Pequea Mine. The curious cleavage relationships were caused by Alleghenian rotation past recumbency as discussed in the text. Some contacts have been outlined in white to enhance visibility.

5. Pequea Mine geologic relationships

The Pequea Mine mineralization consists of a series of quartz veins containing pockets of highly argentiferous galena (Smith, 1977). The ore was localized in fold crests in two thrust-repeated contacts of the Vintage Dolomite just below a basal phyllite of the Conestoga Formation (Fig. 8). Brittle failure of the dolomite during deformation provided permeability and porosity for quartz mineralization while the overlying ductile phyllite localized fluid flow along F_2 flow-hinge permeability traps. Mine workings (Fig. 8) followed these hinge zones down-plunge. The same post-fold mineralization relationships occur ~2 km to the east in a roadcut of Route 324, 100m north of its bridge over Pequea Creek. There, a perfectly planar, unfolded, 20 cm, galena-bearing quartz vein cuts the entire crest of a broad, ~5 m amplitude fold of Vintage Dolomite.

The mine geometry requires the ore to be younger than the imbricate thrusting of the Martic Zone and most, if not all, of the local Taconic folding. As long as there were no younger dates or structures to cap its age, the Pequea mineralization and folding could have been as young as Alleghenian, a potential 200 m.y. time window. Michael Jercinovic and Michael Williams closed this window (Fig. 9) using the UMass Ultrachron to date a monazite crystal. This 1 mm crystal (Fig. 9) grew on the face of a galena specimen collected by Robert Smith as part of a broader study of the mine area (Smith, 1977). It yielded a well-defined Th-U-total Pb peak at 450 Ma $\pm$ 4 (2 sigma count precision) with no sign of overprinting.

Charles Onasch of Bowling Green University analyzed fluid inclusions from a galena-bearing Pequea quartz vein also collected by Robert Smith. The results (Fig. 10) show two distinct populations. A primary set of relatively equi-dimensional inclusions localized along crystal growth zones yields homogenization temperatures of 215 –265 C° with zero salinity. A second set of more irregular inclusions along fracture planes yields homogenization temperatures of 170–200 C° with 10 –15 wt % NaCl. Thermal gradients in such tectonic environments are uncertain but typical thermal gradients of 20° /km would yield depths of 10 –12 km and 7–9 km respectively. The secondary inclusions may well relate to S_3 Alleghenian overprinting.

In summary, Pequea Mine data place a time limit on imbricate thrusting, S_1 and S_2 schistosities, peak metamorphism, and their associated F_1 and F_2 fold systems as late Ordovician. By ~450 Ma, the Martic Zone had developed into a complex, thick, orogenic wedge as part of the evolving Taconic hinterland.

6. The Taconic Foreland Basin

Until recently the general absence of reliable dates in what are now the Dauphin and Martinsburg Formations (Fig. 1) has precluded understanding of details of the internal structure and stratigraphy of the foreland (Faill, 1997b). Reworking of old and new graptolite sites (Ganis et al., 2001) and conodont sites (Repetski et al., 1984a,b, 2001) has provided a new temporal framework of about 50 well-dated points in the foreland basin. Correlated with radiometric determinations worldwide, these fossil sites have typical precisions of 1–2 m.y. (Ross et al., 1982; Cooper, 1999). Using those dated locations, Ganis et al. (2001), Ganis (2004, 2005), and Ganis and Wise (2008) synthesized a new picture of the evolution of the Pennsylvania Taconic foreland, a summary of which is shown on Fig. 11.

6.1. Basin history

The Taconic Orogeny began diachronously along the Appalachians (Table 1 and Hatcher et al., 1989a; Faill, 1997b; van Staal et al., 2004; Hibbard et al., 2007). For the Pennsylvania region, the best starting date for the orogeny is birth of local foreland basins on top of the Cambro-Ordovician carbonate platform (Ganis and Wise, 2008). These basins probably reflect Martic thrusting beginning to load the cratonic edge and initiate a migrating bulge and foreland basin in the style described by Bradley (1989).

These stresses developed local basins in the broad Beekmantown carbonate platform where collection began of such lithologies as the metallurgical grade, high calcium limestones of the Annville Fm., the argillaceous and carbonate mix for cement rock in the

