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Lessons from the foreland basin: Northern Appalachian basin perspectives on the Acadian orogeny

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ABSTRACT

Foreland basin rocks of the northern Appalachian basin in New York and adjacent areas contain a significant Upper Silurian to Devonian record of Acadian orogenesis. Sediment composition, stratal geometry, stratigraphic anomalies, and distribution of volcanic air-fall tephras through time and space provide insights into patterns of tectonism and quiescence, uplift and unroofing, tectonically induced basin flexure, and explosive volcanism in the orogenic belt. Herein, I combine a literature review and new data to examine several aspects of the foreland basin fill and their implications. Established models of Acadian-related impacts on the foreland, including tectophase development, are tested against a more refined high-resolution stratigraphy. Some sedimentary patterns are cyclic; others evolve through time. Initial study of synorogenic conglomerates across 40 m.y. of sedimentation sketches an unroofing history of the orogen. Stratigraphic anomalies delineate a flexural history interpreted directly from the rock record: topographic features in the foredeep migrate toward the craton in tectonically active intervals and toward the orogen during quiescent intervals. In addition, the forebulge undergoes cyclic uplift and leveling. These results differ from predictions in existing models of foreland basin kinematics. Preserved air-fall tephras reflect a history of explosive volcanism along the orogen. Comparisons of igneous rocks from the foreland and orogen portray a larger picture of Lower Emsian magmatism. Finally, I summarize the chronology of foreland basin signatures of orogenesis. Data and interpretations presented here should be compared with the record of Acadian orogenesis from the mountain belt in order to better determine causation and outline a more detailed synthesis of the Acadian orogeny.

INTRODUCTION

Overview

Collision of the eastern margin of Laurentia with a landmass or a series of terranes during the Devonian resulted in major reorganization of the continental margin and the eastern interior. Late Silurian to Devonian orogenesis ("Acadian orogeny") produced a mountain chain that extended from Newfoundland to Alabama, and this event was accompanied by extensive volcanism and plutonism, deformation, and regional and contact metamorphism (Fig. 1). Construction of the orogenic belt and loading of the continental lithosphere resulted in depression of the cratonward interior and formation of a foreland basin ("Acadian foreland basin"; Fig. 1). A portion of the Acadian foreland basin system, the Appalachian basin, contains an important record of Acadian orogenesis. Alternating periods of tectonic activity and quiescence, episodic volcanism, and

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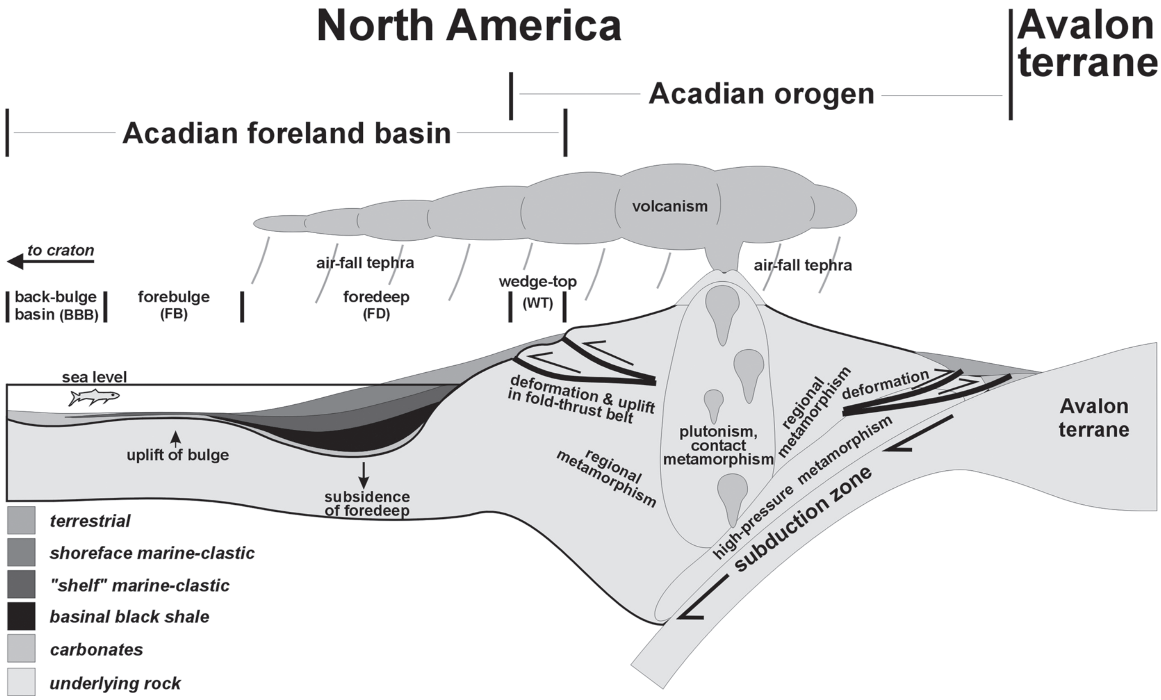


Figure 1. Idealized cross section of the Acadian orogen and foreland basin.

pulses of subsidence and uplift had a strong impact on sedimentation and foreland basin geometry. Initial pulses of orogenesis had a minor impact on the Appalachian basin; later episodes of tectonism, from the Middle to Late Devonian and into the Mississippian, resulted in eventual overflow of the foreland basin onto the craton.

Details of these events in the foreland basin are best accessed through high-resolution stratigraphic analysis of the sedimentary succession. The construction of a detailed framework of correlatable event beds and sedimentary cycles permits fine-scale subdivision of the basin fill. With this correlative framework, a more detailed history of the foreland basin and the coeval orogeny can be inferred.

The purpose of this paper is to summarize different aspects of the sedimentologic and stratigraphic history of the foreland basin fill in the northern Appalachian basin, and their possible implications for events and processes active during the Acadian orogeny. The paper focuses largely on the Lower to Middle Devonian record, but some Upper Silurian and Upper Devonian strata and events are included. The paper will focus primarily on the New York succession, in part due to the author's greater knowledge of the Devonian there, and due to the extensive high-resolution stratigraphic/sedimentologic, sometimes bed-by-bed documentation of the succession. Supplementary data from adjacent areas will sometimes also be utilized.

This paper presents both a review of the literature and new studies and examines data on the sedimentary fill, stratal geometry, and volcanic air-fall tephras from the foreland basin sedimentary succession. Resulting interpretations of events and processes active in the foreland basin are outlined and examined for what they may tell about the timing and character of events and processes active in the orogen (e.g., timing and character of periods of tectonism versus relative quiescence, provenance and unroofing, loading and flexure, and explosive volcanism) through space and time. It is hoped that this will provide a viable overview of the foreland basin record of Acadian orogenesis and prompt more collaborative discussion and study between geologists in the foreland basin and the orogenic belt.

Acadian Orogeny

The Acadian orogeny, as defined by some workers, was a major Late Silurian to Devonian mountain-building event in eastern North America (alternatively, Acadian and Neo-Acadian orogenies of van Staal et al., 2009). It is generally interpreted to have resulted from the collision of North America (Laurentia) with one or more landmasses (e.g., Avalon—Rast and Skehan, 1993; Avalon and Meguma terranes—van Staal, 2007; van Staal et al., 2009), or a series of terranes. A recent alternative hypothesis proposes that the orogen may have, at least in the northern Appalachians, resulted from Laramide-type uplift due to flattening of a subduction zone along an Andean-type continental margin (Murphy and Keppie, 2005). Orogenesis resulted in construction of a mountain chain that extended along the present-day eastern margin of North America from Newfoundland to Alabama (Figs. 1 and 2). The Acadian event produced significant volcanism, plutonism, high-grade metamorphism, and large-scale deformation along the orogen. Devonian and

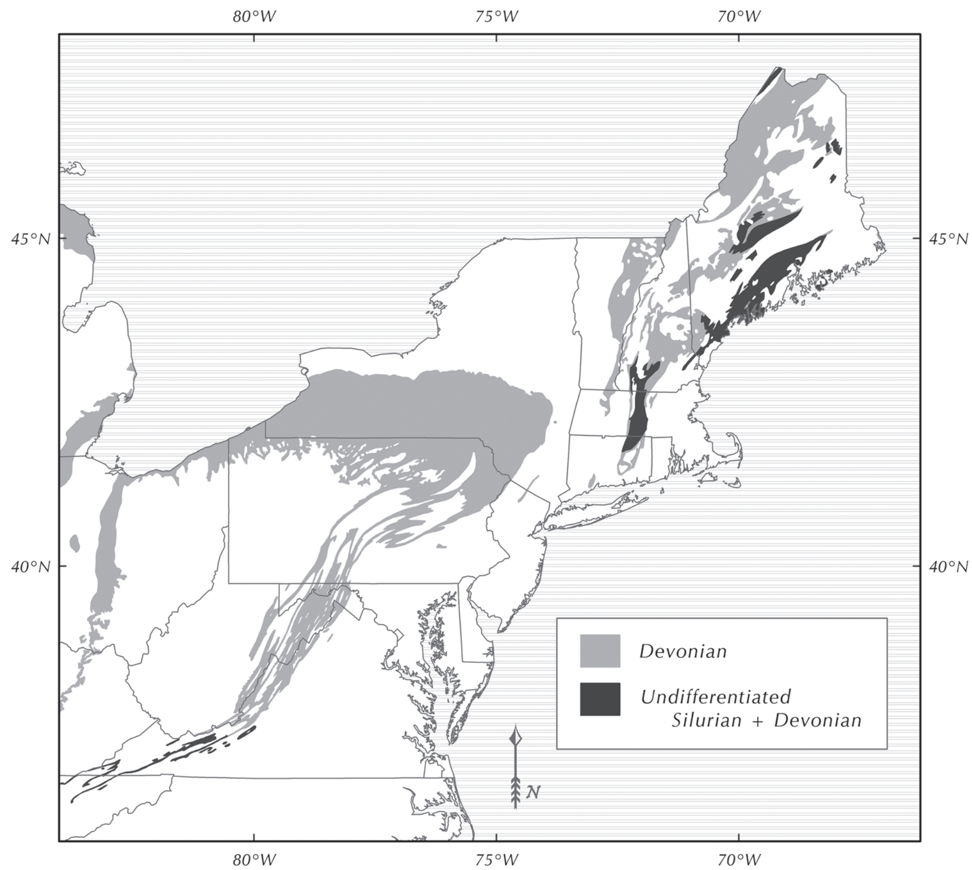


Figure 2. Distribution of Devonian rocks, eastern United States (modified after Schruben et al., 1994).

younger modification by tectonism and deformation, metamorphism, erosion, and later deposition destroyed or buried much of the Acadian rock record, especially in the central to southern Appalachians. A greater amount of Acadian rocks are preserved in New England and Maritime Canada. Even in those areas, however, a large part of the history of the orogeny has been eroded or tectonically overprinted.

The Acadian orogeny is generally associated with a southward-progressive, oblique collision against the eastern Laurentian margin, which extended from the mid- to Late Silurian to Late Devonian or early Mississippian (Rodgers, 1967, 1970; Ettensohn, 1985, 1987). Southwestward-migrating pulses of tectonism during the orogeny, indicated by the distribution of clastic wedges along the orogen, were projected by Ettensohn (1985, 1987) to be associated with collision of successive Laurentian promontories (Gaspe Peninsula, New York, Virginia, and Alabama Promontories, northeast to southwest, respectively; Thomas, 1977).

A detailed history of the advancement of the orogeny across the Acadian foreland basin in Maine and adjacent areas has been documented recently by Bradley et al. (2000). This study, which provides a synthesis of sedimentologic/stratigraphic, igneous, and structural data, indicates Late Silurian onset of orogenesis on the eastern margin of Laurentia in the area of Maine, followed by progressive cratonward migration of the orogen across Maine and into the eastern townships of Quebec by the Late Devonian.

Foreland Basins

A foreland basin is an elongate trough, or "moat," that forms on continental crust between an orogenic belt and the adjacent craton (Dickinson, 1974; Miall, 1995; DeCelles and Giles, 1996). Basins form and flex due to orogenic loading ± subduction-related geodynamics, mantle processes, in-plane stresses, and redistribution of the load via sedimentation (e.g., Beaumont, 1981; Jordan, 1981; Quinlan and Beaumont, 1984; Mitrovica et al., 1989; Cloetingh, 1988; Jordan and Flemings, 1991). Multiple processes may interact with plates of varying flexural rigidity, resulting in a complex history of foreland basin flexure (DeCelles and Giles, 1996; Catuneanu et al., 1997).

Foreland basin systems are composed of four distinct depozones, from the orogenic front to the margin of the craton, respectively: wedge-top, foredeep, forebulge, and back-bulge basin (DeCelles and Giles, 1996; Fig. 1). These zones may shift laterally through time (DeCelles and Giles, 1996). The following descriptions are summarized from DeCelles and Giles (1996).

The wedge-top is the most proximal zone of sediment deposition, situated over the front of the orogenic fold-and-thrust belt (DeCelles and Giles, 1996). It is characterized by coarse sediments that thicken toward the foredeep; it is commonly deformed, with numerous unconformities.

The foredeep is a subsiding trough adjacent to the proximal wedge-top, characterized by a thick sedimentary succession that thins cratonward. This area is the focus of many foreland basin studies. It typically is ~100–300 km wide, with a cumulative sedimentary fill 2–8 km thick. The bulk of the sediment is derived from the orogenic belt.

The forebulge is a zone of possible flexural uplift on the cratonward side of the foredeep. The forebulge may be on the order of 60–470 km in width. It commonly is an area of little to no deposition and/or erosion, characterized by unconformities and/or carbonate deposition, if flooded. Forebulges generally migrate laterally through time, associated with changes in flexural kinematics in a foreland basin system.

The back-bulge basin is a zone of sediment accumulation between the forebulge and craton, and it has a relatively low subsidence rate. Sediment may be derived from the orogenic belt, but also from the craton, the forebulge, and in situ carbonate production, if it is flooded by marine waters. Deposits are relatively thin and tabular.

Figure 3. Uppermost Silurian and Devonian stratigraphy, magnafacies, and data, northern Appalachian basin. Columns on left ("system" to "magnafacies") are modified after Rickard (1975) and Rogers et al. (1990). For key to magnafacies symbols, see Figure 4. White areas in magnafacies column are unconformities. Emsian- and Eifelian-age modifications are after Ver Straeten (1996, 2007). Conodont biostratigraphy is shown in Figure 7. Note that the Union Springs and Oatka Creek Formations represent subdivisions of the "Marcellus Shale" (formerly Marcellus formation) in New York (Ver Straeten and Brett, 2006). Abbreviations: c, carb—carbonate; Ch—chert; Con—Conneaut; dom.—dominant; DS—depositional cycle; Gen—Genesee; intm, intermed—intermediate; L—Ludlow; Lochk—Lochkovian; M—Mississippian; MCZ—Middle Coarse Zone; mix—mixed carbonate and clastic; mQ—milky quartz; Pr—Pragian; Qa—quartz arenite; Silur—Silurian; Sony—Sonyea; tablr—tabular; Tour—Tournaisian.

Acadian Foreland Basin and the Appalachian Basin

The Acadian foreland basin was an elongate trough that formed during the Paleozoic by subsidence adjacent to the Appalachian orogen (Fig. 1). The basin extended from Newfoundland to Alabama. This includes an area termed the "Appalachian basin," an area of slightly deformed to undeformed sedimentary rocks encompassing parts of eight states, from New York to northeastern Tennessee to Ohio. During the Devonian, the Appalachian basin was oriented approximately northeast to southwest, and it has been variously interpreted to be on the order of 25–40°S of the equator (van der Voo, 1983; Witzke and Heckel, 1988; Scotese and McKerrow, 1990). The proximal portion of the Appalachian basin today has predominantly been removed by postorogenic weathering and erosion.

Previous Work

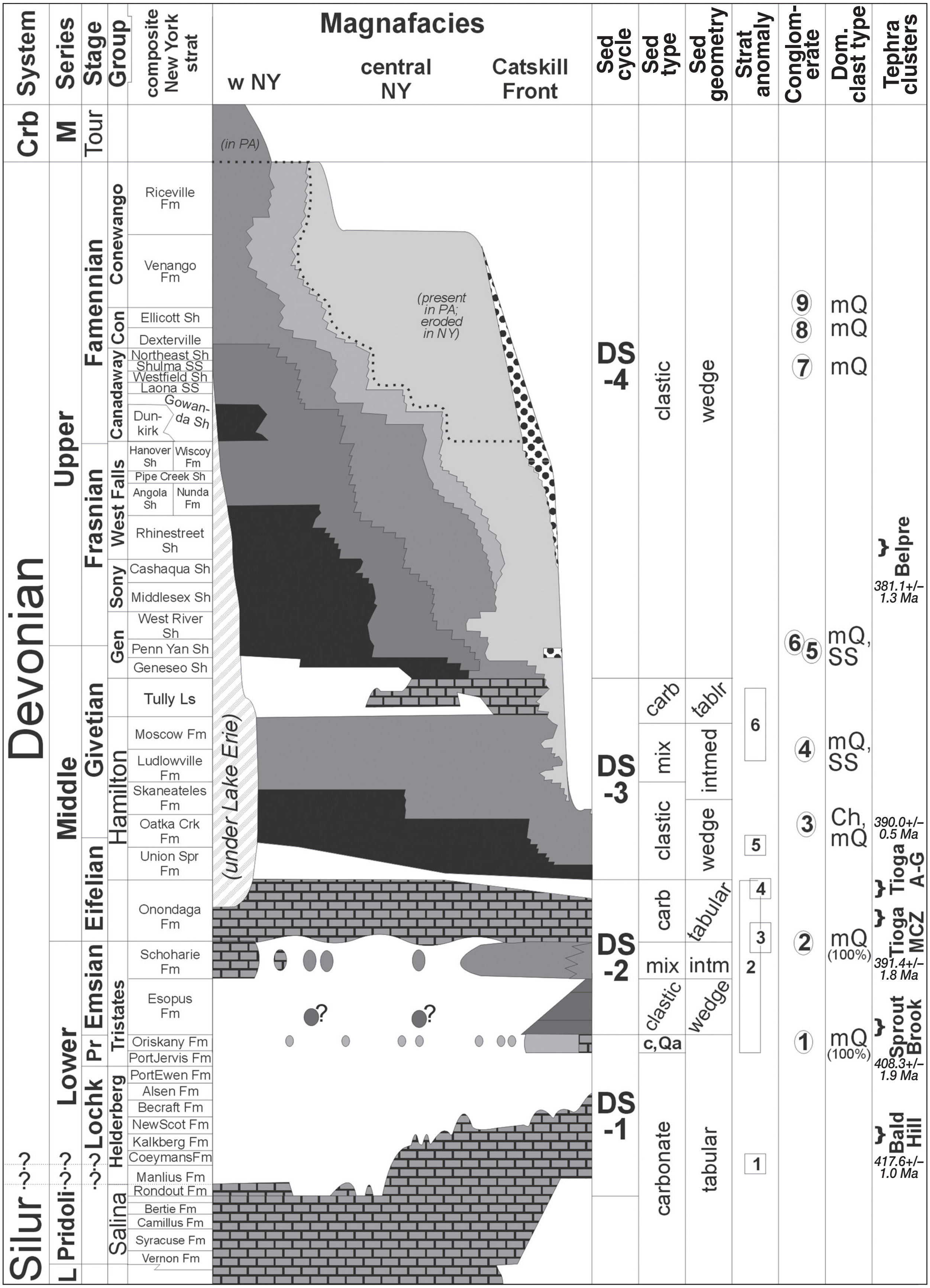
Overview:Northern Appalachian Basin

Since the mid-1800s, the Upper Silurian to Devonian succession in the greater Acadian foreland basin, including the Appalachian basin, has been the focus of innumerable studies. References to specific subjects in the northern part of the Appalachian basin (in New York; Fig. 3), and more broadly across the region include: (1) sedimentologic and stratigraphic studies (e.g., Rickard, 1975, 1989; Brett, 1986; Brett and Baird, 1994, 1996; Bridge and Gordon, 1985; Bridge and Willis, 1994; House and Kirchgasser, 1993; Ver Straeten, 1996, 2007, 2009a; Baird and Brett, 2003; Ebert and Matteson, 2003); (2) Devonian air-fall tephras (e.g., work by Dennison and Textoris, 1970; Dennison, 1983; Conkin and Conkin, 1984; Smith and Way, 1983; Way et al., 1986; Smith et al., 1988; Ver Straeten, 2004a, 2004b); (3) discussions of foreland basin flexure in the northern Appalachian basin as a result Acadian orogenesis (e.g., Brett and Baird, 1994; Ver Straeten and Brett, 2000; Ebert and Matteson, 2003); and (4) sedimentary geology–based studies of the greater Acadian foreland basin/Acadian orogen (e.g., papers in Woodrow and Sevon, 1985; Osberg et al., 1989; Rust et al., 1989; papers in Roy and Skehan, 1993; Robinson et al., 1998; Bradley et al., 2000; Ver Straeten, 2009a). Recent Devonian time scales (Tucker et al., 1998; Kaufmann, 2006; Ogg et al., 2008) provide a more precise, though still debated, framework for the timing and duration of events through the Late Silurian and Devonian (Table 1).

Acadian Tectophases Model of Ettensohn (1985)

Ettensohn (1985) proposed a four-phase model of Acadian orogenesis based largely on the sedimentary record of the Appalachian basin. Four major depositional successions from the upper Lower Devonian (Emsian Stage) through Lower Mississippian were recognized by Ettensohn (1985) on the basis of occurrence and distribution of basinal black shales, clastic wedges, major carbonates, and unconformities. A general northeast and to southwest migration of successive black shale and clastic depocenters was interpreted by Ettensohn (1985, 1987) to reflect southwestward-trending oblique collision and transcurrent strike-slip faulting along an irregular eastern margin of Laurentia. Promontories along the irregular continental margin served to focus greater compression during successive collisions with an Avalonian landmass. This resulted in: (1) greater deformation and relief in the areas of the promontories; (2) concentration of clastic wedges in parts of the foreland basin adjacent to the promontories; and (3) alternating episodes of increased tectonism and relative quiescence (Ettensohn, 1985, 1987).