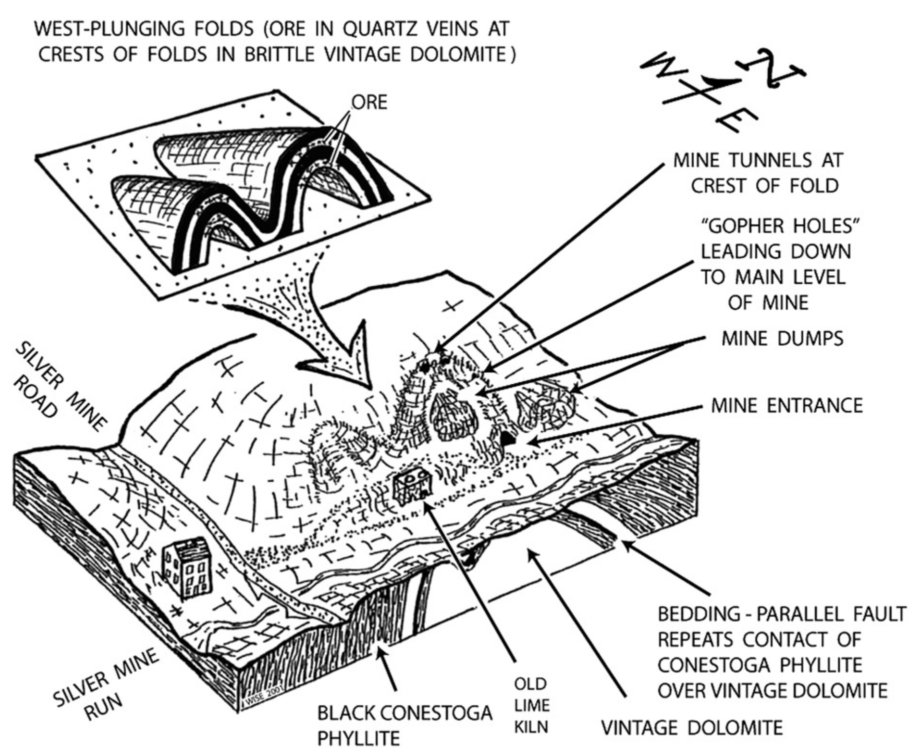

Fig. 8. Block diagram of structures at the Pequea "Silver" Mine. The mine surface workings (only) are easily accessible as part of a township park. Underground workings followed the fold axes down-plunge. Timing relationships are discussed in the text with many more details in a trail guide by Wise (2006).

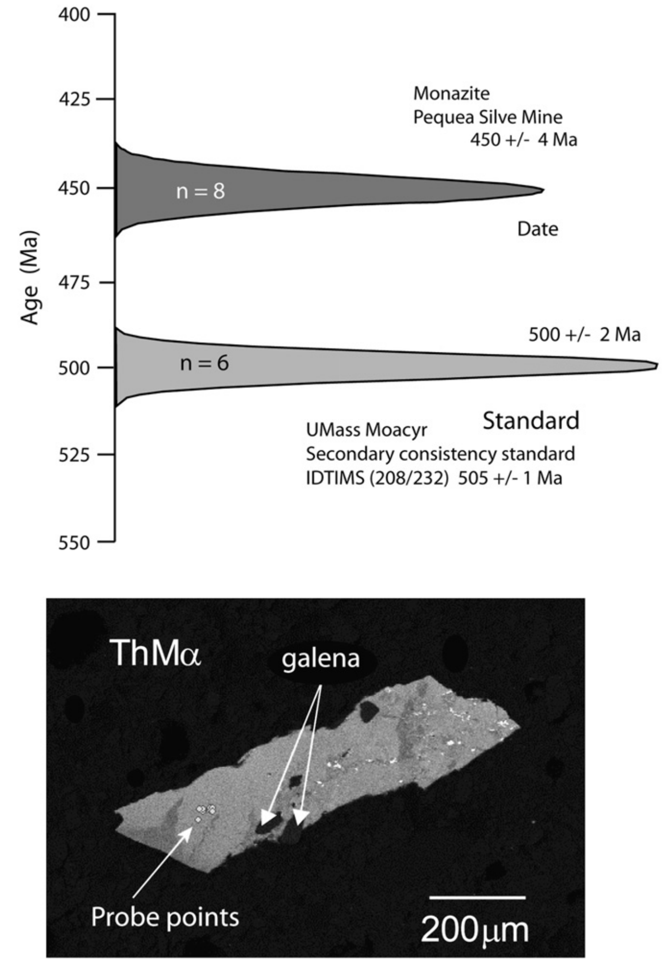

Fig. 9. Th-U-total Pb age data for a Pequea Mine monazite crystal compared to a standard. The crystal supplied by Robert Smith was dated by M. Jercinovic and M. Williams using the UMass Ultrachron (Wise et al., 2007).

Myerstown Fm., local carbonate conglomerates, and some ash beds increasing upward in number and thickness (MacLachlan, 1967; Ganis, 2005). In the region of the future Lebanon Valley nappes (Figs. 1, 3), fossils date this at ~461 Ma (Fig. 11). In eastern-most Pennsylvania, ~100 km along strike, this event started with deposition of the Jacksonburg "cement rock" about one graptolite zone later (~1 m.y.), suggesting the focus of foreland basin activity was initiated in or near the Dauphin region and expanded eastward along strike with time.

A broader style of foreland basins began when the first of two major allochthons of the Dauphin Fm. was finally emplaced across truncated edges of foreland carbonates. The first allochthon includes ~462 –463 Ma deep-water red cherts and red shales. These have ~459 –460 m.y. graptolite-bearing, turbidite covers, presumably deposited during transit through a piggy-back basin before final emplacement at ~458 Ma. A second, even more complex Dauphin allochthon includes lesser allochthons of fossil-bearing, Late Cambrian (~467 Ma) to early Middle Ordovician sandstones, siltstones, black shales, ribbon limestones, and hemipelagites. Other internal allochthons include the ~462 Ma (?) Jonestown volcanics (Fig. 1) whose matrix records intrusion and local baking of rare olistostrome blocks of fossiliferous, Early Ordovician limestones (Lash, 1984). All these lesser, internal allochthons are embedded as olistoliths in the second Dauphin allochthon, the matrix of which is consistently dated over a wide area by graptolites at ~462 –463 Ma. *Final* emplacement of this second allochthon is dated by graptolites in its immediately overlying autochthanous cover of true Martinsburg flysch that has only minor allochthonous debris in its lower beds. This Martinsburg deposition started at ~455 Ma and continued until ~450 Ma. During the following ~7 m.y. the entire pile, carbonates, allochthons, and flysch alike, was deformed into the Lebanaon Valley nappes. Distal parts of these eroded nappes were covered unconformably by Silurian clastics at ~443 Ma.

6.2. *The Hamburg (non)-Klippe*

Stose (1946) proposed the name Hamburg "klippe" for the allochthonous sheets described above, including the Cocalico south (Fig. 1). Even though these rocks have moved at least 70 km, the term "klippe" is misleading. That term has seen widespread use in older literature of the area as summarized by Lash and Drake (1984), Faill (1997a,b), Ganis et al. (2001), and Ganis (2004). Traditionally, a klippe is a remnant of a formerly more extensive thrust sheet that has been isolated from its source by later erosion. Chief Mountain and the Taconic klippen of New England are examples. Unlike these, the Dauphin Formation represents early allochthons that are part of the overall stratigraphy, emplaced into and deformed along with the foreland basin (Ganis and Wise, 2008). The current outcrops relate more to position within the internal stratigraphy of the nappes (Fig. 11) than to any later erosional isolation of thrust sheets. Their tectonic setting is remarkably similar to the "argille scagliosa" allochthons of the Apennine Mountains (Pini, 1999), rocks for which the term "klippe" is rarely used. Accordingly, we believe the term Hamburg "klippe" should be replaced with terms like Hamburg complex, Dauphin Formation, or Dauphin allochthons.

7. Discussion

7.1. *Contrasts along strike*

This Pennsylvania Tectonic story differs more in degree than in kind from that of New England and Southern Quebec (Hatcher et al., 1989b; Drake et al., 1989; Hibbard et al., 2006, 2007). All started with an irregular eastern margin of the Laurentian craton produced by the Neoproterozoic rifting of Rodinia. This margin cooled and slowly sank to form a wide Cambro-Ordovician carbonate platform. An adjacent offshore seaway with outboard microcontinents separated the craton and its carbonate platform from the broader Iapean Ocean (Hibbard et al., 2007). Closing of that seaway drove slope and deep-water deposits as an imbricate wedge onto the platform margin to produce the allochthonous zone of Southern Quebec (Kirkwood and Lavoie, 2007); the classic Taconic allochthons of Vermont and New York (Zen, 1961, 1972; Stanley and Ratcliffe, 1985; Karabinos et al., 1998); and the Martic Zone described herein. In Quebec, the thrusting drove little or no deepwater allochthonous material any great distance onto the foreland. Just north of Albany, the small remnants of Starks Knob (Lash, 1984; Landing et al., 2003; English et al., 2006) are the only indications of allochthonous material driven far onto the foreland. However in Pennsylvania as described above, great sheets of complex deep-water allochthons were emplaced in volumes significant enough to merit a distinct name, the Dauphin Formation.

This Pennsylvania example also differs from the other two, along-strike areas by incorporating the entire foreland basin and its underlying carbonate platform into alpine-scale nappes, possibly the result of a distinctive tectonic setting along a major transform fault. In the area of the future nappes, the shallow-water Beekmantown carbonates have approximately double thickness compared to adjacent areas (Rankin et al., 1989), indicating greater amounts of sinking in a concentrated locality. In the same area, the

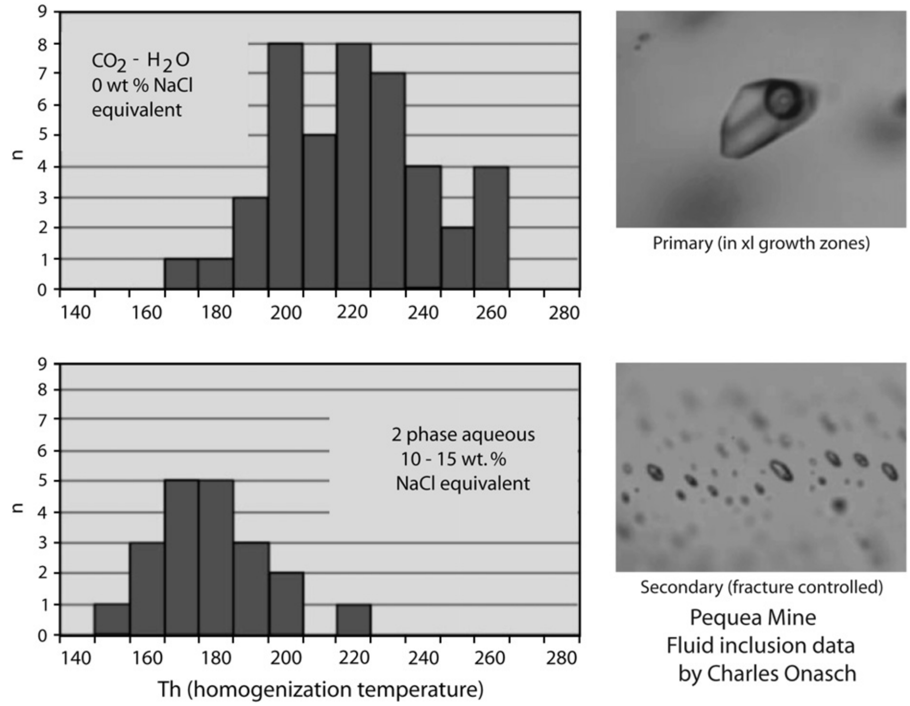

Fig. 10. Homogenization temperatures and compositions of primary and secondary fluid inclusions from Pequea Mine vein quartz (Wise et al., 2007). Figure is courtesy of C. Onasch from samples of R. Smith.

first foreland basins formed one graptolite zone earlier than areas 100 km to the northeast, as noted above. Thus, emplacement of deep-water allochthons should have been easier here, where the platform sank earlier by a much greater amount. The location was also an inside corner of the rifted cratonic edge where later tectonic stresses may have been concentrated. In addition, the thicker stratigraphy made carbonates in deeper portions of the pile more ductile and more susceptible to large-scale flowage. A combination of all these potentially transform-related effects may be responsible for the development in this area of the Dauphin allochthons and Lebanon Valley nappes. Analogous transform locations along the chain may harbor a few of the same characteristics.