Each of these tectonically active to quiescent phases (tectophases I–IV) were marked by: (1) an initial overdeepening period, reflected by basinal black shale deposition, associated with the onset of tectonism in the adjacent Acadian orogen; (2) pro-


System
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Devonian
Upper
Middle
Lower
Silur
Pridoli
L
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pr
Lochk
Conewango
Con
Canadaway
West Falls
Sony
Gen
Hamilton
Tristates
Helderberg
Salina
Riceville Fm
Venango Fm
Ellicott Sh
Dexterville
Northeast Sh
Shulma SS
Westfield Sh
Laona SS
Dun-kirk
Gowan-da Sh
Hanover Sh
Wiscoy Fm
Pipe Creek Sh
Angola Sh
Nunda Fm
Rhinestreet Sh
Cashaqua Sh
Middlesex Sh
West River Sh
Penn Yan Sh
Geneseo Sh
Tully Ls
Moscow Fm
Ludlowville Fm
Skaneateles Fm
Oatka Crk Fm
Union Spr Fm
Onondaga Fm
Schoharie Fm
Esopus Fm
Oriskany Fm
PortJervis Fm
PortEwen Fm
Alsen Fm
Becraft Fm
NewScot Fm
Kalkberg Fm
CoeymansFm
Manlius Fm
Rondout Fm
Bertie Fm
Camillus Fm
Syracuse Fm
Vernon Fm
(in PA)
(present in PA; eroded in NY)
(under Lake Erie)
DS -4
DS -3
DS -2
DS -1
clastic
carb
mix
c,Qa
carbonate
wedge
tablr
intmed
tabular
intm
1
2
3
4
5
6
mQ
Ch, mQ
mQ, SS
(100%)
Belpre
381.1+/– 1.3 Ma
390.0+/– 0.5 Ma
Tioga A-G
Tioga MCZ
391.4+/– 1.8 Ma
Sprout Brook
408.3+/– 1.9 Ma
Bald Hill
417.6+/– 1.0 Ma

TABLE 1. RECENT DEVONIAN TIME SCALES

Stage (or period) boundaries	Tucker et al. (1998) Age	Kaufmann (2006) Age	Ogg et al. (2008) Age
Famennian–Tournaisian (= Dev–Carb boundary)	362 Ma	360.7 ± 2.7 Ma	359.2 Ma
Frasnian–Famennian	376.5 Ma	376.1 ± 3.6 Ma	374.5 Ma
Givetian–Frasnian	382.5 Ma	383.7 ± 3.1 Ma	385.3 Ma
Eifelian–Givetian	387.5 Ma	388.1 ± 2.6 Ma	391.8 Ma
Emsian–Eifelian	394 Ma	391.9 ± 3.4 Ma	397.5 Ma
Pragian–Emsian	409.5 Ma	409.1 ± 3.8 Ma	407.0 Ma
Lochkovian–Pragian	413.5 Ma	412.3 ± 3.5 Ma	411.2 Ma
Pridolian–Lochkovian (= Sil–Dev boundary)	418 Ma	418.1 ± 3.0 Ma	416.0 Ma

Note: Ogg et al. (2008) time scale places the base of the Givetian Stage at a time older than geochronologic age dates for the lower Eifelian Tioga Middle Coarse Zone (391.4 ± 1.8 Ma; Tucker et al., 1998) and the Tioga B K-bentonite (390 ± 0.5 Ma; Roden et al., 1990).

gradation of a major clastic wedge, associated with decreased subsidence and increased sediment transport in the basin; (3) development of a regional unconformity, which Ettensohn (1985) interpreted as associated with the main collisional event; and (4) a return to the first stage (1) or a period of tectonic quiescence marked by widespread carbonate deposition ("stage 4").

Ettensohn (1985) recognized four Acadian tectophases: Tectophase I, Emsian to Lower Eifelian deposition of the Esopus, Schoharie, and Onondaga Formations of New York, New Jersey, and eastern Pennsylvania; and the Needmore Formation of Pennsylvania (upper Lower and lower Middle Devonian); Tectophase II, Upper Eifelian to mid-Givetian deposition of the Hamilton Group and Tully Formation of New York and equivalent strata in Pennsylvania and southward (Middle Devonian); and Tectophase III, Upper Givetian to Famennian Geneseo Formation to Riceville and higher formations in New York, and equivalent strata basinwide (upper Middle Devonian to Upper Devonian). Ettensohn's (1985) projected fourth, Mississippian-age tectophase consists of strata assigned to the Sunbury black shale and overlying Pocono, Borden, and associated clastics that prograded as far west as the Illinois Basin (Matchen and Kammer, 1994).

RESULTS

Sedimentation

Changes in foreland basin sedimentation over time provide key insights into foreland basin and orogenic processes and events. This includes patterns of carbonate versus clastic deposition, and variations in their facies, distribution, geometry, and composition through time and space. These can be interpreted to reflect episodes of tectonic activity versus quiescence, crustal loading and flexure, and erosion and unroofing.

Sediment Type, Magnafacies, and Depositional Trends

Devonian strata of the northern Appalachian basin consist of a mix of carbonates, clastics (including black shales), and mixed clastics-carbonates, along with other, less common lithologies (e.g., chert-rich facies; Figs. 3 and 4). Thick fluvial-dominated terrestrial strata in the Catskill Mountains of eastern New York characterize middle to upper strata in proximal areas of the basin; lower and more distal strata across the state are largely of marine origin. A cross section of Devonian strata across New York and northern Pennsylvania, roughly perpendicular to the strike of the basin and the orogen, is shown in Figure 4.

A macroscale perspective of the Upper Silurian to Devonian succession in the northern Appalachian basin can be seen as four separate depositional phases (similar to the approach of Johnson, 1971; see Fig. 4): phase 1—carbonates, succeeded by an unconformity and quartz arenites with minor carbonates (Upper Silurian Pridoli age through Devonian Lochkovian to Pragian stages, ca. 420–409 Ma). In New York, the strata include the Rondout Formation, the Helderberg Group, the Wallbridge unconformity, and the Oriskany Sandstone. Phase 2—A lower, relatively thin package of basinal clastics in proximal parts of basin is succeeded by mixed clastics and carbonates, and then carbonates (Emsian to lower Eifelian, ca. 409–390 Ma). In New York, these include the Esopus, Schoharie, and Onondaga Formations. Phase 3—A second, thicker package of basinal clastics is succeeded in distal areas of the basin by mixed clastic and carbonates. This is, in turn, succeeded by shallow-marine carbonates; in proximally preserved areas (eastern New York), clastic sediments overfill the basin to above sea level (Upper Eifelian to mid-Givetian, ca. 390–385 Ma). In New York, these strata include the Hamilton Group, Tully Limestone, and lower fluvial-dominated strata in the Catskill Mountains. Phase 4—A third, major package of basinal clastics is gradually succeeded by a progradational, shallowing-up succession of coarser clastics (Upper Givetian to Upper Famennian ± Lower Mississippian, ca. 385–360 Ma). In New York, these include marine strata of the Genesee to Conewango Groups, and time-correlative, proximal terrestrial facies. At the macroscale, all synorogenic clastic magnafacies step cratonward through time (Fig. 4).

Sediment Geometry

The geometry of upper Lower to Middle Devonian strata across New York, approximately perpendicular to the strike of the basin and orogen, undergoes distinct changes through depositional cycles 2 and 3 (Fig. 5). Relatively deep-water, basinal strata

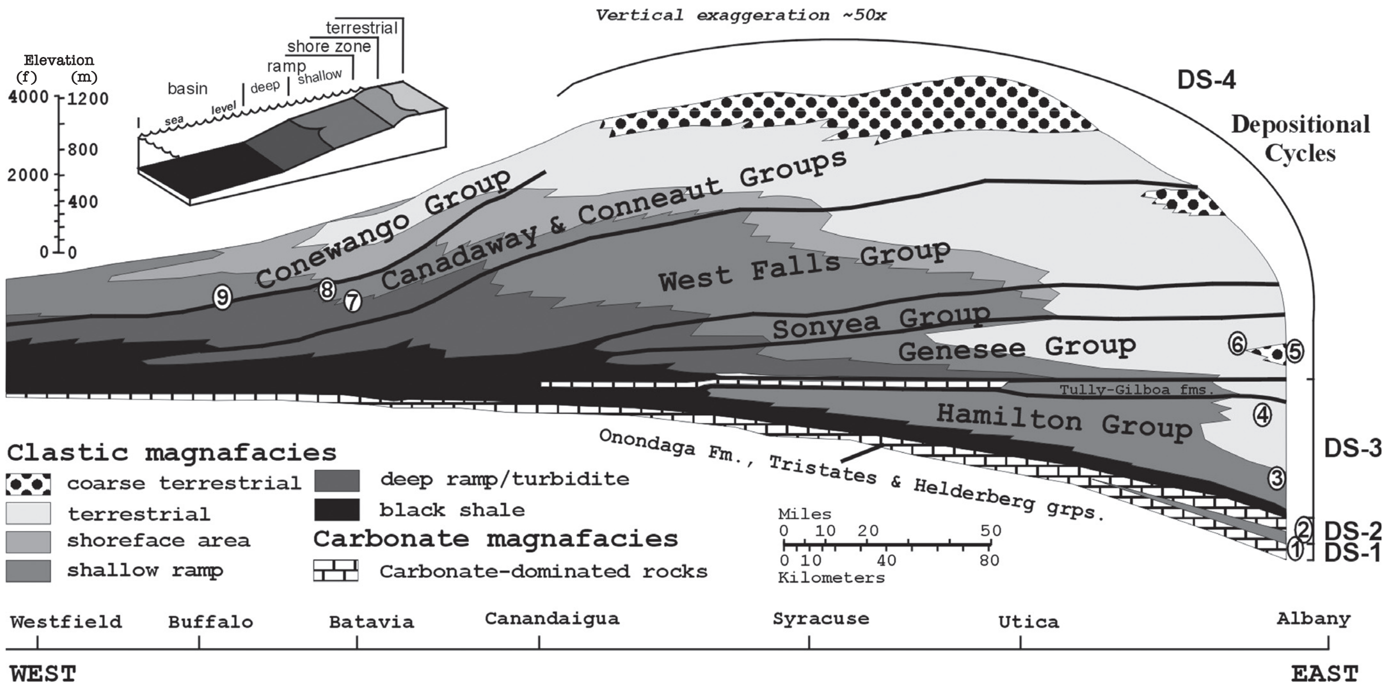

Figure 4. Cross section of Devonian strata, northern Appalachian Basin, New York and northern Pennsylvania. Cross section shows thickness of preserved Devonian strata roughly perpendicular to strike of the basin and the Acadian orogenic belt. Vertical exaggeration ~50×; horizontal distance is >350 km. Figure is modified after Isachsen et al. (2000). Strata occur longitudinally at and/or south of the named cities. Circled numbers 1–9 denote position of conglomerate samples in this study. Boldface numerals 1–4 denote the four separate depositional cycles discussed in this paper.

(Esopus, Union Springs, and Oatka Creek–Mount Marion Formations) have a prominent wedge-shaped geometry, thickening toward the orogen, and a relatively restricted distribution. In contrast, shallow-water carbonates (Onondaga and Tully limestones), and to some degree the quartz arenites at the top of depositional cycle 1 (Oriskany Formation), have a distinct widespread and relatively tabular distribution across the basin transect. Between the basinal clastics and carbonates, intervening transitional strata (Schoharie Formation, and Skaneateles, Ludlowville, and Moscow Formations) have an intermediate geometry and distribution.

Conglomerates: New Results

Conglomerates and breccias form a small amount of foreland basin fill, yet they provide key information about tectonic setting, provenance and unroofing history, and depositional environments. For this paper, clast composition was determined for nine conglomerate beds spanning ~40 m.y. during the Acadian orogeny (Upper Pragian to Middle Famennian stages, ca. 410–370 Ma). Compositions were generally determined using a standard 100 clast count method under a binocular microscope. The six older samples come from relatively proximal strata in eastern New York; the younger three samples come from more distal strata in the southwestern part of the state (Figs. 3 and 4).

The nine conglomerates selected for study are characterized by extraformational, synorogenic clastic pebbles (e.g., quartz, chert, sandstone). In contrast, many conglomerates through the succession feature intraformational clasts (e.g., sideritic or phosphatic nodules, reworked mud clasts, and pedogenic carbonate nodules), often totaling 100% of clasts. The older and younger beds analyzed here are oligomictic in composition, characterized by dominantly milky quartz pebbles. The intervening beds have a petromict (polymict) character, with more diverse clast types including prelithified sandstone/siltstone and/or chert pebbles. Clast types include macrocrystalline (milky) quartz, chert, sandstone/siltstone/quartzite, intraformational clasts (listed above), fossils, and unidentified clasts. Some marine samples also contain shelly fossils; Sample 7 also yielded cobble-sized plant stem fossils and granule- to pebble-sized Upper Devonian charcoal.

The beds were variously deposited in shallow-marine to fluvial environments. Most of the samples are paraconglomerates, with a significant amount of finer-grained (sand- to clay-sized) matrix. Clasts are dominantly pebble sized; some beds also contain some cobbles, and sample 2 is dominated by smaller granules. Clasts in all samples appear well rounded; most are spherical in shape, with some tabular forms in samples 4, 5, and 6.

Results of compositional analyses for each conglomerate bed are shown in Table 2. The conglomerates consist of a vertical succession of initially pure milky (vein) quartz pebbles (samples 1–2, ca. 410–395 Ma), and an intermediate set of mixed compositions, dominated by milky quartz, sandstones (unaltered to slightly metamorphosed), and cherts (samples 3–6, ca. 388–380 Ma). The uppermost set of conglomerates, from western New York, return to milky quartz-dominated clast compositions (samples 7–9, ca. 375–365 Ma). Through the

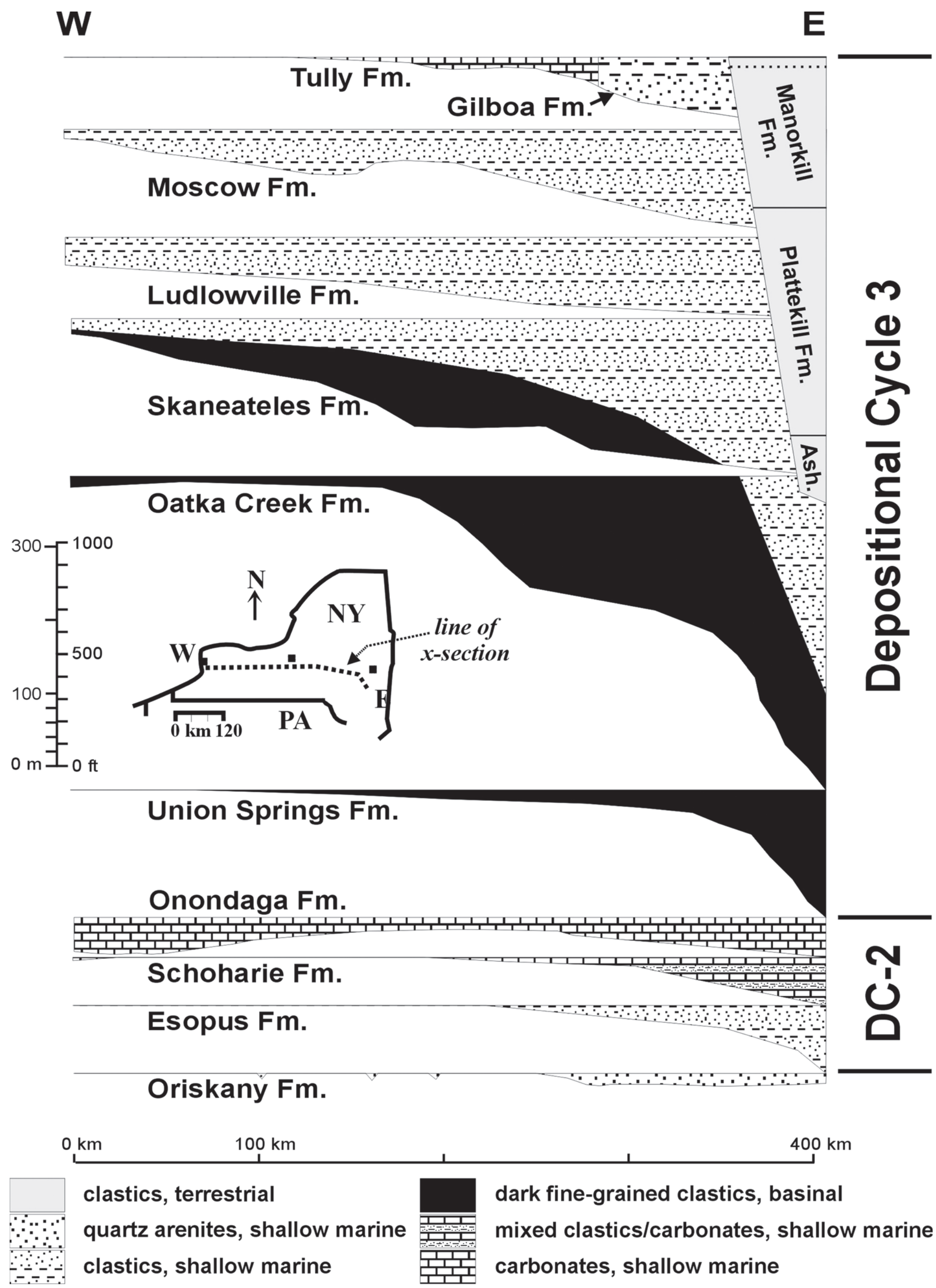

Figure 5. Stratal geometry of upper Lower and Middle Devonian units, New York, showing geometry and generalized facies of strata along the New York outcrop belt between Kingston (southeast) and Buffalo (west). Vertical axis—thickness; horizontal axis—geographic line of cross section on map. Shaded areas denote stratal thickness, by formation; straight lines at top of shaded areas—datum at top of each formation. Note relatively tabular geometry of the Onondaga and Tully Formations, in contrast with the Esopus, Union Springs, and Oatka Creek–Mount Marion formations. Ash.—Ashokan Formation. Figure is modified from Ver Straeten and Brett (1995), with additional data from Rickard (1989; Oatka Creek to Moscow Formations) and Heckel (1973; Tully Formation).

TABLE 2. COMPOSITION OF SOME DEVONIAN CONGLOMERATES, NEW YORK STATE

Sample number	1	2	3	4	5	6	7	8	9
Sample (100 count analysis, or %)	Connelly Cgl.	Kanouse SS	Upper Mt. Marion Fm.	Basal Moscow Fm.	Twilight Park Cgl. (% of 400 clasts)	Cgl., top of Platte Clove	Avg. cgl comp. Rushford Fm	Low Cattaraugus Fm. cgl., Alma	Wolf Creek Cgl.
Age	Upper Pragian	Basal Eifelian	Lower Givetian	Mid-Givetian	~Lower Frasnian	~Lower Frasnian	Lower Famennian	Mid-Famennian	Mid-Famennian
Vein quartz	100	100	40	56	66%	47	*	83	98
Greenish quartz	*	*	1	13	*	2	*	*	*
Total quartz[3]	*	*	*	*	*	*	87%	*	*
Gray chert	*	*	25	*	*	*	*	*	*
Lt-gray, white chert	*	*	3	1	*	*	*	*	1?
Dark-gray chert	*	*	12	*	*	*	*	*	*
Black chert	*	*	3	*	*	*	*	*	*
Banded gray chert	*	*	1	*	*	*	*	*	*
Red chert/jasper	*	*	*	*	1%	2	*	*	p
Sandstone/quartzite	*	*	6	10	30.5%	49	*	*	*
Siltstone	*	*	*	17	1.5%	*	*	*	*
"Lithic fragments"	*	*	*	*	*	*	4%	*	*
Feldspar	*	*	*	*	*	*	2%	*	*
Mica	*	*	*	*	*	*	3%	*	*
Opaques	*	*	*	*	*	*	2%	*	*
Calcite	*	*	*	*	*	*	2%	*	*
Clay-rich clast	*	*	*	*	*	*	*	*	*
Calc. nodule clast	*	*	*	1	*	*	*	*	*
Pyrite nodule clast	*	*	*	1	*	*	*	*	*
Siderite nod. clast	*	*	*	*	0.5%	*	*	*	*
Limonite nod. clast	*	*	*	1	*	*	*	*	*
Hematite, SS matrix	*	*	*	*	*	*	*	16	*
Marine shells	*	*	c	c	*	*	c	*	*
Fish bone	*	*	*	*	*	*	*	1	*
Fossil wood	*	*	*	*	*	*	*	p	*
Fossil charcoal	*	*	*	*	*	*	*	p	*
Unidentified	*	*	9	*	0.5%	*	*	*	1

Note: Results are based on composition of 100 clasts, except in sample 5. Sample 7—mean clast composition of 11 conglomerates from the Rushford Formation (from Smith and Jacobi, 1998). In Sample 7, clast types between 2–4% probably = sand-size grains. Sample 9 is from unknown locality, in New York State Museum collections. c—common; p—present; *—absent.

intermediate mixed-composition set, the lower bed of chert–milky quartz–minor sandstone clasts is succeeded by beds with milky quartz and increasing sandstone clasts, and a steep decline in chert content.

Anomalous Stratigraphic Patterns

The Devonian succession in the northern Appalachian basin features a number of locally to regionally developed stratigraphic anomalies. Lateral shifts of facies belts, depocenters, basinal troughs and highs, and unconformities through time, the development of pinnacle reefs in basinal environments, and other nonpredictive stratal trends indicate that processes other than eustatic sea-level rise and fall and progradational infilling were active at times in the basin's history. This section examines some of these anomalies.

Ordovician to Devonian Basin Cross-Sectional History

Figure 6 presents an east-west, time-rock cross section of Upper Ordovician to Mississippian magnafacies across the northern part of the Appalachian basin in New York. Darkest colors represent basinal environments/magnafacies, which grade through gray scale to the lightest color, representative of terrestrial magnafacies. White areas mark unconformities. The distribution of rock and facies shifts laterally through the vertical scale of time.

Upper Ordovician ramp carbonates, succeeded by progressively westward shifts of basinal to shallow-marine to terrestrial facies, mark the Taconic phase of the Taconian orogeny. A prominent unconformity marks the top of the Ordovician (eustatic Cherokee unconformity), which expands to the east (tectonic Taconic unconformity). Initial Silurian deposition on the western margin of the transect shifts toward central New York through much of the Silurian. Wenlock-age clastics (e.g.,

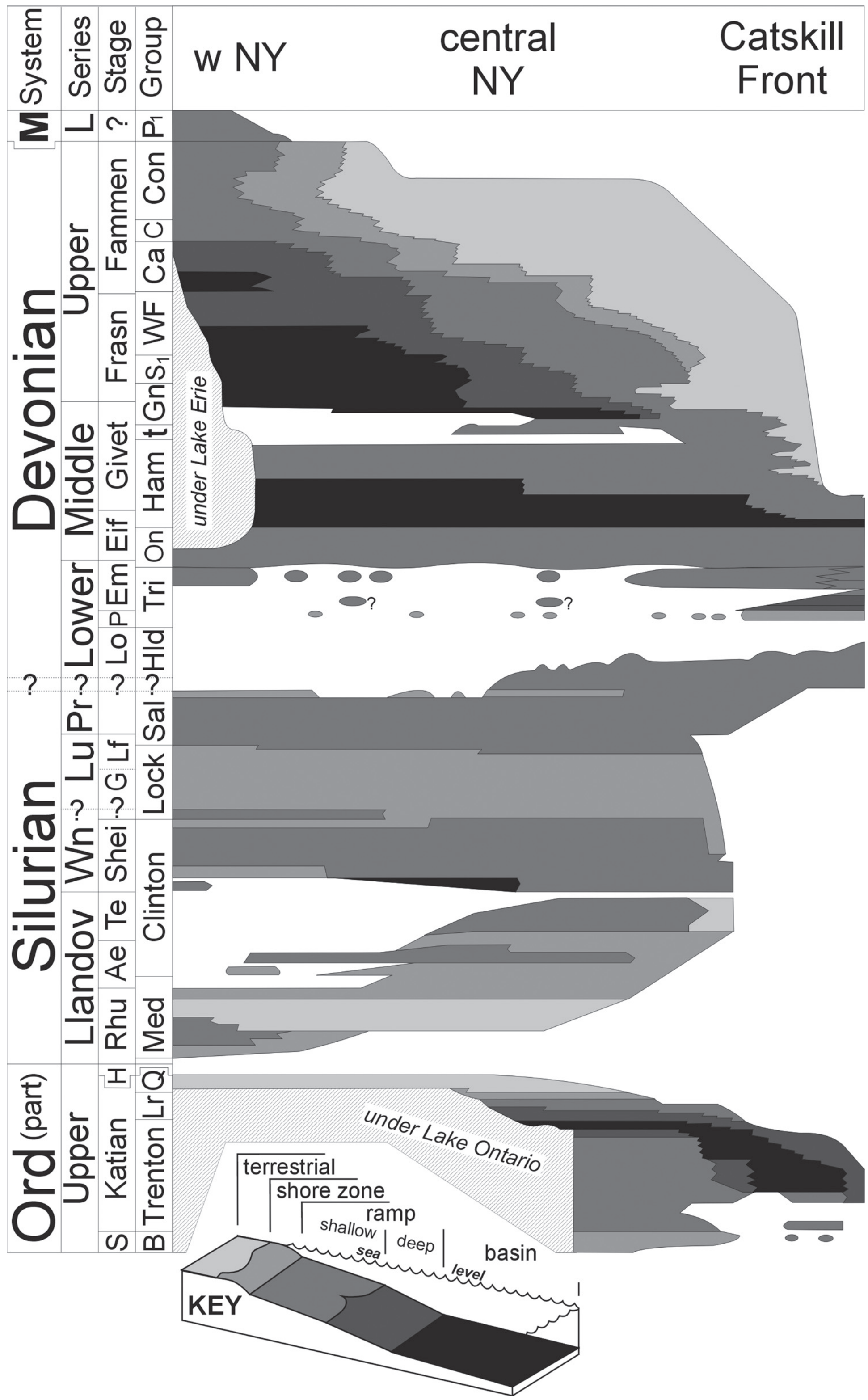

Figure 6. Upper Ordovician to Mississippian cross section, New York State. Generalized time-rock cross section, perpendicular to the strike of the Appalachian basin, shows the distribution of basinal to terrestrial magnafacies. Horizontal distance is ~350 km. Note that the vertical axis (= time) is not scaled similarly between the Upper Ordovician (~12 m.y.), Silurian (~26 m.y.), and Devonian (~58 m.y.), nor calibrated to recent geologic time scales. Figure is modified after Rogers et al. (1990) and Ver Straeten (2007; Emsian and Eifelian Stages). Abbreviations: Ae—Aeronian; B—Black River; C—Conneaut; Ca—Canadaway; Con—Conewango; Eif—Eifelian; Em—Emsian; Fammen—Famennian; Frasn—Frasnian; G—Gorstian; Givet—Givetian; Gn—Genesee; H—Hirnantian; Ham—Hamilton; Hld—Helderberg; L—Lower; Lf—Ludfordian; Llandov—Llandovery; Lo—Lochkovian; Lock—Lockport; Lr—Lorraine; Lu—Ludlow; Med—Medina; On—Onondaga Formation; P—Pragian; P_1—Pocono; Pr—Pridoli; Q—Queenston Formation; Rhu—Rhuddanian; S—Sandbian; S_1—Sonyea; Sal—Salina; Shei—Sheinwoodian; t—Tully; Te—Telychian; Tri—Tristates; WF—West Falls; Wn—Wenlock; groups not shown for Rondout and Tully formations. Stages: stage not shown—Homerian; no stages within Pridoli Series.

Rochester Shale), which are synorogenic clastics derived from the Salinic orogeny.

A short distance below the Silurian-Devonian boundary, subtly beginning at about the Ludlow-Pridoli boundary (Upper Silurian), the rock record undergoes a distinct eastward shift. Finer-scale facies (not shown in Fig. 6) indicate the development of relatively deeper-water "shelf" facies to the east-southeast in New York, in the formerly elevated area of the Taconic unconformity. Facies presumably continued to deepen beyond the eastern preserved margin of the Appalachian basin, into Lower Devonian deep-water flysch facies developed in New England (e.g., Littleton Formation).

A major hiatus characterizes much of the Lower Devonian (Wallbridge unconformity of Sloss, 1963; Figs. 4, 5, and 6) across central to western New York. In eastern New York, a thin wedge of the unconformity is succeeded by proximally deposited strata (Oriskany through Schoharie Formations; Fig. 5). A return to relatively shallow carbonate ramp basin architecture across the entire cross section in the Lower Eifelian Stage (Onondaga Formation) is succeeded by a return to basinal (black shale) facies, soon followed by progressive progradation of synorogenic clastics into the eastern margin of the basin. These clastics soon after overfill the preserved proximal margin of the basin in the Catskill Mountains of eastern New York. The development of another relatively broad unconformity in the late Givetian Stage coincides with another significant Devonian sea-level lowstand and carbonate deposition (Tully Formation). A succeeding sediment-starved flooding unconformity, reestablishment of basinal facies, and black shale deposition mark latest Middle Devonian strata. Overlying Upper Devonian magnafacies patterns show an overall continuation of progradational overfilling of the foreland basin and stepped cratonward migration of all magnafacies (Fig. 6).

Lesser Stratigraphic Anomalies

Eustatic sea-level changes result in synchronous global patterns of sea-level rise and fall. The fact that many Devonian sea-level cycles and depositional sequences in the Appalachian basin have been correlated outside the basin (Johnson et al., 1985; House and Kirchgasser, 1993; Bartholomew, 2006; Ver Straeten, 2009b) indicates that eustasy exerted a strong level of control on sea-level changes in the basin. However, there are locally developed stratal anomalies through the foreland basin fill indicative of tectonic-induced flexure. In this section, we review six specific cases of local to regional trends in litho- and biofacies, stratal distribution, and other proxies for relative sea level that vary from otherwise basinwide patterns. There are many gaps in this record—these represent snapshots of foreland basin kinematics through time.

Stratigraphic Anomaly 1. Ebert and Matteson (2003) reported cryptic unconformities in Upper Silurian–Lower Devonian strata (Manlius and Coeymans Formations) in New York. These regionally angular surfaces erosionally bevel underlying strata in patterns not possible by eustatic sea-level fluctuations. Facies changes through the succession indicate retrograde, toward-the-orogen migration of erosional diastems and deeper-water facies through this time.

Ebert and Matteson (2003) attributed these trends to regional tilting, or the migration of a forebulge or bulge-like features. The latter fits best with their interpretation of the coeval migration of deeper-water environments toward the orogen below and across the Silurian-Devonian boundary, at ca. 418 Ma.

Stratigraphic Anomaly 2. Upper Pragian to Lower Eifelian strata in New York, deposited between ca. 410 and 392 Ma, are characterized by the following succession (Figs. 3 and 5): (1) apparent widespread shallow-marine deposition (upper Pragian Oriskany Sandstone, and minor carbonates); (2) a narrow band of deep-water facies in proximal areas of eastern New York (lower Emsian Esopus Formation), and a broad cratonward unconformity across central to western New York; (3) somewhat more broadly distributed mixed clastic and carbonate facies and fully carbonate facies of intermediate water depths to the east and west, and a spotty occurrence over an unconformity in central New York (upper Emsian Schoharie and equivalent Bois Blanc Formations); and (4) widespread shallow-marine carbonate deposition (lower Eifelian Onondaga Limestone) across the New York cross section (Rickard, 1975; Ver Straeten and Brett, 1995; Ver Straeten, 1996, 2007).

A patchy but broad distribution of Oriskany quartz arenites across eastern to central New York, and their reworking into post-Oriskany Emsian to lowest Eifelian strata across New York (Rickard, 1975; Brett and Ver Straeten, 1994; Brett et al., 2000) indicate their more widespread distribution at the time of deposition (Figs. 3 and 5). This is in contrast to the narrowly restricted distribution of deeper water shales, siltstones, and fine-grained sandstones of the lower Emsian Esopus Formation (Figs. 3 and 5). Top-down erosion of the Esopus beneath a sub-Schoharie unconformity indicates that it originally had a more westward distribution beyond east-central New York.

In summary, this succession indicates a relatively level basin topography in the late Pragian that was succeeded by early Emsian subsidence of the foredeep to the east, and possibly delayed uplift of the forebulge to the west. Through the late Emsian to early Eifelian, basin topography progressively flattened out again, possibly due to both erosional beveling and subsidence of the forebulge. In the early Eifelian, no prominent foredeep or forebulge was apparent in the Appalachian basin cross section.

Stratigraphic Anomaly 3. Ver Straeten and Brett (2000) and Brett et al. (2000) noted anomalous, local patterns of facies change through time in Upper Emsian and Lower Eifelian strata of the Bois Blanc (=Schoharie) and lower Onondaga formations in central to western New York (Fig. 7). Abnormal stratal patterns observed include: eastward migration of locally developed shallow-marine carbonate lithofacies and adjacent cratonward deeper-water facies, and their associated biofacies through time (Fig. 7A); development of a linear trend of pinnacle reefs in

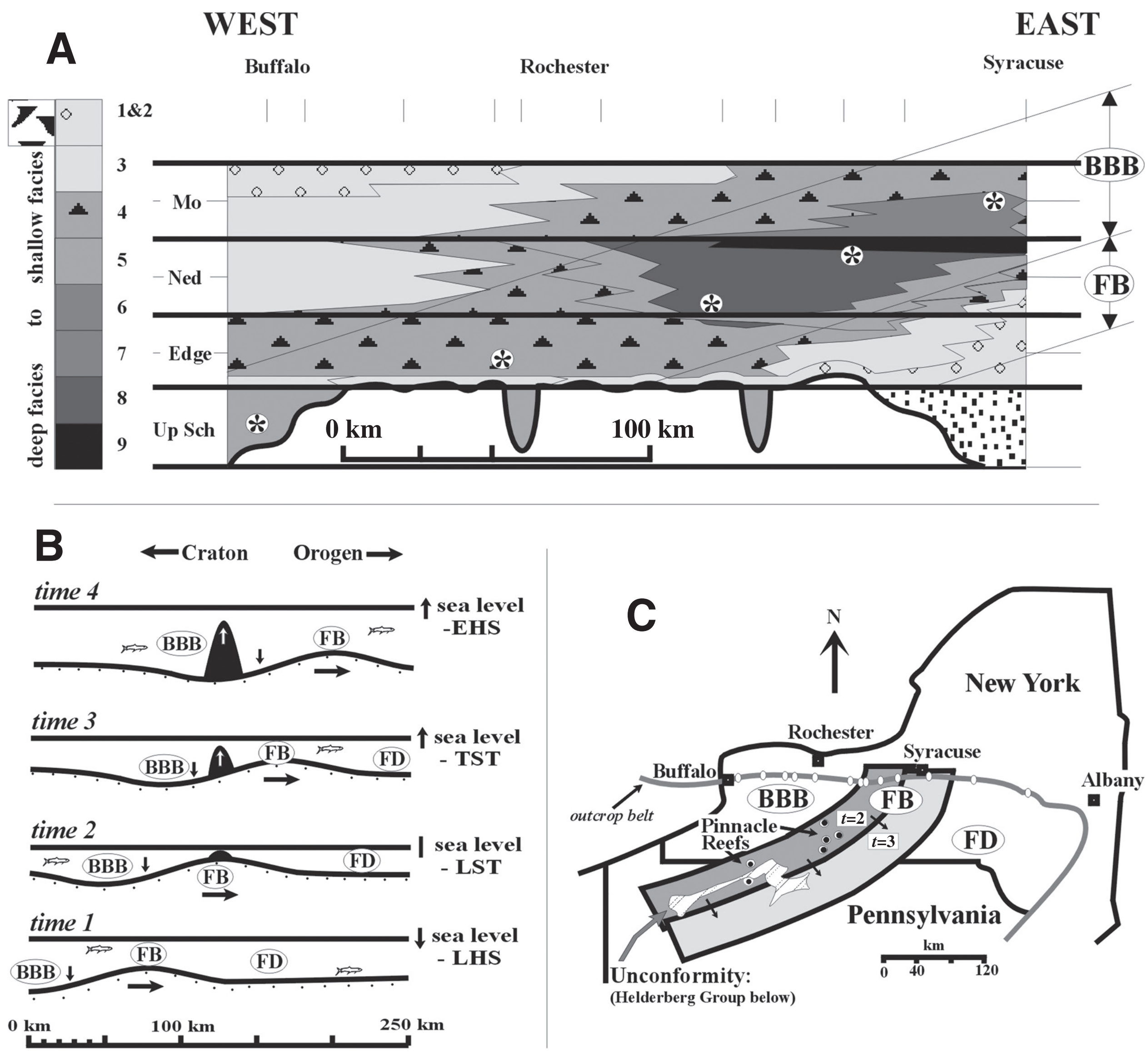

Figure 7. Stratigraphic Anomaly 3, upper Emsian and lower Eifelian strata, western to central New York. Figure illustrates anomalous facies patterns and interpretations of Ver Straeten and Brett (2000). The patterns outline orogenward migration of bulge- and back-bulge basin–like features in uppermost Emsian and lower Eifelian strata, during late stage of depositional cycle 2. BBB—back-bulge basin, FB—forebulge, and FD—foredeep portions of foreland basin system. (A) Facies cross section, upper Bois Blanc and Onondaga Formations, western to central New York; relative depth of facies is shown in side column key. Series of stars indicate geographic position of relatively shallowest water conditions within each time slice. (B) Model for development of Onondaga pinnacle reef in basinal environments. During sea-level lowstand, reef facies developed on bulge within the deep basin. As bulge migrated toward the orogen, reefs underwent rapid "catch-up" growth as eustatic sea level rose, and they subsided into a back-bulge basin. EHS—early highstand systems tract, LHS—late highstand systems tract, LST—lowstand sytems tract, TST—transgressive systems tract of sequence stratigraphy. (C) Map showing distribution, scale, and migration of bulge and cratonward basin during second and third time slices in A (after Ver Straeten and Brett, 2000).

basinal environments (Fig. 7B); and other patterns (Ver Straeten and Brett, 2000; Brett et al., 2000). These trends indicate locally varying water depth changes and inversions of topography through the late Emsian and early Eifelian. These local variations contrast with the record of relative sea-level change throughout the rest of the Appalachian basin at that time (Ver Straeten, 2007).

These trends were interpreted by Ver Straeten and Brett (2000) to indicate the retrograde, orogenward migration of coupled forebulge- and back-bulge basin–like features (Fig. 7C). The relatively small size of the bulge (~80–100 km wide, 20–50 m positive relief), its projected possible distance from the Acadian deformation front at that time, and the lack of a well-defined foredeep in the basin at that time led Ver Straeten and Brett (2000) to speculate that it might represent a smaller-scale flexural "welt."

Stratigraphic Anomaly 4. In western to central New York, the upper part of the shallow-marine Onondaga Limestone (Seneca Member) is fully present. Into eastern New York, the Seneca Member thins; top-down disappearance of Tioga A-G K-bentonites through the member indicates progressive absence of Seneca strata to the east, under a transgressive flooding unconformity. Overlying black shales were deposited in deep-water facies of the foreland basin foredeep. The progressive loss of upper Onondaga strata to the east is interpreted to represent earlier subsidence of the basin closer to the orogen, followed by progressive cratonward migration of the distal margin of the foredeep.

Stratigraphic Anomaly 5. Ver Straeten et al. (1994) described another anomalous, local variation in sea-level trends in Upper Eifelian strata south of Rochester, New York. Throughout the Appalachian basin (New York to southwest Virginia to Ohio), thin carbonates of the Hurley and Cherry Valley Members (lower Oatka Creek Formation of New York) and equivalents represent a deepening-upward succession at the base of a major, third-order sea-level cycle (Ver Straeten et al., 1994; Brett and Baird, 1996; Ver Straeten, 2007). However, south of Rochester, the pattern is reversed: deeper-water facies of the Hurley Member are overlain by coarse-grained, shallow-marine limestones that deeply erode downward into underlying strata (Ver Straeten et al., 1994).

These patterns indicate a local inversion of water depths between deposition of the Hurley and Cherry Valley Members. This in only explainable by a local inversion of seafloor topography. Furthermore, to the west, the Cherry Valley Member rests directly on the Onondaga Formation, then pinches out across the remainder of western New York into Ontario, and reappears further to the west. These trends appear to indicate uplift of the forebulge in areas of the basin parallel to western New York and adjacent Ontario in the late Eifelian.

Stratigraphic Anomaly 6. Brett and Baird (1994), Heckel (1973), and Baird and Brett (2003) documented the movement of topographic features during deposition of upper Hamilton Group strata and overlying Tully Formation (Middle Devonian, mid-Givetian). Overall, the record indicates prograde, cratonward movement of features through to the top of the Hamilton Group, followed by a seemingly abrupt shift to retrograde, hinterlandward migration in the overlying Tully Formation.

In upper Hamilton strata (Upper Ludlowville and Moscow Formations), Brett and Baird (1994) tracked the cratonward movement of the axis of deeper-water environments and adjacent highs across central to western New York. In the overlying Tully Limestone, Heckel (1973) reported a "low anticline" and a cratonward deep-water sag that was bordered further cratonward by shallower, shelf-type facies. Close examination of his detailed facies maps indicates coupled bulge- and back-bulge basin–like features that migrated eastward toward the mountain belt during Tully deposition. Baird and Brett (2003) further supported Heckel's (1973) premise, and reported that the features extend southwestward into central Pennsylvania. The character and movement of these coupled bulge- and back-bulge basin–like features during deposition of the Tully Limestone are similar to those in Anomaly 3, described previously.

Volcanic Air-Fall Tephras in the Foreland Basin Fill

Although they make up a small part of the stratigraphic record, volcanic air-fall tephras are important key beds in sedimentary rock analyses. The widespread correlations of some air-fall tephras provide high-resolution timelines to analyze foreland basin responses (e.g., loading-induced flexure, changes in sedimentation regime) to orogenic activity. They also yield data on the timing and character of igneous activity in source areas, which can be of special significance adjacent to deeply eroded orogenic belts/magmatic arcs like the Acadian orogen.

In this paper, I use the term "tephra" for ancient air-fall beds of volcanic ash. The Devonian tephras in the Appalachian basin generally occur as clay-rich layers (K-bentonites), in which volcanic ash has been altered from volcanic glass to smectite to mixed-layer illite-smectite and potassium-rich illite clays (Weaver, 1963; Hosterman and Whitlow, 1983), with rare to common volcanic phenocrysts. Other tephras, alternatively, are coarse-grained layers ("tuffs") with abundant sand-sized phenocrysts.

Approximately 100 K-bentonites and tuffs are presently known from the Devonian of the Appalachian basin (Fig. 8; Table 3), i.e., many more than documented prior to 1970 (see references in Table 3). These include five clusters of 6–15 or more closely spaced beds, and additional beds that occur through the succession. Some tephras occur widely across the eastern United States (e.g., one or more beds of the Eifelian Tioga A-G zone, and the Frasnian Center Hill K-bentonite); others are only regionally to locally recognized. At present, tephras in Lower to Middle Devonian (Lochkovian through Eifelian) strata are better documented. Up to 50 K-bentonites and tuffs are known from the Eifelian (lower Middle Devonian). Other intervals have yielded few to no beds. Additional searches and documentation are needed through Upper Silurian and Givetian to Famennian strata.

Five major clusters of multiple tephras occur in the Appalachian basin succession (Figs. 8 and 9; Table 2): lower Lower Devonian Bald Hill K-bentonites (Lochkovian; 417.6 ± 1.0 Ma; Tucker et al., 1998); upper Lower Devonian Sprout Brook K-bentonites (lower Emsian; 408.3 ± 1.9 Ma; Tucker et al., 1998); lower Middle Devonian Tioga Middle Coarse Zone (lower Eifelian; 391.4 ± 1.8 Ma; Tucker et al., 1998); lower Middle Devonian Tioga A-G K-bentonites (mid-Eifelian; 390 ± 0.5 Ma; Roden et al., 1990); and the lower Upper Devonian Belpre K-bentonites (mid-Frasnian; 381.1 ± 1.3 Ma; Tucker et al. [1998], who mistakenly identified the dated bed as the Center Hill K-bentonite).