7.2. The Apennine connection

Even though no single cross-section of the Apennines of Italy is a complete duplicate of this Pennsylvania example, much of the above scenario can be applied to that region by merely substituting names and times. The following paragraph does that by adding Apennine details from Bally et al. (1986), Bigi and Costa Pisani

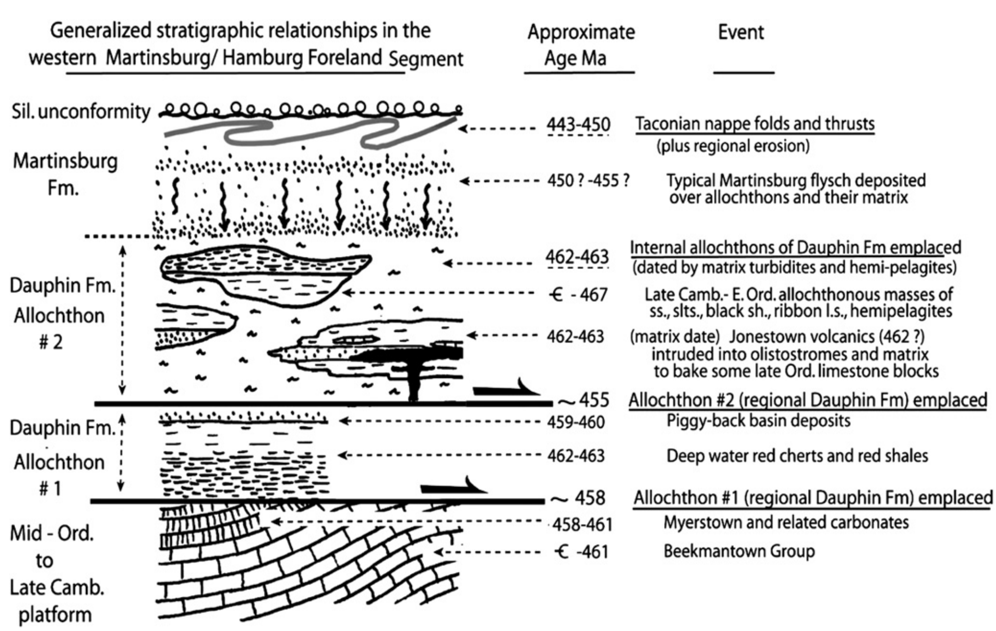

Fig. 11. Dates of pre-Taconic and Taconic foreland stratigraphy and structures. Dates are based on graptolite and conodont fossil ages synthesized into an overall structural picture by Ganis (2005), and Ganis and Wise (2008).

(2005), Boccaletti et al. (1990), Butler et al. (2006), Calamita et al. (1994), Coward et al. (1999) Pini (1999), and Speranza and Chiappini (2002).

After rifting (Triassic opening of Tethys), the broad edge of a cratonic mass (the microcontinent of Adria) lay adjacent to a small ocean basin (Tyrrhenian and former Ligurian Seas). With mantle cooling, a broad portion of the cratonic edge sank slowly enough to collect a variety of mostly carbonate deposits that range from deep water, to slope, to platform lithologies (ubiquitous over almost all of Italy starting with the Triassic). Some marine process, probably roll-back tectonics, shifted the contents of the adjacent basins (the *argille scagliosa* or scaly clay is the best known of a wide variety of these deposits) onto the platform and began to drive a series of foreland basins across it, the basins trailed by and progressively overridden by imbricate thrust and nappe structures. These nappes included the carbonates, foreland basins, and commonly the allochthons but never large basement thrust sheets at the present levels of exposure. This tectonically linked pair, mountain front and foreland basin, continued to migrate inland leaving a mountain chain behind (the modern Apennines), a chain that is now actively overriding (as the Apennine front) its outermost foreland basins (Po and peri-Adriatic).

The analogy breaks down in many details. The argille scagliosa, especially in the Northern Apennines, contains abundant ophiolites whereas these are non-existent in the Dauphin allochthons. The ~6-km thick carbonate platform just east of Rome sank more slowly than adjacent areas along strike and hence received very little of the allochthonous materials in contrast to Pennsylvania where thicker carbonate zones received the most extensive of the allochthons. Along the irregular edge of the Laurentian craton, the timing of initial Taconic deformation was rather haphazard while the first Apennine deformation migrated more or less regularly along strike from early Tertiary in the north to Plio-Pleistocene in the south. At present, extension tectonics are widespread in the Apennines but separation of a distinct, late-stage extension phase is not well documented in the Pennsylvania nappes. Above all, the almost complete lack of syn or post-deformation volcanic or plutonic activity in the Pennsylvania Taconics stands in sharp contrast to the famous Latian Volcanic Province of western Italy. Features like Vesuvius and the Albano Volcano next to Rome could not have gone undetected at our present level of understanding of the Taconic record. The Karabinos et al. (1998) suggestion of a flip in the subduction zone is an attractive mechanism to allow roll-back stresses that drove the advancing system but stopped before significant tectono-thermal processes could mature beneath it.

8. Conclusion

Most geologic literature quite accurately portrays the Appalachians as the deeply eroded product of a long-lived, complex Wilson cycle, the closure half of which was fundamentally *alpine* in nature. However, for at least one location during an early stage, relatively brief, time-span, *Apennine*-style tectonics were the dominant processes.