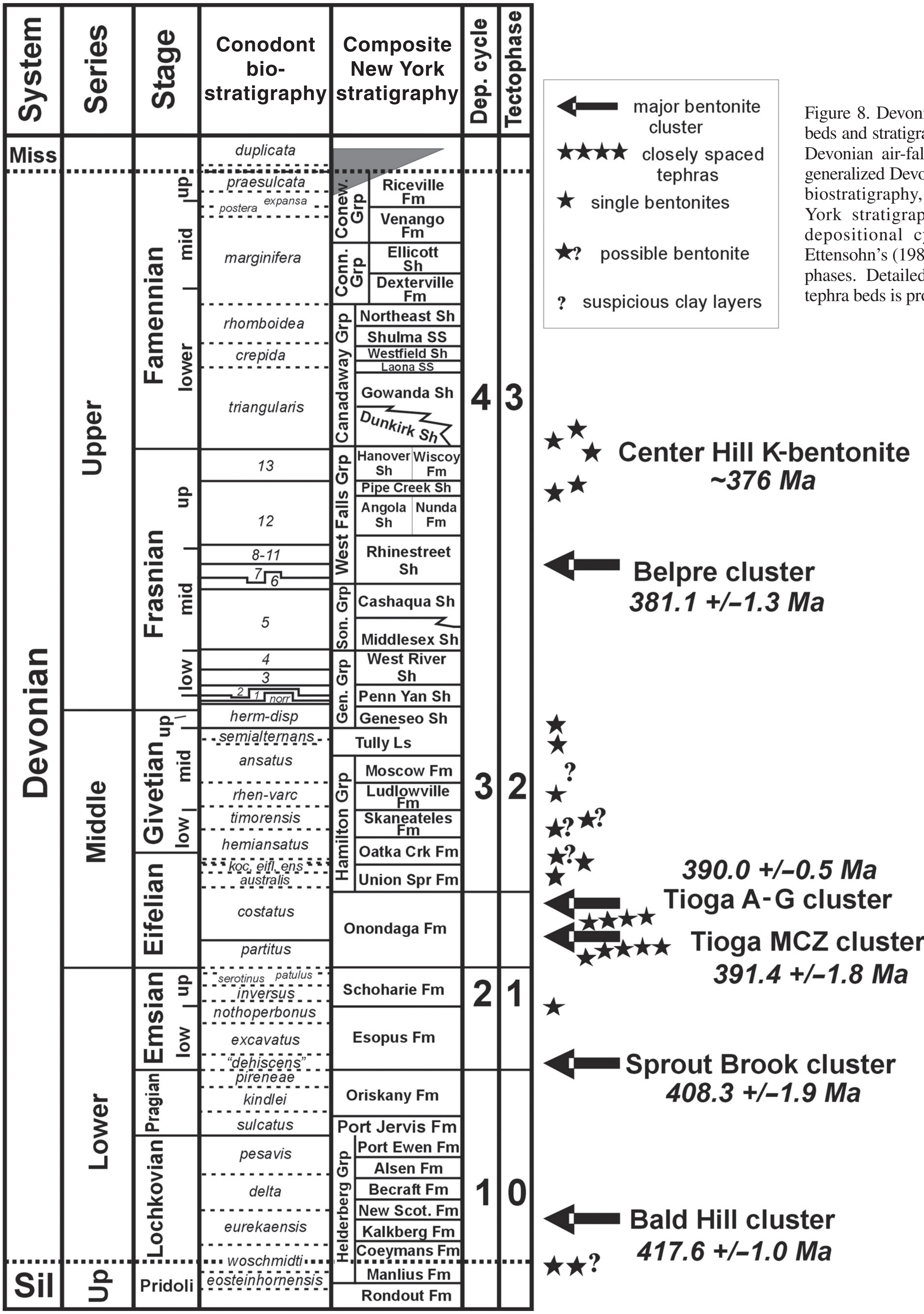

Figure 8. Devonian air-fall tephra beds and stratigraphy. Figure plots Devonian air-fall tephras against generalized Devonian stratigraphy, biostratigraphy, composite New York stratigraphic succession, depositional cycles 1–4, and Ettensohn's (1985) Acadian tectophases. Detailed information on tephra beds is provided in Table 4.

TABLE 3. DOCUMENTED UPPER SILURIAN–DEVONIAN AIR-FALL TEPHRAS, APPALACHIAN BASIN

Stage	Time*	Tephras	No. of beds documented	Geochron / approx. age	Units found in	Key recent sources
Famennian	384–361 Ma	Isolated beds	"A few"	"Close to 376 Ma"	Dunkirk Fm., NY; upper Olentangy Fm., OH	D.J. Over notes; Over and Rhodes (2000); Ver Straeten et al. (2007)
Frasnian	384–376 Ma	Center Hill K-bentonite	1	"Close to 376 Ma"	Upper Hanover Fm., NY; Chattanooga Fm. TN; & equivalents, MI, IA	Hass (1948); Conant and Swanson (1961); Roen and Hosterman (1982); D.J. Over notes; Over (2007)
		Belpre cluster	Up to 8	381.1 ± 1.3 Ma†	Rhinestreet Fm., NY; and equivalents across basin	Collins (1979); Roen and Hosterman (1982); Over (2007), notes; Ver Straeten et al. (2007)
		Additional beds	"A few"	Through Frasnian	Pipe Creek Fm., NY	D.J. Over notes; Over et al. (1998); Ver Straeten et al. (2007)
Givetian	388–384 Ma	Isolated beds	3	Through Givetian	Lower Geneseo Fm., NY	G.C. Baird, D.J. Over notes; Ver Straeten et al. (2007)
		Undocumented clay layers	Several	Through Givetian	Tully Fm., NY; Kashong-Windom mbr. contact, NY; Wanakah Mbr., NY; Butternut Mbr., NY; Otsego Mbr., NY	Batt (1996); Wilcott and Over (2005); G.C. Baird notes; Ver Straeten notes; Ver Straeten et al. (2007)
Eifelian	392–388 Ma	Tioga A-G cluster	Up to 11	390 ± 0.5 Ma§	Onondaga and Union Springs fms., NY; Selinsgrove and Marcellus fms., PA, MD, VA, WV; Columbus & Delaware fms., OH	Conkin and Conkin (1979, 1984); Smith and Way (1983); Way et al. (1986); Brett and Ver Straeten (1994); Ver Straeten (1996, 2004a, 2007)
		Tioga Middle Coarse Zone	Up to 32	391.4 ± 1.8 Ma†	Selinsgrove Mbr. equivalents, VA, WV	Dennison and Textoris (1970, 1978); Dennison (1983); Ver Straeten (2004a, 2007)
		Additional beds	~10	Through Eifelian	Onondaga and Union Springs fms., NY; base of Cherry Valley Mbr., NY; Selinsgrove Mbr. and Marcellus Fm., PA, MD, VA, WV; Columbus and Delaware fms., OH	Conkin and Conkin (1979, 1984); Hanson (1995); Ver Straeten (1996, 2004a, 2007); Ver Straeten notes
Emsian	409–392 Ma	Sprout Brook cluster	Up to 15	408.3 ± 1.9 Ma†	Esopus Fm., NY; Needmore Fm., VA?	Ver Straeten and Brett (1995); Hanson (1995); Ver Straeten (2004a, 2004b); Benedict (2004); Ver Straeten et al. (2005)
		Additional beds	2	Upper Emsian	Schoharie Fm., NY	Ver Straeten (2004a)
Pragian	412–409 Ma	None reported	0	0		
Lochkovian	418–412 Ma	Bald Hill cluster	Up to 15	417.6 ± 1.0 Ma†	Kalkberg & New Scotland fms. (NY); Corriganville & Mandata fms., PA, MD, VA, WV	Smith et al. (1988, 2003); Shaw et al. (1991); Hanson (1995); Ebert and Matteson (2003); Shaw (2003); Ver Straeten et al. (2005)
Pridoli (Silurian)	419–418 Ma		"A few"	"Close to 418 Ma"	Manlius Fm. (NY)	Ebert and Matteson (2003); P. Rubin (2007, personal commun.); Ver Straeten notes

Note: Various data on Devonian air-fall tephras from the Appalachian basin. Additional overviews are presented in Ver Straeten (2004a, 2007). *Key:* IA—Iowa; MD—Maryland; MI—Michigan; NY—New York; OH—Ohio; PA—Pennsylvania; TN—Tennessee; V—Virginia; WV—West Virginia.

*From Kaufmann (2006), except base of Pridoli from Tucker et al. (1998).

†From Tucker et al. (1998).

§From Roden et al. (1990).

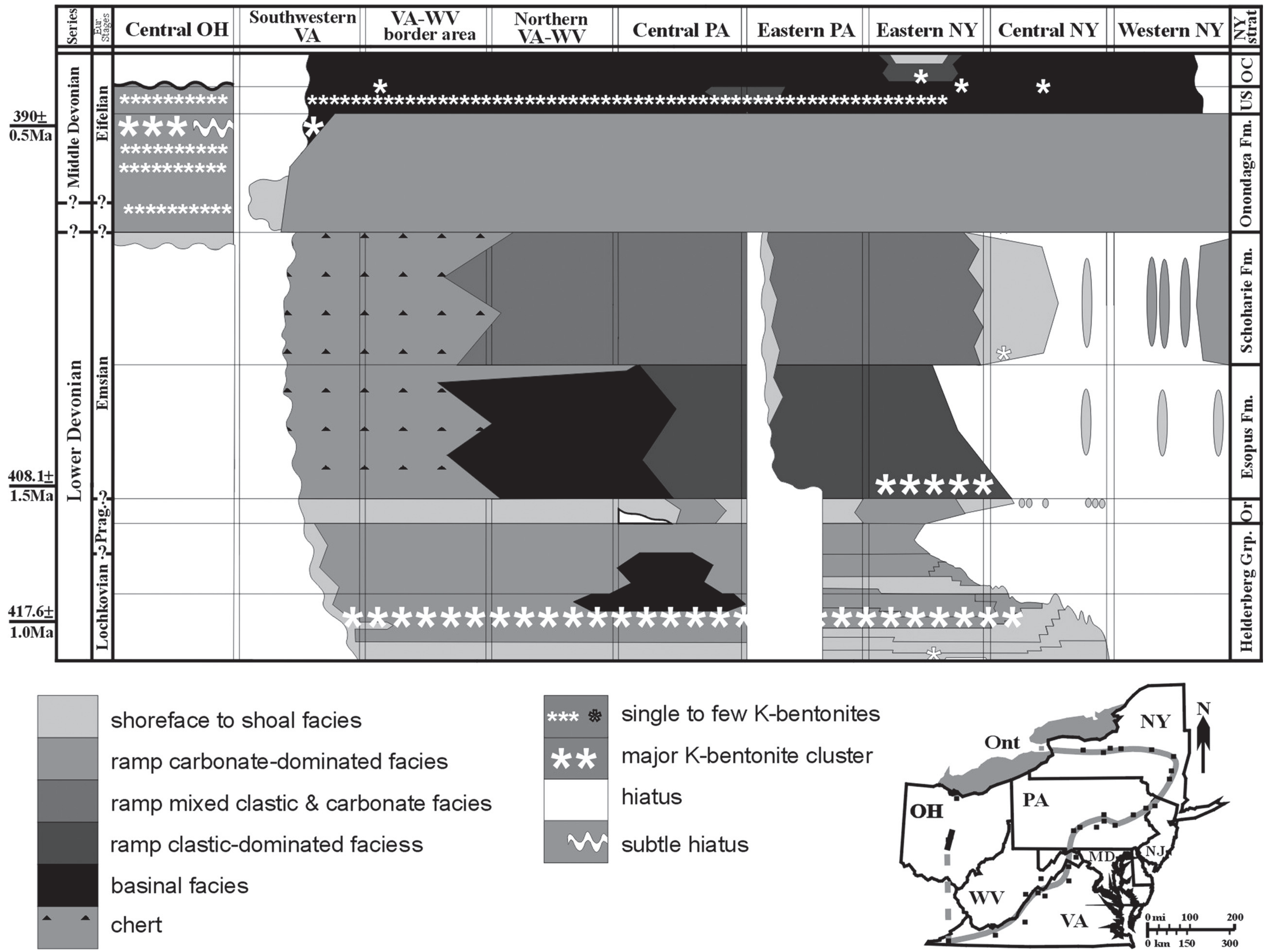

Figure 9. Time-rock distribution of Lochkovian to Eifelian air-fall tephra beds. Time and space distribution is shown for tephras and magnafacies through Lochkovian to Eifelian strata, Appalachian basin. Clusters of multiple tephras are marked by large asterisks. Single or a few closely spaced beds are marked by small asterisks. Tephras variously occur locally to widely across the basin. Abbreviations: Grp.—Group; MD—Maryland; NJ—New Jersey; NY—New York; OC—Oatka Creek; OH—Ohio; Ont—Ontario; Or—Oriskany; PA—Pennsylvania; Prag—Pragian; US—Union Springs; VA—Virginia; WV—West Virginia. Figure is modified after Ver Straeten (2004a).

The distribution of the four Lower to Middle Devonian clusters of air-fall tephras varies geographically (Figs. 9 and 10). The Bald Hill and Tioga A-G clusters occur widely across the basin (Smith et al., 1988, 2003; Way et al., 1986; Ver Straeten, 2004a). At least one bed, apparently of the Tioga A-G cluster, is reported as far west as the Illinois Basin (Collinson, 1968; Droste and Vitaliano, 1973). In contrast, the Emsian-age Sprout Brook and Eifelian-age Tioga Middle Coarse Zone clusters are restricted to the northern and southern parts of the basin, respectively (Ver Straeten, 2004a, 2004b). More data are needed on the Belpre cluster across the eastern United States.

Additional K-bentonite and tuff beds outside of the five major Devonian clusters occur throughout the Devonian strata in the Appalachian basin. These occur scattered between uppermost Silurian through Upper Devonian (Famennian-age) strata. For further information on all of the tephras, see Figures 8, 9, and 10 and Table 2 and references therein.

DISCUSSION

Before discussing the sedimentary record of Acadian orogenesis, a few older misconceptions need to be addressed. Researchers from the foreland basin have projected various Lower to Middle Devonian ages for the initiation of the Acadian orogeny (e.g., King, 1951; Boucot, 1962; Rodgers, 1967; Ettensohn, 1985; Boucot, 1993; Hamilton-Smith, 1993; Castle, 2001). It is now established that the Acadian orogeny began in Maine and New Brunswick in the Late Silurian (Ludlow-age), and earlier to the north in Maritime Canada (Bradley et al., 2000; van Staal, 2007; van Staal et al., 2009). The distinct shift of the Appalachian basin to the east across New York (Fig. 6), beginning at about the Ludlow-Pridoli boundary, likely reflects load-induced flexure at the onset of Acadian tectonism on the continental margin.

One of the issues that has led to these and other misconceptions about the Acadian orogeny is a failure to remember that the modern-day Appalachian basin is only a part of the greater Acadian foreland basin. The proximal portion of the Appalachian basin is largely eroded, and perhaps also covered by younger rocks in the central to southern Appalachians. In New England and into Canada, part of the greater Acadian foreland basin fill is preserved in thick, often highly deformed and metamorphosed strata (e.g., Littleton Formation, New Hampshire and Vermont).

Some authors have interpreted the Algonquin, Findlay, and Cincinnati arches to be the forebulge of the Acadian foreland basin system. Sometime in the late Middle to Late Devonian, the Acadian forebulge migrated into the position of these arches. However, early in the orogeny (early to middle phases of depositional cycle 1), the forebulge of the Acadian foreland basin was orogenward (to the east) of the present-day erosional edge of Devonian strata in eastern New York. Through depositional cycles 2–4, its overall motion toward the craton was interrupted by periods of retrograde movement and, as discussed below, episodes of leveling resulting in little to no apparent relief over the forebulge.

Implications of Data, Part I: Sedimentation Patterns and Depositional Cycles

Four Devonian Appalachian Basin Depositional Cycles and the Acadian Orogeny

Depositional trends of sediment type (carbonate–quartz arenite vs. detrital clastic), marine magnafacies (shallow vs. basinal), sediment geometry (tabular vs. wedge), and basin architecture (ramp vs. foredeep–forebulge–back-bulge basin) outline a cyclic series of sedimentary basin responses to tectonic events in the Acadian orogen. Upper Silurian through Devonian patterns can be delineated into four major Late Silurian to Late Devonian cyclic packages. These depositional cycles begin with early stage deposition of wedge-shaped packages of relatively deep-water, extrabasin-derived clastic sediments, which tend to be narrowly restricted toward the orogen. These early stage fine-grained strata were deposited in basinal settings. Middle-stage deposits are characterized by less distinctly wedge-shaped, intermediate-depth, more widespread facies, generally with increasing carbonate content. Late-stage intrabasinally derived carbonates ± quartz arenites include relatively widespread, shallow-marine facies with tabular geometries, deposited in broad, relatively shallow ramp settings.

Development of the first depositional cycle along the New York transect varies in several ways from these patterns. Basinal clastic facies, with their characteristic deep-water facies and wedge-shaped geometries are not developed in New York outcrops. The entire succession is dominated by carbonates, with a relatively tabular distribution (where not eroded below the Wallbridge unconformity).

The three latter depositional cycles were interpreted by Ettensohn (1985) to reflect tectonically active to quiescent phases (his tectophases I, II, and III) during the Acadian orogeny. The core of his model is built around: (1) The onset of tectonism and resulting subsidence of the basin foredeep, with deposition of the basinal dark gray to black shales; (2) subsequent progradation of clastics; and (3) a return to tectonic quiescence and deposition of carbonates. Overall, Ettensohn's basic model (1985) is a reasonable fit for explaining a large amount of data in the sedimentary basin fill. Closer examination of the rock record indicates that some components of the model do not work, however.

We now know that Acadian orogenesis began in the Late Silurian in Maine and adjacent areas and progressively migrated cratonward through the Early to Late Devonian (Bradley et al., 2000). The earlier initiation of the orogeny was not readily visible to Ettensohn (1985), whose data came from the eroded remnant of the greater Acadian foreland basin, in the Appalachian basin. Early in the Acadian event, the orogen, its deformational front, and most of the Acadian foreland basin system (wedge-top, foredeep, and forebulge of DeCelles and Giles, 1996) were still geographically positioned in New England to easternmost New York. During the initial stages of the Acadian orogeny (first depositional cycle of this paper), existing Devonian outcrops in eastern New York were geographically situated in the cratonward back-bulge basin of the foreland basin system, marked by deposition of the Rondout

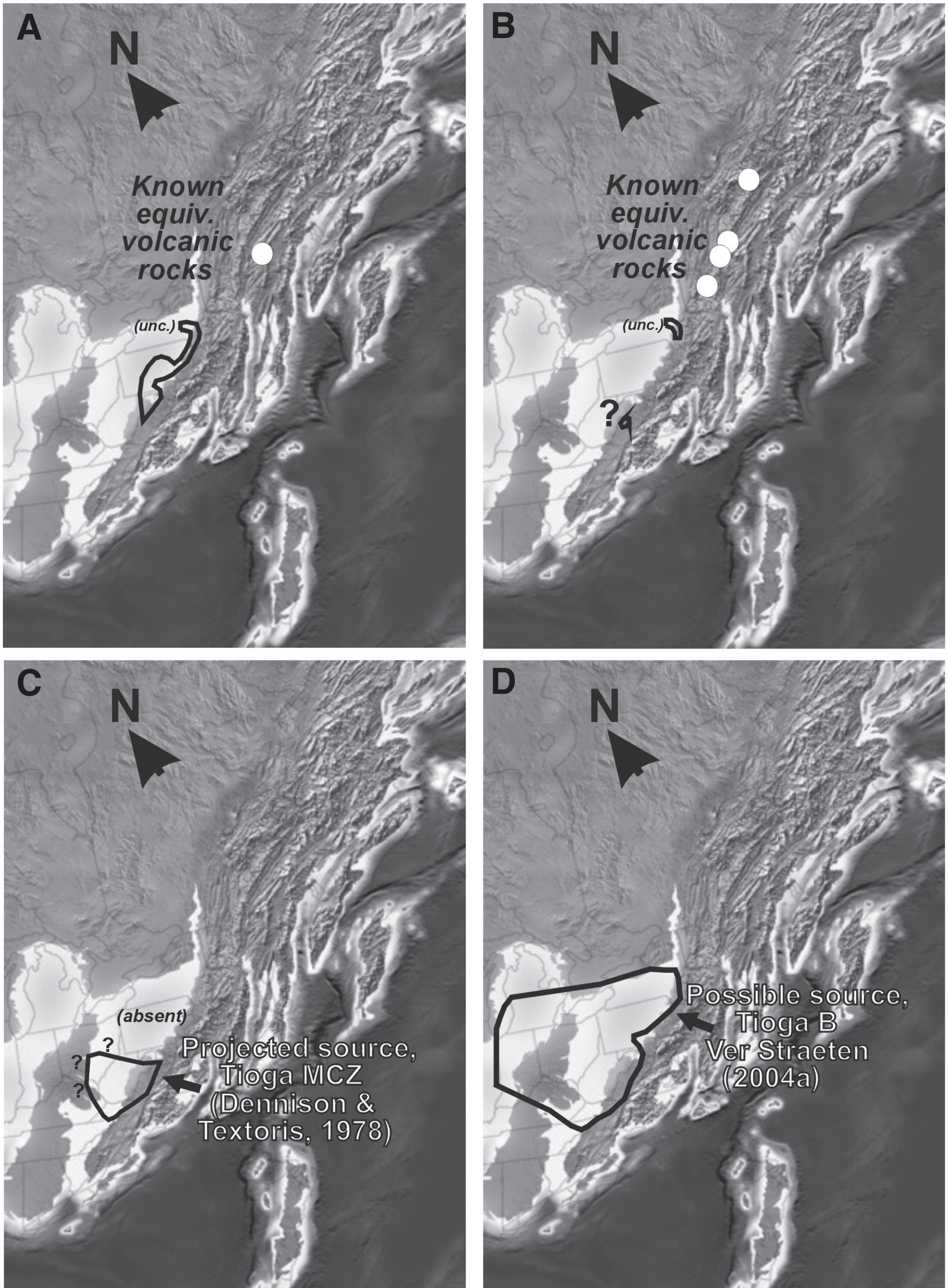

Figure 10. Lower to Middle Devonian tephra clusters, Appalachian basin, and possible source areas. Map distribution of the Bald Hill, Sprout Brook, Tioga Middle Coarse Zone (MCZ), and Tioga A-G tephra clusters are plotted over a paleogeographic map of eastern Laurentia in the Middle Devonian. Potential source areas in A and B are based on known age-equivalent volcanic and plutonic rocks in the Acadian orogen and greater Acadian foreland basin (sources in Table 4); projected source areas in C and D are after Dennison and Textoris (1978) and Ver Straeten (2004a). Abbreviation: unc.—unconformity. Base map is from Blakey (http://jan.ucc.nau.edu/~rcb7/namD385.jpg).

and Helderberg carbonates. Thick, correlative clastic successions in the early Acadian foredeep are preserved as thick, metamorphosed flysch units in northern New England (e.g., Lower Devonian Littleton Formation, Vermont and New Hampshire).

Using the recent Devonian time scale of Kaufmann (2006), which is close to the dates projected by Tucker et al. (1998), the three projected Devonian-age pulses of load-induced subsidence and dark/black shale deposition should fall at ca. 409, 390, and 384 Ma. A gradational return to carbonate deposition ending Ettensohn's (1985) tectophases I and II, interpreted to reflect quiescence and perhaps relative lowering of relief in the orogen, would have developed at or leading up to roughly 394 and 385 Ma. A similar return to relative quiescence in depositional cycle 1 may have occurred around 412 Ma.

Flexural Patterns and Depositional Cycles

Ordovician to Mississippian basin shifts. Major shifts of magnafacies and unconformities through the Middle Ordovician to Lower Mississippian across New York and northern Pennsylvania (Fig. 6) reflect the macroscale flexural history of the Appalachian basin between ~450 and 350 m.y. ago.

Following the Taconian orogeny, Late Ordovician to Late Silurian deposition (Fig. 6) was largely restricted to western and central New York. Overall, eastern New York remained elevated through this time due to flexural rebound of the area during erosional unloading of the Taconian orogen. Until the Late Silurian, the only deposits in southeastern New York (not visible in the cross section) were fluvially deposited quartz arenites and conglomerates of the Shawangunk Formation.

A notable shift of the basin toward the hinterland, beginning at the base of the Pridoli Series (ca. 420 Ma), marks the first major transgression over the Taconic unconformity in eastern New York. This subtle but major shift of subsidence toward the east is most likely a signature of load-induced crustal flexure with the initiation of the Acadian orogeny in the eastern United States. The timing of this event correlates with Bradley et al.'s (2000) onset of the Acadian orogen in Maine.

Carbonate deposition within the back-bulge basin extended through much of depositional cycle 1, above the Taconic unconformity. Subsequent development of the Wallbridge unconformity in the mid–Lower Devonian was related to both eustatic and flexural processes (see following discussion). Succeeding Devonian deposition consisted of three major packages of Acadian-derived clastics, alternating with two carbonate (±quartz arenite) packages (depositional cycles 2–4). The latter part of depositional cycle 4 extended into the Lower Mississippian, and is not discussed here.

Through the Middle to Late Devonian (depositional cycles 3 and 4), clastic sediments underwent progressive, if stepped, progradation toward the craton. Over time, Acadian-derived sediments overfilled the basin, and terrestrial environments extended nearly all across the New York basin transect by the end of the Devonian.

Sea-Level History and Basin Flexure

Johnson et al. (1985) outlined a Euramerican sea-level history for the Pragian to Famennian stages. Although modified some since its publication (e.g., Day et al., 1996; Day, 2006; Ver Straeten, 2009a), their interpretations still form the core outline of Devonian "third-order" cyclicity.

Utilizing the methods of sequence stratigraphy, the Appalachian basin Devonian has been subdivided into a series of third-order depositional sequences (e.g., Dorobek and Read, 1986; House and Kirchgasser, 1993; Brett and Baird, 1996; Filer, 2002; Ver Straeten, 2007, 2009b). These cycles/sequences are correlatable outside of the basin, into the cratonic basins of eastern North America, and directly to the Euramerican framework of third-order transgressive-regressive cycles (Devonian T-R cycles) originally defined by Johnson et al. (1985). This indicates that the Appalachian basin cycles are eustatic in origin.

Figure 11 compares the Euramerican Devonian T-R cycles of Johnson et al. (1985) with third-order sequences in the Appalachian basin for the Lochkovian through Frasnian stages. While the cycles are correlatable, distinct larger-scale variations occur. The Johnson et al. (1985) curve shows an overall deepening from the Pragian through the upper Frasnian. In contrast, the Appalachian basin record shows significantly enhanced deepenings at the beginning of depositional cycles 2–4, in the lower Emsian, the upper Eifelian, and the upper Frasnian. These are followed by overall shallowing trends, until the next major deepening.

Ettensohn (1985) interpreted the Devonian sea-level cycles to have been controlled by Acadian tectonism. It is clear that the major regional transgressions at the beginning of depositional sequences 2–4 (Ettensohn's [1985] tectophases I–III) were the result of load-induced subsidence of the foredeep closely following the onset of renewed Acadian orogenesis. However, these are superposed over global third-order and finer-scale eustatic cycles.

Stratigraphic Anomalies, Basin Flexure, and Tectophase Kinematics

Patterns that emerge from stratigraphic anomalies 2–6 outline a relatively detailed history of basin flexure through the development of depositional cycles/tectophases. These provide an actualistic record of kinematics active during the Acadian orogeny against which to test established models of foreland basin evolution during an orogenic event.

Previous to the onset of depositional cycles 2–4, widespread deposition of relatively tabular, shallow-marine carbonates and/or quartz arenites occurred across broad ramps with relatively little topographic relief. At the transition from depositional cycles 2 to 3, increasing proximal absence of upper Onondaga carbonates (stratigraphic anomaly 4) records progressive cratonward collapse of a shallow carbonate ramp. Crustal loading events in orogenic belts result in subsidence of the foreland (e.g., Quinlan and Beaumont, 1984), in this case, with the apparent onset of a pulse of renewed tectonism in the Acadian orogen. Eastern New York outcrops were not immediately adjacent to the orogenic front during the lower Middle Devonian. This indicates that

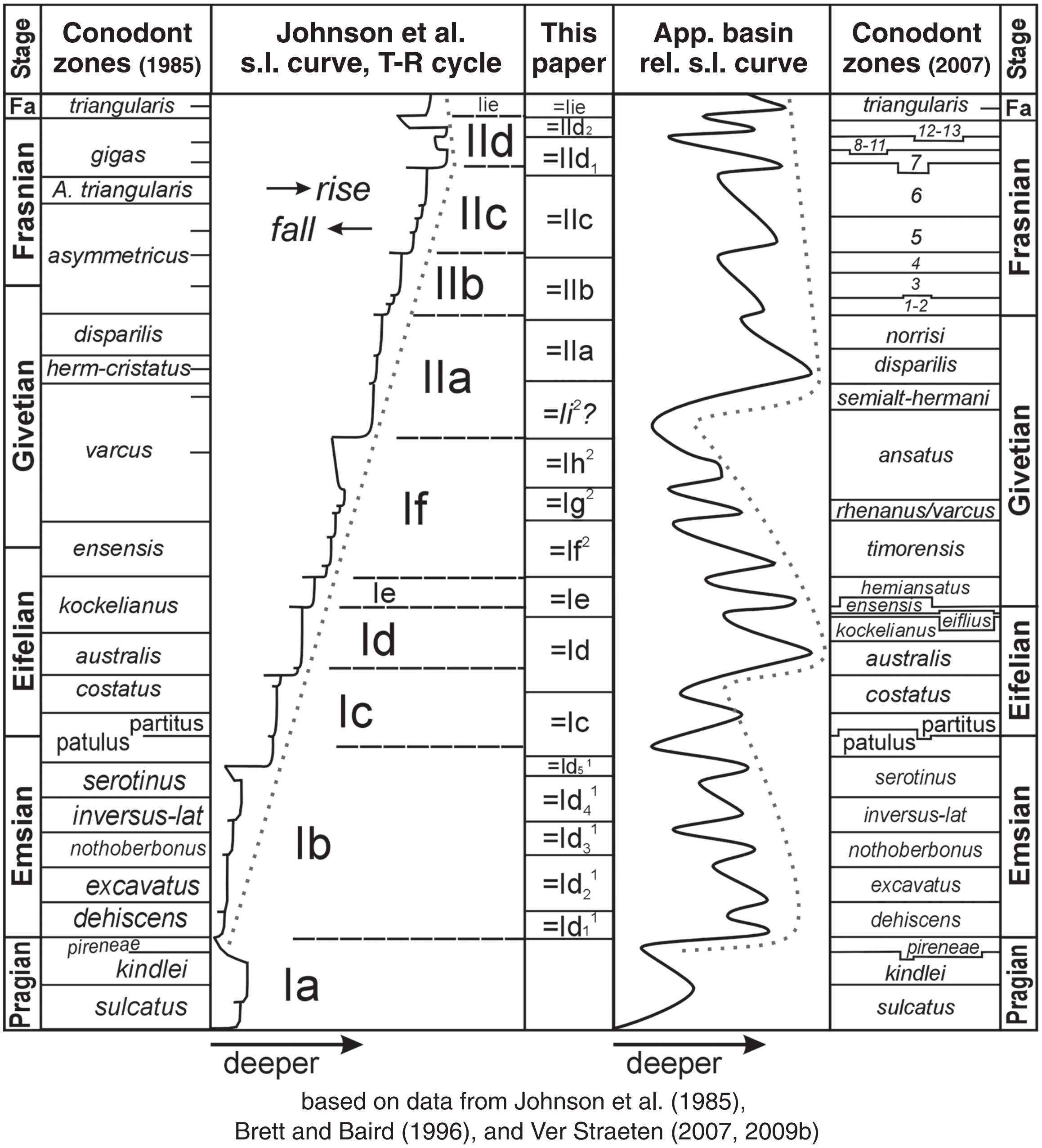

Figure 11. Comparison of Devonian Euramerican and Appalachian basin sea-level trends, showing comparison of Euramerican eustatic sea-level curve (from Johnson et al., 1985) and Appalachian basin relative sea-level curve for Pragian through lower Famennian stages. Note: (1) correlation of sea-level cycles on both sides of the diagram (indicating strong eustatic control on Appalachian basin third-order sequences); (2) overall sea-level rise from upper Pragian to upper Frasnian for Johnson et al. (1985) curve, and contrasting Appalachian basin pattern of three cycles of major deepenings in the lower Emsian, mid-Eifelian, and upper Givetian, followed by overall shallowings: these cycles represent depositional cycles 2–4 of this paper, and Ettensohn's (1985) Acadian Tectophases I, II, and III. Divergence of sea-level curves at tectophase-scale cycles is indicative of Acadian influence on relative sea level. Data for Appalachian basin cycles are from Johnson et al. (1985), House and Kirchgasser (1993), Brett and Baird (1996), Filer (2002), Ver Straeten (2007, 2009b).

there was a time lag between initiation of loading and the onset of subsidence along the New York outcrop belt; the duration of that time is unknown. This pattern is not unique (e.g., Middle Ordovician Trenton Limestone to Utica Shale; Baird and Brett, 2002), and it is presumed to have been active at the onset of depositional cycles 1, 2, and 4.

Basinal, dark, fine-grained clastics represent the initial sediments of depositional cycles 2–4. Subsidence and collapse of the previously established carbonate ramp architecture resulted in establishment or reestablishment of basinal foredeep environments. The distinctive wedge-shaped geometry of early stage sediments at least in part reflects minimal transport of flocculated fine-grained sediments toward the distal margins of the foredeep. However, depositional cycles 2 and 3 (anomaly 5 and part of anomaly 2) indicate that initiation of the early stage of a depositional cycle is followed a short time later by uplift of the forebulge. In depositional cycle 3, the lag time between initial foredeep subsidence (e.g., Onondaga–Union Springs contact) and forebulge uplift in (between the Hurley and Cherry Valley Members, Oatka Creek Formation) is roughly a million to a few million years. This estimate is based on the duration of a single third-order stratigraphic sequence or sea-level cycle (upper Onondaga to basal Oatka Creek strata), which are considered to span 1 to 3 m.y. (Coe, 2003).

Another recurring anomaly is the restricted geographic distribution of initial basinal facies during the early stage of a depositional cycle versus the increasingly widespread distribution of progressively shallower water facies through the middle to late stages (e.g., anomaly 2 and Union Springs to Tully formations; Fig. 5). The increased distribution of the succeeding shallower middle-stage deposits following initial deposits appears to mark gradual topographic leveling of the bulge and adjacent foredeep. This may develop through a combination of flexural leveling, erosional beveling, and infilling of topographically low areas with sediments. By deposition of late-stage carbonates, forebulge and foredeep topography has become relatively flattened. In fact, during depositional cycle 2 (anomaly 2), the central portion of the early stage forebulge across central New York developed into the position of a subtle trough during the late stage.

Middle- to late-stage flexural trends during depositional cycles 2 and 3 indicate cratonward and then orogenward migration of topographic elements in the foreland. The lower part of anomaly 6 (upper Hamilton Group) records cratonward migration of highs and lows in late middle stage of a depositional cycle, succeeded by a reversal to orogenward migration of features early in the late stage (Tully Limestone). The latter pattern of orogenward migration is more clearly shown in anomaly 3 (Bois Blanc and Onondaga Formations). Migration of paired bulge- and back-bulge basin–like structures in anomaly 2 occurred over ~1 m.y. (i.e., approximately half of a third-order sequence).

In summary, flexural trends through a depositional cycle appear to be as follows: (1) early stages characterized by progressive cratonward collapse of carbonate–quartz arenite ramp, subsidence and reestablishment of basinal foredeep architecture due to crustal loading in the orogens, and uplift of the previously subdued forebulge after a short time lag (~1–3 m.y.); (2) middle stages characterized by gradual decreasing topographic expression of the forebulge and foredeep, and migration of topographic elements in the foredeep toward the craton; and (3) late stage characterized by widespread shallow ramp geometry, with relatively level topography over the foredeep and forebulge topography, and migration of topographic elements toward the orogen.

These documented patterns from the Devonian rock record do not fit established models of foreland basin flexure during the Acadian orogeny (e.g., Ettensohn, 1985, 1994, 2004; Castle, 2001). This may be largely due to a lack of high-resolution stratigraphic data from the foreland basin in previous models. For example, Ettensohn (1994) hypothesized that unconformities below the widespread carbonate–quartz arenite packages formed due to cratonward migration of the forebulge ("bulge-moveout") with the onset of loading in the orogenic belt. In contrast, stratigraphic anomalies 3 and 6 clearly indicate retrograde, toward-the-orogen movement of topographic features during those times.

The patterns of flexure through a depositional cycle outlined here also do not clearly fit standard mathematical and computer-generated models of foreland basin dynamics during orogenic episodes. Key models invoke visco-elastic versus elastic flexure of the crust (e.g., Quinlan and Beaumont [1984] and Beaumont et al. [1988] versus Flemings and Jordan [1989, 1990] and Jordan and Flemings [1991]). Key differences include: (1) gradual visco-elastic relaxation of the lithosphere versus no relaxation over time; (2) forebulge migration away from load and widening of the basin versus forebulge migration toward the load and narrowing of the basin during a loading event; and (3) forebulge migration toward the thrusts and narrowing of the basin versus forebulge migration away from load, and widening of the basin during a period of quiescence.

These models do not account for additional influences that may also affect flexure of the basin (e.g., subduction-related geodynamics—Mitrovica et al., 1989; mantle avalanche events—Pysklywec and Mitrovica, 1997; in-plane stresses—Cloetingh, 1988; sediment loading and redistribution—Heller et al., 1993; and the interaction of multiple factors—DeCelles and Giles, 1996; Catuneanu et al., 1997). All of these processes interact with plates of varying flexural rigidity, resulting in a complex history of foreland basin flexure.

The kinematic factors involved in generating the patterns of flexure documented here for the Devonian northern Appalachian basin, therefore, may be rather complex. I will not attempt to interpret them here.

Tephra Patterns and Depositional Cycles

As noted, ~100 Upper Silurian– to Devonian-age air-fall tephra beds are documented from the Appalachian basin (Ver Straeten, 2004a; Ver Straeten et al., 2007; Table 3). Can this database be used as a coarse proxy for paleovolcanism during the Acadian orogeny?

Following explosive eruptions of silica-rich magmas, plumes of airborne tephra are largely transported downwind, where material from the plume (e.g., ash, pumice, volcanic phenocrysts) settles out across all depositional environments. In each environment, a variety of physical, biological, and chemical processes may lead to preservation, amalgamation, mixing, or destruction of a single eruptive event layer (see review in Ver Straeten, 2004a).

Recent studies have indicated that many preserved tephra layers in the sedimentary record have a complex depositional history (e.g., Huff et al., 1999; Riedel et al., 2001; Berkeley and Baird, 2002; Ver Straeten, 2004a, 2008; Benedict, 2004; Ver Straeten et al., 2005; Puspoki et al., 2008; additional references in Ver Straeten, 2004a, 2008). Older assumptions that a single tephra layer in sedimentary rocks represents a single eruptive event do not fit the actual record of many beds. Indications of a complex depositional history include sedimentary structures indicative of reworking, multiple internal layers, a mix of detrital and volcanogenic grains, internal fossil layers, and phenocrysts with distinctly differing geochemical fingerprints.

Ver Straeten (2004a, 2008), Benedict (2004), and Ver Straeten et al. (2005) have shown that several of the Devonian K-bentonites and tuffs discussed here have a complex depositional history. Furthermore, it is unknown how many original airfall layers were mixed with background sediments and have left no easily discernible record of Devonian volcanism. Therefore, the ~100 known Devonian K-bentonites and tuffs from the Appalachian basin do not record a straightforward, unmodified record of Acadian volcanism (Ver Straeten, 2004a).

However, acknowledging the potential preservational biases in the sedimentary record, Ver Straeten (2004a) proposed that the Devonian tephras may provide a relatively coarse record of the timing and nature of explosive Acadian volcanism. Examination of Figure 3 shows that the four major Lower to Middle Devonian tephra clusters occur at or near the transitions between the major depositional cycles (i.e., tectophases of Ettensohn, 1985). Silica-rich volcanism appears to have been less active during intervening middle stages of depositional cycles/tectophases.

Implications of Data, Part II: Noncyclic Data

Conglomerates and Unroofing of the Acadian Orogen

The unroofing history of an orogen is recorded in the synorogenic detritus (conglomerate, sandstone, siltstone, and mudrocks) deposited in the adjacent foreland basin. The composition of extrabasinal, synorogenic conglomerates reflects multiple factors, including the rock exposed in the source area, the durability of the rocks, climate-, weathering-, and transport-related processes active at and between source and final depositional site, and distance transported. Clasts more affected by weathering, corrosion, and/or abrasion disappear from the gravel fraction closer to the source. More resistant clasts (e.g., quartz, chert) may remain as gravel for long periods, and may even be reworked from older sedimentary rock successions. Overall, the degree of rounding of quartz and chert pebbles in samples indicates long travel; and the shape of clasts is generally more related to their composition than to transport and abrasion processes.

No systematic analysis of synorogenic conglomerates from the Devonian Catskill delta complex has been published to date. Compositional data in Table 2 represent a first, preliminary examination of Acadian-derived conglomerates through ~40 m.y. of the Devonian across New York (Figs. 3 and 4).

The most common clasts in the Devonian conglomerates are milky quartz, lithified sandstones, and chert. The milky quartz is commonly white, though at times it may appear pinkish (diffusely scattered hematite) or green (from chlorite). Originally derived from hydrothermal veins in an orogenic belt, the milky quartz could have originated from metamorphic rocks in the Acadian orogen, or older, reworked quartz-rich conglomerates in the foreland. The sandstone clasts, some of which may have undergone low-grade metamorphism, could be derived from a range of Cambrian to Devonian sedimentary rocks. Similarly, chert clasts indicate a sedimentary rock origin, derived from Lower to Middle Paleozoic strata uplifted and exposed in the orogen.

Distinct changes in clast composition through the Devonian conglomerates indicate, at least in part, changes in sediment sources within the drainage basins feeding into the northern Appalachian basin. The two lowest, pure quartz conglomerates were most likely derived from erosion of older sedimentary sources (e.g., Silurian Shawangunk conglomerate). The source rocks became exposed on or near the forebulge/cratonward margin of the foredeep during major eustatic sea-level lowstands (at or near base of Devonian T-R cycles Ia and Ic of Johnson et al. [1985] and Ver Straeten [2009a]; Fig. 11).

The diversity and abundance of chert clasts in sample 3 (lower Givetian–age Mount Marion Formation) denote the exposure of cherty sedimentary rocks in the source area. Ordovician- and Devonian-age chert occurs in eastern New York (e.g., red chert in Ordovician Indian River Formation; green chert in Ordovician Mount Merino Formation; gray to black cherts in lower and Middle Devonian strata, ± Ordovician).

Succeeding upper Middle to lower Upper Devonian conglomerates from eastern New York (samples 4–6) show a sharp decline in chert content, indicating little exposure of chert-bearing rocks in Acadian watersheds draining into eastern New York at that time. Most of the gravel in samples 4–6 consists of milky quartz and reworked sandstone clasts. The sandstones likely originated from uplift and cannibalization of older, prelithified Devonian rocks in the wedge-top, some of which may have undergone low-grade metamorphism prior to uplift and exposure. Milky quartz with chlorite inclusions is interpreted to form in veins within low-grade (greenschist) metamorphic facies.

Overall, Middle to lower Upper Devonian conglomerates indicate unroofing of dominantly sedimentary and low-grade metamorphic rocks in the orogen. These findings agree with sandstone compositional data from Middle to Devonian strata in New York (e.g., Lucier, 1966; Ethridge, 1977; Gale, 1985; summarized in Ver Straeten, 2009a). Additional rare clasts (tuff and granulite clasts—Allen and Friend, 1968; metagabbro clast—Friedman, 1998) in the Twilight Park conglomerate (sample 5) and closely underlying strata indicate at least minimal exposure of igneous and high-grade metamorphic rocks in the source area around the Middle to Late Devonian transition.

A return to milky quartz-rich lithologies in the youngest (Famennian-age) conglomerates in western New York (samples 7–9) appears to indicate another distinct change in provenance. However, sediment transport distance may also affect clast composition. Ethridge (1977) related mineralogic and lithic changes in Upper Devonian sandstones across New York to mechanical abrasion and greater transport distance the sediment traveled. Fine-grained metamorphic rocks (e.g., slate, phyllite) undergo rapid destruction within a few miles in high-gradient streams (e.g., Cameron and Blatt, 1971; Cleary and Conolly, 1971), as would be found in upper parts of the foreland basin wedge-top. Less mechanical wear occurs in low-gradient streams, however (Pollack, 1961; Davies and Moore, 1970), as found on more distal parts of the subaerial delta plain of an overfilled basin foredeep.

Foreland Basin Tephras and Potential Volcanic Sources

Patterns of geographic distribution, bed thickness, and grain size of tephras in the major clusters indicate apparent shifts in the geographic distribution of explosive volcanic activity along the orogen through time (Fig. 10). Restriction of the upper Lower Devonian Sprout Brook cluster to the northeastern part of the Appalachian basin, and similar restriction of the lower Middle Devonian Tioga Middle Coarse Zone to the southern part of the basin appear to reflect sources in the northern and central Appalachians, respectively. In the latter case, Dennison and Textoris (1978) projected a source in northeastern Virginia. The former is further discussed below.