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It is a pleasure to add this paper to a volume honoring Nick Nickelsen and Rick Groshong. We stand among the multitude who have benefited from their work and their friendship through the years. In particular, Nick's insights have been most helpful for over half a century in comparing our Piedmont geology with his beloved Valley and Ridge Province. We salute and thank them for their contributions and friendship. In the early stages of this work, DUW's associations with Ernst Cloos, Jake Freedman, Bob Bentley, Pete Foose, Marv Kauffman, Carlyle Gray, Al Geyer, Dave MacLachlin, Sam Root, John Rodgers, and E-an Zen as well as Nick helped shape fundamental questions and their answers. These evolved during teaching and mapping supervision of a generation of Franklin and Marshall College students with especially strong contributions by Tom Anderson, Noel Potter, and Steven Schamel. In later years, associations began or continued with Ed Beutner, Terry Engelder, Rodger Faill, Pete Geiser, Bob Hatcher, and Sam Root. In more recent years Gale Blackmer, Hal Bosbyshell, Alex Gates, Mary Beth Gray, Tim Lutz, Jim Hibbard, Scott Howard, Jay Parrish, Lee Ann Srogi, Cees van Staal, Dave Valentino, Mike Williams and Gil Wiswall have helped both authors understand regional structures. The facilities of Franklin and Marshall College and University of Massachusetts at Amherst have been used throughout the study. The present synthesis would have been impossible without Bob Smith's samples, the monazite date of Mike Jercinovic and Mike Williams, the fluid inclusion data of Charlie Onasch, and the conodont dates of John Repetski. Reviews by Gale Blackmer, Mike Williams, the Umass Structural Geology Seminar, and Anonymous were most helpful. We thank all the above as well as Bill Dunne, Terry Engelder and Mary Beth Gray for editing and guiding this well-deserved celebration of Nick and Rick's contributions to our science.

References

Bally, A.W., Burbi, L., Cooper, C., Ghelardoni, R., 1986. Balanced sections and seismic reflection profiles across the Central Apennies. Memorie della Societa Geologica Italiana 35, 237–410.

Bigi, S., Costa Pisani, P., 2005. From a deformed peri-Tethyian carbonate platform to a fold-and-thrust-belt: an example from the Central Apennies (Italy). Journal of Structural Geology 27 (3), 523–539.

Blackmer, G.C., 2004a. Speculation on the tectonic history of the Glenarm Group and associated parts of the Wissahickon Formation. Field Conference of Pennsylvania Geologists Annual Guidebook 69, 15–27.

Blackmer, G.C., 2004b. Bedrock geology of the Coatesville Quadrangle, Chester County, Pennsylvania. Pennsylvania Geological Survey. 4th Series Atlas 189b, CD-ROM.

Boccaletti, M., Calamita, F., Deiana, G., Gelati, R., Lentini, F., Massari, F., Moratti, G., Pescatore, T., Ricci Lucchi, F., Tortorici, L., 1990. Migrating foredeep-thrust belt system in the Northern Apennines and Southern Alps. Palaeography Palaeoclimatology Paleoecology 77, 3–14.

Bosbyshell, H., 1999. Distribution of overprinting metamorphic mineral assemblages in the Wissahickon Group, southeastern Pennsylvania. Geological Society of America Special Paper 330, 41–58.

Bradley, D.C., 1989. Taconic plate kinematics as revealed by foredeep stratigraphy, Appalachian Orogen. Tectonics 8 (5), 1037–1049.

Bromery, R.W., et al., 1959. Aeromagnetic maps of the Quarryville and Conestoga Quadrangles, Lancaster County, Pennsylvania. US Geological Survey Geophysical Investigations Maps GP 218, 219.

Bukeavich, J.R., Srogi, L., Blackmer, G.C., 2006. Metamorphism and deformation in the Glenarm Wissahickon in SE Pennsylvania Piedmont. Geolological Society of America Abstracts with Programs 38 (2), 24.

Butler, R.W.H., Tavarnelli, E., Grasso, M., 2006. Structural inheritance in mountain belts: an Alpine-Apennine perspective. Journal of Structural Geology 28 (11), 1893–1908.

Calamita, F., Cello, G., Deiana, G., Paltrinieri, W., 1994. Structural styles, chronology, rates of deformation and time-space relationships in the Umbria-Marche thrust system (central Apennines, Italy). Tectonics 13 (4), 873–881.

Cloos, E., Hietanen, A., 1941. Geology of the "Martic Overthrust" and the Glenarm Series in Pennsylvania and Maryland. Geological Society of America Special Paper 35, 207.

Cooper, R.A., 1999. The Ordovician time scale-calibration of graptolite and conodont zones. Acta Universitatis Carolinae Geologia 43 (1/2), 1–4.

Coward, M.P., DeDonatis, M., Mazzoli, S., Paltrinieri, W., Wezel, F.C., 1999. Frontal part of the Northern Apennine fold and thrust belt in the Romagna-Marche area (Italy): shallow and deep structural styles. Tectonics 18, 599–674.

Dewey, J.C., 2005. Orogeny can be short. Proceedings of the National Academy of Sciences 102 (430), 15286–15293.

Dorsch, J., 2001. Silurian rebound unconformity in Pennsylvania and its relationship to the "classical" Taconic Unconformity. Geological Society of America Abstracts with Programs 33 (6), 78.

Drake, A.A., Sinha, A.K., Laird, J., Guy, R.E., Thomas, W.A., 1989. The Taconic Orogen. In: Hatcher Jr., R.D., Viele, G.W. (Eds.), The Appalachian-Ouichita OrogenGeological Society of America DNAG Series F-2, pp. 101–177.

English, A.M., Landing, E., Baird, G.C., 2006. Snake Hill – reconstructing eastern Taconic foreland basin litho-and biofacies from a giant mélange block in eastern New York, USA. Paleogeography, Paleoclimatology, Paloeecology 242, 201–213.

Ettensohn, F.R., Brett, C.E., 2002. Stratigraphic evidence from the Appalachian Basin for continuation of the Taconian Orogeny into Early Silurian time. Physics and Chemistry of the Earth 27 (1-3), 279–288.

Faill, R.T., 1997a. A geologic history of the north-central Appalachians, Part 1, Orogenesis from the Mesoproterozoic through the Taconic Orogeny. American Journal of Science 297, 551–619.