In contrast, the widespread distributions of the lower Lower Devonian Bald Hill and lower Middle Devonian Tioga A-G clusters make it more difficult to project possible source areas. Based on thickness and grain size of the Tioga B K-bentonite, Ver Straeten (2004a) projected a possible source area for the Tioga A-G cluster southeast of eastern Pennsylvania outcrops. Although little data are available to help determine potential sources for the Bald Hill K-bentonites (e.g., regional variations in bed thickness and grain size), volcanics from the same biozones and/or with overlapping dating errors in northeastern Maine and adjacent New Brunswick could indicate a source (Ebert and Matteson, 2003). Overall, the trends appear to indicate Lower Devonian igneous sources of silicic tephra in the New England section of the Acadian orogen, with a shift to the central Appalachians during the Middle Devonian (Fig. 10).

Comparing Foreland Basin and Orogenic Belt Data: An Example

Lower Emsian Igneous Activity in the Foreland and Orogen

Lower Emsian igneous rocks occur in both the foreland basin and the Acadian orogen (Fig. 12). This includes the Sprout Brook K-bentonites cluster (408.3 ± 1.9 Ma; Tucker

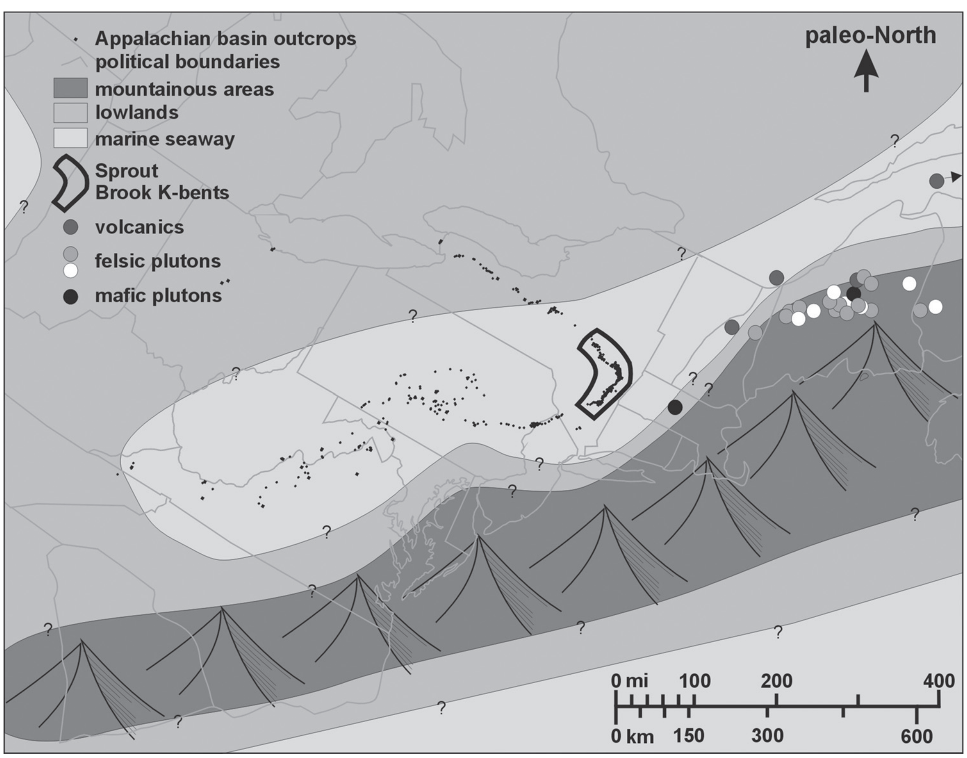

Figure 12. Lower Emsian igneous rocks, Acadian orogen and foreland. Map shows the distribution and character of lower Emsian–age igneous rocks within margin of errors with the Sprout Brook K-bentonites cluster in the northeastern part of the Appalachian basin. For detailed information and references, see Table 4. Positions of the front edge of the orogen and marine strata in Maine and adjacent areas are after Bradley et al. (2000).

et al., 1998), which is restricted to the northeastern part of the Appalachian basin (Ver Straeten, 2004b). Numerous lower Emsian volcanic and magmatic rock units with error ranges that overlap with the Sprout Brook K-bentonites are documented in the Acadian orogen, predominantly from Maine (see Fig. 12; Table 4).

In north-central to western Maine, a major package of rhyolitic ash-flow tuffs was erupted from five major volcanic centers in the Piscataquis volcanic belt (Traveler and Kineo rhyolites and equivalent rocks). Rankin and Hon (1987) conservatively estimated the preserved volume of the Traveler Rhyolite alone to be ~800 km^3. Ver Straeten (2004b) pointed out that this volume is comparable to major Cenozoic tuffs in the western United States (e.g., Timber Mountain, Paintbrush, and Lava Creek tuffs with volumes of 900 km^3, 1000 km^3, and 1000 km^3, respectively; Christiansen, 1979, p. 31). The bottom and top of the Traveler Rhyolite has been dated at 407.3 ± 0.5 and 406.7 ± 1.4 Ma. The Kineo Rhyolite yielded an age of 406.3 ± 3.8 Ma (Bradley et al., 2000). These volcanic rocks are all within the range of error for the Sprout Brook K-bentonites.

New geochronologic age dates have recently been reported for Emsian-age plutons in Maine, New Hampshire, and northern Massachusetts (Table 4; Fig. 12). Lower Emsian plutons with error bars that overlap with those of the Sprout Brook K-bentonites are shown in Table 4; slightly younger lower Emsian plutons also occur in the region (Bradley et al., 2000).

Additional lower Emsian volcanogenic rocks are reported from the greater Acadian foreland basin in Canada and the northeastern United States (Table 4; Fig. 12). Most to all of these are air-fall tephras interbedded with sedimentary strata in the Gaspe Peninsula, Quebec, New Brunswick, and New Hampshire.

No igneous rocks of Emsian age are known from south of New England due to erosion and cover by younger rocks, as previously noted. However, with close to no record of air-fall tephras in the southern part of the Appalachian basin, it is possible that

TABLE 4. LOWER EMSIAN IGNEOUS ROCKS, ACADIAN OROGEN AND FORELAND

Igneous rock type	Unit	Composition	Locality	Age (Ma)	References
Volcanic	Sprout Brook K-bentonites	K-bentonites, from high-silica rhyolites	NY; VA?	408.3 ± 1.9	Ver Straeten and Brett (1995); Hanson (1995); Ver Straeten (2004a, 2004b); date from Tucker et al. (1998)
	Traveler Fm.	Rhyolite	ME	407.3 ± 0.5; 406.7 ± 1.4	Rankin (1968); Rankin and Hon (1987); dates for lower and upper Traveler Fm. from Rankin and Tucker (1995)
	Kineo Fm.	Rhyolite	ME	406.3 ± 3.8	Boucot and Heath (1969); date from Bradley et al. (2000)
	York River Fm.	Bimodal	Que (Gaspe Pen.)	(Lower Emsian)	Poole and Rogers (1972, p. 152); Doyon and Valiquette (1987)
	Val d'Amour Formation	Rhyolite (+more?)	New Brunswick	407.4 ± 0.8	Wilson (2004)
	Littleton Fm.	(Tuff layer)	NH	407 ± 2	Tucker and Rankin, *in* Bradley et al. (2000)
	Littleton Fm.	Bimodal	NH	(Lower Emsian)	Billings (1937, 1956); A.J. Boucot (1993, personal commun.)
Plutonic	Bald Mtn. pluton	Granodiorite	ME	408	Bradley et al. (2000)
	Ebeemee pluton	Granite	ME	407.8 ± 2.4; 405.7 ± 2.6	Bradley et al. (2000)
	Berry Brook pluton	Gabbro, diorite	ME	410	Ludman and Idleman (1998)
	Harrington pluton	Granite	ME	406.9 ± 1	Bradley et al. (2000)
	Haskell Hill pluton	Granite	ME	408.0 +5/–4	Tucker et al. (2001)
	Katahdin pluton	Quartz monzonite	ME	406.9 ± 0.4	Rankin and Tucker (1995)
	Mattamiscontis pluton	Granite	ME	406.9 ± 3.6	Bradley et al. (2000)
	Moxie Pluton, eastern part	Gabbro	ME	406.3 ± 3.8	Bradley et al. (2000)
	Redington pluton	Granite	ME	407.6 ± 4.7	Solar et al. (1998)
	Russell Mtn pluton	Granodiorite	ME	406.0 ± 1.3	Bradley et al. (2000)
	Sebec Lake pluton	Granodiorite	ME	407.8 ± 2.5	Bradley et al. (2000)
	Shirley-Blanchard pluton	Granodiorites	ME	406.9 ± 1.4	Bradley et al. (2000)
	Skiff Lake pluton, Pokiok batholith	Granite	NB	409.0 ± 2	Bevier and Whalen (1990)
	S. Roxbury pluton	Granite	ME	408.2 ± 2.5	Solar et al. (1998)
	Swift River pluton	Leucogranite	ME	407.9 ± 1.9	Solar et al. (1998)
	Wamsutta pluton	Quartz diorite	NH	408.2 ± 2.0	Eusden et al. (2000)
	Spaulding pluton	Tonalite	NH	408 ± 2	Robinson and Tucker (1996)
	Prescott pluton	Gabbro	MA	407 +3/–2	Tucker and Robinson (1990)

Note: Basic data and sources on lower Emsian igneous rocks from the greater Acadian foreland basin and the Acadian orogen. Error bars of all units listed overlap with error bars of the Sprout Brook K-bentonites in the Appalachian basin.

there was only minor explosive Emsian-age volcanic activity in the southern Acadian orogen.

The high concentration of igneous rocks in the northern Appalachians and restricted preservation of air-fall tephras largely in the northeast portion of the Appalachian basin suggest that the Sprout Brook K-bentonites originated from sources in New England, possibly even in part from the Traveler Rhyolite (Ver Straeten, 2004b). Westward-directed transport by winds would have carried tephra plumes from New England out over the northeastern edge of the Appalachian basin, where material would have been deposited in the seaway.

SUMMARY

Evidence from the Acadian orogen and northern Appalachian basin indicates Upper Silurian onset of orogenesis on the continental margin in the northeastern United States. Bradley et al. (2000) indicated that following initiation of the orogeny, the foreland basin and orogenic front migrated cratonward across Maine into southeastern Quebec by the Late Devonian. Following initial migration of the foreland basin toward the orogen in the Late Silurian, the back-bulge basin, forebulge, and foredeep portions of the foreland basin system progressively migrated cratonward through the New York outcrop belt. Using the time scale of Kaufmann (2006), a distinct shift of the foreland basin system occurred at ca. 420 Ma, with the migration of marine facies from western to eastern New York and into New England. Deformed Devonian strata in eastern New York may reflect migration of the wedge-top and orogenic front also moving into the present-day outcrop belt by the Late Devonian. A detailed outline of events recorded in the foreland basin fill in the northern Appalachian basin, with some additional information from other areas, is provided in Table 5 and summarized in Figure 13.

Upper Silurian and Devonian strata across New York and the Appalachian basin can be subdivided into four major depositional cycles. Each one of these is characterized by recurring changes in rock type, geometry, depth-related facies, flexural trends, and occurrence of air-fall tephra beds. The beginning of the major depositional cycles is marked by the onset of clastic sedimentation, with wedge-shaped geometries and relatively deep-water facies indicative of significant subsidence in the basin foredeep. Distal areas of the foredeep undergo delayed, subtle uplift of a forebulge during the early phases of the cycles. These shifts in the early phases of depositional cycles indicate distinct pulses of tectonism, uplift, and loading in the Acadian orogen.

Middle phases of depositional cycles feature decreasing clastic input and upward-increasing carbonate content, and less pronounced wedge-shaped geometries of more widely distributed, shallower-water strata. Flexural data indicate cratonward movement of topographic features in the foreland basin system. Sedimentary trends during middle phases appear to indicate decreasing tectonism ± topography in the orogenic belt.

Deposition of carbonates during late phases of a depositional cycle indicates sharp decrease to lack of detrital clastic input from the orogen. Accompanying trends (e.g., relatively level foreland basinal topography, tabular stratal geometries) appear to indicate intervals of relative quiescence in the orogenic belt previous to the onset of renewed tectonism in the orogenic belt. Flexural data indicate orogenward migration of foreland topographic features.

Major clusters of volcanic air-fall tephras are documented at or near the onset of the first three depositional cycles, at 418, 408, and 391–390 Ma. Recognizing potential biases of tephra preservation in foreland basin sediments, they appear to mark episodes of increasing felsic magmatic activity in the orogenic belt.

The provenance of Acadian-derived sediments in the northern Appalachian basin, based on new conglomerate compositional data, indicates initial sourcing of intrabasinal milky quartz deposits between ca. 410–390 Ma. Beginning around 388 Ma, sedimentary and low-grade metamorphic rocks were dominantly exposed and eroding in the orogen. Initially chert-rich sedimentary sources quickly disappeared however. Possible cannibalization of Devonian sandstones, some of which had undergone low-grade metamorphism, occurred between ca. 386 and 383 Ma. Younger conglomerates (post–375 Ma) in western New York yield milky quartz-rich pebble compositions associated with greater weathering in the orogen, and possibly greater transport distance and destruction of less durable clasts.

Depositional cycles 2–4 were recognized by Ettensohn (1985) as the first three of his four Lower Devonian to Lower Mississippian tectonically active to quiescent "tectophases." Ettensohn (1985) missed an older, Upper Silurian to Lower Devonian tectophase (depositional cycle 1 of this paper). Some aspects of Ettensohn's model (1985, 1987, 1994, 2004) explain the sedimentary data well; others do not hold up to more detailed stratigraphic analyses.

Using the time scale of Kaufmann (2006), the onset of separate depositional cycles/tectophases occurred at ca. 420, 408, 390, and 384 Ma. These ages approximate (or closely post-date) the onset of orogenic uplift, deformation, and loading in the orogenic belt, and foreland basin subsidence. Depositional cycles 1–4 and their respective Acadian tectophases have durations of 14, 18, 6, and greater than 24 m.y., respectively.

Researchers in the Acadian orogen should look for signatures of major pulses of tectonism and succeeding relative quiescent periods, and compare ages of magmatic and volcanic rocks with the record of air-fall tephras from the foreland basin strata. Foreland basin researchers should examine the relatively high-resolution flexural patterns outlined in this paper, which do not fit the standard conceptual models, and adjust the models as needed. Upper Silurian–Devonian sedimentary geologists in the Appalachian basin, and the greater Acadian foreland basin system, should continue to document high-resolution, Acadian-related data of the foreland basin fill, including Upper Devonian air-fall tephras.

TABLE 5. NORTHERN APPALACHIAN BASIN EVENTS: SIGNATURES OF ACADIAN OROGENESIS

Depositional Cycle I: Early phase (Upper Silurian Ludlow to Pridoli series, ca. 420–418), upper Salina Group to Manlius Formation (?).

Earliest evidence of Acadian orogeny in eastern United States.

- Ludlow-age initiation of tectonism in Maine (Bradley et al., 2000).
- Upper Ludlow to Pridoli shift of Appalachian basin toward the continental margin.
- Possible early stage on an early Acadian tectophase?
- Angular unconformities develop in eastern New York, related to flexure of basin; unknown relationship to forebulge.
- A few possible tephras in upper strata (Manlius Formation, New York, ca. 418 Ma).
- Documented equivalent plutonic and volcanic rocks in Maine, New Brunswick.

Depositional Cycle I: Middle Phase (Lower Devonian Lochkovian Stage, ca. 418–411 Ma), Coeymans to Port Jervis Formations.

- Little sedimentologic evidence of orogenesis in northern Appalachian basin through Lochkovian Stage. Minor tongues of fine-grained clastics in deeper-water carbonates (New Scotland, Port Ewen Formations). Minor black shales in deep basin center (Pennsylvania).
- Eastern New York positioned in back-bulge basin. Wedge-top, foredeep, and forebulge in New England.
- Widespread cluster of volcanic air-fall tephras (Bald Hill K-bentonites cluster; 417.6 +/–1.0 Ma; Tucker et al., 1998) in Appalachian basin.
- Documented equivalent plutonic and volcanic rocks in Maine, New Brunswick.

Depositional Cycle I: Late Phase (Lower Devonian Pragian Stage, ca. 411–409 Ma), Wallbridge unconformity and Oriskany Formation.

- Erosion of underlying strata below Wallbridge unconformity; overlain by coeval quartz arenite and conglomerate, and minor carbonates (Oriskany, Connelly, and Glenerie Formations, respectively).
- Oligomictic conglomerates (Connelly Formation), 100% milky (vein) quartz; probably derived from erosion of older intrabasinal quartz conglomerates.
- Formation of Wallbridge unconformity across North America, associated with a major global sea-level lowstand. Continuous sedimentation in deep portions of Appalachian basin.
- Unconformity development may also be associated with migration of forebulge through proximal preserved margin of Appalachian basin; although Oriskany Sandstone appears to have been widespread across the shallow basin transect in New York, associated with relatively level basin topography during late phase of depositional cycle.
- Wedge-top and foredeep in New England, easternmost New York.

Depositional Cycle II: Early Phase (Lower Devonian, lower Emsian Stage, ca. 409–403 Ma), lower to middle Esopus Formation.

- Subsidence and migration of margin of basin foredeep into proximal portion of northern Appalachian basin, eastern New York.
- Possible slightly delayed uplift of forebulge to west (central to western New York).
- Distinct wedge-shaped geometry of clastic strata, thickening toward orogen.
- Back-bulge basin undocumented.
- Initial deposition of synorogenic clastics (dark-gray to black shales, some sandstones) in Appalachian basin.
- Cluster of air-fall tephras (Sprout Brook K-bentonites; 408.3 ± 1.9 Ma; Tucker et al., 1998). Restricted to northeast portion of Appalachian basin.
- Extensive coeval plutonic and volcanic rocks in northern Appalachians, especially Maine; also New Hampshire, Vermont, New Brunswick, Quebec.
- Wedge-top and bulk of foredeep in New England; latter extends into easternmost New York.

Depositional Cycle II: Middle Phase (Lower Devonian, upper Emsian Stage, roughly 403–394 Ma), upper Esopus and Schoharie Formations.

- Initial progradation of sand-rich facies into eastern New York (upper Esopus Formation). Followed by gradual decline of clastic input into basin, and increasingly mixed carbonate-clastic rocks (Schoharie Formation) deposited in northern Appalachian basin.
- More widespread deposition of intermediate depth facies in Appalachian basin.
- Stratal geometry is decreasingly wedge-shaped.
- Basin topography begins to level out; decreased subsidence in proximal foredeep.
- Forebulge remains to west, with less pronounced topography. Carbonates lap onto the western margin of the forebulge.
- Little air-fall volcanic tephra recorded in Appalachian basin.
- Some dated plutonic and volcanic rocks in northern New England.
- Wedge-top and proximal portion of foredeep likely in New England; latter extends into easternmost New York.

Depositional Cycle II: Late Phase (Middle Devonian Eifelian Stage, ca. 394–390 Ma), Onondaga Formation.

- Widespread deposition of carbonates in northern and western parts of Appalachian basin; mixed carbonates and clastics in central to southern part of basin.
- Oligomictic proximal conglomerates (Kanouse Sandstone), composed of 100% vein quartz.
- Relatively tabular stratal geometry.
- Foredeep poorly developed, forebulge absent to depressed; basin geometry of widespread shallow-marine conditions.
- Orogenward migration of bulge-like and back bulge–like features recorded, uppermost Emsian through lower Eifelian.
- Deposition of Tioga Middle Coarse Zone K-bentonite and tuffs in southern part of basin (391.4 ± 1.8 Ma; Tucker et al., 1998), in middle Onondaga-equivalent strata. Up to 32 beds reported from proximal outcrops in Virginia.
- Deposition of Tioga A-G K-bentonite cluster (390 ± 0.5 Ma; Roden et al., 1990) in upper Onondaga and lower Union Springs Formations. Widespread across Appalachian basin, and likely into Michigan and Illinois basins; occurs at the top of the carbonate succession, in the transition to the beginning of tectophase II.
- Additional air-fall tephras documented.
- Age-equivalent igneous source rocks largely unknown; volcanic activity appears to have migrated south of New England.

(*Continued*)

TABLE 5. NORTHERN APPALACHIAN BASIN EVENTS: SIGNATURES OF ACADIAN OROGENESIS (*Continued*)

Depositional Cycle III: Early Phase (Middle Devonian, upper Eifelian–Lowest Givetian Stage, ca. 390–388 Ma), Union Springs and Oatka Creek formations.

- Sharp pulse of subsidence of foredeep; time-transgressive subsidence toward craton at carbonate–black shale transition (eastern to central New York). Foredeep better developed, and more cratonward than in tectophase I.
- Slightly delayed uplift of forebulge.
- Development of back-bulge basin in southern Ontario.
- Deposition of black shale–rich strata in foredeep (Marcellus Shale).
- Pronounced wedge-shaped stratal geometry, thickening toward the orogen.
- Starved unconformity over bulge (western New York); possible subaerial exposure?
- Dark shale deposition in back-bulge basin (Ont.) grades to carbonates on cratonward margin (OH).
- Some minor air-fall tephras.
- Wedge-top, some of marine portion and all of subaerial foredeep in New England.

Depositional Cycle III: Middle Phase (Middle Devonian, lower to middle Givetian Stage, ca. 388–385 Ma), Skaneateles to Moscow Formations.

- Subsidence begins to decrease in foredeep.
- Basinal black shale facies grade to dark-gray to gray mud rocks, with upward-increasing sand content toward the mountain belt, and increasing carbonate content toward the craton.
- Polymictic proximal conglomerates (approx. marine shoreface), with varied pebble compositions.
- Stratal geometry less distinctly wedge-shaped.
- Overfilling of proximal margin of preserved basin (i.e., eastern New York) with synorogenic clastics; terrestrial, fluvial-dominated facies move into foredeep in Appalachian basin.
- Maximum progradation of coarse (sandstone) facies into marine basin in upper middle part of interval (Ludlowville Formation). Followed by increasing mud, carbonate content.
- Few air-fall tephras recognized.
- Possible decreased prominence of forebulge.
- Documented cratonward migration of depocenters and adjacent topographic highs (upper Ludlowville and Moscow Formations).
- Wedge-top, some of subaerial foredeep beyond preserved margin of Appalachian basin, in New England, possibly easternmost New York.

Depositional Cycle III: Late Phase (Middle Devonian, upper middle Givetian, ca. 385 Ma), Tully Formation.

- Culmination of increasing carbonate trends lead to deposition of Tully Limestone.
- Relatively tabular strata geometry to carbonates; thicker sand-rich clastics east of bulge-like feature.
- No large, prominent forebulge recognized.
- Flexural trend across basin undergoes sharp shift from cratonward to orogenward; orogenward migration of bulge-like and adjacent basinal features recorded in lower (to middle) Tully Formation.
- A few possible air-fall tephras may occur; more investigation needed.
- Wedge-top, some of subaerial foredeep in New England, easternmost New York.

Depositional Cycle IV: Early Phase (Middle to Upper Devonian, upper Givetian to middle Frasnian, ca. 385–383 Ma), Geneseo to Penn Yan (?) Formations.

(*Note:* Less detail is known about developmental stages within tectophase III.)

- Sharp pulse of subsidence of foredeep; foredeep in more cratonward position than in tectophase II.
- Sediment-starved unconformity on top of Tully Ls.; in western New York, corrasional erosion of carbonates.
- Flooding unconformity succeeded by black shale deposition, with distinct wedge-shaped geometry.
- Wedge-top, some of subaerial foredeep in New England, easternmost New York, beyond present-day outcrop belt.

Depositional Cycle IV: Middle Phase (Upper Devonian, Frasnian to Famennian Stages, ca. 383–361 Ma), West River (?) to Riceville Formations (and younger strata in Pennsylvania and Ohio).

- Continued progradation of subaerial fluvial facies into and overfilling proximal foredeep.
- Pulses of conglomerate deposition, increasing upward during Frasnian Stage. Polymictic proximal conglomerates in fluvial facies, with varied pebble compositions.
- Overall progradation of mud- to sand-rich facies into basin, with cratonward migration of magnafacies (including terrestrial facies).
- Progradation is stepped, associated with cyclic sea-level changes; major black shale tongues (e.g., Middlesex, Rhinestreet, Pipe Creek Formations) develop in western New York in deeper parts of cycles.
- Mid-Frasnian deposition of Belpre K-bentonites cluster (381.1 ± 1.3 Ma; Tucker et al., 1998); some additional tephras known, sometimes widespread. More investigation needed, especially in the Famennian Stage.
- Front edge of foreland basin wedge-top/orogenic fold-and-thrust belt may migrate into Hudson Valley (eastern New York).
- Later distal deposition (Famennian Stage) of oligomictic conglomerates (approx. marine shoreface) in western New York; dominated by milky (vein) quartz.

Note: Chronological outline of key Upper Silurian to Lower Mississippian depositional, flexural, and volcanic events and processes recorded in the foreland basin fill in the northern Appalachian basin, with some additional information from other areas. For details, see text and accompanying figures and tables. Dates utilized are based on Devonian time scale of Kaufmann (2006).

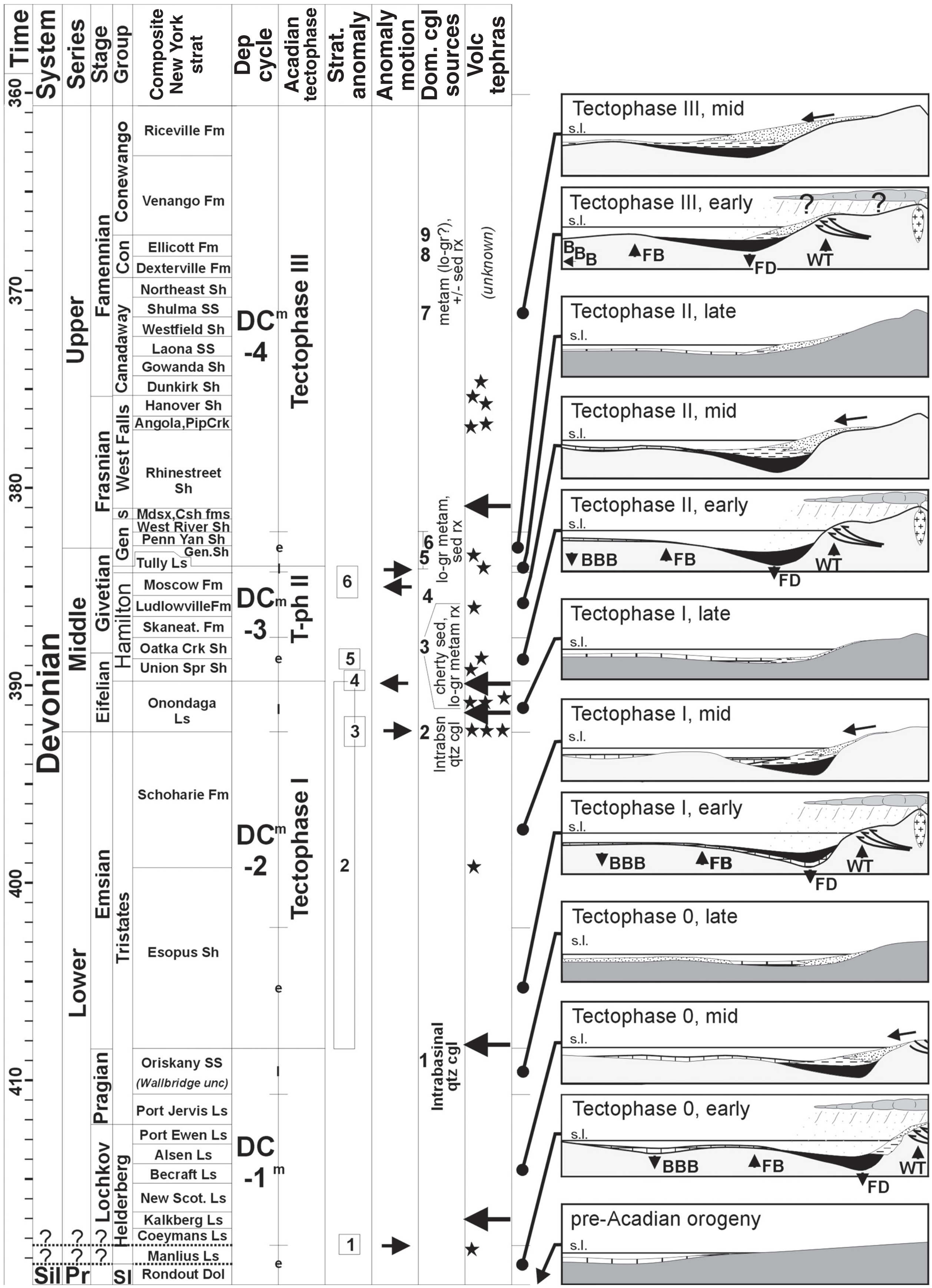
Time
System
Series
Stage
Group
Composite New York strat
Dep cycle
Acadian tectophase
Strat. anomaly
Anomaly motion
Dom. cgl sources
Volc tephras
360
370
380
390
400
410
Devonian
Sil
Pr
Upper
Middle
Lower
Famennian
Frasnian
Givetian
Eifelian
Emsian
Pragian
Lochkov
Conewango
Con
Canadaway
West Falls
Gen
Hamilton
Tristates
Helderberg
Sl
Riceville Fm
Venango Fm
Ellicott Fm
Dexterville Fm
Northeast Sh
Shulma SS
Westfield Sh
Laona SS
Gowanda Sh
Dunkirk Sh
Hanover Sh
Angola,PipCrk
Rhinestreet Sh
Mdsx,Csh fms
West River Sh
Penn Yan Sh
Gen.Sh
Tully Ls
Moscow Fm
LudlowvilleFm
Skaneat. Fm
Oatka Crk Sh
Union Spr Sh
Onondaga Ls
Schoharie Fm
Esopus Sh
Oriskany SS
(Wallbridge unc)
Port Jervis Ls
Port Ewen Ls
Alsen Ls
Becraft Ls
New Scot. Ls
Kalkberg Ls
Coeymans Ls
Manlius Ls
Rondout Dol
DC[m] -4
DC[m] -3
DC[m] -2
DC -1[m]
Tectophase III
T-ph II
Tectophase I
metam (lo-gr?), +/- sed rx
lo-gr metam, sed rx
cherty sed, lo-gr metam rx
Intrabsn qtz cgl
Intrabasinal qtz cgl
(unknown)
Tectophase III, mid
Tectophase III, early
Tectophase II, late
Tectophase II, mid
Tectophase II, early
Tectophase I, late
Tectophase I, mid
Tectophase I, early
Tectophase 0, late
Tectophase 0, mid
Tectophase 0, early
pre-Acadian orogeny
s.l.
BBB
FB
FD
WT

Figure 13. Summary of foreland basin data and patterns, with cartoon model of interpreted evolution of the Acadian orogen. Conglomerates not noted as "intrabasinal" are derived from the Acadian orogen. Tectophases I–III are from Ettensohn (1985). Letters e, m, and l straddling the depositional cycle/tectophase line denote their early, middle, and late stages; horizontal bars mark stage boundaries. Vertical axis is based on Kaufmann (2006) time scale. Abbreviations: cgl—conglomerates; DC—depositional cycle; dom.—dominant; intrabsn—intrabasinal; lo-gr metam—low-grade metamorphic; qtz—quartz; rx—rocks; sed—sedimentary; s.l.—sea level; WT—wedge-top; BBB—back-bulge basin; FB—forebulge; and FD—foredeep portions of foreland basin system.

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REFERENCES CITED

Allen, J.R.L., and Friend, P.F., 1968, Deposition of the Catskill facies, Appalachian region: With notes on some other Old Red Sandstone basins, *in* deVries Klein, G., ed., Late Paleozoic and Mesozoic Continental Sedimentation, Northeastern North America: Geological Society of America Special Paper 106, p. 22–74.

Baird, G.C., and Brett, C.E., 2002, Indian Castle Shale: Late synorogenic siliciclastic succession in an evolving Middle/Late Ordovician foreland basin, eastern New York State, *in* Mitchell, C.E., and Jacobi, R., eds., Taconic Convergence: Orogen, Foreland Basin, and Craton: Physics and Chemistry of the Earth, v. 27, p. 203–230.

Baird, G.C., and Brett, C.E., 2003, Shelf and off-shelf deposits of the Tully Formation in New York and Pennsylvania: Faunal incursions, eustasy and tectonics, *in* Konigshof, P., and Schindler, E., eds., Mid-Palaeozoic Bio- and Geodynamics: Frankfurt, Germany, Courier Forschunginstitut Senckenberg, no. 242, p. 141–156.

Bartholomew, A.J., 2006, Middle Devonian Faunas of the Michigan and Appalachian Basins: Comparing Patterns of Biotic Turnover between Two Paleobiogeographic Subprovinces [Ph.D. dissertation]: Cincinnati, Ohio, University of Cincinnati, 286 p.

Batt, R.J., 1996, Faunal and lithological evidence for small-scale cyclicity in the Wanakah Shale (Middle Devonian) of western New York: Palaios, v. 11, p. 230–243, doi: 10.2307/3515232.

Beaumont, C., 1981, Foreland basins: Geophysical Journal of the Royal Astronomical Society, v. 65, p. 291–329.

Beaumont, C., Quinlan, G., and Hamilton, J., 1988, Orogeny and stratigraphy: Numerical models of the Paleozoic in the eastern interior of North America: Tectonics, v. 7, p. 389–416, doi: 10.1029/TC007i003p00389.

Benedict, L., 2004, Complexity of Devonian K-Bentonites in the Appalachian Foreland Basin: Geochemical and Physical Evidence Supporting Multi-Layered K-Bentonite Horizons [M.S. thesis]: Albany, State University of New York at Albany, 258 p.

Berkeley, J.L., and Baird, G.C., 2002, Calcareous K-bentonite deposits in the Utica Shale and Trenton Group (Middle Ordovician), of the Mohawk Valley, New York State: Physics and Chemistry of the Earth, v. 27, p. 265–278.

Bevier, M.L., and Whalen, J.B., 1990, U-Pb geochronology of Silurian granites, Miramichi terrane, New Brunswick, *in* Radiogenic Age and Isotopic Studies, Report 3: Ottawa, Geological Survey of Canada Paper 89-2, p. 93–100.

Billings, M.P., 1937, Regional metamorphism of the Littleton-Moosilauke area, New Hampshire: Geological Society of America Bulletin, v. 46, p. 463–566.

Billings, M.P., 1956, The Geology of New Hampshire, Part II: Bedrock Geology: Concord, New Hampshire State Planning and Development Commission, 203 p.

Boucot, A.J., 1962, Appalachian Siluro-Devonian, *in* Coe, K., ed., Some Aspects of the Variscan Fold Belt: Manchester, Manchester University Press, p. 155–163.

Boucot, A.J., 1993, Comments on Cambrian-to-Carboniferous biogeography and its implications for the Acadian orogeny, *in* Roy, D.C., and Skehan, J.W., eds., The Acadian Orogeny: Recent Studies in New England, Maritime Canada, and the Autochthonous Foreland: Geological Society of America Special Paper 275, p. 41–49.

Boucot, A.J., and Heath, E.W., 1969, Geology of the Moose River and Roach River Synclinoria, Northwestern Maine: Maine Geological Survey Bulletin 21, 117 p.

Bradley, D.C., Tucker, R.D., Lux, D.R., Harris, A.G., and McGregor, D.C., 2000, Migration of the Acadian Orogen and Foreland Basin across the Northern Appalachians of Maine and Adjacent Areas: U.S. Geological Survey Professional Paper 1624, 49 p.

Brett, C.E., 1986, The Middle Devonian Hamilton Group of New York: An overview, *in* Brett, C.E., ed., Dynamic Stratigraphy and Depositional Environments of the Hamilton Group (Middle Devonian) in New York State, Part I: New York State Museum Bulletin 457, p. 1–4.

Brett, C.E., and Baird, G.C., 1994, Depositional sequences, cycles, and foreland basin dynamics in the late Middle Devonian (Givetian) of the Genesee Valley and western Finger Lakes region, *in* Brett, C.E., and Scatterday, J., eds., New York State Geological Association 66th Annual Meeting Guidebook: Rochester, New York State Geological Association, p. 505–589.

Brett, C.E., and Baird, G.C., 1996, Middle Devonian sedimentary cycles and sequences in the northern Appalachian Basin, *in* Witzke, B.M., Ludvigson, G.A., and Day, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton: Geological Society of America Special Paper 306, p. 213–241.

Brett, C.E., and Ver Straeten, C.A., 1994, Stratigraphy and facies relationships of the Eifelian Onondaga Limestone (Middle Devonian) in western and west central New York State, *in* Brett, C.E., and Scatterday, J., eds., New York State Geological Association 66th Annual Meeting Guidebook: Rochester, New York State Geological Association, p. 221–269.

Brett, C.E., Ver Straeten, C.A., and Baird, G.C., 2000, Anatomy of a composite sequence boundary: The Silurian-Devonian contact in Western New York State, *in* New York State Geological Association 72nd Annual Meeting Field Trip Guidebook: Geneva, New York State Geological Association, p. 39–74.

Bridge, J.S., and Gordon, E.A., 1985, Quantitative interpretation of ancient river systems in the Oneonta Formation, Catskill magnafacies, *in* Woodrow, D.L., and Sevon, W.D., eds., The Catskill Delta: Geological Society of America Special Paper 201, p. 163–182.

Bridge, J.S., and Willis, B.J., 1994, Marine transgressions and regressions recorded in Middle Devonian shore-line deposits of the Catskill clastic wedge: Geological Society of America Bulletin, v. 106, p. 1440–1458, doi: 10.1130/0016-7606(1994)106<1440:MTARRI>2.3.CO;2.

Cameron, K.L., and Blatt, H., 1971, Durabilities of sand size schist and volcanic rock fragments during fluvial transport, Elk Creek, Black Hills, South Dakota: Journal of Sedimentary Petrology, v. 41, p. 565–576.

Castle, J.W., 2001, Appalachian basin stratigraphic response to convergent-margin structural evolution: Basin Research, v. 13, p. 397–418, doi: 10.1046/j.0950-091x.2001.00157.x.

Catuneanu, O., Beaumont, C., and Waschbusch, P., 1997, Interplay of static loads and subduction dynamics in foreland basins: Reciprocal stratigraphies and the "missing" peripheral bulge: Geology, v. 25, p. 1087–1090, doi: 10.1130/0091-7613(1997)025<1087:IOSLAS>2.3.CO;2.

Christiansen, R.L., 1979, Cooling units and composite sheets in relation to caldera structure, *in* Chapin, C.E., and Elston, W.E., eds., Ash-Flow Tuffs: Geological Society of America Special Paper 180, p. 29–42.

Cleary, W.J., and Conolly, J.R., 1971, Distribution and genesis of quartz in a piedmont-coastal plain environment: Geological Society of America Bulletin, v. 82, p. 2755–2766, doi: 10.1130/0016-7606(1971)82[2755:DAGOQI]2.0.CO;2.

Cloetingh, S., 1988, Intraplate stresses: A new element in basin analyses, *in* Kleinspehn, K., and Paola, C., eds., New Perspectives in Basin Analysis: New York, Springer-Verlag, p. 305–330.

Coe, A.L., 2003, The Sedimentary Record of Sea-Level Change: New York, Cambridge University Press, 288 p.

Collins, H.R., 1979, Devonian Bentonites in Eastern Ohio: American Association of Petroleum Geologists Bulletin, v. 63, p. 655–660.

Collinson, C., 1968, Devonian of the north-central region, United States, *in* Oswald, D.H., ed., International Symposium on the Devonian System: Calgary, Alberta Society of Petroleum Geologists, v. 1, p. 933–971.

Conant, L.C., and Swanson, V.E., 1961, Chattanooga Shale and related rocks of central Tennessee and nearby areas: U.S. Geological Survey Professional Paper 357, 91 p.

Conkin, J.E., and Conkin, B.M., 1979, Devonian pyroclastics in eastern North America, their stratigraphic relationships and correlation, *in* Conkin, J.E., and Conkin, B.E., eds., Devonian-Mississippian Boundary in Southern Indiana and Northwestern Kentucky, Field Trip 7: Ninth International Congress of Carboniferous Stratigraphy and Geology Field Trip Guidebook: Louisville, Kentucky, University of Louisville, p. 74–141.

Conkin, J.E., and Conkin, B.M., 1984, Paleozoic Metabentonites of North America: Part 1. Devonian Metabentonites in the Eastern United States and Southern Ontario: Their Identities, Stratigraphic Positions, and Correlation: University of Louisville Studies in Paleontology and Stratigraphy 16, 136 p.

Davies, D.K., and Moore, W.R., 1970, Dispersal of Mississippi sediments in the Gulf of Mexico: Journal of Sedimentary Petrology, v. 40, p. 339–353.

Day, J.E., 2006, Overview of the Middle–Upper Devonian sea level history of the Wapsipinicon and Cedar Valley Groups, with discussion of new conodont data from the subsurface Cedar Valley Group of southeastern Iowa, *in* Day, J., Luczaj, J., and Anderson, R., eds., New Perspectives and Advances in the Understanding of Lower and Middle Paleozoic Epeiric Carbonate Depositional Systems of the Iowa and Illinois Basins: Iowa Geological Survey Guidebook 26, p. 1–22.

Day, J., Uyeno, T.C., Norris, A.W., Witzke, B.J., and Bunker, B.J., 1996, Middle-Upper Devonian relative sea-level histories of North American cratonic interior basins, *in* Witzke, B.J., Ludvigson, G.A., and Day, J., eds., Paleozoic Sequence Stratigraphy: Views from the North American Craton: Geological Society of America Special Paper 306, p. 259–276.

DeCelles, P.G., and Giles, K.A., 1996, Foreland basin systems: Basin Research, v. 8, p. 105–123, doi: 10.1046/j.1365-2117.1996.01491.x.

Dennison, J.M., 1983, Internal stratigraphy of Devonian Tioga ash beds in Appalachian Valley and Ridge Province: Geological Society of America Abstracts with Programs, v. 15, no. 6, p. 557.

Dennison, J.M., and Textoris, C.A., 1970, Devonian Tioga tuff in northeastern United States: Bulletin Volcanologique, v. 34, p. 289–294, doi: 10.1007/BF02597791.

Dennison, J.M., and Textoris, C.A., 1978, Tioga bentonite time-marker associated with Devonian shales in Appalachian basin, *in* Schott, B.L., Overbey, W.K., Jr., Hunt, A.E., and Komar, C.A., eds., Proceedings of the First Eastern Gas Shales Symposium: U.S. Department of Energy Publication MERC/SP-77-5, p. 166–182.

Dickinson, W.R., 1974, Tectonics and Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, 204 p.

Dorobek, S.L., and Read, J.F., 1986, Sedimentology and basin evolution of the Siluro-Devonian Helderberg Group Central Appalachians: Journal of Sedimentary Petrology, v. 56, p. 601–613.

Doyon, M., and Valiquette, G., 1987, Devonian and Tertiary volcanism in the Lemieux Dome, central Gaspe, Quebec: Geological Association of Canada and Mineralogical Association of Canada Joint Annual Meeting Program with Abstracts (Geological Association of Canada), v. 12, p. 38.

Droste, J.B., and Vitaliano, C.J., 1973, Tioga bentonite (Middle Devonian) of Indiana: Clays and Clay Minerals, v. 21, p. 9–13, doi: 10.1346/CCMN.1973.0210103.

Ebert, J.R., and Matteson, D.K., 2003, Distal stratigraphic effects of the Laurentia-Avalon collision: A record of early Acadian (Pridoli-Lochkovian) tectonism in the Helderberg Group of New York State, USA, *in* Konigshof, P., and Schindler, E., eds., Mid-Palaeozoic Bio- and Geodynamics: Frankfurt, Courier Forschunginstitut Senckenberg, no. 242, p. 157–167.

Ethridge, F.G., 1977, Petrology, transport, and environment in isochronous Upper Devonian sandstone and siltstone units, New York: Journal of Sedimentary Petrology, v. 47, p. 53–65.

Ettensohn, F.R., 1985, The Catskill delta complex and the Acadian orogeny: A model, *in* Woodrow, D.L., and Sevon, W.D., eds., The Catskill Delta: Geological Society of America Special Paper 201, p. 39–49.

Ettensohn, F.R., 1987, Rates of relative plate motion during the Acadian orogeny based on the spatial distribution of black shales: The Journal of Geology, v. 95, p. 572–582, doi: 10.1086/629150.

Ettensohn, F.R., 1994, Tectonic control on formation and cyclicity of major Appalachian unconformities and associated stratigraphic sequences, *in* Dennison, J.M., and Ettensohn, F.R., eds., Tectonic and Eustatic Controls on Sedimentary Cycles: Tulsa, Society for Sedimentary Geology (SEPM), Concepts in Sedimentology and Paleontology 4, p. 217–242.

Ettensohn, F.R., 2004, Modeling the nature and development of major Paleozoic clastic wedges in the Appalachian basin, USA: Journal of Geodynamics, v. 37, p. 657–681, doi: 10.1016/j.jog.2004.02.009.