Faill, R.T., 1997b. A geologic history of the north-central Appalachians; Part 2, The Appalachian Basin from the Silurian through the Carboniferous. American Journal of Science 297, 729–761.

Faill, R.T., 1998. A geologic history of the north-central Appalachians; Part 3, The Alleghany Orogeny. American Journal of Science 298, 131–179.

Freedman, J., Wise, D.U., Bentley, R.D., 1964. Pattern of folded folds in the Appalachian Piedmont along the Susquehanna River. Geological Society of America Bulletin 75, 621–638.

Ganis, G.R., 2004. Ordovician graptolite faunas and stratigraphic construction of the Martinsburg/Hamburg foreland segment, central Appalachians, North America. PhD thesis, University of Leicester, Leicester, UK, 153 pp.

Ganis, G.R., 2005. Darriwilian graptolites of the Hamburg succession (Dauphin Formation), Pennsylvania, and their geologic significance. Canadian Journal of Earth Sciences 42 (05), 791–813.

Ganis, G.R., Wise, D.U., 2008. Taconic events of Pennsylvania: a 15–20 m.y. orogenic cycle viewed with graptolite and conodont dates in the foreland basin. American Journal of Science 308, 167–183.

Ganis, G.R., Williams, S.H., Repetski, J.E., 2001. New biostratigraphic information from the western part of the Hamburg klippe, Pennsylvania, and its significance for interpreting the depositional and tectonic history of the klippe. Geological Society of America Bulletin 113, 109–128.

Gates, A.E., 1991. Terranes and tectonics of the Maryland and Southeast Pennsylvania Piedmont. Guidebook of Virginia Museum of Natural History 2, 1–28.

Gohn, G.S., 1976. Sedimentology, stratigraphy, and paleogeography of lower Paleozoic carbonate rocks, Conestoga Valley, southeastern Pennsylvania. PhD thesis. University of Delaware, Newark, DE, 314 pp.

Gray, C., 1959. Nappe structures in Pennsylvania. Geological Society of America Bulletin Abstracts 70 (11), 1611.

Gray, C., Root, S.I., 1999. Structural geology of the Great Valley and Piedmont Lowland. In: Schultz, C.H. (Ed.), The Geology of PennsylvaniaPennsylvania Geological Survey and Pittsburgh Geological Society, pp. 256–267.

Gray, C., Geyer, A.R., McLaughlin, D.B., Moseley, J.R., 1958. Geological Map of the Lebanon Quadrangle, Pennsylvania. Geological Atlas of Pennsylvania Fourth Series 167C, with text.

Hatcher Jr., R.D., 2002. Alleghanian (Appalachian) Orogeny, a product of zipper tectonics; rotational transpressive continent-continent collision and closing of ancient oceans along irregular margins. Geological Society of America Special Paper 364, 199–208.

Hatcher Jr., R.D., 1989a. In: Thomas, W.A., Viele, G.W. (Eds.), The Appalachian-Ouachita Orogeny in the United States. Geological Society of America DNAG Series, F-2, 767 pp.

Hatcher Jr., R.D., Thomas, W.A., Geiser, P.A., Snoke, A.W., Mosher, S., Wiltschko, D.V., 1989b. The Appalachian-Ouachita Orogen. In: Hatcher Jr., R.D., Thomas, W.A., Viele, G.W. (Eds.), The Appalachian-Ouachita Orogeny in the United States. The Geology of North America DNAG Series, F-2. Geological Society of America, pp. 233–318.

Hatcher Jr., R.D., Lemiszki, P.J., Whisner, J.B., 2007a. Character of rigid boundaries and internal deformation of the southern Appalachia foreland fold-thrust belt. In: Sears, J.W., Harms, T.A., Evenchick, C.A. (Eds.), Inquiries into the Evolution of Orogenic Systems. Geological Society of America Special Paper, 433. Whence the Mountains?, pp. 243–276.

Hatcher Jr., R.D., Bream, B.R., Merschat, A.J., 2007b. Tectonic map of the southern and central Appalachians: a tale of three orogens and a complete Wilson cycle. In: Hatcher Jr., R.D., Carlson, M.P., McBride, J.H., Catalan, J.R.M. (Eds.), 4-D Framework of Continental Crust. Geological Society of America Memoir, 200, pp. 595–632.

Hibbard, J., van Staal, C., Rankin, D., Williams, H., 2006. Lithotectonic Map of the Appalachian Orogen, Canada-United States of America. Geological Survey of Canada, Map 02096A, 2 sheets, scale 1, 1500000.

Hibbard, J., van Staal, C., Rankin, D., 2007. A comparative analysis of pre-Silurian crustal 'building blocks' of the northern and southern Appalachians. In: Wintsch, R. (Ed.), Rodgers Memorial Issue, Part 1. American Journal of Science, 307, pp. 23–45. 1.

Higgins, M.W., 1972. Age, origin, regional relations, and nomenclature of the Glenarm Series, central Appalachian Piedmont: a reinterpretation. Geological Society of America Bulletin 83, 989–1026.

Jonas, A.I., Stose, G.W., 1926. Geology and mineral resources of the New Holland Quadrangle, Pennsylvania. Pennsylvania Geological Survey, 4th series, Atlas 178, 40.

Jonas, A.I., Stose, G.W., 1930. Geology and mineral resources of the Lancaster Quadrangle, Pennsylvania. Pennsylvania Geological Survey, 4th series, Atlas 168, 106.

Karabinos, P., 2001. How do orogenies end? An example from the Taconic Orogeny in the Northern Appalachians. Geological Society of America Abstracts with Programs 33 (6), 206.