Eusden, J.D., Jr., Guzofski, C.A., Robinson, A.C., and Tucker, R.D., 2000, Timing of the Acadian orogeny in northern New Hampshire: The Journal of Geology, v. 108, p. 219–232, doi: 10.1086/314396.

Filer, J.K., 2002, Late Frasnian sedimentation cycles in the Appalachian basin: Possible evidence for high frequency eustatic sea-level changes: Sedimentary Geology, v. 154, p. 31–52, doi: 10.1016/S0037-0738(02)00159-8.

Flemings, P.B., and Jordan, T.E., 1989, A synthetic stratigraphic model of foreland basin development: Journal of Geophysical Research, v. 94, p. 3851–3866, doi: 10.1029/JB094iB04p03851.

Flemings, P.B., and Jordan, T.E., 1990, Stratigraphic modeling of foreland basins: Interpreting thrust deformation and lithospheric rheology: Geology, v. 18, p. 430–434, doi: 10.1130/0091-7613(1990)018<0430:SMOFBI>2.3.CO;2.

Friedman, G.M., 1998, Greenschist pebble in fluvial Catskill magnafacies of New York dates an Acadian event at Iapetus oceanic spreading center: Northeastern Geology and Environmental Sciences, v. 20, p. 145–156.

Gale, P.E., 1985, Diagenesis of the Middle to Upper Devonian Catskill Facies Sandstones in Southeastern New York State [M.S. thesis]: Cambridge, Massachusetts, Harvard University, 241 p.

Hamilton-Smith, T., 1993, Stratigraphic effects of the Acadian orogeny in the autochthonous Appalachian Basin, *in* Roy, D.C., and Skehan, J.W., eds., The Acadian Orogeny: Recent Studies in New England, Maritime Canada, and the Autochthonous Foreland: Geological Society of America Special Paper 275, p. 153–164.

Hanson, B., 1995, A Geochemical Study of Rhyolitic Melt Inclusions in Igneous Phenocrysts from Lower Devonian Bentonites [Ph.D. dissertation]: Albany, State University of New York at Albany, 470 p.

Hass, W.H., 1948, Upper Devonian bentonite in Tennessee: American Association of Petroleum Geologists Bulletin, v. 32, p. 816–819.

Heckel, P.H., 1973, Nature, Origin, and Significance of the Tully Limestone: Geological Society of America Special Paper 138, 244 p.

Heller, P.L., Beekman, F., Angevine, C.L., and Cloetingh, S.A.P.L., 1993, Cause of tectonic reactivation and subtle uplifts in the Rocky Mountain region and its effect on the stratigraphic record: Geology, v. 21, p. 1003–1006, doi: 10.1130/0091-7613(1993)021<1003:COTRAS>2.3.CO;2.

Hosterman, J.W., and Whitlow, S.I., 1983, Clay Mineralogy of Devonian Shales in the Appalachian Basin: U.S. Geological Survey Professional Paper 1298, 31 p.

House, M.R., and Kirchgasser, W.T., 1993, Devonian goniatite biostratigraphy and timing of facies movements in the Frasnian of eastern North America, *in* Hailwood, E.A., and Kidd, R.B., eds., High Resolution Stratigraphy: Geological Society of London Special Publication 70, p. 267–292.

Huff, W.D., Muftuoglu, E., Kolata, D.R., and Bergstrom, S.M., 1999, K-bentonite bed preservation and its event stratigraphic significance: Acta Universitatis Carolinae–Geologica, v. 43, p. 491–493.

Isachsen, Y.W., Landing, E., Lauber, J.M., Rickard, L.V., and Rogers, W.B., 2000, Geology of New York: A Simplified Account (second edition): New York State Museum Educational Leaflet 28, 294 p.

Johnson, J.G., 1971, Timing and coordination of orogenic, epeirogenic, and eustatic events: Geological Society of America Bulletin, v. 82, p. 3263–3298, doi: 10.1130/0016-7606(1971)82[3263:TACOOE]2.0.CO;2.

Johnson, J.G., Klapper, G., and Sandberg, C.A., 1985, Devonian eustatic fluctuations in Euramerica: Geological Society of America Bulletin, v. 96, p. 567–587, doi: 10.1130/0016-7606(1985)96<567:DEFIE>2.0.CO;2.

Jordan, T.E., 1981, Thrust loads and foreland basin evolution, Cretaceous, western United States: American Association of Petroleum Geologists Bulletin, v. 65, p. 2506–2520.

Jordan, T.E., and Flemings, P.B., 1991, Large scale stratigraphic architecture, eustatic variation, and unsteady tectonism: A theoretical evaluation: Journal of Geophysical Research, v. 96, p. 6681–6699, doi: 10.1029/90JB01399.

Kaufmann, B., 2006, Calibrating the Devonian time scale: A synthesis of U-Pb ID-TIMS ages and conodont stratigraphy: Earth-Science Reviews, v. 76, p. 175–190, doi: 10.1016/j.earscirev.2006.01.001.

King, P.B., 1951, The Tectonics of Middle North America: Princeton, New Jersey, Princeton University Press, 203 p.

Lucier, W.A., 1966, The Petrology of the Middle and Upper Devonian Kiskatom and Kaaterskill Sandstones: A Vertical Profile [Ph.D. thesis]: Rochester, New York, University of Rochester, 92 p.

Ludman, A., and Idleman, B., 1998, The Berry Brook gabbro; NW-most Siluro-Devonian mafic magmatism in the Coastal lithotectonic belt, Maine: Geological Society of America Abstracts with Programs, v. 30, no. 1, p. 58.

Matchen, D.L., and Kammer, T.W., 1994, Sequence stratigraphy of the Lower Mississippian Price and Borden Formations in southern West Virginia and eastern Kentucky: Southeastern Geology, v. 34, p. 25–41.

Miall, A.D., 1995, Collision-related foreland basins, *in* Busby, C.J., and Ingersoll, R.V., eds., Tectonics of Sedimentary Basins: Boston, Massachusetts, Blackwell Science, p. 393–424.

Mitrovica, J.X., Beaumont, C., and Jarvis, G.T., 1989, Tilting of continental interiors by the dynamical effects of subduction: Tectonics, v. 8, p. 1079–1094, doi: 10.1029/TC008i005p01079.

Murphy, J.B., and Keppie, J.D., 2005, The Acadian orogeny in the northern Appalachians: International Geology Review, v. 47, p. 663–687, doi: 10.2747/0020-6814.47.7.663.

Ogg, J.G., Ogg, G., and Gradstein, F.M., 2008, The Concise Geologic Time Scale: New York, Cambridge University Press, 184 p.

Osberg, P.H., Tull, J.F., Robinson, P., Hon, R., and Butler, J.R., 1989, The Acadian orogen, *in* Hatcher, R.D., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F2, p. 179–232.

Over, D.J., 2007, Conodont biostratigraphy of the Chattanooga Shale, Middle and Upper Devonian, southern Appalachian Basin, eastern United States: Journal of Paleontology, v. 81, p. 1194–1217, doi: 10.1666/06-056R.1.

Over, D.J., and Rhodes, M.K., 2000, Conodonts from the Upper Olentangy Shale (Upper Devonian, central Ohio) and stratigraphy across the Frasnian-Famennian boundary: Journal of Paleontology, v. 74, p. 101–112, doi: 10.1666/0022-3360(2000)074<0101:CFTUOS>2.0.CO;2.

Over, D.J., Reynolds, S.A., Rhodes, M.K., and Wichtowski, J.L., 1998, Conodonts, ash horizons, Kellwasser Intervals, high-energy events, and the Frasnian-Famennian boundary in the deep shelf and basin facies of the Appalachian Basin: Geological Society of America Abstracts with Programs, v. 30, no. 2, p. 66.

Pollack, J.M., 1961, Significance of compositional and textural properties of South Canadian River channel sands, New Mexico, Texas, and Oklahoma: Journal of Sedimentary Petrology, v. 31, p. 15–37.

Poole, W.H., and Rodgers, J., 1972, Appalachian geotectonic elements of the Atlantic provinces and southern Quebec, *in* Glass, D.J., 24th International Geological Congress, Guidebook to Excursion A-63-C63: Montreal, 200 p.

Puspoki, Z., Kozak, M., Kovacs-Palffy, P., Szepesi, J., McIntosh, R., Konya, P., Vincze, L., and Gyula, G., 2008, Geochemical records of a bentonitic acid-tuff succession related to a transgressive systems tract—Indication of changes in the volcanic sedimentation rate: Clays and Clay Minerals, v. 56, p. 23–38, doi: 10.1346/CCMN.2008.0560103.

Pysklywec, R.N., and Mitrovica, J.X., 1997, Mantle avalanches and the dynamic topography of continents: Earth and Planetary Science Letters, v. 148, p. 447–455, doi: 10.1016/S0012-821X(97)00045-9.

Quinlan, G., and Beaumont, C., 1984, Appalachian thrusting, lithospheric flexure, and the Paleozoic stratigraphy of the eastern interior of North America: Canadian Journal of Earth Sciences, v. 21, p. 973–996, doi: 10.1139/e84-103.

Rankin, D.W., 1968, Volcanism related to tectonism in the Piscataquis volcanic belt, an island arc of Early Devonian age in north-central Maine, *in* Zen, E-An, White, W.S., Hadley, J.B., and Thompson, J.B., Jr., eds., Studies of Appalachian Geology: Northern and Maritime: New York, Wiley Interscience, p. 355–369.

Rankin, D.W., and Hon, R., 1987, Traveler Rhyolite and overlying Trout Valley Formation and the Katahdin Pluton: A record of basin sedimentation and Acadian magmatism, north-central Maine, *in* Roy, D.C., ed., Geological Society of America Centennial Field Guide, Northeastern Section: Boulder, Colorado, Geological Society of America, p. 293–301.

Rankin, D.W., and Tucker, R.D., 1995, U-Pb age of the Katahdin-Traveler igneous suite, Maine, local age of the Acadian orogeny, and thickness of Taconian crust: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. 224.

Rast, N., and Skehan, J.W., 1993, Mid-Paleozoic orogenesis in the North Atlantic: The Acadian orogeny, *in* Roy, D.C., and Skehan, J.W., eds., The Acadian Orogeny: Recent Studies in New England, Maritime Canada, and the Autochthonous Foreland: Geological Society of America Special Paper 275, p. 1–25.

Rickard, L.V., 1975, Correlation of the Silurian and Devonian Rocks in New York State: New York State Museum Map and Chart Series 24, 16 p., 4 plates.

Rickard, L.V., 1989, Stratigraphy of the Subsurface Lower and Middle Devonian of New York, Pennsylvania, Ohio, and Ontario: New York State Museum Map and Chart Series 39, 59 p., 40 plates.

Riedel, J.L., Pringle, P.T., and Schuster, R.L., 2001, Deposition of Mount Mazama tephra in a landslide dammed lake on the upper Skagit River, Washington, USA, *in* White, J.D.L., and Riggs, N.R., eds., Volcaniclastic Sedimentation in Lacustrine Settings: International Association of Sedimentologists Special Publication 30, p. 285–298.

Robinson, P., and Tucker, R., 1996, The "Acadian" in central New England: New problems based on U-Pb ages of igneous zircon and metamorphic monazite and sphene: Geological Society of America Abstracts with Programs, v. 28, no. 3, p. 94.

Robinson, P., Tucker, R.D., Bradley, D.C., Berry, H.N., IV, and Osberg, P.H., 1998, Paleozoic orogens in New England, U.S.A.: GFF (Geological Society of Sweden Quarterly Journal), v. 120, p. 119–148.

Roden, M.K., Parrish, R.R., and Miller, D.S., 1990, The absolute age of the Eifelian Tioga ash bed, Pennsylvania: The Journal of Geology, v. 98, p. 282–285, doi: 10.1086/629399.

Rodgers, J., 1967, Chronology of tectonic movements in the Appalachian region of eastern North America: American Journal of Science, v. 265, p. 408–427.

Rodgers, J., 1970, The Tectonics of the Appalachians: New York, Wiley Interscience, 271 p.

Roen, J.B., and Hosterman, J.W., 1982, Misuse of the term "bentonite" for ash beds of Devonian age in the Appalachian basin: Geological Society of America Bulletin, v. 93, p. 921–925.

Rogers, W.B., Isachsen, Y.W., Mock, T.D., and Nyahay, R.E., 1990, New York State Geological Highway Map: New York State Museum Educational Leaflet 33, Plate 3.

Roy, D.C., and Skehan, J.W., eds., 1993, The Acadian Orogeny: Recent Studies in New England, Maritime Canada, and the Autochthonous Foreland: Geological Society of America Special Paper 275, 171 p.

Rust, B.R., Lawrence, B.A., and Zaitlin, D.A., 1989, The sedimentology and tectonic significance of Devonian and Carboniferous terrestrial successions in Gaspe, Quebec: Atlantic Geology, v. 25, p. 1–13.

Schruben, P.G., Arndt, R.E., Bawiec, W.J., King, P.B., and Beikman, H.M., 1994, Geology of the Conterminous United States at 1:2,500,000 Scale—A Digital Representation of the 1974 P.B. King and H.M. Beikman Map: U.S. Geological Survey Digital Data Series DDS-11, scale 1:2,500,000.

Scotese, C.R., and McKerrow, W.S., 1990, Revised world maps and introduction, *in* McKerrow, W.S., and Scotese, C.R., eds., Paleozoic Paleogeography and Biogeography: Geological Society of London Memoir 12, p. 1–21.

Shaw, G.J., 2003, Trace element chemistry of individual apatite phenocrysts as a tool for fingerprinting altered volcanic ash beds: Assessing interbed and intrabed variation at local and regional scales: Geological Society of America Bulletin, v. 115, p. 933–942, doi: 10.1130/0016-7606(2003)115<933:TECOIA>2.0.CO;2.

Shaw, G.J., Chen, Y.-A., and Scott, J., 1991, Multiple K-bentonite layers in the Lower Devonian Kalkberg Formation–Cobleskill, N.Y.: Geological Society of America Abstracts with Programs, v. 23, no. 1, p. A-126.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: American Association of Petroleum Geologists Bulletin, v. 74, p. 93–114.

Smith, G.J., and Jacobi, R.D., 1998, Fault-induced transgressive incised shoreface model for the Canadaway Group, Catskill delta complex: Journal of Sedimentary Research, v. 68, p. 668–683.

Smith, R.C., and Way, J.H., 1983, The Tioga ash beds at Selinsgrove Junction, *in* Nickelsen, R.P., and Cotter, E., eds., Silurian Depositional History and Alleghenian Deformation in the Pennsylvania Valley and Ridge: Danville, Pennsylvania, 48th Annual Field Conference of Pennsylvania Geologists, p. 74–88.

Smith, R.C., II, Berkheiser, S.W., Jr., and Way, J.H., 1988, The Bald Hill bentonite beds: A Lower Devonian pyroclastic-bearing unit in the northern Appalachians: Northeastern Geology, v. 10, p. 216–230.

Smith, R.C., II, Berkheiser, S.W., Jr., and Way, J.H., 2003, Bald Hill bentonites A, B, and C: History and new data since 1988, *in* Gold, D.P., Fleeger, G.M., and Way, J.H., eds., Geology of the Edge: Selected Geology of Bedford, Blair, Cambria, and Somerset Counties: Altoona, Pennsylvania, 68th Annual Field Conference of Pennsylvania Geologists Guidebook, p. 73–77.

Solar, G.S., Pressley, R., Brown, M., and Tucker, R.D., 1998, Granite ascent in convergent orogenic belts; testing a model: Geology, v. 26, p. 711–714, doi: 10.1130/0091-7613(1998)026<0711:GAICOB>2.3.CO;2.

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

Tucker, R.D., and 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, v. 102, p. 1404–1419, doi: 10.1130/0016-7606(1990)102<1404:AASOTB>2.3.CO;2.

Tucker, R.D., Bradley, D.C., Ver Straeten, C.A., Harris, A.G., Ebert, J.R., and McCutcheon, S.R., 1998, New U-Pb ages and the duration and division of Devonian time: Earth and Planetary Science Letters, v. 158, p. 175–186, doi: 10.1016/S0012-821X(98)00050-8.

Tucker, R.D., Osberg, P.H., and Berry, H.N., III, 2001, The geology of a part of Acadia and the nature of the Acadian orogeny across central and eastern Maine: American Journal of Science, v. 301, p. 205–260, doi: 10.2475/ajs.301.3.205.

van der Voo, R., 1983, Paleomagnetic constraints on the assembly of the Old Red continent: Tectonophysics, v. 91, p. 271–283, doi: 10.1016/0040-1951(83)90045-8.

van Staal, C.R., 2007, Pre-Carboniferous tectonic evolution and metallogeny of the Canadian Appalachians, *in* Goodfellow, W.D., ed., Mineral Resources of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods: Ottawa, Geological Association of Canada, Mineral Deposits Division, Special Publication 5, p. 793–818.

van Staal, C.R., Whalen, J.B., Valverde-Vaquero, P., Zagorevski, A., and Rogers, N., 2009, Pre-Carboniferous, episodic accretion-related, orogenesis along the Laurentian margin of the northern Appalachians, *in* Murphy, J.B., Keppie, J.D., and Hynes, A.J., eds., Ancient Orogens and Modern Analogues: Geological Society of London Special Publication 327, p. 271–316, doi: 10.1144/SP327.13.

Ver Straeten, C.A., 1996, Stratigraphic Synthesis and Tectonic and Sequence Stratigraphic Framework, Upper Lower and Middle Devonian, Northern and Central Appalachian Basin [Ph.D. thesis]: Rochester, New York, University of Rochester, 800 p.

Ver Straeten, C.A., 2004a, K-bentonites, volcanic ash preservation, and implications for Lower to Middle Devonian volcanism in the Acadian orogen, eastern North America: Geological Society of America Bulletin, v. 116, p. 474–489, doi: 10.1130/B25244.1.

Ver Straeten, C.A., 2004b, Sprout Brook K-bentonites: New interval of Devonian (early Emsian?) K-bentonites in eastern North America: Northeastern Geology and Environmental Science, v. 26, p. 298–305.

Ver Straeten, C.A., 2007, Basinwide stratigraphic synthesis and sequence stratigraphy, upper Pragian, Emsian and Eifelian Stages (Lower to Middle Devonian), Appalachian basin, *in* Becker, R.T., and Kirchgasser, W.T., eds., Devonian Events and Correlations: Geological Society of London Special Publication 278, p. 39–81.

Ver Straeten, C.A., 2008, Volcanic ash bed formation and condensation processes: A review and examination from Devonian stratigraphic sequences: The Journal of Geology, v. 116, p. 545–557, doi: 10.1086/591991.

Ver Straeten, C.A., 2009a, The classic Devonian of the Catskill front: A foreland basin record of Acadian orogenesis, *in* Vollmer, F.W., ed., New York State Geological Association Annual Fieldtrip Guidebook: New Paltz, New York State Geological Association, p. 7-1–7-54.

Ver Straeten, C.A., 2009b, Devonian T-R cycle Ib: The "lumping" of Emsian sea level history, *in* Over, D.J., ed., Studies in Devonian Stratigrapy: Proceedings of the 2007 International Meeting of the Subcommission on Devonian Stratigraphy and IGCP 499: Palaeontographica Americana, v. 63, p. 33–48.

Ver Straeten, C.A., and Brett, C.E., 1995, Lower and Middle Devonian foreland basin fill in the Catskill Front: Stratigraphic synthesis, sequence stratigraphy, and the Acadian orogeny, *in* Garver, J.I., and Smith J.A., eds., New York State Geological Association 67th Annual Meeting Guidebook: Schenectady, New York State Geological Association, p. 313–356.

Ver Straeten, C.A., and Brett, C.E., 2000, Bulge migration and pinnacle reef development, Devonian Appalachian foreland basin: The Journal of Geology, v. 108, p. 339–352, doi: 10.1086/314402.

Ver Straeten, C.A., and Brett, C.E., 2006, Pragian to Eifelian strata (middle Lower to lower Middle Devonian), northern Appalachian Basin—A stratigraphic revision: Northeastern Geology, v. 28, p. 80–95.

Ver Straeten, C.A., Griffing, D.H., and Brett, C.E., 1994, The lower part of the Middle Devonian Marcellus "Shale," central to western New York State: Stratigraphy and depositional history, *in* Brett, C.E., and Scatterday, J., eds., New York State Geological Association 66th Annual Meeting Guidebook: Rochester, New York State Geological Association, p. 270–321.

Ver Straeten, C.A., Ebert, J.R., Bartholomew, A., Benedict, L.J., Matteson, D.K., and Shaw, G.H., 2005, Devonian stratigraphy and K-bentonites in the Cherry Valley–Schoharie Valley region, *in* Rodbell, D.T., ed., Northeast Section Meeting Field Trip Guidebook: Boulder, Colorado, Geological Society of America, p. D1–D57.

Ver Straeten, C.A., Over, D.J., and Baird, G.C., 2007, Devonian K-bentonites and tuffs: A record of Caledonian magmatism from the Appalachian foreland basin (eastern U.S.): Geological Society of America Abstracts with Programs, v. 39, no. 1, p. 53.

Way, J.H., Smith, R.C., and Roden, M., 1986, Detailed correlations across 175 miles of the Valley and Ridge of Pennsylvania using 7 ash beds in the Tioga zone, *in* Sevon, W.D., ed., Selected Geology of Bedford and Huntington Counties: Huntington, Pennsylvania, 51st Annual Field Conference of Pennsylvania Geologists, p. 55–72.

Weaver, C.E., 1963, Interpretative value of heavy minerals from bentonites: Journal of Sedimentary Petrology, v. 33, p. 343–349.

Wilcott, M.J., and Over, D.J., 2005, Comparison of two Devonian ashes: Kashong-Windom boundary and lower Rhinestreet Shale, western New York State: Geological Society of America Abstracts with Programs, v. 37, no. 1, p. 73.

Wilson, R.A., 2004, Geology of the Campbellton area, northern New Brunswick: Atlantic Geoscience Society, Colloquium & Annual General Meeting: Moncton, New Brunswick, Atlantic Geoscience Society, Abstracts volume, p. 31.

Witzke, B.J., and Heckel, P.H., 1988, Paleoclimatic indicators and inferred Devonian paleolatitudes of Euramerica, *in* McMillan, N.J., Embry, A.F., and Glass, D.J., eds., Devonian of the World I: Canadian Society of Petroleum Geologists Memoir 14, p. 49– 63.

Woodrow, D.L., and Sevon, W.D., eds., 1985, The Catskill Delta: Geological Society of America Special Paper 201, 246 p.

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