Karabinos, P., Samson, S.D., Hepburn, J.C., Stoll, H.M., 1998. Taconian orogeny in the New England Appalachians: collision between Laurentia and the Shelburn Falls arc. Geology 26 (3), 215–218.

Kirkwood, D., Lavoie, D., 2007. The Lower Paleozoic successions in the Quebec City area: tectono-stratigraphy and sedimentology. In: Corriveau, L., Clark, T. (Eds.), Guidebook for Field Trips in Southern Quebec. New England Intercollegiate Geological Conference Guidebook, 99, pp. 1–48.

Knopf, E.B., Jonas, A.I., 1929. Geology of the McCalls Ferry and Quarryville Quadrangles. US Geological Survey Bulletin 799, 156.

Landing, E., Pe-Piper, G., Kidd, W.S.F., Azmy, K., 2003. Tectonic setting of outer trench slope volcanism: pillow basalt and limestone in the Taconian orogen of eastern New York. Canadian Journal of Earth Sciences 40, 1773–1787.

Lash, G.G., 1984. The Jonestown volcanic rocks, Eastern Pennsylvania- Near trench volcanism in the central Appalachians. Geological Society of America Abstracts with Programs 16 (1), 46.

Lash, G.G., Drake Jr., A.A., 1984. The Richmond and Greenwich slices of the Hamburg klippe in eastern Pennsylvania-stratigraphy, sedimentology, structure, and plate tectonic implications. US Geological Survey Professional Paper 1312, 40.

Lyttle, P.T., Epstein, J.B., 1987. Geologic map of the Newark 1x2 degree quadrangle, New Jersey, Pennsylvania, and New York. US Geological Survey Miscellaneous Investigations. Map I-1715.

Mackin, J.H., 1935. The problems of the Martic Overthrust and the age of the Glenarm series in southeastern Pennsylvania. Journal of Geology 43 (4), 356–380.

MacLachlan, D.B., 1967. Structure and stratigraphy of the limestones and dolomites of Dauphin County, Pennsylvania. Pennsylvania Geological Survey, 4th Series, General Geology Report G44, 168.

MacLachlan, D.B., 1990. Paleozoic carbonates of the continental margin in the Lancaster–York Valley, Pennsylvania. Field Conference of Pennsylvania Geologists Annual Guidebook, 116–122.

Meisler, H., Becher, A.E., 1971. Hydrology of the carbonate rocks of the Lancaster 15-minute quadrangle, southeastern Pennsylvania. Pennsylvania Geological Survey Bulletin W26, 149.

Miller, B.L., 1935. Age of the schists of the South Valley Hills. Geological Society of America Bulletin 46, 715–756.

Pini, G.A., 1999. Tectosomes and Olistostromes in the Argille Scagliosa of the Northern Apennines, Italy. Geological Society of America Special Paper 335, 70.

Pyle, J.M., Bosbyshell, H., Blackmer, G., 2006. Refining the metamorphic and tectonic history of the southeastern Pennsylvania Piedmont; recent results from monazite and zircon geochronology and accessory-phase thermometry. Geological Society of America Field Guide 8, 83–112.

Rankin, D.W., 1976. Appalachian salients and recesses; late Precambrian continental breakup and the opening of the Iapetus Ocean. Journal of Geophysical Research 81 (32), 5605–5619.

Rankin, D.W., Drake, A.A., Glover, L., Goldsmith, R., Hall, L., Murray, D.P., Ratcliffe, N. M., Read, J.F., Secor, D.T., Stanley, R.S., 1989. Pre-orogenic terranes. In: Hatcher, R. D., Thomas, W.A., Viele, G.W. (Eds.), The Geology of North America, The Appalachian-Ouachita Orogen in the United States. Geological Society of America DNAG series, F-2, pp. 7–100.

Ratcliffe, N.M., 2006. Tremadocian to Pridolian accretionary arc, collisional and post-collisional aspects of the Taconide Zone. Northeastern US Geological Society of America Abstracts with Programs 38 (2), 9.

Repetski, J.E., 1984a. Conodonts from the Greenwich slice of the Hamburg klippe near Greenawald, Pennsylvania. Field Conference of Pennsylvania Geologists Annual Guidebook 49, 92–93.

Repetski, J.E., 1984b. Conodonts from Spitsenburg. Field Conference of Pennsylvania Geologists Annual Guidebook 49, 94–101.

Repetski, J.E., Ganis, G.R., 2001. Non-Laurentian (?) Ordovician conodonts from Eastern North America, in: Hamoumi, N. (compiler), The Gonwanan platform during Ordovician times. Climatic eustatic and geodynamic evolution: Official business meeting and field excursion of the subcommission on Stratigraphy/International Union of Geological Sciences, Rabat, 9.

Rodgers, J., 1968. The eastern edge of the North American continent during the Cambrian and Early Ordovician. In: Zen, E., White, E.S., Hadley, J.B., Thompson Jr., J.B. (Eds.), Studies of Appalachian Geology: Northern and Maritime. Interscience Publishers, New York, pp. 141–149.

Rodgers, J., 1970. The Tectonics of the Appalachians. Wiley-Interscience, New York, 271 pp.

Rodgers, J., 1971. The Taconic Orogeny. Geological Society of America Bulletin 62, 1141–1178.

Root, S.I., MacLachlan, D.B., 1978. Western limit of the Taconic allochthons in Pennsylvania. Geological Society of America Bulletin 89, 1515–1528.

Ross, R.J., 27 co-authors, 1982. The Ordovician System in the United States, correlation chart and explanatory notes. International Union of Geological Sciences. Publication 12, 73.

Sasseville, C., Tremblay, A., Clauer, N., 2006. Tectonic evolution of the Taconic Allochthons, Quebec Appalachians: insights from detailed structural analysis and K-Ar dating. Geological Society of America Abstracts with Programs 38 (2), 20.

Sinha, A.K., 2004. The magmatic record of the Taconic orogenic cycle; evidence from ion probe U/Pb ages of zircons from the central Appalachian orogen. Geological Society of America Abstracts with Programs 36 (2), 75.

Smith II, R.C., 1977. Zinc and lead occurrences in Pennsylvania. Pennsylvania Geological Survey Mineral Resources Report 72, 318.

Speranza, F., Chiappini, M., 2002. Thin-skinned tectonics in the external Apennines, Italy: new evidence from magnetic anomaly analysis. Journal of Geophysical Research 107 (B11), 2290, doi:10.1029/2000JB000027.

Stanley, R., Ratcliffe, N., 1985. Tectonic synthesis of the Taconian Orogeny in Western New England. Geological Society of America Bulletin 96, 1227–1250.

Stose, G.W., 1930. Unconformity at the base of the Silurian in southeastern Pennsylvania. Geological Society of America Bulletin 41, 629–657.

Stose, G.W., 1946. The Taconic sequence in Pennsylvania. American Journal of Science 244, 665–696.

Stose, G.W., Jonas, A.I., 1927. Ordovician shale and associated lava in southeastern Pennsylvania. Geological Society of America Bulletin 38, 505–536.

Stose, G.W., Jonas, A.I., 1933. Geology and mineral resources of the Middletown Quadrangle, Pennsylvania. US Geological Survey Bulletin 840, 86.

Stose, G., Jonas, A., 1939. Geology and mineral resources of York County, Pennsylvania. Pennsylvania Geological Survey, 4th Series County Report 67.

Thompson, P.J., Repetski, J.E., Walsch, G.J., Ratcliffe, N.M., Thompson, T.B., Laird, J., 2002. Middle Ordovician conodonts in northern Vermont provide a stratigraphic link across the Green Mountain Anticlinorium and constrain the timing of Taconian metamorphism. Geological Society of America Abstracts with Programs 34 (1), 29.

Thomas, W.A., 1977. Evolution of Appalachian-Ouachita salients and recesses from reentrants and promontories in the continental margin. American Journal of Science 277, 1233–1278.

Thomas, W.A., 2005. Tectonic inheritance at a continental margin. GSA Today 16 (2), 4–10.

Tucker, R.D., Robinson, P., 1990. Age and setting of the Bronson Hill magmatic arc; a re-evaluation based on U-Pb zircon ages in southern New England. Geological Society of America Bulletin 102 (10), 1404–1419.

Valentino, D.W., 1994. Lithofacies and deformation history of the Octoraro Formation and the relationship to the Pleasant Grove-Huntingdon Valley shear zone. Field Conference of Pennsylvania Geologists Annual Guidebook 59, 25–34.

Valentino, D.W., 1999. Late Paleozoic dextral transpression in the crystalline core of the Pennsylvania reentrant. Geological Society of America Special Paper 330, 59–71.

Valentino, D.W., Gates, A.E., Glover, L., 1994. Late Paleozoic transcurrent assembly of the central Appalachian Piedmont. Tectonics 13, 110–126.

Van Staal, C.R., Lissenberg, C.J., Zagorevski, A., McNicoll, V.J., Bedard, J.H., Pehrsson, S., 2004. A new look at the tectonic processes involved in the Ordovician Taconic Orogeny in the Newfoundland Appalachians: evidence for multiple accretion of (infant) arc terranes. Geological Society of America Abstracts with Programs 36 (5), 481.

Wise, D.U., 1970. Multiple deformation, geosynclinal transitions, and the Martic problem in Pennsylvania. In: Fisher, G.W., Pettijohn, F.J., Reed, J.C., Weaver, K.N. (Eds.), Studies of Appalachian Geology: Central and Southern. Interscience Publishers, New York, pp. 317–333.

Wise, D.U., 2004. Pennsylvania salient of the Appalachians: a two-azimuth transport model based on new compilations of Piedmont data. Geology 32, 777–780.

Wise, D.U., 2006. The Pequea Silver Mine of Lancaster County, Pennsylvania. Pennsylvania Geology 36 (1), 2–13.

Wise, D.U., Faill, R.T., 2002. Lancaster transverse seismic zone (Pennsylvania): strain concentration at lateral ramps of basement nappes (?). Northeastern Geology and Environmental Sciences 24 (3), 171–175.

Wise, D.U., Kauffman, M.E., 1960. Some tectonic and structural problems of the Appalachian Piedmont. Field Conference of Pennsylvania Geologists Annual Guidebook 25, 99.

Wise, D.U., Werner, M.L., 2004. Pennsylvania salient of the Appalachians; a two-stage model for Alleghanian motion based on new compilations of Piedmont data. Geological Society of America Special Paper 383, 109–120.

Wise, D.U., Smith II, R.C., Jercinovic, M.J., Ganis, G.R., Onasch, C.M., Repetsk, J.E., Williams, M.L., 2007. Tectonic implications of a new 450 ma monazite date and T/P data from the Martic thrust zone, Pequea "Silver" Mine, SE Pennsylvania. Geological Society of America, Northeast Section Abstracts with Programs Paper 13-5.

Zagorevski, A., van Staal, C.R., McNicoll, V.J., 2007. Distinct Taconic, Salinic, and Acadian deformation along the Iapetus suture zone, Newfoundland Appalachians. Canadian Journal of Earth Sciences 44 (11), 1567–1585.

Zen, E., 1961. Stratigraphy and structure at the north end of the Taconic Range in west-central Vermont. Geological Society of America Bulletin 72 (2), 293–338.

Zen, E., 1972. Some Revisions in the Interpretation of the Taconic Allochthon in West-Central Vermont. Geological Society of America Bulletin 83 (9), 2573–2587.